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A holistic two-step decision-making process to optimise multiple objectives over various remanufacturing activities for automotive products

by

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A thesis presented in fulfilment of the requirement for the degree of Doctor of Philosophy
2020

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Acknowledgements

I am deeply grateful for the work of the members of the Department of Design, Manufacturing and Engineering, each of them provided me with invaluable guidance and support during my PhD experience. I would like to thank Dr. Winifred L. Ijomah, my first supervisor. Without her mentoring, insights, support and encouragement, this thesis would not have been achieved. I am also indebted to Dr. Andy Wong, my second supervisor, for his tireless efforts to teach and mentor me during the process. I also want to thank my Thai government for providing me with financial support to graduate from the University of Strathclyde. I am very grateful to all the interviewees for their information and for the time they spent to involve in my research, though all of them had a busy schedule. I would also like to thank my friends for their inspiration and encouragement that allowed me to remain concentrated and motivated during my project. Last but not least, I want to thank my parents and my brother, who have loved me and encouraged me to do the best over time.

List of Abbreviations

ACSA	An ant colony search algorithm
AHP	Analytical hierarchy process
ADM	Additive manufacturing
ANP	Analytic Network Process
CBR	Case-based reasoning
CC	Cases with component commonality
DET	Detectability
DTO	Disassembly-to-order
ELECTRE	Elimination et choice translating reality
ELV	End-of-life vehicles
EOL	End-of-Life
ERP	Enterprise resource planning
FMEA	Failure mode and effects analysis
GA	Genetic algorithm
GRA	Grey Relational Analysis
HALG	Hierarchical attributed liaison graph
HR	Heuristic
ICA	Improved co- evolutionary algorithm
IR	Independent remanufacturer
LCA	Life cycle assessment
MCDM	Multi-criteria decision making
MILP	Mixed integer linear programming
MINLP	Mixed integer non-linear programming
MIP	Mixed integer programming
MMRP	Modified materials requirements planning
MRP	Material requirement planning
MSD	Multi-period stochastic dynamic program
MTO	Make-to-order
NCC	Cases without component commonality

NN	The nearest neighbourhood algorithm
NP	Non-linear programming
OC	Optimal control
OCC	Occurrence
OER	Original equipment remanufacturer
PESTEL	Political, economic, societal, technical, environmental and legal aspects
PHM	Proportional hazard model
POM	Production and operations management
PROMETHEE	Preference ranking organization method for enrichment of evaluations
RMRP	Reverse material requirement planning
ROP	Reorder point
RPN	Risk priority number
SJR	SCIMAGO journal ranking
SLR	Systematic literature review
TOPSIS	Technique of order preference similarity to the ideal solution
TRIZ	Theory of inventive problem solving

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Abstract

Remanufacturing is the process which used products are reworked to at least to as new condition and are given at least the same guaranty as equivalent new products. Remanufacturing is the most effective process among other recovery options because it can bring economic benefits and positive environmental impacts. Decision-making in the remanufacturing industry is more complicated than conventional manufacturing due to uncertainties of quality, quantities and return time of used components. Previous studies have developed numerous strategies for optimising remanufacturing outcomes. However, there is a lack of research to study integrated decision-making over multiple remanufacturing activities with consideration of under-studied factors. A decision made at one remanufacturing activity would significantly impact the decisions made in subsequent activities, which will affect remanufacturing outcomes. Also, tacit knowledge is not enough for making decisions since companies always have new threats or opportunities.

Therefore, this study developed a systematic and holistic way to integrate different decisions over multiple remanufacturing activities to make better decision-making and improve remanufacturing outcomes. This research studied the two-step decision-making to select the best recovery options and to find the optimal number of components/products in each remanufacturing activity. This study used case studies and mathematical modelling to enhance the ability to research various perspectives. This can lead to a higher quality of the decision model which is the research output.

This first step of the decision model revealed whether additive manufacturing is a suitable recovery option in several scenarios by considering four objectives: maximising profit, minimising time, maximising recovered mass and maximising the reliability of components. This enhanced effectiveness of decision making because of the ability to assess a greater number of options properly. This research finding will help remanufacturers to find new business opportunities by increasing the ability to recover automotive components such as crankshafts.

The second step of the decision model can provide remanufacturing companies with material planning. The optimisation objectives of the model are maximising profit, minimising time or both. The findings from the sensitivity analysis contribute to the literature and real practice by quantifying and controlling the impact of component commonality on the objectives under various reworking scenarios defined by the percentage of reworked components, reworking time, and reworking cost.

Chapter 1 Introduction

1.1 What is Remanufacturing?

Remanufacturing is a process which enables used products to have a like-new functionality with as-new warranty (BSI, 2009, Ijomah, 2002). The remanufacturing process includes disassembly, cleaning, inspection and sorting, reworking, components' replacement, reassembly and testing (Parkinson and Thompson, 2003). However, there is misunderstanding of the meaning of remanufacturing. Remanufacturing tends to be mistaken for recycling, reusing or reconditioning. Customers perceive remanufactured products as second-hand products with lower quality than new products.

The Definitions of other End-of-Life (EOL) options are shown as follows:

1. Reconditioning is the process to enable used products to acquire an acceptable standard but not a like-new condition. Warranties usually cover only major wearing components (Ridley, 2013).

2. Refurbishment is the process to rebuild used products or components to be under acceptable working conditions. The quality and warranty of refurbished products may not be equal to new products (Ridley, 2013).

3. Repairing is the process to rectify specific faults of products. Its warranty covers only those parts which have been attended to (Ijomah et al., 2004).

4. Reuse is the process to use original products several times without changing their original purpose (Ridley, 2013).

5. Cannibalization is the process to remove a functional component from an unserviceable component to replace an unserviceable component in a serviceable component (Corps, 1998).

6. Recycling is the process to convert waste into reusable material.

Remanufacturing is the most effective process among other recovery options because it can lead to economic benefits and positive environmental impacts. The price of remanufactured products is typically 30-40% of the price of new products (Mukherjee and Mondal, 2009). Remanufacturing has the potential to help manufacturers to reduce waste, manufacturing cost, disposal cost and energy usage. Manufacturers can save about 50% of the total cost, 60% energy, and 70% of materials on that of new products when they use remanufactured products (Xu et al., 2012). According to Liu et al. (2014) and Sutherland et al. (2008), a remanufactured engine consumes only 25 % of the energy consumption for the production of a new engine and remanufacturing one engine could save 5480 Mega Joule (Peng et al., 2019). It is also stated by the Scottish Institute For Remanufacture (2016) that remanufacturers can reduce energy usage by 50% to 80% compared with new production.

Although remanufacturing is an efficient process, not all goods can be remanufactured. A remanufacturable product should not have these characteristics: non-consumable products, easy to find available components at a reasonable price, and slow product obsolescence (Parkinson and Thompson, 2003).

1.2 Challenges in remanufacturing

Remanufacturers confront challenges in their production planning and control which can be categorised into specific characteristics according to Guide (2000), Ian et al. (2015), Rajagopalan(2002) and Kshonze and Okulicz (1998).

1. The uncertainty considering timing and number of returned products.

It is challenging to forecast the availability of cores (used products) for industries. Moreover, it is difficult to balance ‘make to order’ and ‘make to stock’ policy (Rajagopalan, 2002, Ian et al., 2015).

2. The ability to balance returned products with demand.

The uncertainty of product demand may lead to challenges in price setting and inventory keeping. If dismantled components are not utilized in the remanufacturing process, They will be kept in store as inventory and used when the opportunity arises Hence, this uncertainty influences stock level management (Ian et al., 2015).

3. The uncertain recovery rate of return products.

Products can be arrived often or arrived very infrequently. These characteristics have an effect on purchasing lots. For example, remanufacturers may take long lead times to find suitable cores when they require specific cores (Guide, 2000).

4. The need for reverse logistics.

This describes how products are gathered from end-users to remanufacturers. The decision making involves a number of locations of return-back centres, the incentive to return products, transportation alternatives and third-party providers (Guide, 2000).

5. The difficulty of material matching.

In some industries with MTO (make-to-order) products, such as copiers and network equipment, the customers hold ownership of the products and require the same specific components returned to them (Guide, 2000). If the lead time of production planning is short, it is expensive to get the replacement components because of short notices. Purchasing new components for the small batch is expensive. Also, each remanufactured product consists of common components and specific components with serial numbers. This leads to complicated resource planning and material management. There is complexity and uncertainty in remanufacturing, especially in engine remanufacturing. A remanufacturer has to follow set standards to substitute remanufactured components which are undersized or oversized to assemble engines. This method results in wide variations since each component of the batch requires different compensations (Kshonze and Okulicz, 1998).

6. The uncertainty of material's routing.

Uncertain routing is a result of the uncertain condition of returned products. Uncertainty in remanufacturing is higher than that in conventional manufacturing. Disassembly of each product varies which leads to complex resource planning, scheduling, shop floor control and material management (Guide, 2000).

7. The uncertainty of processing times.

Because it is difficult to discover defects before the disassembly, cleaning and inspection processes, it takes more time to repair and replace components, which can cause penalty costs and higher operation costs (Ian et al., 2015).

1.3 Type of remanufacturers

There are three types of remanufacturers consisting of the original equipment remanufacturer (OER), the independent remanufacturer and the contract remanufacturer (Lund T., 1984).

The OER produces and trades not only new products but also remanufactured products. Some OERs lease products rather than sell them. An independent remanufacturer buys flawed products and remanufactures them that they did not manufacture or design. The contract remanufacturer remanufactures products under contract with the OEMs who will own the title of the product.

1.4 Remanufacturing activities

Remanufacturing consists of seven key activities to turn cores into remanufactured products/components including core acquisition, disassembly, cleaning, inspection, reworking, reassembly, and testing (Ijomah, 2002) as seen in Figure 1.1.

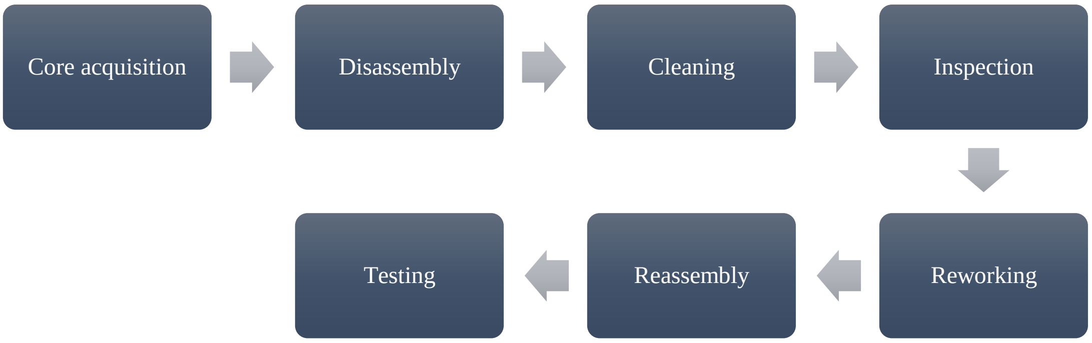


Figure 1.1 Seven key activities in remanufacturing

According to the British Standard (PAS 3100:2014) for remanufactured automotive components, the specifications for activities in the process control system, can be defined as:

1. Core acquisition is the activity that sorts and pre-assesses all received cores and identifies and stores suitable cores to maintain adequate numbers for remanufacturing.

2. Disassembly is the activity that disassembles cores to component level.

3. Cleaning is the activity to provide cleaning of disassembled components by washing, media cleaning or buffing.

4. Inspection is the activity to examine components to confirm suitability.

5. Reworking is the activity to improve faulty components through machining, polishing or adding material to maintain the quality, strength and function of the component.

6. Reassembly is the activity to assemble components to produce remanufactured products.

7. Testing is the activity to test products after final assembly to ensure the acceptability of the product’s characteristics.

1.5 Material planning in the remanufacturing industry

This research was inspired by Östlin et al. (2008) who described three decision-making points during 5 remanufacturing activities as illustrated in Figure 1.2. Table 1.1 shows the three decision-making questions defined by Östlin et al. (2008).

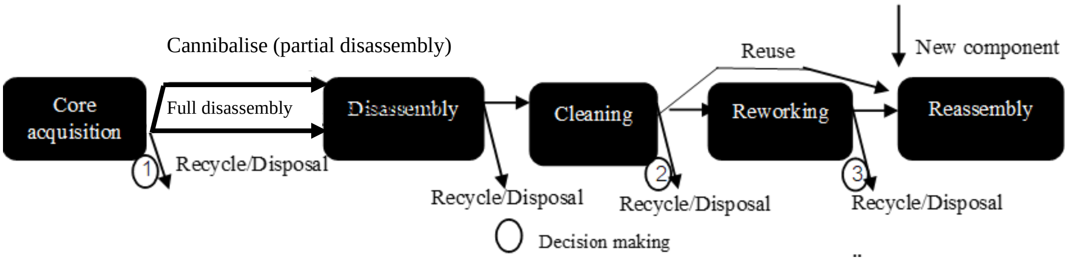


Figure 1.2 Selection of EOL options for different remanufacturing activities (Östlin et al. 2008)

Table 1.1 Decision making during multiple remanufacturing activities

(Östlin et al. , (2008)

Decision-making questions	1. What should be done with pre-disassembled cores?	2. What should be done with components after disassembling cores?	3. Which components can be reassembled into products?
Alternatives	full disassembly for remanufacturing, cannibalising or recycling core	reuse, rework or recycle components	reused components, reworked components or new components
Factors used in decision-making	• Core acquisition cost • Potential cost for disassembly, reworking, reassembly, new components • Inventory levels and value of components • Future needs • Required quality level	• Potential cost for reworking and new components • Inventory levels and value of components • Lead time to rework or to buy new components • Future needs • Required quality level	• Inventory level and value of components • Lead time of reprocessed components or new components

Planning at aggregate level is on how to balance demand and supply of products while material planning depends on the uncertain quantity of recovered components from returned cores. Therefore, components used in reassembly are categorised into 4 types (Östlin et al. (2008) as follows:

1. Components that are usually replaced.

Some automotive components, such as sealing and pistons, are usually recycled without disassembly and replaced with the new components since they are too worn to reuse again (Ridley, 2013).

2. Components that can be either reused or reprocessed.

   Some of the automotive components are always remanufactured and reused including clutches, brake shoes, engine blocks, starters, alternators, water pumps, and carburetors(Kutz, 2006) Unusable components that can be ordered before the reassembly date.

3. Unusable components that need to be ordered by forecasting.

   The decision sequence to plan material at the component level is shown in Figure 1.3. The usually replaced components are ordered after needs are confirmed. Then, components are reused if they can be reused or reworked within the lead time. If they cannot be reused, it is necessary to purchase new ones. If the demand for new components can be confirmed within the order lead time, the remanufacturers will order them after inspection. If new components cannot be ordered within the lead time, then the new components are typically ordered based on forecasts.

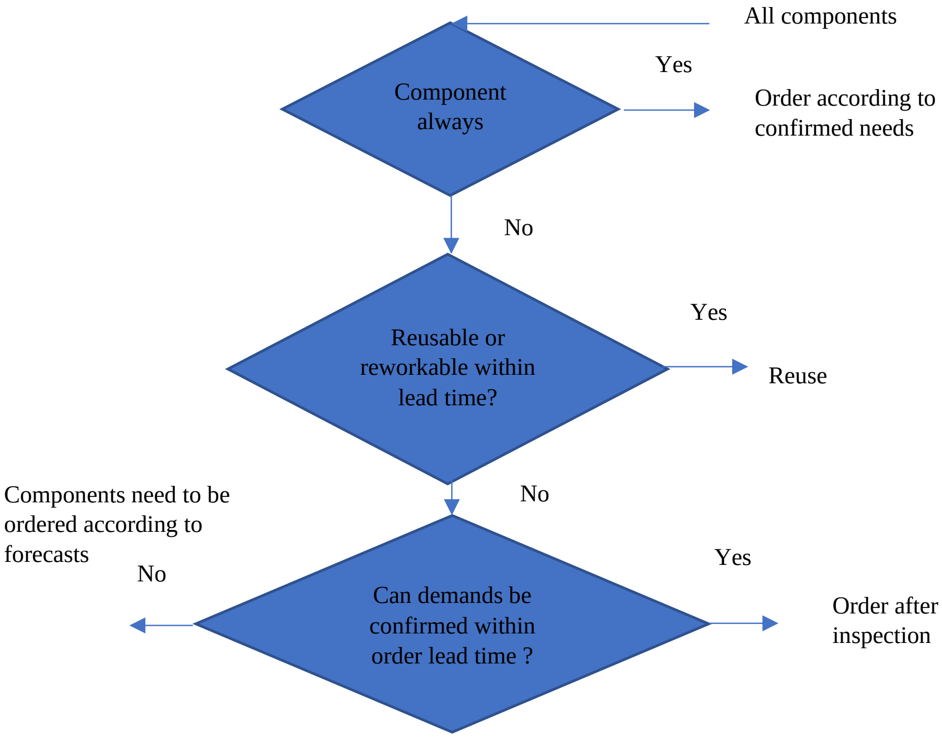


Figure 1.3 The decision sequence to plan material at the component level (Östlin et al., 2008)

If components are held for too long, they can generate unnecessary inventory costs. Well-organized planning and control of inventory can mitigate this issue. One tool called ‘AC analysis’ can group components into categories depending on their importance. In general, a minority of components account for the majority of product value. These important components require special control. AC analysis which depends on component value and usage rate was used in make-to-order policy (Hautaniemi and Pirttilä, 1999). The components with low value and low usage rate are categorized into C-type components while the rest are grouped into A-type components. Reorder Point (ROP) is usually used to manage Type C components while the inventory management of Type A components depends on their lead time compared to the final assembly schedule and the demand distribution pattern.

Since some components need to be replaced, this can lead to some problems (Östlin et al., 2008): (1) long lead times in purchasing products, (2) lack of suppliers for specific components, (3) invisibility of components requirement, (4) unresponsive vendors because purchase quantities are lower than minimum purchase requirements, and (5) lack of components available in production. However, the operators can mitigate the severity of problems by using a well-organized remanufacturing schedule (Daniel et al., 2000). In order to handle these problems, the most common methods are reorder point, Kanban and Material Requirement Planning. Reorder Point (ROP) is one of the most common principles since it is a simple method. When an inventory level is lower than a reorder point (r), a new lot-size (Q) is ordered (Axsäter and Rosling, 1994). MRP is a fixed planning horizon of periods which is based on external demand for each period, the lead time, safety stock of the item and the order quantity (Axsäter and Rosling, 1994). The control policy for different types of products (Östlin et al., 2008) is shown in Table 1.2.

Table 1.2 The control policy for different types of products (Östlin et al., 2008)

	Group 1 low demand high value	Group 2 high demand high value	Group 3 low demand low value	Group 4 high demand low value
Control	Manually influenced, based on MRP	MRP based on forecast	Reorder point	Reorder point
Control Priorities	Reduce obsolescence, order quantities, cannibalisation	Precise order quantities, effective safety stocks, forecasting, supplier collaboration	Reduce material handling and inventory cost, cost-effective control, stockout costs	Stockout costs, safety stock, cost-effective control

Although Östlin et al.,'s model (2008) covered integrated processes in remanufacturing, the model is generic and cover only the breadth of cases by using qualitative methodology. The framework may lack the depth of information for a specific industry. For example, it did not consider component commonality in any decision-making points. Component commonality is an important consideration for the automotive remanufacturing industry since it can increase the reusability of cores. Therefore, this thesis will aim to fill these gaps by using a mixed methodology (qualitative and quantitative methodology) to obtain a better understanding of the decision-making framework of the automotive remanufacturing industry.

1.6 Decision-making to optimise remanufacturing outcomes

This research developed the decision-making framework on how to optimise remanufacture profit, remanufacturing time, remanufacture reliability and reusable mass of components in the automotive remanufacturing.

Decision-making about each remanufacturing activity will affect succeeding remanufacturing activities (Sitcharangsie et al., 2019). Decision-making becomes even more complex when considering the decision factors associated with each single activity and the correlation between these decision factors across multiple activities simultaneously. Inspection and testing were not examined in this study since remanufacturers have no alternative but to follow OEMs specifications to operate full processes of inspection and testing to guarantee the quality of remanufactured products. Also, cleaning was not considered in this research since the PhD has finite duration and resource (personnel, money). Further research could extend your work by including cleaning because of its importance. Hence, the scope of this review will only cover four remanufacturing activities as shown in Figure 1.4. which shows major decisions across different remanufacturing activities. It should be noted that some decisions can be made for a single activity while others can be made over two or more activities.

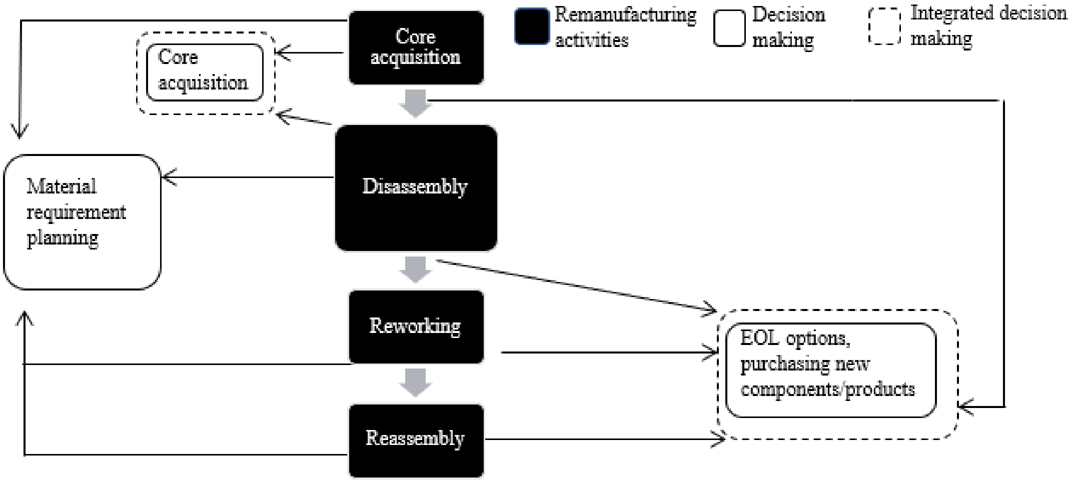


Figure 1.4 Streams of decision-making regarding remanufacturing activities

Over the past few years, various methods for optimising remanufacturing outcomes have been developed to make decisions such as identifying the best End-Of-Life (EOL) options, acquiring the right amounts of cores, applying suitable cleaning techniques, and considering component commonality across different product families. The scope of this study will cover 3 such decisions: the best End-Of-Life (EOL) options, acquiring the right amounts of cores, and planning components with the consideration of component commonality

1.6.1 End Of life (EOL) options

Since not all used products/components can be remanufactured, other EOL options are considered. According to Östlin (2008) regarding common practices in remanufacturing, the selection of EOL options can be made for remanufacturing activities as shown in Figure 1.2. EOL options can be determined before and after disassembly, after cleaning, during and after reworking and during reassembly. While the common EOL options considered are reuse, remanufacture, recycling and disposal, other EOL options mentioned in the literature include reconditioning, replacement, repair, salvage, incineration, reuse and cannibalisation as can be seen in Table 1.3.

Table 1.3 Other EOL options discussed in the literature

Other EOL options	References
Reconditioning	(Jun et al., 2007), (Shokohyar et al., 2014), (Yang et al., 2015)
Refurbishment	(Meng et al., 2017b), (Mashhadi and Behdad, 2017), (Ziout et al., 2014)
Repair	(Qian et al., 2015),(Qian et al., 2015), (Liu et al., 2016), (Liu et al., 2016), (Ziout et al., 2014)
Salvage	(Pazoki and Abdul-Kader, 2016), (Steeneck and Sarin, 2017)
Incineration	(Ziout et al., 2014), (Chan, 2008), (Bufardi et al., 2004)
Cannibalisation	(Karaulova and Bashkite, 2016), (Wadhwa et al., 2009)

1.6.2 Acquiring the optimal number of cores

Core acquisition is an activity to balance the demand and return of cores by considering the quantities, return timing and quality of the cores (Wei et al., 2015). Core acquisition usually occurs in pre-disassembly but can also be considered during disassembly. This is because remanufacturers usually have more information about the condition of cores after disassembling and they can then decide if new cores are needed.

1.6.3 Planning for required material by considering component commonality

In remanufacturing, material requirement planning (MRP) considers the unpredictable reusability of components from cores and the uncertain processing times of each activity during remanufacturing (Depuy et al., 2007). Therefore, MRP in remanufacturing is more complex than that of traditional manufacturing. Component commonality can offer companies numerous advantages. Remanufacturers can sell more products to obtain high revenues if different types of products require standardised components. Moreover, the operators are familiar to remanufacture the same standardized components with specific tools. Although considering component commonality is beneficial in terms of economic and environmental perspectives for material planning, it usually complicates the planning decisions in remanufacturing and makes it difficult to calculate the optimal number of used products to fulfil the demand for components because these components can be sourced from different used products or need to use different routings.

1.7 Significance of this research

There is an increasing environmental awareness in the industry. For example, the End of Life Vehicles (ELV) Directive of the European Union (EU Directive 2002/ 525/EC) sets targets for reuse, recycling, and recovery of vehicles. Manufacturers need to extend the products' lifecycles in an environmentally friendly manner. Therefore, decision-making on recovery options such as reuse, recycling or remanufacturing is an important research area.

Decision-making for the remanufacturing industry is more complex than for traditional manufacturing since there are uncertainties regarding quality, quantities and return timing of used components. Making such decisions becomes a complex process with regard to balancing the utilization of recovered components and purchasing new required components. This study focused on the automotive remanufacturing industry since the automotive industry is the most dominant target of remanufacturing in the world, which accounts for two-thirds of remanufacturing business (IRMA, 2019). Also, due to that nature of automotive products, for example they contain recoverable materials with complex bill of materials, it is also a significant area to study.

A simple judgment concerning recovery options can be made if the component is not within the specification range, as it should be replaced. However, the judgement to recover may not be sound if the component is closer to the lower limits of specifications since after recovery the remaining life of the component would not be long enough to justify the recovery cost. Also, new recovery options such as additive manufacturing can increase the capability to recover components beyond their existing capability. Most decisions on recovery options are based on tacit knowledge which may lack accuracy.

Over the past few years, various methods of optimising remanufacturing outcomes have been developed to make decisions such as identifying the best recovery options, acquiring the right amounts of cores, and considering component commonality across different product families. A decision on one remanufacturing activity will greatly affect the decisions on subsequent activities, which will affect remanufacturing outcomes, i.e. productivity, economic performance, effectiveness, and the proportion of cores that can be salvaged.

Therefore, a systematic and holistic way of integrating different decisions over multiple remanufacturing activities is needed to improve remanufacturing outcomes, which is currently a major knowledge gap.

1.8 The domain of the research

The research is in the field of Production and Operations Management (POM) because it is the integration of processes, operational decisions, company policies and technologies to maximise the effectiveness of a company (Voss et al., 2002). Also, all cases being investigated are in the UK automotive remanufacturing industry.

1.9 Research aims and objectives

This research aim is to provide a systematic and holistic decision making to optimise automotive remanufactured products.

In order to achieve the research aim, this research has the six following objectives:

1. To understand remanufacturing and review existing decision-making in remanufacturing from research papers and the industry and find the knowledge gaps between existing models and real practice.

2. To develop a decision-making framework on how to optimise automotive remanufactured components.

3. To develop a mathematical model to select the best recovery options for used products and components.

4. To develop a mathematical model to find the optimal number of components/products for each remanufacturing activity.

5. To conduct a sensitivity analysis about reworking costs, reworking time, percentage of reworked components and component commonality patterns which affect the profits of the remanufacturing business.

6. To validate the model by using expert review of the findings.

1.10 Research questions

After reviewing the literature and conducting a critical analysis, the research gaps were identified. In order to fulfil those gaps, six research questions are proposed. Chapter 2 will provide further details on how these research questions have been formed from the literature review. The six research questions are:

- What are the factors affecting decision-making in remanufacturing?
- What are the decision sequences?
- What are the possible recovery options for components from different automotive remanufacturing companies?
- How can we select the best recovery options for components with specific faults?
- How can we find the number of required components/ products for each of the activities in remanufacturing?
- How do reworking costs, reworking time, percentage of reworked components and component commonality patterns affect the remanufacturing business?

1.11 The deliverables of the research

The principal deliverables of the research were:

1. An integrated decision-making framework to optimising remanufacture profit, remanufacture time, remanufacture reliability and reusable mass of automotive components in the remanufacturing.

2. A mathematical model for selecting the best recovery option for components with specific faults.

3. A mathematical model for finding the optimal number of components/products for each of the remanufacturing activities.

4. A sensitivity analysis of reworking costs, reworking time, percentage of reworked components and component commonality patterns which affect the profits of the remanufacturing business.

1.12 Contribution to knowledge

This research can contribute to several areas of knowledge. These will be demonstrated in Chapters 4 – 6.

1.12.1 The novelty of the research

This study is the first contribution to knowledge regarding the following areas:

The novelty of the research	Chapter 4	Chapter 5	Chapter 6
• This research studied and developed, for the first time showing how to integrate different decisions over multiple remanufacturing activities to improve remanufacturing outcomes. Recovery options were mostly considered together with either disassembly or purchasing new orders in previous studies. While this is the first research study the integration of the optimal number of components/products for each of the remanufacturing activities and recovery options.	✓		
• A holistic enhanced framework considered under-studied factors in the decision-making of remanufacturing. The first step of the decision model is about selecting the best recovery options for components. The second step of the decision model is about finding the number of required components/ products for each remanufacturing activity. The first step of decision model considered reusable mass of component which is an under-studied factor. The second step of decision model considered availability, demand, quantity of components/products, component commonality and which are under-studied factors.		✓	✓

The novelty of the research	Chapter 4	Chapter 5	Chapter 6
• A framework enables economic, engineering and environmental objectives to for the first time, be considered simultaneously in the decision-making.		✓	
• This study can solve current issues which can be added to the existing knowledge. This research studied optimising used components at each level of their failure by selecting the best recovery options. This research is novel since it compared existing recovery options (e.g. replacement and re-machining) and new recovery options (e.g. additive manufacturing) for the crankshaft which is a common and expensive component in the automotive remanufacturing industry. Additive manufacturing is a new and popular method in the industry which could possibly exceed the current recoverability of crankshafts. This model showed whether such additive manufacturing is the most suitable recovery option or not. This knowledge will help remanufacturers to increase the reusability of crankshafts which could lead to increased profit of the remanufacturing companies.		✓	
• Insights from the sensitivity analysis of the second stage of the decision model contribute to the literature through the quantifying and controlling of the effect of component commonality on the objectives under different reworking scenarios. These scenarios are characterised by the percentage of reworked components, reworking time and reworking cost. If reworking costs and the percentage of reworked components increase, the effect of the component commonality on profit fluctuation increases. These circumstances can be controlled by reducing reworking costs, selecting specific patterns of component commonality that generate high profits, or choosing the suitable percentage of reworked components depending on different scenarios.			✓

1.12.2 Uniqueness of the research

This study uses new approaches to solve the similar problems identified by previous studies. Different data collection and analysis can make a difference which can be added to the body of knowledge.

Uniqueness of the research	Chapter 4	Chapter 5	Chapter 6
• Previous work about decision-making in remanufacturing were conducted by either qualitative or quantitative approaches. This research is unique since it was conducted by a mixed-method approach.	✓	✓	✓
• All the research studied in the field used mixed-integer linear programming to optimise the remanufacturing plan for product families. This is the first study additionally conducted a sensitivity analysis of the percentage of reworked components, reworking time, reworking costs and component commonality which may affect remanufacturing profits .			✓

1.13 Research Beneficiaries

The output of this research is beneficial not only for academia but also the industry. The academic beneficiary is new knowledge about decision-making in remanufacturing which can be used in further research. The industry will gain a systematic and holistic decision-making framework which will integrate different decisions over multiple remanufacturing activities to improve remanufacturing productivity.

1.14 Thesis Structure

Chapter 1 Introduction

This chapter briefly describes the concept of remanufacturing, the challenges of remanufacturing, the type of remanufacturers, remanufacturing activities, decision-making to optimise remanufacturing outcomes, the significance of the research, new research approaches, research aims and objectives and the beneficiaries of the research.

Chapter 2 Literature review

This chapter reviews the literature on how to optimise remanufacturing outcomes and the methodology used in decision-making.

Chapter 3 Research design

This chapter describes the research design. It first discusses how and why a mixed methodology (quantitative and qualitative methodology) approach has been selected by complementing the philosophical concept of the research. The ontology of the research directed the research design, data collection, interpretation method and how to present and validate the research findings.

Chapter 4 Factors used in the decision-making of the automotive remanufacturing

This chapter identifies the factors used in the decision-making of the automotive remanufacturing. The chapter begins with the preliminary factors from the literature review and the empirical study. Then the results are compared between the existing literature and findings from case studies. Finally, the factors are refined into 10 final lists which are used in the decision-making framework.

Chapter 5 Decision-making Step 1

This chapter is about selecting the best recovery options for components with specific faults. This chapter begins with a mathematical formulation. Then the model is tested with numerical examples to find the best recovery options depending on different situations. The last section of this chapter discusses the validation of the decision-making model Step 1.

Chapter 6 Decision making Step 2

This chapter is about developing a model to find the number required components/ products for each remanufacturing activity. The chapter starts with the model description and mathematical formulations. Then the optimisation results are shown. Next, a sensitivity analysis about reworking costs, reworking time, percentage of reworked components and component commonality patterns which affect the profit of remanufacturing business are studied. The last section of this chapter discusses the validation of the decision-making model Step 2.

Chapter 7 Conclusion

The final chapter of the thesis summarises the key findings of the research and how this research achieved its goal. It also discusses the limitations of the research and further research in the future.

1.15 Summary of Chapter 1

This chapter has introduced the concept of remanufacturing, remanufacturing problems, types of remanufacturers, remanufacturing activities, decision - making to maximise remanufacturing outcomes, the importance of research. The chapter also presented research aims and objectives and identified the deliverables and originality of the research. The next chapter will determine the findings of a literature review.

Chapter 2 Literature review

This research used not only a systematic literature review (SLR) but also rapid reviews to review the literature. Although a systematic literature review (SLR) is an acceptable academic review method to cover all possible relevant literatures, it always takes many months, or even years, to produce results (Higgins and Cochrane Collaboration, 2019, Reidenbach, 2011). Therefore, this research also adopted rapid reviews to review the literature. Rapid reviews are used to answer specific questions in a shorter time with fewer resources than SR (Featherstone, 2015). The topics reviewed by this research are divided into two main areas: 1. Decision-making to optimise products and components in remanufacturing; 2. Tools and techniques used in decision- making in remanufacturing and end-of-life options.

2.1 Decision makings to optimise products and components in remanufacturing

2.1.1 Review Methodology

In order to obtain a better understanding of the key decisions made to optimise products and components in remanufacturing, five automotive remanufacturing companies were visited and a literature review was carried out. These companies included one independent remanufacturer, three contract remanufacturers and one OER (original equipment remanufacturer) which are the three typical types of remanufacturers. To be specific, three companies were specialists in engines, one in transmissions and one in the diesel injection systems. The components produced by these five companies are the most commonly remanufactured components in the automotive sector. To conduct the literature review, the authors adopted the three stages recommended by Sánchez-Meca (2010) and Suárez et al. (2017), which are: 1. formulation of the problem 2. criteria for inclusion and exclusion of articles and 3. the search and selection of articles.

2.1.1.1 Formulation of the problem

The first procedure was to identify the questions which would provide the answers required by this study. These research questions are as follows:

1. What are the key decisions made in remanufacturing?
2. What are the under-studied factors for each major decision?
3. What future research methods should be applied for each major decision?
4. What knowledge gaps are there in the multiple decisions across multiple remanufacturing activities?

2.1.1.2 Criteria of inclusion and exclusion of articles

This procedure is to set the same search protocols for all the papers included in order to guarantee the consistency of the search results. The following criteria were used:

- Temporal scope: This study was conducted during March 2018. The selected papers cover the period from 1996 to 2018.
- Research quality: In order to cover all the relevant and qualified evidence, the selected articles were papers written in the first two quarters (Q1 and Q2) chosen by SJR (SCIMAGO journal ranking) or review articles cited by the articles from Q1 and Q2. SJR (SCIMAGO journal ranking) is an alternative method of checking the quality of papers because SJR shows a larger collection of journals and includes open access papers (Falagas et al., 2008). Also, SJR depends on the prestige of the cited journals over a period of three years(Suárez et al., 2017). It has been recommended to select the suitable papers from Q1 which includes the top 25% cited journals (Bornmann and Marx, 2014, Bornmann and Williams, 2017) . Therefore, the first two quarters (i.e. Q1 and Q2) of the highest ranking journal papers were chosen to include a greater number of eligible papers than those obtained by the previous method. The second type of articles included were review articles since analysing review articles can provide an overview of areas of interest (Featherstone, 2015). Although the review article are excluded by the SJR, it is cited in the top 50% cited journals as shown in Table 2.1. Also, additional relevant papers were found from the review article. These additional relevant papers are in Q1 or Q2 which helped to guarantee the research quality.
- Area of knowledge: After reviewing the literature and visiting the five automotive remanufacturing companies, the authors found that the main decisions are based on the identification of the best End-Of-Life (EOL) options, acquiring the right amounts of cores, and Material requirement planning (MRP) with the consideration of component commonality in remanufacturing.
- Publication language: Papers not written in English were excluded.

2.1.1.3 Article search and selection

This procedure shows how this study selected articles to fulfil the criteria from section 2.1.1.2. The procedure is divided into two methods: traditional SLR (systematic literature review) and an additional method.

Firstly, traditional SLR was conducted in this study since this method is acceptable for a wide range of academic research areas. SLR includes or excludes criteria from its search terms and shows how to check the quality of sources (Morgan and Gagnon, 2013, Merli et al., 2018). Three well-known databases, Scopus, Web of Science and ScienceDirect, were used in order to cover multi-disciplinary areas. By using the SJR assessment, the first two quarters of the highest-ranking journal papers were chosen by searching the keywords. The keywords used for making decisions are shown in Figure 2.1. Then, abstracts of all the papers selected from the SLR were read. Subsequently, a complete analysis was conducted of all relevant papers and duplicate papers were omitted.

After the traditional SLR, further steps were employed to identify any additional review articles since SLR may not include all the necessary evidence. Although the review article was not chosen by SJR but it was cited by Q1 and Q2 which helped to guarantee the research quality. Therefore, to compensate for the limitation of searching for keywords, these additional steps were applied to core acquisition since a comprehensive review article had already been conducted on the topic of core acquisition as reported in Table 2.1

In conclusion, the combination of SLR and the additional steps can help reveal new findings that are not reported in those review articles, hence increasing the comprehensiveness of review findings. The final results of the paper selection are detailed in Figure 2.1.

Table 2.1 List of review articles

Review article	Review topic	Chosen by SJR	Cited by Q1 and Q2 papers	Type of articles	Description
Wei et al., 2015	Core acquisition		✓	Journal paper	Core acquisition management in remanufacturing.

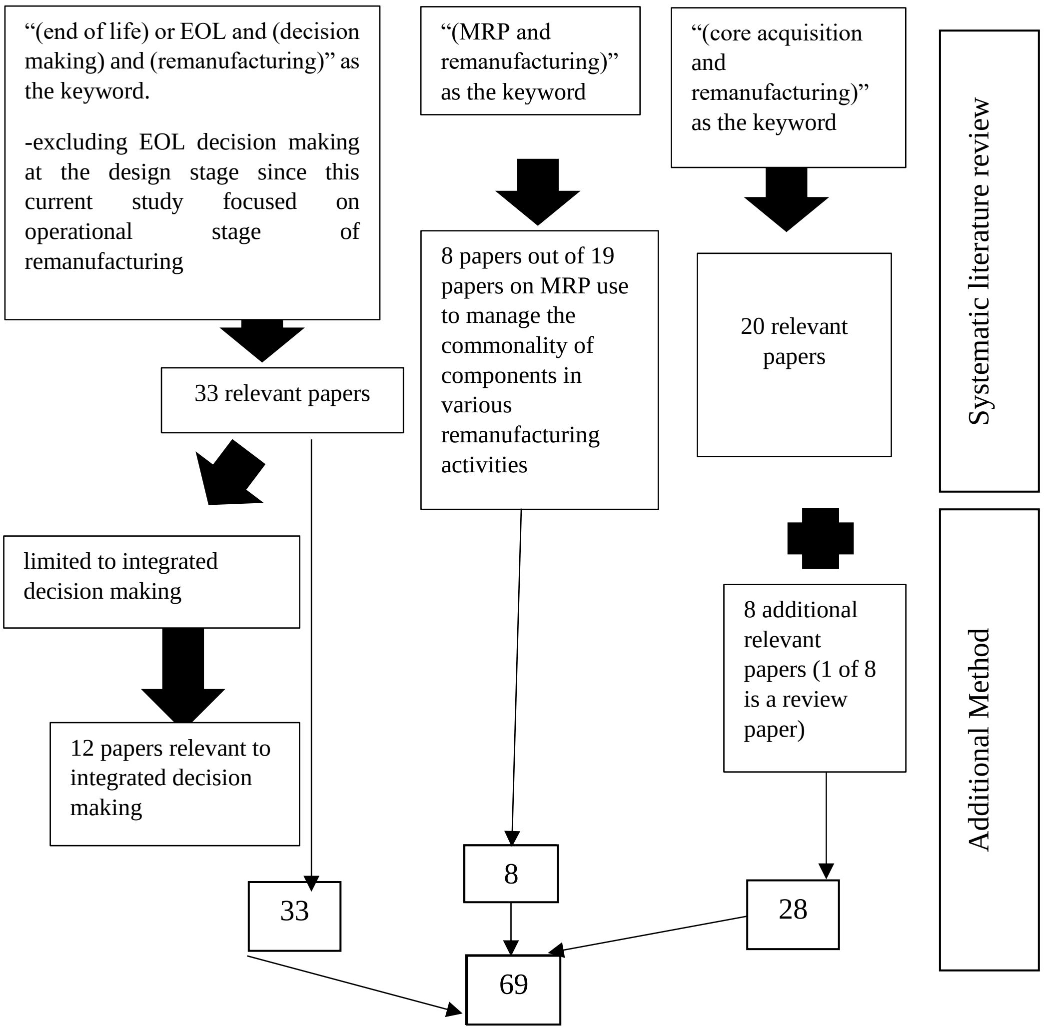


Figure 2.1 Paper selection

2.1.2 End of life (EOL) options

Table 2.2 reports a total of 33 papers which examine EOL options between 2001 and 2018. For ease of comparison, each paper is characterised by the types of products examined, the level of decisions developed, the methodologies applied to determine the best EOL options, and the types of decision factors considered in the EOL selection. Regarding the types of products, it was found that most research papers examined the selection of EOL options over electronic (42%) or automotive products (33%). Hence, research opportunities are noted for other under-researched industries such as industrial tooling and aerospace which usually use remanufactured products (CRR, 2010).

Table 2.2 Decision makings in EOL options

References	Products	Level of decision	Methods			Economic factors			Engineering factors				Environment factor	Social factor	Legal/ political factor
			Mixed	Quantitative	Qualitative	Return time	Monetary factors	Demand-supply factors	Quality	Product family	Products factor	Technical feasibility			
Murayama et al., 2001	N/A	product	FMEA									1*			
Lee et al., 2001	coffee machine, pager	product		MIP, LCA			1*				1		1*		
Bufardi et al., 2004	vacuum cleaner	component	ELECTRE				1*						1*	1*	
Jun et al., 2007	turbocharger	component		MIP, Pareto optimal			1*		1*						
Chan, 2008	electrical shaver	component		GRA			1*						1*	1*	
Wadhwa et al., 2009	brown good	product	Fuzzy logic, TOPSIS				1*	1*	1*				1*		1*
Lee et al., 2010	Mouse	component/ subassembly/product		MIP	HALG		1*					1			1
Ghazalli and Murata, 2011	computer,telephone, TV, audio system	product, part and component level	AHP	NN	CBR		1*					1	1*		
Ma et al., 2011	automatic pencil, telephone	part and subassembly		MIP, Heuristic	And/or graph		1*					1	1		
Jun et al., 2012	turbocharger	component		MINLP, GA			1*		1						
McKenna et al., 2013	automotive	N/A		Sensitivity of factors, LCA			1*	1							
Ondemir and Gupta, 2014a	N/A	component		MIP			1*		1*				1*		
Shokohyar et al., 2014	Notebook	component		GA, MINLP, Pareto			1*						1*		
Ziout et al., 2014	fuel cell stack	component	AHP		PESTEL		1*	1*			1*	1*	1*	1*	1*
Ondemir and Gupta, 2014b	N/A	component		MIP			1*	1	1*				1*		
Qian et al., 2015	Engine	component		LCA			1*		1*						
Yang et al., 2015	alternator, hedge trimmer	component		MIP	HALG		1*		1				1*		

References	Products	Level of decision	Methods			Economic factors			Engineering factors				Environment factor	Social factor	Legal/ political factor
			Mixed	Quantitative	Qualitative	Return time	Monetary factors	Demand-supply factors	Quality	Product family	Products factor	Technical feasibility			
Kwak, 2015	Alternator	component		Pareto, MIP			1 *		1	1			1 *		
Pazoki and Abdul-Kader, 2016	Printer	product		MINLP, sensitivity analysis			1 *					1			
Kwak and Kim, 2016	alternator, desktop	product		MIP			1 *		1				1 *		
Wang et al., 2016	Bulldozer	component		MIP			1 *			1					
Liu et al., 2016	Engine	component		GA			1 *		1						
Yang et al., 2016c	Telephone	product and component		GA (NSGAII), Pareto		1	1 *					1	1 *		1
Meng et al., 2016a	N/A	product and component	Fuzzy logic, Promethee	MIP		1	1 *	1	1			1	1 *		1
Meng et al., 2016b	N/A	N/A		ICA		1	1 *	1	1			1	1		
Li et al., 2016b	Vehicle	component		LCA									1 *		
Karaulova and Bashkite, 2016	truck, machinery	product		LCA,	TRIZ		1 *					1 *	1 *		
Meng et al., 2017a	Engine	component		GA (NSGAII), Pareto			1 *		1				1 *	1*	
Meng et al., 2017b	N/A	component		PHM			1 *		1 *						
Mashhadi and Behdad, 2017	N/A	N/A		MIP, clustering algorithm			1 *	1	1		1			1	
Cho et al., 2017	Computer	component		GA, ACSA			1 *	1	1						
Steeneck and Sarin, 2017	N/A	product		MIP			1 *	1	1						
Omwando et al., 2018	power control drive	product	Fuzzy logic				1 *					1 *	1 *		
Total						3	31	9	17	2	3	11	20	5	5

* = objectives , FMEA = Failure mode and effect analysis, MIP = mixed integer programming, LCA = life cycle assessment, GRA= Grey Relational Analysis, HALG = hierarchical attributed liaison graph, AHP = analytical hierarchy process, NN = The nearest neighbourhood algorithm, CBR = case-based reasoning, MINLP = mixed integer non-linear programming, GA = Genetic algorithm, ICA = Improved co- evolutionary algorithm TRIZ=Theory of Inventive Problem Solving , PHM = proportional hazard model, ACSA = an ant colony search algorithm

EOL options can be categorised into product-level and component-level. Han et al. (2013) pointed out that most previous studies examined only EOL options at product-level because selecting EOL options at component-level was much more complex. However, review results indicate that 22 of 33 papers examined the selection of EOL options at component-level which became more popular after 2013. Findings from this thesis reinforce the fact that EOL options at component-level are more practical in real life (Han et al., 2013). In addition, observations made from company visits show that remanufacturers tend to consider EOL options for each component of the product rather than for the whole product. For example, different EOL options are often considered for the crankshaft which is one of the engine components. Therefore, choosing EOL options at component-level is surely an important topic for further study.

From 2001-2018, mixed integer programming (MIP) was the most frequently used method to select the best EOL option when considering two or more decision factors (13 of 33 papers). Genetic algorithms (GA) were the next most frequently used method (6 of 33 papers), followed by LCA (5 papers) and Pareto optimal (5 papers), fuzzy logic (3 papers), MINLP (3 papers) and AHP (2 papers). LCA was the most commonly used method to consider the environmental factors (e.g. Li et al.(2016) and Karaulova and Bashkite (2016)). Table 2.3 shows that metaheuristics (GA, ICA and ACSA), MINLP and AHP, were never used before 2012. Since 2012, metaheuristics have become more common since these methods are deemed more efficient and effective when dealing with the selection of EOL options with two or more decision factors, which is also known as multi-criteria decision making (Ma et al., 2011, Jun et al., 2012, Yang et al., 2016b, Meng et al., 2016). MINLP has received more attention since 2012 (Jun et al., 2012) as some economic factors such as recovery cost might be non-linearly associated with product quality (Jun et al., 2007) as shown in Figure 2.2. The subjective weighting method (ex. AHP, point allocation, ranking) is also beneficial for the selection of EOL options when the nature of remanufacturing is uncertain. The subjective weighting method can reduce inaccuracy between the assumptions and real practice because the weighting is determined by experts who gain knowledge from past experience. In short, it is believed that more researchers will employ GA, other metaheuristics, MINLP and subjective weighting methods to select the best EOL options.

Table 2.3 Methods used in selecting EOL options

Method	2001	2004	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Others	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	
MIP	✓		✓			✓				✓	✓	✓	✓	
LCA	✓								✓		✓	✓		
Fuzzy logic					✓							✓		✓
Pareto			✓							✓	✓	✓	✓	
Metaheuristics(GA)								✓		✓		✓	✓	
Metaheuristics (ICA /ACSA)												✓	✓	
MINLP								✓		✓		✓		
AHP							✓			✓				

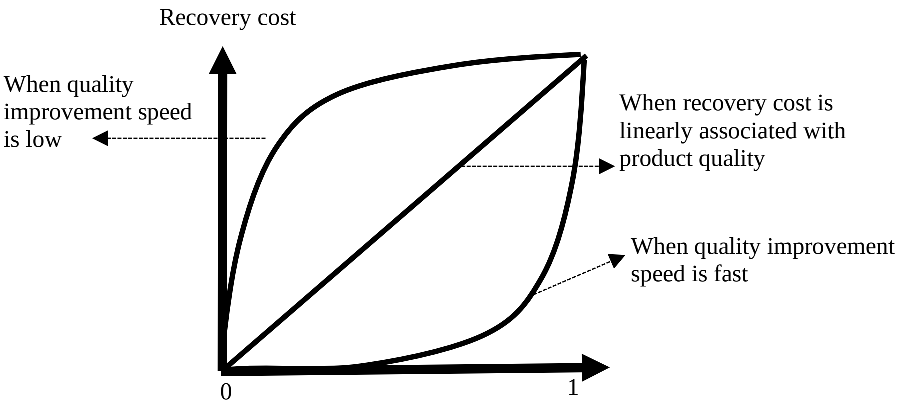


Figure 2.2 The relationship between recovery cost and quality (Jun et al., 2007)

Figure 2.3 shows that 64% of all papers examined two or more decision factors (objectives) when selecting EOL options. This helps to reinforce the fact that selecting EOL options is often formulated as multiple criteria decision making (MCDM) problems. Having said that, three studies were found to study a single objective such as engineering (Murayama and Shu, 2001, Hu et al., 2014), or the environment (Li et al., 2016). 57% of all papers considered economic factors (e.g. McKenna et al. (2013) and Steeneck and Sarin (2017)) or economic and environmental factors (e.g. Lee et al. (2001) and Ghazalli and Murata (2011)) while other factors have been under-studied. Since 2014, some objectives have been examined together which was never the case in studies between 2001 and 2013. For example, Ondemir and Gupta (2014a) and Karaulova and Bashkite (2016) focused on economic, engineering and environmental factors simultaneously, while Li et al.(2016) emphasised the environmental objectives and Ziout et al. (2014) considered multiple objectives including the economic, environmental, engineering, social and legal factors at the same time. Findings from this thesis suggest that researchers have tended to consider more factors (objectives) in recent years (2014-2018) as seen in figure 2.4. This tendency will probably be the future direction as such a holistic approach is required to consider multiple factors for supporting sustainable production (Ziout et al., 2014). This view is also supported by Carpenter and Sanders (2009) who stated that PESTEL (political, economic, societal, technical, environmental and legal aspects) have been used successfully in operational frameworks for various types of organisations.

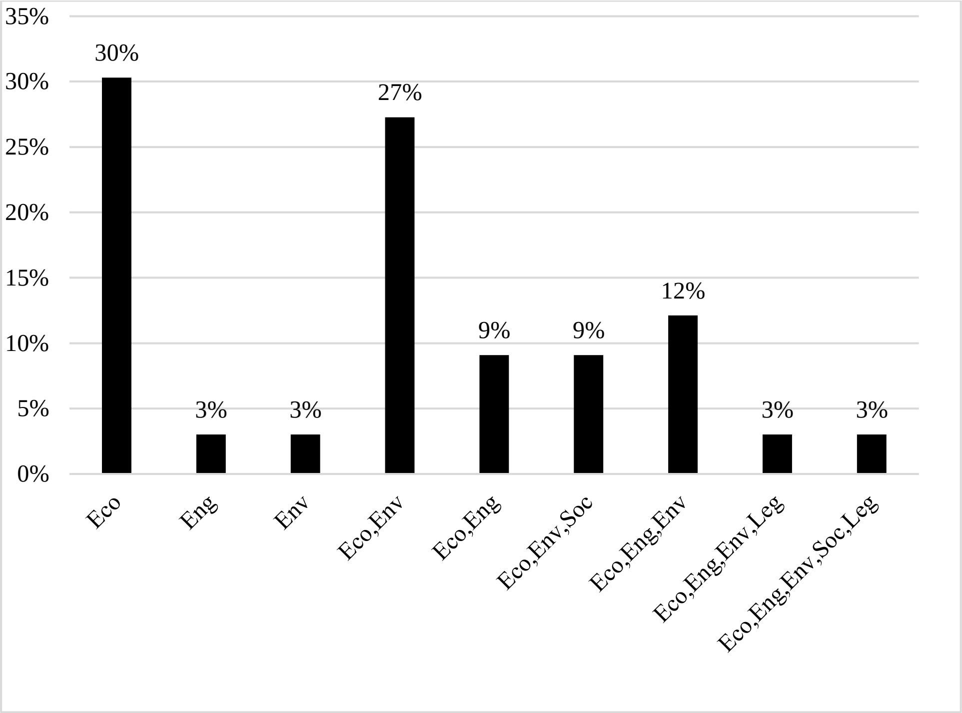


Figure 2.3 Percentage of papers by objectives

Eco = Economic, Eng = Engineering, Env = Environmental, Soc = Social, Leg = Legal

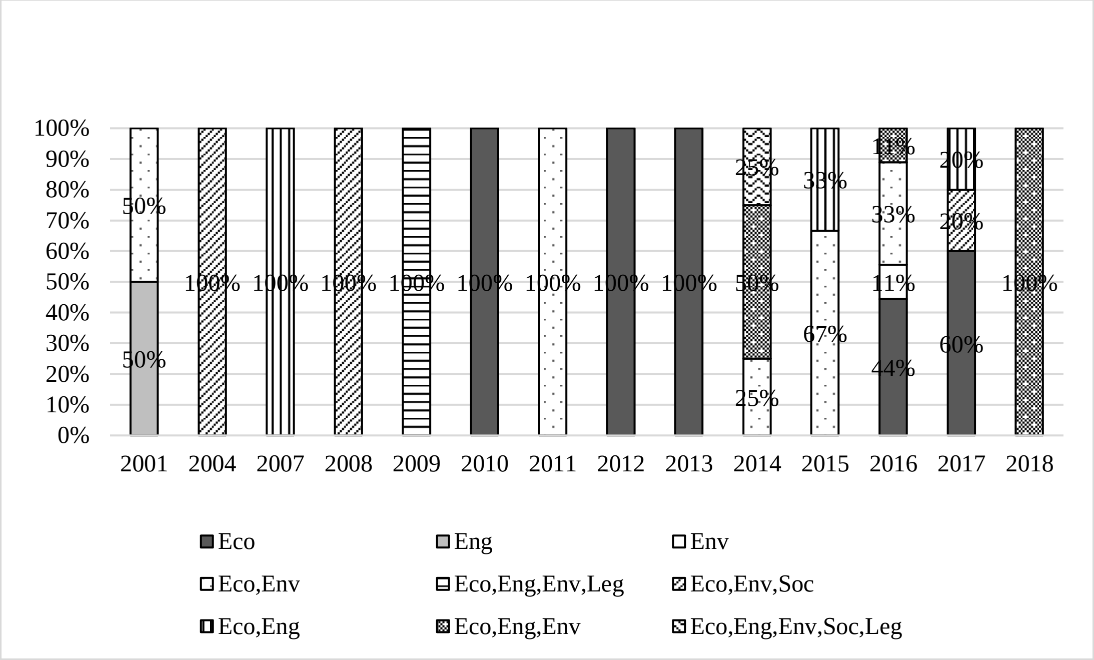


Figure 2.4 Percentage of papers by objectives for each publication year

Eco = Economic, Eng = Engineering, Env = Environmental, Soc = Social, Leg = Legal

2.1.3 Core acquisition management

In the following sub-sections, the types of factors and optimisation methods used in core acquisition management are reviewed.

2.1.3.1 Factors in core acquisition management

- Acquisition price

Acquisition price can be categorised into two types including linear and non-linear functions. The majority of research papers (8 of 12 papers) assumed that the acquisition price is a linear function as follows. Acquisition price (A) = uN , where u is a constant unit acquisition cost and N refers to the number of acquired products/components (Galbreth and Blackburn, 2006, Yang et al., 2014, Bulmus et al., 2014, Teunter and Flapper, 2011, Seidi and Kimiagari, 2010). However, some researchers have suggested that acquisition can also be a non-linear function because the uncertain return rate of used-product returns and the fluctuating demand for remanufactured products will influence the acquisition price dynamically. In the non-linear case, Galbreth and Blackburn (2006) considered that acquisition price is an increasing convex function over time because of the scarcity of products. In addition, the acquisition price can fluctuate over time depending on the serviceable inventory level (Cai, 2014, Xie et al., 2015).

- Demand rate and return rate

When core acquisition is being mathematically modelled, both the demand rate of remanufactured products and the return rate of cores are assumed to be in different forms: deterministic, stochastic or random. Deterministic forms are usually adopted as it helps simplify the models. However, in real practice, both demand rate and return rate are highly uncertain, especially for independent remanufacturers who have less control over both customer demand and customer return. Therefore, more complex models have been developed for stochastic and random forms. To improve model accuracy, stochastic models have been developed with both demand rate and return rate following certain probability distributions. Whereas both demand rate and return rate can be deemed as random functions which were inspired by a real industrial case (e.g. Zhou and Yu (2011)). Tables 2.4 shows all three forms used for both the demand and the return rate, each with examples from the literature. It should be noted that there are a limited number of research papers which assume random demand rate and random return rate.

Table 2.4 The list of papers categorised by types of demand rate and types of return rate

	Type	References
Demand rate of remanufactured products	Deterministic	Galbreth and Blackburn, 2006, Wei and Tang, 2014, Pokharel and Liang, 2012, (Kang and Hong, 2011), Yang et al., 2014
	Stochastic	Guide et al., 2003, Galbreth and Blackburn, 2006, Teunter and Flapper, 2011, Clottey, 2012, Cai, 2014, Lechner and Reimann, 2014, Yang et al., 2014, Yang et al., 2016b, Yang et al., 2016a
	Random	Xie et al., 2015, Zhou and Yu, 2011, Clottey, 2016
Return rate of cores	Deterministic	Wei and Tang, 2014, Kang and Hong, 2011, Xie et al., 2015
	Stochastic	Shi et al., 2011, Zhou and Yu, 2011, Xu, 2012, Guide et al., 2003, Clottey, 2012, Cai, 2014, Clottey, 2016
	Random	Zhou and Yu, 2011, Clottey, 2016

- Quality level

The remanufacturers, such as ReCellular (Guide and Wassenhove, 2001) and Caterpillar (Wei et al., 2015) have classified cores into different quality levels (or grades) which help determine the remanufacturing costs. In cases of multiple grades of cores, the quality distribution of each grade can be divided into two types: discrete and continuous. Although discrete distribution is less realistic, it is more frequently used than continuous distribution which is more complex. If discrete distribution is applied, cores of the same grade have the same quality level and remanufacturing costs. The number of cores at each grade is assumed to be deterministic (Guide et al., 2003, Galbreth and Blackburn, 2006, Seidi and Kimiagari, 2010, Teunter and Flapper, 2011, Pokharel and Liang, 2012, Yang et al., 2014, Yang et al., 2016a). With regard to continuous distribution, Ferguson (2011) has proposed that the returned cores have quality $q \in [0, 1]$ as shown in Figure 2.5, where 0 is the minimum quality of returned cores, 1 is the maximum quality of returned cores and the quality probability density function changes over time (Wei et al., 2015). Also, Robotis et al. (2012) have assumed that only a portion from 0 to 1 of the whole product is remanufacturable (Wei et al., 2015).

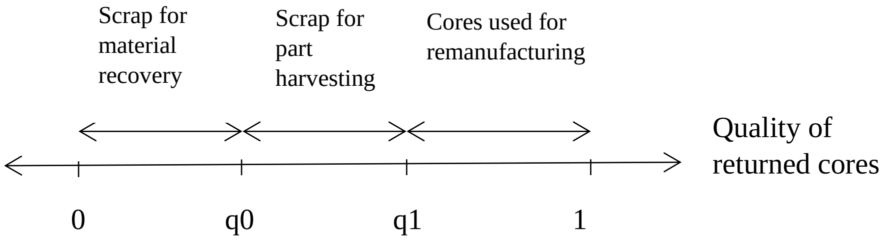


Figure 2.5 The classification of returned cores adopted by Ferguson (2011)

2.1.3.2 The modelling approach in core acquisition management

According to a review by Wei et al. (2015), the most widely recognised technique to optimise the return quantities is through adjusting acquisition effort. Some of the most commonly used modelling approaches are game theory (Bulmus et al., 2013), optimal control (Zhou and Yu, 2011), Markov chain (Vercraene et al., 2014) and mixed integer programming(Nenes and Nikolaidis, 2012). Findings from this thesis also uncover other modelling approaches such as non-linear programming(Seidi and Kimiagari, 2010), real option valuation (Wei and Tang, 2014), Bayesian estimation of distributed lag model (Clottey, 2012, Clottey, 2016) and multi-period stochastic dynamic programming (Xie et al., 2015). Table 2.5 illustrates that most papers about core acquisition (14 of 20) use optimal control as the modelling approach since optimal control is a mature mathematical discipline in science and engineering.

Table 2.5 shows that researchers mostly consider demand, acquisition price, remanufacturing costs and return rates when optimising core acquisition. There has been limited research which has considered product lifecycles, activity-based costs, changeable prices, capacity constraints, safety stock, activity-based quantity, part levels, timing constraints, component commonality, remanufacturing yield, optimal remanufacturing level and environmental factors. Moreover, most studies assume that the demand and return rate are deterministic or stochastic while quality is deemed as uncertain but can only be specified by certain probability distributions. In real practice, remanufacturers face challenges due to uncertainties such as unpredictable customer demand for remanufactured products, unknown availability of the returned products/components and the unpredictable condition of returned products/components. Therefore, there are opportunities for future research to focus on random demand rate, return rate and quality of cores, which is more realistic. Also, under-researched factors should be included in the decision making process. For example, quality may be considered as a function of operational time or the useful life of a product since the condition of products/components usually varies over time. In addition, quality can be also considered as a function of recovery cost which is less subjective as recovery effort is a good reflection of the quality of returned products/components. If the cores are of better quality, less effort will be needed to recover the cores into a like-new condition.

Table 2.5 Review findings about factors and modelling approach used in core acquisition

References	Economic factors																																	Engineering factors							Environmental factors		Modelling approach
	Monetary factors													Demand-supply factors				Quantity factors													Timing factors						Quality factors						
	sales price of new products	sales price of remanufactured	manufacturing cost	remanufacturing cost	storage cost	disposal cost	disassembly cost	replacement cost	transporting cost	salvage value of surplus used	backordering cost	acquisition price	set-up cost	economic benefits	demand of remanufactured products	consumer's willingness to pay	unlimited supply	returned cores	volume of usable cores in inventory	safety stock	number of parts	number of new components	quantity of cores from brokers	remanufacturing quantity	No. of manufactured parts	acquisition quantity	No. of disassembled products/parts	No. of disposed parts	No. of shortages	No. of parts shipped from collection	expected sale	inventory holding time	remanufacturing time	production time	transition matrix	component commonality	product lifecycle	remanufacturing yield	remanufacturing cycle	quality grade	optimal remanufacture-up-to level	environmental benefits	carbon emissions	
Guide et al., 2003		1		1								1			1		1	1																						1				OC
Galbreth and Blackburn, 2006				1							1	1			1		1							1														1		1				OC
Lu, 2009				1																																		1	1					OC
Seidi and Kimiagari, 2010				1	1		1		1		1	1							1	1	1			1		1		1	1	1			1					1		1				NP
Teunter and Flapper, 2011				1							1	1			1									1		1														1	1			OC
Zhou and Yu, 2011	1	1	1	1	1						1	1			1			1	1														1	1										OC
Kang and Hong, 2011			1	1	1	1	1								1			1	1						1		1	1							1	1								MIL
Clottey, 2012															1			1	1			1	1															1						B
Pokharel and Liang, 2012								1		1	1	1			1											1														1				OC
Wei and Tang, 2014		1			1					1					1			1																										R,NP
Cai, 2014			1	1	1						1	1			1			1	1			1		1		1														1				OC
Bulmus et al., 2014	1	1	1	1								1				1		1						1	1	1														1				OC

References	Economic factors																																		Engineering factors							Environmental factors		Modelling approach
	Monetary factors														Demand-supply factors				Quantity factors													Timing factors			transition matrix	component commonality	product lifecycle	Quality factors						
	sales price of new products	sales price of remanufactured	manufacturing cost	remanufacturing cost	storage cost	disposal cost	disassembly cost	replacement cost	transporting cost	salvage value of surplus used	backordering cost	acquisition price	set-up cost	economic benefits	demand of remanufactured products	consumer's willingness to pay	unlimited supply	returned cores	volume of usable cores in inventory	safety stock	number of parts	number of new components	quantity of cores from brokers	remanufacturing quantity	No. of manufactured parts	acquisition quantity	No. of disassembled products/parts	No. of disposed parts	No. of shortages	No. of parts shipped from collection	expected sale	inventory holding time	remanufacturing time	production time				remanufacturing yield	remanufacturing cycle	quality grade	optimal remanufacture-up-to level	environmental benefits	carbon emissions	
Lechner and Reimann, 2014	1		1	1								1			1			1													1													OC
Yang et al., 2014						1						1			1											1														1				OC
Xie et al., 2015				1	1						1	1			1			1																										MSD
Clottey, 2016					1								1		1			1	1							1						1												B
Mitra, 2015	1	1	1	1																																								OC
Yang et al., 2016b				1										1	1									1		1														1		1	1	OC
Mutha et al., 2016																										1											1							OC
Yang et al., 2016a						1						1			1											1														1			1	OC
Total	4	5	6	13	7	3	2	1	1	2	7	12	1	1	15	1	2	10	6	1	1	2	1	6	2	10	1	2	1	1	1	1	2	1	1	1	1	4	1	10	1	1	2	

OC-optimal control, NP-non-linear programming, MIL- mixed integer linear programming, B-Bayesian estimation of distributed lag model, R- real option valuation, MSD- multi-period stochastic dynamic program

2.1.4 MRP with consideration of component commonality in remanufacturing

Component commonality, which means using the same components in several products, was promoted as an effective approach to reduce inventory and/or inventory-related costs (Su et al., 2012, Menezes et al., 2016, Subramanian et al., 2013). When multiple products use the same components, product varieties can be differentiated by assembling unique components into the common components (Lee and Tang, 1997, Lee and Sasser, 1995, Garg and Tang, 1997). The advantages of component commonality of manufacturing systems as found in earlier studies (Xu and Li, 2008, Wazed, 2010, Leung, 2010, Chen and Chang, 2008, Hernandez-Ruiz et al., 2016, Deza et al., 2018) are the reduction of inventories, the reduction of costs (installation, inventory and manufacturing costs), the reduction of operational time (setup time, product development time and lead times), enhanced productivity, and the increasing of flexibility and economies of scale.

The available planning tools (MRP (Material requirement planning), MRP II, ERP (Enterprise resource planning), ERP II, etc.) are frequently used to solve problems of production planning and control in manufacturing as well as remanufacturing systems (Raupp et al., 2015, Tenhiälä and Helkiö, 2015, Koh et al., 2011, Tan et al., 2012). The majority of previous studies related to component commonality have been focusing on the mathematical models to determine the optimal degree of component commonality (Menezes et al., 2016). However, very few studies have considered component commonality and multiple activities of operation simultaneously based on review of more than 100 articles about manufacturing and remanufacturing from 1965-2018 (Wazed, 2010, Sitcharangsie et al., 2019, Takai, 2018, Menezes et al., 2016).

As shown in Table 2.6, only 8 papers have been deemed relevant to production planning and control by considering component commonality and multiple activities of remanufacturing simultaneously (Kwak (2015), Sitcharangsie et al. (2019)). Component commonality is an important area as it places more challenges on the planning of remanufacturing activities (Kim et al., 2007, Gupta and Taleb, 1994, Krupp, 1993). Research in this area has established an optimal remanufacturing plan for multiple product types which have some components in common. This research is different from Disassembly-To-Order (DTO) studies since the purpose of these studies focus on all remanufacturing activities not only product disassembly.

According to Morgan and Gagnon (2013), whilst reverse MRP (RMRP) which is for remanufacturing processes can predict the demand for all components of products, RMRP without other methods cannot accomplish other economic objectives such as minimising costs or maximising profits. Nonetheless, linear integer programming models can find the optimal solution for problems with capacity constraints while also meeting cost-based objectives. The present research study has found that the majority of research studies in this field (7 out of 8) solved the problem with multiple remanufacturing activities by mixed- integer linear programming. The main objective of these studies is related to the monetary-based objective of maximising profits or minimising costs by planning how to disassemble and remanufacture end-of-life products. Kwak (2015) is the only research study which considered two objectives: maximising profits and maximising energy savings. This may indicate a lack of relevant research in considering multiple objectives decision making and trade-offs between those objectives. The current study will, therefore, addresses two objectives: maximising profit and minimising operational time due to their importance towards business goals.

Several constraints have been considered by different papers. All 8 papers considered the balance of the quantity of components going through the system as a constraint since the number of input components should be equal to the number of output components. 5 of them considered capacity of remanufacturing activities since each of them have the limitation. Half of the research considered environmental regulations, limitation in core availability and the constraint that the the number of recovered items must not be more than the demand. Also, only Kwak (2015) considered the constraint that the number of remanufactured products cannot exceed the total number of collected of cores.

Although the products used in these studies are different, the main remanufacturing activities considered are core acquisition, disassembly, reassembly, the purchase of new components and disposal. According to Sitcharangsie (2019), component reworking is an additional activity and most of the previous studies overlook the importance of this activity. In total, this study considered 6 key activities which are core acquisition, disassembly, reassembly, the purchase of new components, component reworking and disposal since those remanufacturing activities are important to enhance the applicability of the approach to real practice. As mentioned before, all these studies considered multiple constraints but they tended to overlook how each of the factors might affect the optimisation of remanufacturing outcomes, and this could be achieved through sensitivity analysis. Kim et al. (2006) is the only study applying sensitivity analysis to examine how the capacity of collection/disassembly site might affect the cost savings of remanufacturing business. The main decision criteria in real practice are percentage of reworked components (number of reworked components : the sum of the number of reworked components and the number of new components) (Ziout et al., 2013, Meng et al., 2017a, Yang et al., 2015, Ziout et al., 2014), reworking time (Ghazalli and Murata, 2011), reworking cost (Liu et al., 2016, Krikke et al., 1998)and component commonality(Östlin et al., 2008).

However, no research paper considered the sensitivity of these criteria. Thus, they were research gaps.

In conclusion, this study can fill the research gap by considering all 6 key remanufacturing activities and component commonality with an aim to optimise two objectives : maximising profit and minimising operational time.

Table 2.6 Review results about MRP planning by considering component commonality and multiple remanufacturing activities

Author	Method	Product using as an example	Objectives	Constraints						Considered remanufacturing activities	Sensitivity analysis						Objective Trade-off
				Flow volume balance	Capacity of activities	Environmental regulations	Limited core availability	Recovered item are not more than demand	Remanufactured products cannot exceed the total collection		Component commonality	% reworked components	Reworking cost	Reworking time	Capacity of collection site	Capacity of disassembly site	
Ferrer and Whybark(2001)	MMRP, RMRP, MILP, HR	Automotive components	Minimise core purchased	✓	✓		✓	✓		Core acquisition, disassembly, reassembly							
Franke et al.(2006)	MILP	Mobile phones	Maximise profit	✓	✓			✓		Sorting,disassembly, cleaning, testing, reassembly							
Kim et al.(2006)	MILP	N/A	Maximise total cost savings	✓	✓	✓				Core acquisition, assembly, spare part procurement, refurbishment, disposal					✓	✓	
Langella (2007)	HR	N/A	Minimise cost	✓						Core acquisition, spare part procurement, disassembly, disposal							
Xanthopoulous and Lakovou(2009)	MILP	Electrical heat appliances	Maximise profit	✓	✓	✓	✓			Storage, recycling, non-destructive disassembly,remanufacturing							
Kwak and Kim (2011)	MILP	Mobile phones	Maximise profit	✓		✓	✓	✓		Product take-back, data scrubbing, product conditioning, disassembly, part conditioning, spare part procurement, reassembly, software update, disposal							
Ji et al.(2015)	MILP, Lagrangian HR	Manual valves and Pneumatic valves	Minimise total cost	✓	✓					Core acquisition, spare part procurement, disassembly, disposal							
Kwak (2015)	MILP	Alternators	Maximise profit, Maximise environmental saving	✓		✓	✓	✓	✓	Take back, disassembly, part reconditioning , reassembly, disposal, spare purchasing, material recycling, part resaling							✓
This study	MILP	Engines	Maximise profit Minimise time	✓			✓	✓	✓	Core acquisition, Disassembly, Part reworking, Reassembly, Spare purchasing, Disposal	✓	✓	✓	✓			✓

MMRP = Modified materials requirements planning, RMRP = Reverse materials requirements planning, HR = Heuristic,MI LP = Mixed integer linear programming

2.1.5 Integrated decision making

It should be noted that there are 12 papers from End-of-life (EOL) options which consider integrated decision making. Table 2.7 summarises those papers in terms of decision types examined, decision making steps (simultaneous step /multi steps), methodology applied and decision factors considered. Review results from this thesis suggest that EOL options were mostly considered together with either disassembly level (6 papers) or purchasing new orders (6 papers), followed by EOL options with disassembly sequences (5 papers) and EOL options with core acquisition (1 paper). Decision making on EOL options in remanufacturing is always taken together with either purchasing new orders or core acquisition. When remanufacturers decide to recycle or to dispose of components, they need to purchase new or used components/products to replace those components which are unusable. Also, decisions on the level of disassembly usually affect decisions on EOL options since the reusability of cores becomes clearer after disassembly.

Since integrated decision making is complex, some previous authors have applied various methods to reduce the difficulties of modelling. For example, previous authors used and/or graphs (Ma et al., 2011), liaison graphs (Lee et al., 2010) and transition matrices (Kang and Hong, 2011) to make decision making simpler on disassembly sequence. Moreover, previous authors (Lee et al., 2001, Lee et al., 2010, Ma et al., 2011, Liu et al., 2016, Wang et al., 2016) applied multi-steps in the decision making or applied GA/heuristics/metaheuristics (Ma et al., 2011, Liu et al., 2016, Meng et al., 2016) to reduce computation time.

Table 2.7 shows that the decision factors considered in integrated decision making can be categorised into four groups: economic, engineering, environmental and legal. Some of these factors, due to their quantitative nature (e.g. monetary factors, environmental impact), are commonly used as objectives for mathematical modelling. The review from this thesis also reveals that economic factors are mostly examined (8 of 12) followed by both economic and environmental factors (4 of 12) while other factors are under-studied.

In conclusion, opportunities for further research about integrated decision making are detailed as follows:

- Considering multiple objectives could be useful for future research since the decision making involving PESTEL perspectives (political, economic, societal, technical, environmental and legal aspects) is widely successful across a number of organisations (Carpenter and Sanders, 2009).

- There is a research opportunity to consider under-studied factors since they are also found to be useful in real practice. These factors are availability, demand, quantity of components/ products, return rate, lead time, recoverability, disassembly sequence, product lifecycle, component commonality, environmental impact, recovery rate, incineration capacity, hazardous materials and maximum disposal rate.
- Further studies about integrated decision making may consider more decision types. Integrated decision making between core acquisitions with EOL options could be given more attention since there are still a limited number of papers on this topic.

Table 2.7 Review results about integrated decision making

Authors	Decision types						Steps of decision making		Methods		Decision Factors																	
											Economic								Engineering					Environmental				Legal
											Monetary factors				Process factors													
	EOL options	disassembly sequence	disassembly level	purchasing new components /products	core acquisition	manufacturing	simultaneous	multiple steps	Quantitative	Qualitative	economic value of components /products	sequence-based cost	activity-based cost	profit	availability	demand	return rate	lead time	recoverability	disassembly sequence	quality	product lifecycle	component commonality	environmental impact	recovery rate	incineration capacity	hazardous materials	Max. disposal rate (by weight)
Lee et al., 2001	1		1					1	MIP, LCA		1*								1					1*				
Teunter, 2006	1	1	1				1		DP				1	1*							1							
Lee et al., 2010	1	1	1					1	MIP	HALG	1		1	1*	1													1
Kang and Hong, 2011	1	1	1			1	1		MIP	TM			1*			1		1		1			1					
Ma et al., 2011	1	1	1					1	2 step HR	And/or graph	1			1*										1	1	1		
Ondemir and Gupta, 2014b	1			1			1		MIP		1		1	1*		1					1*	1		1*				
Kwak, 2015	1			1			1		Pareto, MIP		1		1	1*					1				1	1*				
Kwak and Kim, 2016	1			1			1		MIP		1		1	1*							1	1		1*				
Liu et al., 2016	1			1				1	GA		1		1	1*							1							
Meng et al., 2016b	1	1	1				1		M		1	1	1	1*	1		1	1		1	1						1	
Wang et al., 2016	1			1	1			1	MIP				1*										1					
Steeneck and Sarin, 2017	1			1		1	1		MIP		1		1			1	1				1							
Total	12	5	6	6	1	2	7	4			9	1	10	8	2	3	2	2	2	2	6	2	2	5	1	1	1	1

* = objectives , MIP = mixed integer programming, LCA = life cycle assessment, DP= dynamic programming, HALG = hierarchical attributed liaison graph, TM= transition matrix, HR = Heuristics, GA = Genetic algorithm, M= Metaheuristics

2.1.6 Proposed research questions

As have been discussed, there is lack of research study about integrated decision making between core acquisitions with EOL options. Therefore, this study covers integrated decision making to select the best recovery options for components and find the optimal number of required components/products at each remanufacturing activity which also include core acquisition. To address this research gap, this research analyses decision making in remanufacturing from a broader perspective which includes consideration of previous literatures and current industrial practice. This leads to two questions:

- What are the factors affecting decision making in remanufacturing?
- What are the decision sequences?

The following research question is:

- What are the possible recovery options for components from different automotive remanufacturing companies?

This research question is considered since this research consider how to select the best recovery option, the possible recovery options are reviewed from current automotive remanufacturing companies because some recovery option are considered by some companies but not by other companies. The recovery option that remanufacturers disregard may give them new/additional business opportunities.

The next question is:

- How to select the best recovery options for component with specific faults?

Since this research reviews current practice, some practical knowledge is examined. The best recovery option for components with specific faults should be considered because the suitable recovery option is selected depending on the failure of used components

The last two questions are:

- How to find number of required components/ products in each activities of remanufacturing?
- How reworking cost, reworking time, % of reworked component and component commonality pattern affect the remanufacturing business

The first question is considered because planning core acquisition with selecting the best recovery options is important study according to the research gaps identified in the literature . This research found that planning for core acquisition has a significant impact on other remanufacturing activities as well. Therefore, the optimal number of required components/ products in each activity of remanufacturing is considered to increase the advantage of this research. The first question leads to question 2 because the optimal number of required components/ products in each activity of remanufacturing depends on different situations. Reworking cost, reworking time, percentage of reworked component and component commonality pattern are under-researched factors identified by the author from literature review. Also, these factors are identified that can affect the remanufacturing business when the author visited various automotive remanufacturing companies.

2.2 Review of tools and techniques used in decision-making in remanufacturing and end-of-life options

2.2.1 Review methodology

This research adopted a rapid review to review this topic because several studies in the literature have already reviewed the tools and techniques used in decision-making in sustainable manufacturing. Booth (2016) suggested that a rapid review is suitable to assess what is already known about practical knowledge. A rapid review is primarily a systematic review in which the researcher takes a valid, but less-time consuming method, to reveal findings quickly (Boland et al., 2014). The protocol suggested by Boland et al. (2014) is illustrated in Table 2.8. After searching the keywords “Decision-making” and “remanufacturing” or “end of life options” from Scopus, the author selected only review articles written in English, then read the titles and abstracts. As a result, 2 papers were found to be relevant to this topic. Those two review articles are Sitcharangsie et al. (2019) and Zarte et al.(2019). In order to compensate for the limited sources for these search terms, this research included review articles from (Ziout et al., 2014) and (Ilgin et al., 2015). These two review articles reviewed tool and techniques in decision-making in sustainable manufacturing because remanufacturing is categorized as a type of sustainable manufacturing. Also, these two articles ((Ziout et al., 2014) and (Ilgin et al., 2015) were cited by Sitcharangsie et al. (2019) and Ziout et al. (2014) who gathered research papers from 1994 to 2013 and Ilgin et al.(2015) who covered published papers from 1996 to 2014. Therefore, there are 4 review articles including Ziout et al. (2014), Sitcharangsie et al. (2019), Ilgin et al., (2015) and Zarte et al.(2019). Furthermore, this current study will extend the reviewed papers from 1991 to 2017. All those papers can be categorized into 4 topics. These topics are multi-objective optimisation techniques, multi-criteria analysis technique, grey decision making and failure analysis. This research was conducted to solve multiple criteria problems, therefore multi-criteria optimisation techniques and multi-criteria analysis are both relevant topics. Also, operators in remanufacturing always have to deal with uncertainty of operational time, costs and quality of components in the operation. Some of the data that is required to operate a remanufacturing system is missing or unpredictable, therefore it is necessary to include grey decision making in this research. The last relevant topic is failure analysis since this research involves decision-making on components with some faults, therefore a review of the failure analysis method will be useful for this research. Table 2.9 shows examples of articles which adopt each technique to make a decision in remanufacturing.

Table 2.8 The protocol suggested by Boland et al. (2014)

The protocol	The details of the protocol	How this research applied the protocol to review this topic
Defining a question	Clearly defined and well-focused	What are the tools and techniques used in decision-making for remanufacturing
Searching	Predefined and explicitly stated	
	Limited by: • Search of only one database • Narrow time frame • Reliance on published literature only	Limited by: • Search from Scopus only • From 2015-2020 • Reliance on published papers only
Definition of inclusion and exclusion criteria	More exclusive than the systematic review	• Select only review articles • “Decision-making” and “remanufacturing are keywords • Select only articles written in English • Include relevant review articles cited by articles obtained from search of keywords
Screening titles and abstracts; selecting full text papers	Limited by single person screening	After reading titles and abstracts, 2 review articles are relevant.
Analysis and synthesis	Narrative synthesis only	
Replication	Explicit methods and replicable	

Table 2.9 Examples of articles which adopt each technique to make a decision in remanufacturing/ select EOL options

Tools/techniques		**Examples of research papers which apply the method**
Multi-objective optimisation techniques		
Multi-objective linear and non-linear programming	Linear programming	(Yang et al., 2015, Wang et al., 2016, Kwak and Kim, 2016)
	Non-linear programming	(Galbreth and Blackburn, 2006, Yang et al., 2014, Clottey, 2016)
Heuristic	Branch and Bound	(Subramani and Dewhurst, 1991)
	Wave propagation	(Srinivasan and Gadh, 1998)
	Neural network	(Hsin-Hao et al., 2000), (Seidi and Kimiagari, 2010)
	Near optimal search	(Hesselbach et al., 2001)
Metaheuristics	Expert system (Petri nets)	(Zha and Lim, 2000)
	GA	(Dini et al., 1999), (Jun et al., 2012), (Shokohyar et al., 2014)
	Ant colony system	(Failli and Dini, 2001, Cho et al., 2017)
	Scatter search	(González and Adenso-Díaz, 2005)
Multi-criteria analysis technique		
	AHP	(Jiang et al., 2011), (Yang et al., 2015), (Ghazalli and Murata, 2011)
	ELECTRE	(Bufardi et al., 2004)
	Case-based reasoning	(Ghazalli and Murata, 2011)
	Pareto	(Meng et al., 2017a), (Shokohyar et al., 2014), (Kwak, 2015), (Hula et al., 2003), (Takeuchi and Saitou, 2006), (Jun et al., 2007), (Yang et al., 2016b)
	Topsis	(Remery et al., 2012)
	PESTEL	(Ziout et al., 2014)
Grey decision-making		
	Fuzzy logic	(Ma and Okudan Kremer, 2015), (Remery et al., 2012),
	Grey relational analysis	(Chan, 2008)
	Case-based reasoning (CBR)	(Ghazalli and Murata, 2011)
	Entropy between Upper and Lower bound	(Pandey and Thurston, 2009)
	Sensitivity analysis	(Pazoki and Abdul-Kader, 2016)
Failure	FMEA, RPN (REP, OCC, DET)	(Diallo et al., 2017), (Murayama and Shu, 2001)

2.2.2 Multi-criteria optimisation technique

Linear or non-linear programming can solve multi-criteria optimisation problems in general. For example, Yang et al. (2015) developed a multi-objective mixed integer programming for EOL strategy planning for components of returned products by considering economic, engineering and environmental factors as trade-offs. Kwak and Kim (2016) developed a multi-criteria decision model by using mixed integer programming to select the best options between remanufacturing products or producing brand-new products. The decision criteria of Kwak and Kim (2016) are unit production cost, environmental impact, and net profit. Pazoki and Abdul-Kader (2016) adopted mixed integer non-linear programming to find the optimal number of units to be remanufactured or salvaged by considering profit and the value of components decreasing over time.

However, if the problems become more complex, heuristics and metaheuristics are used to solve the problems. Heuristics is a technique to find acceptable solutions for a difficult model. A meta-heuristic is an extension of the heuristic concept by exploiting ideas and concepts from other topics to solve the problem of a model which uses an artificial system. For example, Srinivasan and Gadh (1998) adopted wave propagation to reduce geometric complexity in selective disassembly by considering costs and time. Another example is Failli and Dini (2001) who used an ant colony system which is a metaheuristic method to optimise disassembly sequences of end-of-life products by considering two optimisation objectives: cost and time.

2.2.3 Multi-criteria analysis technique

Analytical hierarchy process (AHP), ELECTRE and TOPSIS can solve conflicts by pairwise comparison of criteria and alternatives (Ilgin et al., 2015, Remery et al., 2012, Bufardi et al., 2004). However, these approaches require considerable time and comparisons of criteria (Remery et al., 2012).

The analytical hierarchy process (AHP) is a method to weight tangible and intangible factors (Ilgin et al., 2015). It is the most common method used in the multi-criteria decision-making process in the literature review, however, AHP uses weighting systems on a scale which give subjective result (Ilgin et al., 2015). For example, AHP is used for the selection of a remanufacturing technology portfolio (Jiang et al., 2011), and EOL strategy of the components of returned products (Ziout et al., 2014, Ghazalli and Murata, 2011).

In contrast, ELECTRE uses intrinsic value to weight criteria (Remery et al., 2012). For example, ELECTRE is used to select the best recovery options for end-of-life products by considering economic and environmental perspectives (Bufardi et al., 2004). According to

ELECTRE, there are three parameters for each criterion including the indifference threshold, the preference threshold and the veto threshold. These parameters are considered as uncertainties to assess alternatives (Bufardi et al., 2004). However, ELECTRE only gives a partial ranking for alternatives (Remery et al., 2012).

The TOPSIS method has been frequently used to manage environment and waste (Gumus, 2009, Vinodh et al., 2012, Siba Sankar et al., 2013). For example, Remery et al. (2012) evaluated the best product end-of- life strategy during the early design phase by using TOPSIS. The shortest distance to the best and the longest distance from the worst alternative are compared for each alternative (Ilgin et al., 2015, Remery et al., 2012).

The Pareto method is also a common method to manage conflicts for multiple aspects by considering every perspective at the same time. The Pareto optimal solution has been used in tradeoff decision-making involving more than two aspects such as social impacts, recovery profits and energy savings (Meng et al., 2017a). According to real practice, it requires immediate decision-making for recovery processes, therefore the Pareto optimal solution might be an effective tool for an EOL options strategy (Shokohyar et al., 2014, Hula et al., 2003, Takeuchi and Saitou, 2006, Yang et al., 2016b).

Ziout et al. (2014) used a different technique to analyse multi-criteria problems. They used PESTEL analysis (Political, Societal, Technical, Environmental and Legal aspects of an organisation's work environment) as a holistic method to consider all the relevant factors in the decision to rank suitable recovery options and select the best option for end-of-life products. The reason is that PESTEL analysis has been successfully applied as a comprehensive framework for studying a company's macro environment in different business sectors (Ziout et al., 2014).

2.2.4 Grey decision-making

'Grey' decision-making is used for situations which are uncertain. As the characteristics of factors for decision-making in remanufacturing are usually uncertain, the tools for grey decision-making are useful.

Herrera and Herrera-Viedma (2000) showed that fuzzy set theory is commonly applicable for use in decision-making where the information is uncertain (Remery et al., 2012) . The fuzzy logic method changes the designer's opinion and company objectives which are uncertain into related weights which are measurable (Ma and Okudan Kremer, 2015, Remery et al., 2012).

A grey relational analysis approach can rank EOL options according to the degree of uncertainty (Chan, 2008). This method includes partly known and partly unknown information. Also, it can measure the similarity and differences of two data sequences which do not show a clear linear relationship. A grey relational analysis calculates the grey relational coefficients and grades of each component for EOL options (Chan, 2008).

The case-based reasoning (CBR) is a quick approach to find the best EOL option without the need for the decision of an expert. CBR used the nearest neighbourhood (NN) algorithm to find the similarity between the previous information and the current situation (Ilgin et al., 2015 and(Ghazalli and Murata, 2011). (Ghazalli and Murata, 2011) used an NN algorithm to set the goal value. If the algorithm found the value of any case is less than the setting value, the returned product is not remanufacturable (Ghazalli and Murata, 2011).

The maximum entropy principle is commonly applied in engineering and business models when probability distributions of random variables are estimated from incomplete information (Pandey and Thurston, 2009). It can help to minimize assumptions over what is already recognized. An example of the applicability of this tool is shown in (Pandey and Thurston, 2009). The effective age of remanufactured products is shown as a curve of maximum entropy value degradation. This curve lay between the maximum and minimum bounds of the information distribution without preference of a maximum or minimum value.

A sensitivity analysis is used to study the effect of uncertain factors considered in remanufacturing. For example, Pazoki and Abdul-Kader (2016) used a sensitivity analysis to study the effects of changing the values of primary selling prices, remanufacturing rates, salvage values and deterioration rates on the decision about the optimal number of units to be remanufactured or salvaged.

2.2.5 Failure analysis

FMEA (Failure modes and effects analysis) is used to analyze the frequent failure mode of automotive waste which can help to support the design of remanufactured products (Murayama and Shu, 2001). RPN (Risk priority number) is a frequently used method to prioritise tasks. RPN is the product of REP (Repairability), OCC (Occurrence) and DET (Detectability) as established by Murayama and Shu (2001). It was used to improve the remanufacturing and reusing of returned products through design and management. Products with the highest RPN show the highest risk, therefore they require the most urgent solutions.

2.3. Summary of Chapter 2

This chapter has reviewed and discussed the literature on how to optimise remanufacturing outcomes, and the methodology used in multi-criteria decision-making. The author found that there are opportunities for further research areas as following.

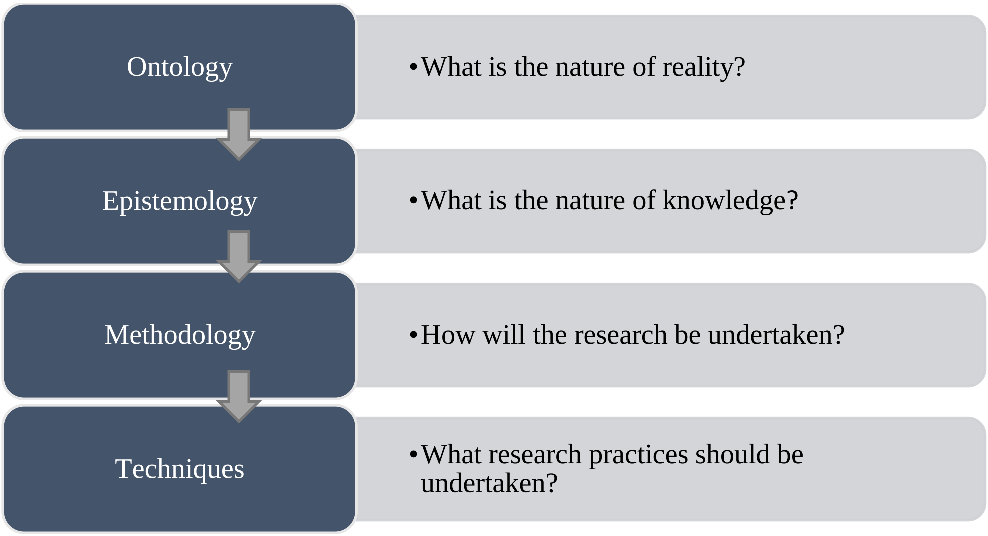
- Further research should study integrated decision making of the optimal number of components/products for each of the remanufacturing activities and recovery options.
- The decision making should consider multiple objectives including economic, engineering and environmental objectives simultaneously.
- Further research should study availability, demand, quantity of components/products, lead time, component commonality and recovery rate which are under-studied but important factors in the decision-making of remanufacturing.

The findings from this chapter had an influence on the research design and methodology which will be discussed in Chapter 3. Moreover, the research gaps can raise questions which will be answered by the results of work described in Chapters 4 to 6.

Chapter 3 Research design

3.1 Introduction

This chapter aims to provide an overview of the approach taken in order to develop the research methodology including the selected research methods and tools plus how the data was collected and analyzed. It is important to develop an appropriate research design and to select a suitable research method and tools in order to obtain valid information to guarantee research quality (Edmondson and McManus, 2007). A diagram of the design used for the research strategy using building blocks is presented in Figure 3.1.



Source:(Simpson, 2019)

Figure 3.1 Research strategy design with building blocks

3.2 Philosophical approach of the research

According to Creswell (2017) and Easterby-Smith (2012), the qualitative and quantitative paradigms are the two main paradigms which form the basis of research design. The qualitative paradigms and quantitative paradigms have their origins in phenomenology and positivism respectively. Phenomenology and positivism have five different philosophical concepts: ontology, epistemology, axiology, rhetoric and methodology which affect research design (Gummeson, (1993).

3.2.1 Ontology

Ontology is related to the nature of reality (Gummeson, (1993, Creswell, 2017). A specific paradigm will conclude what is a fact. In order to know a fact, this research needs to ask two questions: what type of information must be collected and how the information is obtained. This question will also lead to other questions such as data is analysed and to some degree how the results will be presented. Therefore, the validity of the research findings depends on the ability of the researcher to show consistency between the findings and the reality. Gummeson (1993) explained that quantitative research requires only non-subjective data to gain knowledge. In contrast, qualitative research assumes that reality is subjective and constructed by the persons involved in the research. Creswell (2013) suggested that for the qualitative paradigm, each person involved in the research has a different perception of the situation. Each perception is equally important, therefore, each participant's viewpoint is equally important when used in collecting and analysing the research data.

3.2.2 Epistemology

Epistemology is related to the nature of knowledge and the things that can be known (Creswell, 2017, Meredith *et al*., 1998). Therefore, it determines the relationship between the researcher and those being studied. The quantitative paradigm assumes that in order to acquire knowledge, it is necessary to use proven rules and logic. Consequently, the evidence of the research is more likely to be assessed objectively. In contrast, the nature of qualitative research requires the researcher to interact with those being studied, so the researcher will obtain subjective knowledge. Also, the subjective opinions of those being studied can influence the perception of the researcher.

3.2.3 Axiology

According to Agazzi (2015), axiology is concerned with human values which affect perception, actions and decisions. Axiology assumes that quantitative data is collected and analyzed without the researcher's personal views or values while qualitative research is concerned with the effect of human values on the researcher and those being researched.

3.2.4 Rhetoric

According to Creswell(2007), rhetoric refers to the language of research communication.

The author explains that quantitative research uses objective data and is often expressed by mathematical formulae. Also, the language used in quantitative research is typically formal, precise and impersonal. Whereas, qualitative research uses subjective and personal data, and can often be expressed in a more informal and descriptive style.

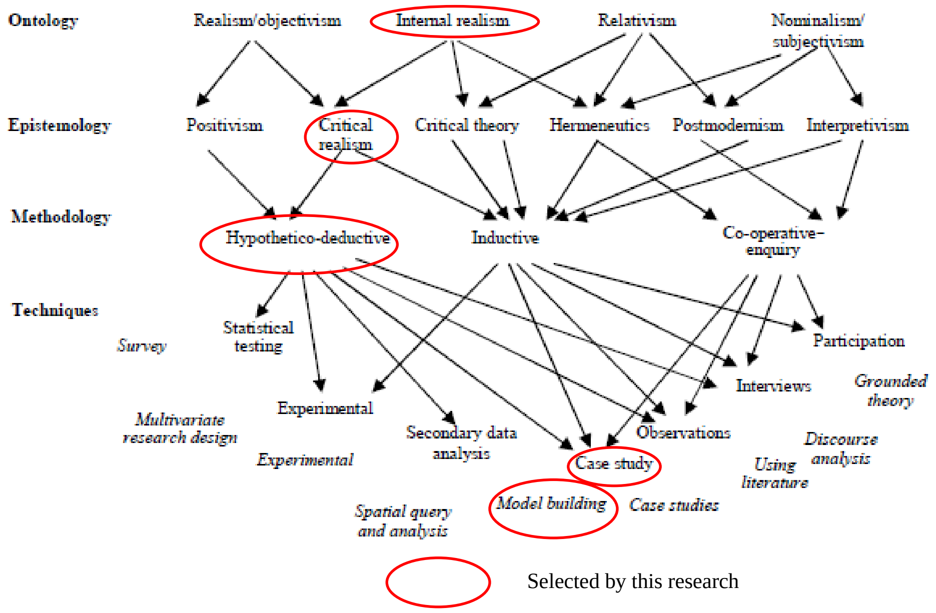
3.2.5 Methodology

Methodology describes the research process. The objective of the research methodology is to demonstrate an effective structure by complementing the philosophical concepts in the research design (Easterby-Smith et al., 1993, Creswell, 2013).

Where methodology is considered, the ontological issue is the most important philosophical concept because it will control the type of data collected, the data collection, the interpretation method and the presentation of the research findings. Therefore, an effective research design must show a consistent thread across all the five philosophical concepts specified above, namely, ontology, epistemology, axiology, rhetoric and methodology.

3.2.6 The relationship between ontology, epistemology and research methods

Research methods are a set of techniques for data collection and data analysis to investigate a situation (Easterby-Smith, 2012, Croom, 2008). A researcher who decides to choose a particular ontology must select a complementary epistemology. Any particular epistemology will lead the researcher to use certain methods and techniques as shown in Figure 3.2 below.



Source: adapted from Easterby-Smith et al. (2012)

Figure 3.2 The relationship between ontology, epistemology, methodology and techniques

Before describing the justification of each choice, the following paragraphs describe the definitions of the selected ontologies, epistemology, methodology and techniques.

3.2.6.1 Selected ontology

Internal realism

Proponents of this ontology believe that it is almost impossible to gain all the facts within the truth. It needs the researcher to reveal findings by obtaining the facts from studies and interpreting them into the truth (Easterby-Smith, 2012).

3.2.6.2 Selected Epistemology

Critical realism

Proponents of this epistemology believe that truth exists and the research should make efforts to discover findings. Critical realism is better than positivism in terms of the ability to identify similar patterns in cases (Easton, 2010) because positivism cannot identify them.

3.2.6.3 Selected Methodology

Hypothetico-deductive

This method refers to the scientific method which requires several steps of reasoning and observation to produce and test proposed explanations (i.e., hypotheses and/or theories) of questioning interpretations in nature (Lawson, 2015). The purpose of the method is to extract useful information and provide accurate prediction of future situations.

3.2.6.4 Selected techniques

Case study

A case study has different meanings which were defined by Gerring (2006).
‘To refer to a work as a “case study” might mean: (a) that its method is qualitative, small-N (with a small number of cases), (b) that the research is holistic, thick (a more or less comprehensive examination of a phenomenon), (c) that it utilises a particular type of evidence (e.g., ethnographic, clinical, non-experimental, non-survey-based, participant-observation, process-tracing, historical, textual, or field research), (d) that its method of evidence gathering is naturalistic (a “real-life context”), (e) that the topic is diffuse (case and context are difficult to distinguish), (f) that it employs triangulation (“multiple sources of evidence”), (g) that the research investigates the properties of a single observation, or (h) that the research investigates the properties of a single phenomenon, instance, or example.’ In order to avoid confusion of the definitions of case study in this research, case study in this study means the qualitative method which uses interviewing, observations and documents as multiple evidence to obtain

a better understanding of the phenomenon in real practice of a small number of case study companies.

Mathematical modelling

Mathematical modelling is the technique of interpreting issues from an application area to mathematical formulations which is tractable (Neumaier, 2004). The hypothetical and numerical analysis of mathematical modelling gives knowledge, answers and direction for the users. Mathematical modelling can give accuracy and enables an intensive understanding of the framework modeled, plans the better way to design or control a system by utilising modern computing capabilities.

After giving the definitions of selected ontology, epistemology, methodology and techniques, this paragraph describes the justification of these choices.

The objectives of this research are to identify the factors and decision sequences that can be used to optimise the value of remanufacturing products, to develop a model to find the best recovery options for components and find the optimal number of products and components for each remanufacturing activity. Internal realism is therefore the chosen ontology because the author of this study believes that before developing a new theory, it is necessary to explore the existing facts to extend the theory. In order to develop the decision model to solve new problems of remanufacturing, it is necessary to discover the decision factors and decision sequences which are facts which already exist. Also, these facts require the efforts of the researcher to reveal them, therefore, critical realism is selected. Hypothetico-deductive was the selected methodology because this method uses multiple times of reasoning and observation to test the new theory developed by this study. Regarding the selected ontology, epistemology and methodology, most techniques could be selected. However, a case study and mathematical modelling were selected for this study as seen in Figure 3.2. This study used a case study because it is a suitable empirical approach to study in-depth details of a phenomenon. A case study approach was used to understand the decision making in automotive remanufacturing through interviews, observation and documents. The results from the case studies were the decision factors and decision sequences used to develop a decision-making framework to optimise the remanufacture of automotive components. Mathematical modelling was used to test the qualitative decision-making framework. Such a quantitative method can provide a high precision of the variables in the decision model. Therefore, the combination of these techniques can enhance the ability to conduct research from various perspectives. This can lead to a higher quality of the decision model which is the research's output.

3.3 Research methodology

According to Creswell (2013), there is an obvious distinction between philosophical paradigms. This leads to different research methods, which are qualitative or quantitative and which have different advantages and disadvantages. This research adopted a qualitative and quantitative method known as the mixed method for two reasons:

1. The research questions mentioned in 1.10 of Chapter 1 need qualitative and quantitative answers. Therefore, this study's research questions cannot be adequately addressed by qualitative or quantitative research alone.
2. A mixed approach leads to the robustness of the research (Creswell, 2017). It will provide more insights because it can cover the depth and breadth of the problem. In the case of qualitative research, subjective information can draw a rich picture that helps the researcher to produce a conceptual framework to explain the phenomenon where there is a lack of existing theories which are capable of defining a specific situation. After establishing a conceptual framework, quantitative research can be used to test theories and hypotheses in a cause-and-effect order.

In this study, the research questions need exploration of decision factors and decision sequences in remanufacturing by a qualitative method (case study) to extend the existing decision-making framework because there are new threats or opportunities for remanufacturing business which previous studies may not have covered. Moreover, the quantitative method (mathematical modelling) was used to confirm the interpretation of the qualitative analysis and to extend the qualitative findings.

3.3.1 Process of mixed methodology

The sequential exploratory strategy which is one of the mixed method strategies is selected for three reasons. Firstly, this strategy is suitable for evaluating the elements of emerging theory from the results of a qualitative phase by using quantitative data and results (Morgan, 2016). Secondly, this design is often used when the researchers develop new tools because existing tools are not available for the new problems (Creswell, 2017). Thirdly, qualitative findings can be generalised from multiple samples and the researcher can determine the distribution of a phenomenon within a chosen population (Morse, 1991). This study adopted this research strategy by collecting and analysing qualitative data (decision factors, decision sequences, issues in automotive remanufacturing) to extend the existing theory. Moreover, this study used the analysed results to develop a qualitative tool (a conceptual framework to optimise the remanufacture of automotive components - see Figure 4.1) and test a tool with a sample of a population through mathematical modelling.

By following the sequential exploratory strategy, the process of a mixed methodology can achieve these research objectives as can be seen in Figure 3.3. The detail of the tasks of each process in a mixed methodology is described in Table 3.1.

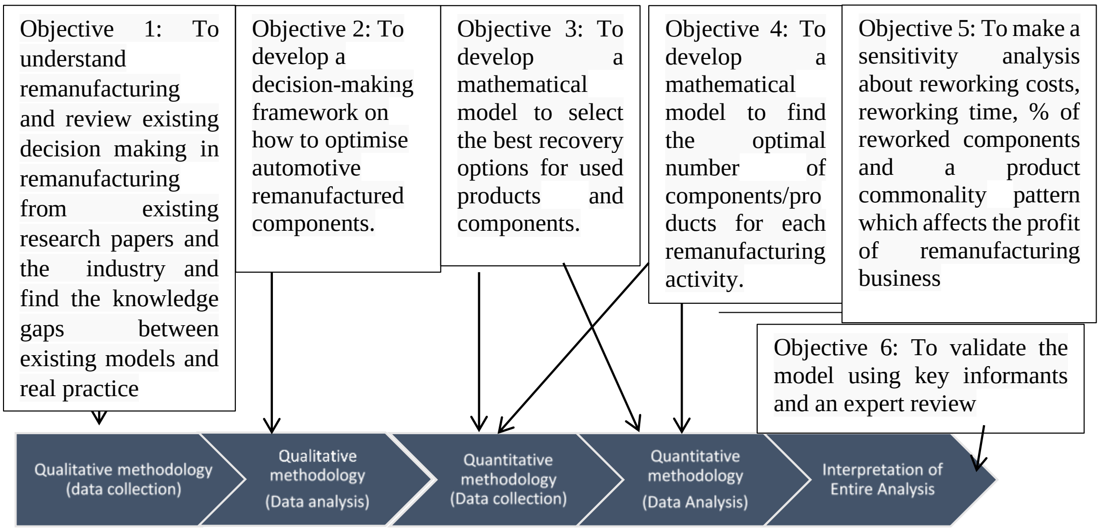


Figure 3.3 The process of mixed methodology and achieved goals

Table 3.1 The details of tasks for each process in a mixed methodology approach

Process of developing a decision-making framework	Detail of tasks
Qualitative methodology (data collection)	1. Understood remanufacturing through literature review and observation of remanufacturing companies 2. Reviewed all decision factors in remanufacturing from literature / industry 3. Interviewed respondents about alternatives for recovery options and steps in decision-making
Qualitative methodology (Data analysis)	1. Refined factors used in decision-making on recovery options 2. Developed the decision-making framework on how to optimise remanufacture profit, remanufacturing time, remanufacture reliability and reusable mass of components in the automotive remanufacturing
Quantitative methodology (Data collection)	1. Found cost, time, revenue, reusable mass to use in computation in goal programming

	from companies, secondary data from previous research, commercial website such as Alibaba, e-bay.
Quantitative methodology (Data Analysis)	1. Selected the best recovery options by goal programming to • Maximise recovery profits • Maximise reusable mass of components (kg) • Minimise operational time • Maximise reliability of components 2. Found no. of required components/ products in each activity of remanufacturing 3. Studied sensitivity analysis about reworking cost, reworking time, percentage of reworked components and component commonality patterns which affect the profit of re-manufacturing business
Interpretation of entire analysis	1. Reported the qualitative findings 2. Reported the quantitative results

Initially, the decision-making factors in remanufacturing were found from reviewing the relevant literature and case studies. Also, recovery options and steps in decision-making were discussed with 5 case study companies. The details of each case study are shown in Table 3.2. The information obtained from the case studies combined with the answers from management teams and operational engineers because they have ability to make the decision therefore it enhanced the internal validity of this research. Next, the decision factors were refined by removing similar items on the lists. Then, the decision-making framework for optimising automotive remanufacturing was developed from the final factors. Optimising in this instance means maximising profit, minimising time, maximising the reuse rate of the material and maximising the reliability of components. The author developed a mathematical model and used quantitative data as input to help the interpretation of the decision-making framework. Point allocation was used to give an importance score for each factor. The importance score for each factor was obtained from the expert opinions of directors, managers and production engineers involved in decision-making process in remanufacturing. The sources of information about cost, time, revenue, reusable mass were the remanufacturing companies , previous studies, and commercial websites such as Alibaba and e-bay. If real data was not possible, this study used secondary data or assumptions agreed by the remanufacturing experts. After inputting all the values into the model, goal programming was used to solve two questions: 1. The best recovery options of components 2. The number of required components/ products in each remanufacturing activity. Moreover, this research study used a sensitivity analysis of reworking cost, reworking time, percentage of reworked components and the component commonality patterns which affect remanufacturing profits because remanufacture has high level of uncertainty in real practice. After validating the findings by reviewing them with the help of experts, the author was able to conduct a complete analysis of this research.

Table 3.2 The detail of each case study

Case study	Products	Type of remanufacturer	Position of key informants
A	Engine	OEM, contract	Production manager
B	Engine	IR, Contract	Director, Senior manager, production engineer, MRP management staff and shop-floor staffs
C	Engine	IR	Director, manager
D	Transmission	IR, Contract	Director
E	Fuel injection	IR, Contract	Director, Manager

The details of the qualitative and quantitative methods are provided in Sections 3.3.2 and 3.3.3.

3.3.2 The Qualitative Method and its justification

Case study method was selected because it is suggested by Meredith (1998), Chetty (1996) and Eisenhardt (1989) as an effective method for qualitative research. Also, Yin (2014) proposed that case studies help to obtain holistic and meaningful characteristics of organisational and managerial procedures. Furthermore, the case study has many advantages in building a theory. Since multiple sources of information are required for analysis, the researcher can develop a rich picture of the phenomenon from various perspectives (Gummeson, 1993, Romano, 1989, Chetty, 1996). Since the emergent theory has been tested by various sources where the research was conducted, it can enhance the credibility of the research findings (Lang, 1994, Romano, 1989).

3.3.3 Selected quantitative techniques and justification

Mathematical modelling is a quantitative technique used in this study because it determines a system's behaviour in a controlled environment under several scenarios (Meredith 1998). This method is frequently used in operational management to obtain an optimal solution for problems in different situations.

Mathematical modelling was used to reinforce the decision-making framework by letting users to input data in the model. The results change depending on the input. After that, the results of trials were validated by experts. Mathematical modelling can solve 3 questions: 1. The best recovery option for components with specific faults, 2.The optimal number of components needed for each of the remanufacturing activity in order to enhance the operation performace and 3. A sensitivity analysis of the reworking costs, reworking time, percentage of reworked components and the component commonality patterns which affect remanufacturing profits. The quantitative tools used to achieve these solutions are point allocation, goal programming and sensitivity analysis.

This research involved multi-criteria decision making (MCDM), which could give better solutions since it is a holistic method which not only uses economic factors but also environmental and engineering factors. In addition, the nature of an optimisation analysis is usually stochastic with simulated based models and involving complex calculations to determine the theoretical knowledge which may not always be applicable in real practice. However, the management of recovery options has no theoretical mathematical background, therefore, the models require various assumptions. Inaccuracy between assumptions and real practice in recovery options may lead to making the wrong decisions. Since decision-making in remanufacturing can be uncertain, subjective judgement may be necessary to discover solutions (Özcan et al., 2017). Point allocation-goal programming has not been used to select recovery options in remanufacturing but this study will use point allocation together with goal programming since the proposed framework is developed holistically rather than on an ad hoc experience-based approach. Also, point allocation will use the subjective results from experts who derive lesson learned from previous mistake to reduce the inaccuracy of the assumptions.

Table 3.3 shows the differences between AHP (Analytical hierarchy process) and point allocation. AHP, the most common method used in multi-criteria decision-making process in the literature review can solve the conflict by a pairwise comparison of criteria and alternatives (Ilgin et al., 2015). However, AHP require considerable time and many comparisons between the criteria (Remery, 2012). Point allocation is used for weighting factors in this project since computation is easier than AHP. Also, it is user-friendly because it allows decision makers to make trade-offs (Deng et al., 2000). Point allocation allows participants to allocate 100 points between the criteria. Researchers have suggested that this method could be inappropriate if there are more than 6 criteria, and this project has less than 6 criteria for participants to use to make decisions. Mustajoki et al. (2004) recommended that a simple point allocation system is suitable with a small number of criteria. Also, Winterfeldt and Edwards (1986) pointed out that the point allocation method was more trustworthy than direct rating in a test-retest situation. Point allocation has been used successfully in various fields of management, for example, water resources management (Yurdusev and O'Connell, 2005), material selection (Rao and Patel, 2010) and industrial robot selection (Rao et al., 2011).

Table 3.3 The differences between point allocation and AHP (after RPA 2004) adapted from Zardari (2015)

Method	Information	Result	Transparency	Computation	Costs
Point allocation	Quantitative	Distance to target/ranking	Medium	Simple	Low
AHP	Qualitative	Performance scores/ranking	low	Complex	Medium

Goal programming (GP) is an effective tool for trading-off several conflicting objectives such as maximizing profit and minimizing environmental impacts in the decision-making process. GP is a practical MCDM method since it has the ability to choose an infinite number of alternatives. Also, it can be used for large scale problems. It is frequently used for production planning problems (Aalaei and Davoudpour, 2016), and generally, it is used together with MCDM techniques such as AHP (Trivedi and Singh, 2017), TOPSIS (Chi and Trinh, 2016), PROMETHEE (Yilmaz and Dağdeviren, 2011) and ANP (Lee and Kim, 2000). Therefore, this study used GP together with point allocation which is one of the MCDM techniques.

Sensitivity analysis is one of the acceptable quantitative tools for model validation (Cumming et al., 1976, Henderson and Nutt, 1980, Landry et al., 1983). According to Saltelli (2002), sensitivity analysis can help to investigate uncertain quantification. This tool studies the effects of changing inputs on model behaviors and their output (Landry et al., 1983, Beisbart and Saam, 2019, Saltelli, 2002). It is used to obtain reliable results and valuable information and can also increase the credibility of the results from the model (Saltelli et al., 2008, Campolongo et al., 2007, Law and Kelton, 1991).

3.3.4 Design of case study

According to Yin (2014), a research design is not only a plan on how to conduct the research but also shows the link between the empirical findings and the research questions. Between the research questions and their answers, there are logical explanations to link the two of them. The question of this research is: What are the factors that affect decision-making in remanufacturing. Many researchers (McCutcheon and Meredith, 1993, Voss et al., 2002) have recommended that the existing literature could help the researcher to have a better research direction. New findings may be obtained when the case study is conducted (Eisenhardt, 1989), or the findings may reinforce existing knowledge.

As seen in Figure 3.4, in a deductive procedure, the findings from the existing literature were reviewed to develop a conceptual framework before collecting empirical data from case studies. The empirical findings from the case studies are used to assess the existing factors in the framework to find out whether they can be confirmed or not (Christensen, 2006, Eisenhardt and Graebner, 2007, Creswell, 2013). Furthermore, an inductive procedure was used to expand the new factors (Creswell, 2013) and this would be repeated continuously until the results are saturated (Siggelkow, 2007).

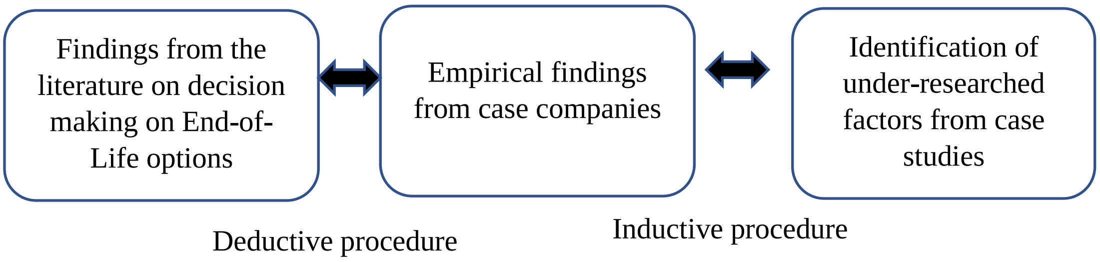


Figure 3.4 The inductive and deductive procedures of this research (Priyono, 2015)

This study used information from the case studies because they are useful to develop theory in operations management (Voss et al., 2002). The information can be used to validate previous empirical studies and study topics more deeply. Since this research area is relevant to operational management which is developing continuously, case studies are suitable to investigate emergent practices.

There are several procedures to conduct the case studies as shown below: (Voss et al., 2002, Eisenhardt, 1989, Yin, 2014, Priyono, 2015).

- Procedure 1: Selecting the objective of the case study

It is necessary for the researcher to identify the objective of the case study and justify why that particular case study has been selected. Case study is used in the numbers of including exploration of under-researched areas, building theory, testing theory and extending/refining theory (Eisenhardt, 1989, Meredith, 1998, Voss et al., 2002) as follow:

1. Exploration – to discover research areas for theory development

2. Theory building- to indicate key variables, the relationships between variables and to explain how these relationships were established

3. Theory testing - to test the early-stage of theories and forecast further results

4. Theory extension/refinement- to improve the existing theories from the observed results

This research used case studies for two objectives:

1. Exploration of an under-researched area

Case study can be used to explore and get a better understanding of emergent knowledge (Flynn et al., 1990, Meredith, 1998). This will enable the researcher to present new knowledge clearly, for instance, to identify the factors that affect the processes (McCutcheon and Meredith, 1993).

2. Theory extension

Case study is used to develop theory from existing evidence. Meredith et al. (1998) and Yin (2014) suggested that theory developed by case studies can be used in various situations to forecast different results. If the theory has been tested in different situations and different populations and the theory is still holds , the developed theory is more relevant than before and can be claimed as theory extension (Meredith, 1998).

- Procedure 2: Gaining access to the case study companies

The potential case study companies were selected from university contacts and search engine results. Then, these companies were contacted by telephone, e-mail, or face-to-face meetings at conferences with the top management of the companies. Next, those managers who were interested in the study were e-mailed a document in order to provide them with information about the research and what kind of support they would be required to provide for the case study. If the company agreed to participate, a company visit was arranged by follow-up phone calls and e-mails.

- Procedure 3: Selecting number of cases

A multiple case study method was selected since it was suggested by Romano (1989), Yin (2014), Chetty (1996) and Eisenhardt (1989) that multiple case studies can help generalise the phenomenon and create theory better than studying a single case only. The reason is that the evidence from multiple sources can be compared. Firstly, it can show similarities between cases that can help to create better understanding of the phenomenon. Secondly, it can test the emergent theory and avoid coincidence. Although, there is no set rule for the number of cases required for multiple case study thus suggestions for the number of cases to be used in a multiple case study vary. In operations and supply chain management, 3 to 11 cases were used as case studies (Pagell, 2004, Wu et al., 2010, Matos and Hall, 2007). Chetty (1996) and Romano (1989) suggested conducting between four and ten in order to obtain enough information to build a theory by generalisation of the case studies while avoiding data overload. Eisenhart (1989) suggests seven cases as the maximum that a person can mentally process. Yin (2014), Eisenhardt (1989) and Gummeson (1993) suggest that data should be collected until the result is saturated. Therefore, this research reviewed the results of multiple case studies until it was clear that significant new findings were no longer emerging implying that there was no need for additional cases. The factors used in decision-making were brainstormed by 5 companies. The list of case study companies is shown in Table 3.4. The decision-making process used in this research requires 2 steps: 1. Select the best recovery options and 2. Find the number of required components/products in each of the remanufacturing activities. The second step in the decision-making process initially used the information from three engine remanufacturers. These three companies include an independent remanufacturer and two contract remanufacturers. The list of companies the authors used for their information as input is presented in Table 3.5.

Table 3.4 Case study companies involved in brainstorming the decision factors using in remanufacturing

Case study	Products	Type of remanufacturer	Position
Company A	Engine	OEM, contract	Production manager
Company B	Engine	IR, Contract	Director, Senior manager, production engineer, MRP management staff and shop-floor staffs
Company C	Engine	IR	Director, manager
Company D	Transmission	IR, Contract	Director
Company E	Fuel injection	IR, Contract	Director, Manager

Table 3.5 Case studies that the authors used for their information as an input for the second step of decision-making

Case study	Products	Type of remanufacturer
Company B	Engine	IR, Contract
Company C	Engine	IR
Company G	Engine	IR, Contract

- Procedure 4: Identifying the criteria to select case studies

Case studies were selected based on the possibility of contributing to new theoretical knowledge (Yin, 2014, Meredith, 1998). If the number of case studies is too great, there may be difficulties in identifying similarities between the cases. Also, if cases are too similar, it would be difficult to conduct cross-case analysis since they show similar characteristics.

Since selecting cases is a vital consideration, the population was a constant factor across the samples. This study's case studies involve automotive remanufacturers who produce high-value automotive components in the UK. The researcher chose to study only the automotive remanufacturing industry because the automotive sector is the largest market in the remanufacturing industry (Steinhilper, 1998), remanufacture is mature there thus it would be possible to obtain adequate information to fuel the research . Also, the UK is one of the leading production locations for the automotive remanufacturing sector. The high-value automotive components were selected for this study because they were important components which can generate a high proportion of income for remanufacturers.

- Procedure 5 : Data collection and analysis

There are six different sources of evidence including documentation, archival records, interviews, direct observation, participant observation and physical artefacts suggested by Yin (2014). These sources of evidence provide opportunities for researchers to conduct two types of triangulation: data triangulation and source of data triangulation (Yin, 2014). Therefore, this research used multiple sources of information including observation, interviews and documents. Multiple sources of data were used to triangulate the evidence. Semi-structured interviews were the main source of evidence. The questionnaires were designed for specific roles in the companies. Many members of staff were interviewed where possible. The interviewed staff held different positions: director, production manager, core manager, production engineer, MRP staff, and shop-floor staff. The second source of evidence was observation through personal guided tours of remanufacturing facilities. During the tours, an engineer and a manager described the remanufacturing activities, the decision- making for each of the remanufacturing activities and the factors affecting the decision-making. Moreover, there was also information such as evidence from documentation such as company brochures, the criteria used to check the quality of cores, websites, industry standards, and contracts between companies and customers. These documents were used to verify the operational factors which were discussed with the interviewees. Table 3.6 shows the details of data collection from the case study companies.

Table 3.6 Details of data collection from the case study companies.

Companies	Date	Method of collection	Duration	Topics addressed	Informants
A	March 2017	Observation, interview, documents	1 hr	End-of-life options, challenges to manage cores, operational strategy to manage cores, decision-making on EOL options, factors in decision-making on EOL options, failure modes, core management	Production Manager
	October 2017		1 hr	MRP planning regarding product family, End-of-life options, environmental factors in the operation, planning disassembly/reassembly of complex products, stability and predictability of factors, operational time	Production Manager
B	January 2018	Observation, interview, documents	1 hr	End-of-life options, challenges to manage cores, operational strategy to manage cores, decision-making on EOL options, factors in decision-making on EOL options, failure modes, core management	Production engineer
	September 2018		4.5 days	Remanufacturing activities, time spent on remanufacturing activities, decision-making in remanufacturing activities, failure modes, additive manufacturing	Director, Senior manager, production engineer, MRP management staff and shop-floor staff
C	May 2018	Observation, interviews, documents	1.5 hr	Material flow, remanufacturing activities, factors used in decision-making for each remanufacturing activity, decision sequence	Director
	June 2018		1.5 hr		Manager
D	April 2017	Observation, interview, documents	1 hr	Material flow, remanufacturing activities, factors used in decision-making for each remanufacturing activity, decision sequence	Director
	October 2017		1 hr	MRP planning regarding product family, End-of-life options, environmental factors in the operation, planning disassembly/reassembly of complex products, stability and	Director

				predictability of factors, operational time	
E	November 2017	Observation, interview, documents	3 hr	End-of-life options, challenges to manage cores, operational strategy to manage cores, decision-making on EOL options, factors in decision-making on EOL options, failure mode, core management	Director, Core manager
G	June 2019	Interview, documents	30 minutes	Production volume, cost and operational time of engine remanufacturing	Director

This research adopted several techniques to present the data analysis as proposed by Miles & Huberman (2014). Firstly, the researcher starts with a description. Then, the research used graphs, tables and figures to give the better presentation of results.

- Procedure 6 : Identifying the output of case study research

The output of the case studies research is a conceptual framework (Eisenhardt, 1989, Yin, 2011). The new knowledge emerges when there are particular findings within and across cases. Iterations between the findings are required to develop new theory (Eisenhardt, 1989).

- Procedure 7 : Identifying how to guarantee the quality of the research

There are strategies to guarantee research quality including validity evaluation (Flynn et al., 1990, Yin, 2014) and the use of triangulation (Yin, 2014, Easterby-Smith et al., 2002).

In order to guarantee the quality of the research, this study was conducted through several assessments which were (Yin, 2014, Flynn et al., 1990):

1. Construct validity: identifying the right measurement for studied concepts
2. Internal validity: identifying causal relationship between concepts
3. External validity: establishing the field to generalise the main findings
4. Reliability: ensuring that the study can be repeated and show the same results

Table 3.7 demonstrates the relationships of validity assessment, the techniques, how this study applied the techniques and the research phase which applied the techniques

Table 3.7 The validity assessment of this research

Validity assessment	Techniques	Techniques Applied	Research Stage
Construct validity	Multiple sources of evidence	Multiple sources of information including observation, interviews and documents	Data collection
Internal validity	Pattern matching	Comparison of empirically based pattern with a predicted pattern	Data analysis
	Explanation building	Build general explanation from several cases	Data analysis
	Logic models	Matching empirically observations to theoretical predictions	Data analysis
External validity	Replication logic in multiple case studies	Findings tested by multiple case studies showing same results	Research design
Reliability	Case study protocol	This research followed rule 3.3.4 in page 59-65 on the research questions, research objectives, the number of case studies, and criteria to select case studies and data collection	Data collection

3.3.5 Review of results by experts

This research used experts to validate the results of the research since case study has proven effectiveness in remanufacture research, such as Ridley (2013), Ijomah et al. (2004) and Priyono (2015).

The first step in the decision-making process was validated by 10 participants as shown in Table 3.8. Firstly, the validation was arranged at the International Conference on Remanufacture 2019 (ICoR2019). The participants were 3 different persons from industry and 5 remanufacture academics. After developing the model from their comments, the first step in the decision-making was tested by an additional two persons from the remanufacturing industry and it was found that the results were saturated. For Step 2 in the decision-making, 4 companies were involved in the validation. Two of these companies were different from those who provided the information for modelling. The validation of the second step was stopped when the 4 companies reviewed the model because the results were found to be the same which satisfied the experts from industry that the simulation results were reasonable. Table 3. 9 shows the participants who were involved in the validation of the second step in the decision-making process.

Table 3.8 Companies/institutions involved in the validation of the first step in decision-making: Selection of the best recovery options

Validation at the conference			
Company/Institution	**Products**	**Type of remanufacturer**	**Position**
Persons from Industry			
Company B	Engine	IR, Contract	Senior production manager
Company F	Engine	OEM	Production engineer
Company G	Engine	IR, Contract	Director
Academics			
Linkoping University			Remanufacture academic
Linkoping University			Professor with focus on industry-led remanufacture research as well as knowledge transfer to the remanufacture industry
University of Brighton			Principal lecturer specializing in remanufacturing research and knowledge transfer
Hochschule Trier, Umwelt-Campus Birkenfeld			Remanufacture researcher
Universidad de la República			Assistant Professor / remanufacture academic
Validation after the conference			
Company/Institution	**Products**	**Type of remanufacturer**	**Position**
Company B	Engine	IR, Contract	Production Engineer
Company H	Engine (Marine)	IR, Contract	Quality Manager

Table 3.9 Companies involved in the validation of the second step in decision-making

Case study	Products	Type of remanufacturer	Position
Company B	Engine	IR, Contract	Production Engineer
Company G	Engine	IR, Contract	Director
Company H	Engine (Marine)	IR, Contract	Quality Manager
Company I	Engine cooling system	IR, Contract	Sales Director

The validation criteria for the model in the research were sufficiency, clarity and suitability (Landry et al., 1983, Ijomah, 2002). Therefore, these criteria were used to validate step 1 in the decision-making process. According to the suggestion from Rocco et al., (2003), the author used semi-structured and structured questions for validation. Those questions were closed-ended questions with numerical answers and open-ended questions. The author used this approach because a variety of questioning methods can answer specific problems to match the needs of stakeholders. Moreover, the mixed data (qualitative and quantitative data) was taken to increase the ability of the author to describe and analyse the validation data using different types of data collection methods.

After validation of Step 1, the author used the same method to validate Step 2 but with some modifications. It was found that the validation of Step 2 was improved from the validation of Step 1 as follows:

1. 4 criteria of reasonableness of simulation results, clarity of the model, sufficiency of the model, and applicability of the model were used in the validation of Step 2.

1.1 Applicability which is a part of suitability, but has a more specific meaning. Applicability was recommended to be a criterion in the simulation model.

1.2 Reasonableness of the simulation results was used in validation. Determining how representative the output data are is one of the validation techniques for a simulation model (Beisbart and Saam, 2019, Law and Kelton, 1991). This validation technique was adopted for Step 2 because the model considered only 2 main components to simplify the modelling while in reality an engine comprises hundreds of types of components. If the proposed system is not similar to the existing system or the existing system shows no definitive output, the experts who are specialized in the system are required to review the simulation output for reasonableness (Law and Kelton, 1991, Beisbart and Saam, 2019, Cohen et al., 1998). This technique is suitable for no-data situations or applications with high uncertainty regarding model parameters, variables and structure because the reasonableness of the simulation results is more significant than their accuracy in this situation (Beisbart and Saam, 2019). Also, the simulation result from this type of situation was suggested to use a touchstone benchmark which has no strict metrics for measurement. Usually, the validation can be achieved by a qualitative approach to measure the reasonableness of the simulation result.

2. Although there is no specific rule as to how to measure these 4 criteria (reasonableness of simulation results, clarity of the model, sufficiency of the model, and applicability of the model), the author selected an approach based on the nature of the criteria. The reasonableness of the simulation results was measured by remanufacturers scoring them because the remanufacturers are specialists in the area who always notice the operation in remanufacturing, thus they can measure how the simulation result is reasonable. Other criteria can include clarity, sufficiency and applicability of the model which are described by qualitative data since the nature of these criteria require qualitative techniques for understanding the detailed information which is complex.

3. The author used a qualitative approach in the validation of Step 2 by asking the participants detailed information about how to improve the model in terms of clarity, sufficiency and applicability. Although Step 1 was validated by the clarity, sufficiency and suitability of the model through quantitative evidence (i.e. the scores given by the experts) and qualitative evidence (detailed information about how to improve the model), the author found that the qualitative data was useful to help the author to improve the model.

3.3.6 Simulation Model

Simulation is a common analytical modelling method in operations research (Meredith, 1998). It consists of a conceptual model expressed in terms of equations which contain multiple parameters. The simulation in this study is deterministic. After changing the value of the factors, the simulation was rerun to see the effects (Meredith, 1998).

3.3.6.1 Measurement criteria for the model

In some situations, the parameters are assumed in the model rather than being obtained from real data, this can reduce the similarity of the model to real practice (Law and Kelton, 1991). Therefore, it is necessary to measure the quality of the model to ensure that it can simulates reality closely. There are three criteria which need to be applied to the simulation model.

1. Verification - This criteria checks whether translation of the conceptual simulation model (eg. flowcharts and assumptions) is correct (Law and Kelton, 1991).

2. Validation - This criteria checks whether the model has reached a set benchmark or not (Landry et al., 1983).

3. Credibility - This criteria checks whether the simulation model and its results are acceptable to the manager/client. The model should be valid, and can be used in decision-making (Law and Kelton, 1991).

3.3.6.2 Procedures for developing a simulation model

The procedures to develop a simulation model, suggested by Law and Kelton (1991), include 4 procedures, (collect and analyze data, construct and verify the program, run the model and analyse the output and finally sell results to industry), with five steps for developing the simulation model. These steps are conducting case studies from real practice, developing a conceptual model, simulating the program, correcting results and implementing results. Figure 3.5 illustrates the relationship between the procedures, the measurement criteria and the stages for developing a simulation model.

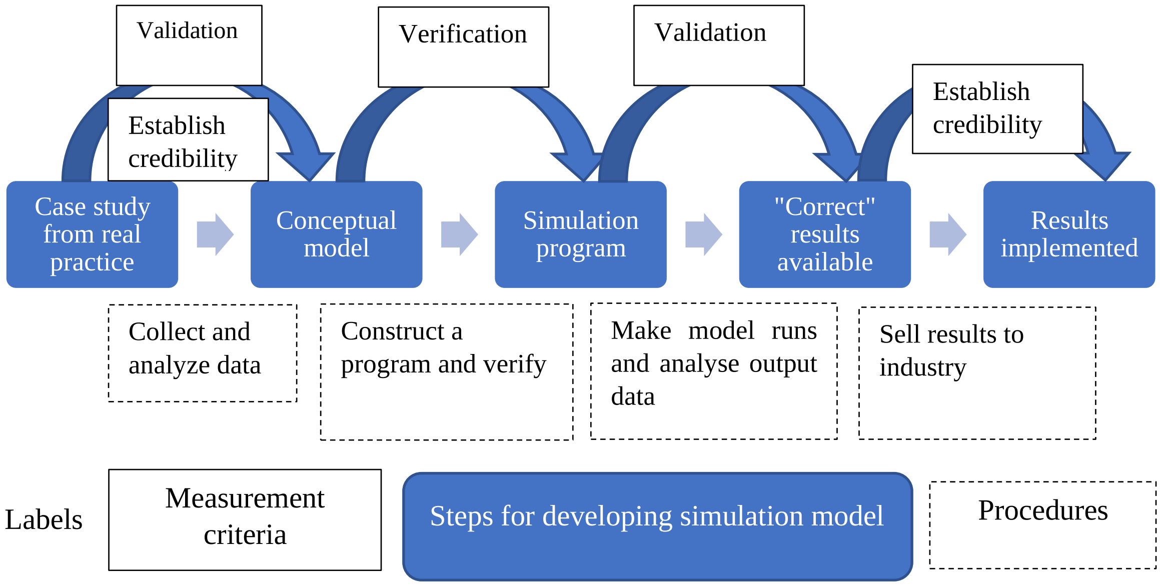


Figure 3.5 Procedures for developing a simulation model (Law and Kelton, 1991)

1. Collecting and analyzing data to develop a conceptual model

In the first step, information is collected and used to identify operational procedures and the range of data value in the model. A model should contain only enough detail to capture the principle of the system. In order to build the conceptual model, the modeler needs to discuss the conceptual model with the people who work in the operation of the actual system. Also, it is necessary to interact with the decision-makers. These actions increase the validity and the credibility of the model by ensuring the assumptions of the model are accurate, complete and consistent.

The methodology used to check the validity of information from the case studies is triangulation of information and key informants (Stake, 1995, Creswell, 2007, Romano, 1989, Gummeson, 1993). The triangulation of information can help support the development of the theme by using multiple sources of information (e.g. observations, interviews and documents). Romano (1989) suggested that triangulation requires a minimum of three different methods to be effective. Since no one has all the required knowledge to answer all the questions, the study requires multiple key respondents including directors, production managers, and production engineers from each of the participating organizations because they are the key persons who can make a decision in remanufacturing (Voss et al., 2002).

Thus, this study involved three different data collecting methods via semi-structured interviews, direct observation and company documents analysis . Also, the author interviewed employees of the organisations from three different levels, including directors, managers and production engineers.

2. Constructing and verifying a program

The author decided that Excel was the most appropriate program to use since it is a user-friendly, powerful program which can solve optimisation problems through goal seeking with shorter execution times. After using the program, it was necessary to verify the simulation model. The simulation was run under various settings of the input. Then the output was checked to see whether the results were reasonable. The simulation model performance was checked by running it to with simplified assumptions. If the estimates were very close to the true values, then there was some confidence that the computer program was correct.

3. Making a model run and analysing the output data.

This procedure can help the modeler to see the results after the simulation.

4. Selling the results to industry representatives.

Since industry representatives understand the operation and have expertise in the field, they should be responsible for testing the simulation results. Testing the model with real data can provide the closest simulation of real practice. However, sometimes the information required for this is not accessible**.** Also, at the early stage the proposed system is not similar to the real life system, so similar results cannot be obtained. However, there are some alternatives that can be used to develop a valid and credible model which include the four following steps:

1. Develop a model with high face validity

If possible, the modeler is required to obtain operational information from machine operators, manufacturing and industrial engineers, managers, vendors and blueprints. Also, secondary data and existing theory are valid information for use in the model.

2. Test the assumptions of the model empirically by conducting a sensitivity analysis. This can show the output and behavior of the model by changing the input.

3. Use high face validation

It is not always possible to validate a simulation model entirely because some of the required data do not exist in the real system. Therefore, a face validation method can be used as an alternative but is more subjective (Beisbart and Saam, 2019, Law and Kelton, 1991, Louloudi, 2012). Face validation requires the opinions of experts who have broad and detailed knowledge of the system in both normal and unusual situations. Although this method seems very subjective, it has many advantages. Firstly, face validation is used in a Turing test which requires a human expert to observe the different behavior between the real system and a simulation model from using available outputs from both. This method is useful to build correctness, logic and input-output relationships within the model. Secondly, face validation is usually useful in the early stages of a project when the data is not always available because it helps to model the normal and possibly abnormal conditions of the system through parameters and the model structure. If quantitative comparisons are impossible, the face validation method is also useful to check whether there are faults in the behavior of the simulation model when it is compared with the real system.

4. Ask participants to check the credibility of the model

After the model had been improved, the model developer should ask the participants about the credibility of the model. In order to validate the simulation results, the modeler will ask whether the participants from industry accept the simulation model and its results (Law and Kelton, 1991, El Barky, 2011). If the participants accept the improvements in the model, it has been validated.

3.4 Summary of Chapter 3

The purpose of chapter 3 is discussing the research design, including the philosophy suitable for research questions and research contexts, research methods appropriate to the research questions proposed, and how the quality of research are ensured.

Various research philosophies have been investigated to understand and this chapter described the justification of the selected philosophy. The selected methodology is mixed methodology to cover depth and breadth of the research. The case study and mathematical modelling were selected to use in this study. Also, the chapter 3 discussed data collection, interpretation method and how to present and validate the research findings. The next chapter will show factors affecting decision making in remanufacturing.

Chapter 4 Factors affecting decision-making in remanufacturing

This chapter describes how the author identified the important factors which affect decision-making in remanufacturing. Firstly, the author performed cohort studies from the literature and then predicted a list of factors for the study. Then, the author interviewed five case studies with participating companies about the decision making in their operation which can reveal additional factors affecting decision making. This step is intended to examine whether evidence confirms, disconfirms or extends existing studies. Subsequently, findings from empirical studies were compared with existing studies. The final procedure was refining factors to be the final lists which were used to build a decision-making framework.

4.1 Preliminary factors influencing decision-making in remanufacturing

Twenty-one decision factors in remanufacturing, listed in Table 4.1, were obtained from the literature review in chapter 2. These decision factors can be divided into two types: product-level factors and component-level factors. Also, these factors can be categorised into 3 groups: engineering factors, business factors and environmental factors. Engineering factors are further divided into two groups: product factors and process factors. Business factors include market factors, demand/supply factors and legal/political factors. Environmental factors include resource conservation factors and pollution factors.

Table 4.1 The decision factors in remanufacturing from the literature review

Product (P) / Component (C) level	Factors
Engineering factors: Product factors	
P, C	1. Physical life of products/components (Rahimifard et al., 2009, Mangun and Thurston, 2002)
P, C	2. Technological cycle of products/components (Lebreton and Tuma, 2006) (Zwolinski et al., 2006, Rose, 2000)
C	3. Condition of components
C	a. Type of damage (Shu and Lam, 2001)
C	b. Severity of damage (Shu and Lam, 2001)
C	c. Completeness of components (Shu and Lam, 2001)
C	d. Completeness of products (Shu and Lam, 2001)
C	e. Area of fault (Shu and Lam, 2001)

Product (P) / Component (C) level	Factors
C	4. Reusability (Zhou et al., 2012)
P, C	5. Product safety (Shokohyar et al., 2014)
Engineering factors : Process factors	
C	1. Time to recover products/components(Ghazalli and Murata, 2011) and time to buy new products/components (Östlin, 2008)
Business factors: Market factors	
C	1. Value of components (Rahimifard et al., 2009, Zwolinski et al., 2006)
C	2. Recovery costs (Liu et al., 2016, Krikke et al., 1998)
C,P	3. Investment costs (Amin and Zhang, 2013, Boks and Stevels, 2001)
Business factors: Demand/supply factors	
C	1. Availability of components (Rajagopalan, 2002, Ian et al., 2015)
C	2. Inventory level (Östlin et al., 2008)
C	3. Minimum purchasing numbers from suppliers ((Östlin et al., 2008)
C	4. Future demand(Östlin et al., 2008)
Business factors: Legal/Political factors	
P	1. Compliance with laws(Iakovou et al., 2009)
C	2. Reusable mass of components (Ziout et al., 2013, Meng et al., 2017a, Yang et al., 2015, Ziout et al., 2014)
Environmental factors: Pollution factors	
C	1.Waste disposal (Ziout et al., 2013)
C	2. Carbon dioxide emissions (Ziout et al., 2013, Caudill and Dickinson, 2004)

4.2 Empirical studies about factors influencing decision-making in remanufacturing

This research adopted multiple case studies to generalise the phenomenon and create theory. Multiple data sources were used, including observations, interviews and documents to triangulate evidence. The main source of evidence was semi-structured interviews. The questionnaires were designed for specific roles in companies. Multiple staff members were interviewed wherever possible. The staff interviewed included directors, managers, core managers, production engineers, MRP staff and shop-floor staffs. The questionnaires and answers are shown in Appendix I page 218 - 273.

The second source of evidence was observation through personal guided tours of remanufacturing plants. During these tours, engineers and managers identified the remanufacturing activities, the decision-making for each of the remanufacturing activities and the decision factors involved. Moreover, there was also additional evidence from documentation such as company brochures, websites, OEM standards, and contracts between companies and clients. This documentation was used to validate the operational factors discussed with the respondents.

Five companies (A, B, C, D and E) were involved in the empirical studies.
Company A is an OEM remanufacturer who has produced engines for almost 35 years. Company A separates remanufacturing and manufacturing lines. Remanufacturing accounts for 95% of their activities while the other 5% focused on the production of new automotive spares. Company A employs 56 shop-floor workers and 42 office workers. The average production is 80 engines per month, each of which is priced at more than 1000 pounds.

Company B has specialised in remanufacturing for more than 40 years. The company has 150 employees. Company B is a contract remanufacturer who produce remanufactured diesel engines for its customers. 85% of their business activities is remanufacturing and the remaining 15% is dedicated to new production. Overall, 15,000 units are produced annually at an average price of 750 pounds per unit.

Company C is an independent remanufacturer who has produced diesel engines for 39 years. The company has four employees. Two hundred fifty units of diesel engines were sold per year for tractors, vans, buses and power generators. Each unit costs 1000-10000 pounds. Most of its customers are returning customers in the public sector.

Company D is a contract remanufacturer who has produced transmissions for cars, trucks, buses and torque converters for over 40 years. The cheapest component is sold at about 15,000 units annually while the most expensive products are sold at ten units annually. The products sold belong to different price ranges. Their business consists of 95% of remanufactured products while the remaining 5% is made up by new production.

Company E is a contract remanufacturer that supplies remanufactured fuel injection systems. They have been operating in the remanufacturing industry for 48 years. Ninety-five percentage of their work is remanufacturing while the remaining is repairing. Most of its repair services are available to B2B customers (95%). The average production per month is 5000 injectors and 1300 fuel pumps at an average price of 400 pounds per unit.

The details about the data collection from the case study companies are available in Table 4.2 The data collection was conducted from March 2017 to September 2018 through three methods including observations, interviews and documents. Additional details about questions and answers of each interview are available in Appendix I. The author interviewed multiple staff members employed in different positions in the companies to gain a better understanding of remanufacturing from different perspectives.

Table 4.2 Details of data collection from the case study companies.

Companies	Date	Method of collection	Duration	Topics addressed	Informants
A	March 2017	Observation, interview, documents	1 hr	End-of-life options, challenges to manage cores, operational strategy to manage cores, decision-making on EOL options, factors in decision-making on EOL options, failure modes, core management	Production Manager
	October 2017		1 hr	MRP planning regarding product family, End-of-life options, environmental factors in the operation, planning disassembly/reassembly of complex products, stability and predictability of factors, operational time	Production Manager
B	January 2018	Observation, interview, documents	1 hr	End-of-life options, challenges to manage cores, operational strategy to manage cores, decision-making on EOL options, factors in decision-making on EOL options, failure modes, core management	Production engineer
	September 2018		4.5 days	Remanufacturing activities, time spent on remanufacturing activities, decision- making in remanufacturing activities, failure modes, additive manufacturing	Director, Senior manager, production engineer, MRP management staff and shop-floor staff
C	May 2018	Observation, interviews, documents	1.5 hr	Material flow, remanufacturing activities, factors used in decision-making for each remanufacturing activity, decision sequence	Director
	June 2018		1.5 hr		Manager
D	April 2017		1 hr	Material flow, remanufacturing activities, factors used in decision-making for each	Director

Companies	Date	Method of collection	Duration	Topics addressed	Informants
		Observation, interview, documents		remanufacturing activity, decision sequence	
	October 2017		1 hr	MRP planning regarding product family, End-of-life options, environmental factors in the operation, planning disassembly/reassembly of complex products, stability and predictability of factors, operational time	Director
E	November 2017	Observation, interview, documents	3 hr	End-of-life options, challenges to manage cores, operational strategy to manage cores, decision-making on EOL options, factors in decision-making on EOL options, failure mode, core management	Director, Core manager

4.3 Factors influencing decision-making in remanufacturing obtained from the literature review and brainstorming

Twenty-eight factors influencing decision-making in remanufacturing, listed in Table 4.3, were obtained from the literature review and brainstorming. The factors about decision making in remanufacturing activities were extracted from the interviews with companies, documentations and observations during the company visits. Most of the factors match the lists from the review of the existing literature. Nevertheless, this research found some new factors when combining answers from multiple cases.

Table 4.3 The decision factors in remanufacturing from the literature review and brainstorming

Product level (P)/ component level (C)	Factors	Remark	Confirmed	New list
Engineering factors: Product factors				
P,C	1. Physical life of products/components (Rahimifard et al., 2009, Mangun and Thurston, 2002)	It is the time duration from product purchase until the product no longer meets original requirements.	✓	
P, C	2. Technological cycle of products/components (Lebreton and Tuma, 2006 , Zwolinski et al., 2006, Rose, 2000)	It is the time duration before products or components are out of date.	✓	
C	3. Condition of components	It is the physical characteristics of components.	✓	

Product level (P)/ component level (C)	Factors	Remark	Confirmed	New list
C	a. Type of damage (Shu and Lam, 2001)	The types of damage are deformation, burnt, wear, cracks, corrosion, holes, fractures, fastener failure, dents, loose, design flaws.	✓	
C	b. Severity of damage (Shu and Lam, 2001)	It is the degree of damage when it is under the OEM specification and cannot be improved.	✓	
C	c. Completeness of components (Shu and Lam, 2001)	Components should be intact without any missing parts.	✓	
C	d. Completeness of products (Shu and Lam, 2001)	Products should be intact without any missing components .	✓	
C	e. Area of fault (Shu and Lam, 2001)		✓	
C	g. Number of faults(Du et al., 2017)			✓
C	4. Reusability (Zhou et al., 2012)	It is the characteristics of components/products which enable them to meet original specifications.	✓	
P,C	5. Working environment of components*			✓
P,C	6. Product safety (Shokohyar et al., 2014)		✓	
Engineering factors : Process factors				
C	1. Time to recover products/components(Ghazalli and Murata, 2011) and time to buy new products/components (Östlin, 2008)		✓	
P	2. Guidelines to remanufacture components from customers*(Sitcharangsie et al., 2017)			✓
P	3. Available technology/recovery techniques*(Sitcharangsie et al., 2017, International Conference on Advanced Concepts			✓

Product level (P)/ component level (C)	Factors	Remark	Confirmed	New list
	in Mechanical Engineering Iași, 2014)			
Business factors: Market factors				
C	1. Value of components (Rahimifard et al., 2009, Zwolinski et al., 2006)	It can be defined into 2 terms: a. Salvage value of used components b. Value of remanufactured components	✓	
C	2. Recovery costs (Liu et al., 2016, Krikke et al., 1998)	It includes 7 costs of activities: a. Purchase costs of new components b.Disassembly costs c. Cleaning costs d. Assembly costs e. Reworking costs f. Test costs h. Inspection costs	✓	
C, P	3. Investment costs (Amin and Zhang, 2013, Boks and Stevels, 2001)		✓	
Business factors: Demand/supply factors				
C	1. Availability of components (Rajagopalan, 2002, Ian et al., 2015)		✓	
C	2. Inventory level (Östlin et al., 2008)		✓	
C	3. Minimum purchasing numbers from suppliers (Östlin et al., 2008)		✓	
C	4. Future demand (Östlin et al., 2008)	It includes 2 sources of future demand : a. Replacement with a different type of product b. Replacement of products from same product family.	✓	
P	5. Minimum demand for remanufactured products (Arifin, 2019, Luo, 2015)	Remanufacturers allow customers to make orders when orders are equal or more than the minimum demand.		✓
Business factors: Legal/Political factors				
P	1. Compliance with laws (Iakovou et al., 2009)		✓	

Product level (P)/ component level (C)	Factors	Remark	Confirmed	New list
P	2. Global markets specific regulations*(Kojima, 2017)			✓
P	3. Future policies related to the industry*(Liu et al., 2015)			✓
Environmental factors: Resource Conservation factors				
C	1. Reusable mass of components (Ziout et al., 2013, Meng et al., 2017a, Yang et al., 2015, Ziout et al., 2014)	It is the weight of reusable parts obtainable from reusing products.	✓	
Environmental factors: Pollution factors				
C	1.Waste disposal (Ziout et al., 2013)		✓	
C	2. Carbon dioxide emissions (Ziout et al., 2013, Caudill and Dickinson, 2004)			

The following sections elaborate how companies considered each factor in their decision making.

4.3.1 Engineering factors: Product factors

4.3.1.1 Physical life of products/components

Companies B, C, D: Whether to replace the components from disassembled cores with new components or remanufacture them depends on residual life of components. If the components are severely damaged and expected residual life is low, they are no longer remanufactured. Soft parts such as seals which are worn through time are always replaced. Hard parts such as transmission cases are examined and measured. If their conditions are within the standard, then remanufacturers reuse them. Only 10% of transmission cases are replaced because they are too worn, e.g. cracked cases.

Company E: After being used for 3 years, a diesel injection system needs to be improved for performance. The remanufacturer has a business opportunity to offer remanufactured products when such engines are 3 to 15 years old.

4.3.1.2 Technological cycle of products/components

Company A: If company A finds out that collected parts could cause failure, they record the data in their system and reject obsolete components in the next round of remanufacturing to make sure they can guarantee their warranty.

Companies B, C, E: If the components are obsolete, it is difficult for remanufacturers to find the tools and materials. For example, old-designed components such as seals of driveshafts are usually replaced with new ones.

4.3.1.3 Condition of components

According to Company A, the condition of cores is the most important factor for them to decide on the recovery process. Both the internal and external conditions of cores are equally important as they investigate cracks, wear, and damage to decide whether to reuse or remanufacture them.

Condition of components mentioned by companies includes type of damage, severity of damage, completeness of components, completeness of products, area of fault and number of faults

- Type of damage

Companies A, B, C: If the damage is serious or the affected automotive parts are expensive, the remanufacturer rejects the parts immediately. Overall, the companies try to fix it first, but if it is not worth remanufacturing, they replace the faulty components with new components.

If specific components are burnt out, such as a crankshaft, companies cannot do much to recover it. It is too risky to remanufacture cores because the remanufacturer remanufactures premium products and wants product life to cover its warranty. Moreover, it is impossible to remanufacture some components with cracks. If the core has some design flaws, companies try to modify it first, otherwise they scrap it. If they find dented components, they fix them by welding and machining. When components are loose, they replace/remachine components to meet the specifications.

Company D: The remanufacturer checks the damage of valve bodies which are one of the main components of automatic transmission. If the fault is from heat damage, then the valve body may be too burnt which can cause metal contamination. The remanufacturer then scraps the whole core (automatic transmission).

Company E: They reject components with faults in a specific area because these faults can cause engine damage. Those critical faults are housing cracks of diesel injection pumps, nozzles burnt off, and body damage to injectors.

Severity of damage

Companies A, B, C, D, E: Severely damaged parts are not remanufactured because it is not cost-effective since the life of products will not be long enough to cover the warranty remanufacturers offer to the customer.

Company C: If all expensive components are severely damaged, the remanufacturer does not remanufacture them. For example, the company cannot remanufacture components of engines if engines have been run without oil since this severely damages components.

- Completeness of components

Companies B, C, E remanufacture only components without any missing parts because small components are not available in the market. Suppliers sell only intact components.

- Completeness of products

Companies B, C, E: Small products, such as injectors, can only be remanufactured if there are no components missing because small components are not available in the market. Suppliers sell only complete components.

- Area of fault

Companies A, B: If damage occurs on critical areas of components, those components are not remanufacturable. For example, the fillet area on main/pin journal of the crankshaft is a critical area where remanufacturers cannot recover those components to a like-new condition. However, if the damage does not occur on the fillet area, the main/pin journal of the crankshaft can be recovered by remachining.
Company C: If the crack occurs on the top bore of an engine block, it can be recovered by additive manufacturing. However, if the crack occurs on the bottom bore of an engine block, remanufacturers need to replace the entire engine block.
Company D: If the valve body of automatic transmission is too burnt, then the remanufacturer rejects it.
Company E: If any damage is found on the main body of an injector, the company reject the whole component.

- Number of faults

Company B: The company does not allow its workers to remanufacture a used cylinder head which has more than one crack from the glow plug hole to the valve seats.
Companies A, E: Several areas/types of damage cannot be accepted for remanufacturing.

4.3.1.4 Reusability

Companies B, C: Some components are recovered by different methods depending on their reusability rate. For example, if some components are always found to be worn, remanufacturers always replace them. Such components include pistons, bushing, bearings, timing chain tension, water pumps, oil pumps, gaskets, and seal fasteners. Remanufacturers reuse some components such as bolts if there is no obvious fault on them. Some outer components are usually washed and reused such as cylinder head covers, intake manifolds, oil pan gaskets, and exhaust manifolds. Finally, some components, such as cylinder heads, engine blocks and crankshafts, are dealt with on a case by case basis depending on reusability.

4.3.1.5 Working environment of components

Company C: Due to metal fatigue of used products, the company considers using new components ahead used components depending on the residual life of the components. If the working environment of products is extreme such as for marine use or fire engines, company C will offer new components. The company chooses used components for mild working environments such as dusty areas.

4.3.1.6 Product safety

Companies B,C: Their operation is compliant with the law and follows OEM specifications. Therefore, the decision on recovery options considers product safety as the criterion.

4.3.2 Engineering factors : Process factors

4.3.2.1 Time to recover products/components and time to buy new products/components

Company A: Purchasing plan covers 6 months ahead due to the different lead time of each product/component. The lead time of 80% of required products is 4 weeks, but this can be up to 10 weeks.

Companies B, C, D, E: Lead time affects how companies order new/used components. If customers want products immediately, then remanufacturers consider the lead time before the order, thus increasing its internal cost and ultimately the selling price.

4.3.2.2 Guidelines to remanufacture components from customers

Companies B, E: Remanufacturers decide to remanufacture products if they have the ability to access the specifications of components and test data (e.g. Running with full power, using fuel spray) of the O.E. manufacturer.

Company C: Manual specifications and experience are required for remanufacturers to decide whether to remanufacture components or not.

4.3.2.3 Available technology/recovery techniques

Companies B, C, E: Remanufacturers select the best recovery options with their available technology/techniques.

4.3.3 Business factors: Market factors

4.3.3.1 Value of components

Companies B, C: Remanufacturers consider these factors to evaluate the profitability of remanufacturing components. For example, remanufacturers will consider availability and price of components before deciding whether to remanufacture products or not .

Companies B, E: If new components such as new oil pumps are cheap, it is not worth remanufacturing used components. They replace the components with new components.

4.3.3.2 Recovery costs (Liu et al., 2016, Krikke et al., 1998)

Companies B, C, E: They decide to buy new components instead of recovering used components depending on costs. They select the cheapest recovery option because they have specific profit margins to meet. Costs include energy costs, material costs, labour costs and overhead costs.

4.3.3.3 Investment costs

Company B: Although there are new recovery techniques or new recovery options available in the industry to recover cylinder heads/ crankshafts, the company needs to test the quality of those remanufactured components internally, which means the company needs to invest on new recovery technology and new testing methods. Therefore, company B does not remanufacture components with new techniques/technology since a huge upfront investment is required.

4.3.4 Business factors: Demand/supply factors

4.3.4.1 Availability of components

Companies A, B, C, E: The primary difficulty of remanufacturing products is the availability of components. The companies do not remanufacture components if their mating component is missing. Remanufacturers provide various models of automotive components. It may be hard or expensive to source the right components at the right time because those automotive components might be obsolete or produced in small volumes. Moreover, not all customers return cores to remanufacturers. One core might give 50-90% of usable components. However, the remanufacturer does not know the quantity or types of required new components until they strip the cores.

Company D: If there are enough cores, they scrap the poor ones. If there are not enough cores, they accept the poor ones and recover them.

Company E found that the best time to launch remanufactured products is after 3 years of introducing those new products into the market because there is a good demand and core availability.

4.3.4.2 Inventory level

Companies A, B: They use what is left in the inventory before ordering new components.

4.3.4.3 Minimum purchasing numbers from suppliers

Companies A, B, C: Another factor they considered was the availability of components and fasteners. Occasionally, they can buy only a complete assembly of components from their parent company. It is difficult to find the individual components because they come from sub-suppliers. Although smaller components are cheap per unit, the suppliers allow the remanufacturer to buy high volumes of them. Therefore, this factor influences companies to purchase the complete assembly of components rather than to buy smaller components if they need only a small number of sub-components.

4.3.4.4 Future demand

Companies A, B, C: They remanufacture used products before buying a new one. They group cores into similar categories. They may consider ten potential cores. If they cannot find core number 1, they use number 2 instead. Usually, cylinder blocks, crankshafts, and conrods are common components for products within the same family. Once companies know roughly the amount of remanufactured components required for the next few months, they strip the engine and stock components before getting an order. They use computers for MRP planning which they use to try to match the component numbers required with the available component numbers of cores (crankshafts, cylinder heads, blocks) in stock. If companies cannot find any used components, they find components in their new component stock. If they cannot find any new components in their stocks, they buy new/used components globally from core brokers/suppliers.

4.3.4.5. Minimum demand of remanufactured products

Company B: If the demand for a number of remanufactured products from customers is too low, the company does not remanufacture that order because it will not generate enough profit.

4.3.5 Business factors: Legal/Political factors

4.3.5.1 Compliance with laws

Companies B, C: It is normal practice for all companies to operate their businesses within the law.

4.3.5.2 Global markets specific regulations

Company B: In China, the specifications of products follow Chinese regulations.

4.3.5.3 Future policies related to the industry

Company B: In the next few years, diesel engines will be prohibited in the UK. Therefore, in the future, diesel engines will not be remanufactured. The company is going to remanufacture electrical engines in the future.

4.3.6 Environmental factors: Resource Conservation factors

4.3.6.1 Reusable mass of components

Companies B, C: Although these factors are not currently considered, it is suggested that OEM might consider this factor in the future. This finding is in line with the literature which explains that decisions regarding EOL options should also consider material recovery.

4.3.7 Environmental factors: Pollution factors

4.3.7.1 Waste disposal

Company B: Remanufacturing could help to reduce waste by reusing old cores instead of scrapping them.

4.3.7.2 Carbon dioxide emissions

None of the companies consider carbon dioxide emissions since they are small companies.

In conclusion, 38 out of 39 factors were addressed by empirical studies.

4.4 New findings from the lists of factors

Multi-case studies can reveal the decision factors considered by companies. Table 4.4 shows what decision factor each company consider in remanufacturing. It shows there are 7 new factors which have not been found in the preliminary decision factors obtained from the literature review in section 4.1

Table 4.4 Lists of factors affecting decisions in remanufacturing

		Considered by company					New lists
		A	B	C	D	E	
Product level (P)/ component level (C)	**Engineering factors: Product factors**						
	Product's remaining life						
P	1. Physical life		1	1	1	1	
P	2. Technological cycle	1	1	1		1	
C	3. Condition of component						
C	a. type of damage	1	1	1	1	1	
C	b. severity of damage	1	1	1	1	1	
C	c. completeness of components		1	1		1	
C	d. completeness of products		1	1		1	
C	e. area of fault	1	1	1	1	1	
C	g. number of faults*	1	1			1	*
C	4. Reusability		1	1			
P,C	5. Working environment of components*			1			*
P,C	6. Product safety		1	1			
	Engineering factors : Process factors						
C	1. Lead time to reprocess products/components or buy new products/components	1	1	1	1	1	
P	2. Guidelines to remanufacture components from customers		1	1		1	*
P	3. Available technology/techniques to recover		1	1		1	*
	Business factors: Market factors						
C	1.Value of components		1	1		1	
C	a. salvage value of used components		1	1		1	
C	b. value of remanufactured components		1	1		1	
C	2. Recovery cost		1	1		1	
C	a. purchasing cost		1	1		1	
C	b. disassembly cost		1	1		1	
C	c. cleaning cost		1	1		1	
C	d. assembly cost		1	1		1	
C	e. pre-assembly, painting cost		1	1		1	
C	f. test cost		1	1		1	
C	h. inspection cost		1	1		1	
C	3. Investment cost		1				
	Business factors: Demand/supply factors						
C	1.Availability of core	1	1	1	1	1	
C	2.Inventory level	1	1				
C	3.Minimum number of purchases from suppliers	1	1	1			
C	4.Future demand	1	1	1			

		Considered by company					New lists
		A	B	C	D	E	
C	a. replacement with a different type of product	1	1	1			
C	b. replacement of products in the same product family	1	1	1			
P	5.Minimum demand for remanufactured products		1				*
	Business factors: Legal/Political						
P	1.Compliance with laws		1	1			
P	2.Global markets: specific regulations		1				*
P	3.Future policies		1				*
	Environmental factors: Resource Conservation						
C	1.Reusable mass of components		1	1			
	Environmental factors: Pollution						
C	1.Waste disposal		1				
C	2.Carbon dioxide						

The new factors were validated by comparing them with existing factors obtained from previous studies. It was found that the following decision factors have been addressed by previous studies:

1. Number of faults(Du et al., 2017)

2. Guidelines to remanufacture components from customers (Sitcharangsie et al., 2017)

3. Available technology/recovery techniques (Sitcharangsie et al., 2017, International Conference on Advanced Concepts in Mechanical Engineering Iași, 2014)

4. Minimum demand for remanufactured products (Arifin, 2019, Luo, 2015)

5. Global markets specific regulations (Kojima, 2017)

6. Future policies related to the industry (Liu et al., 2015)

Working condition of components is the only new factors addressed by only one company and was not confirmed by other previous studies, so this factor was removed from the list. Therefore, there are 27 factors in total in this step.

4.5 Validation assessment of the relevant decision factors

Since many researchers have studied this topic, this research checked internal validity by two methods: pattern-matching and logic models. Additionally, the author gathered information from five case studies to build a general explanation which is one of the internal validation techniques. The validity assessment of the relevant decision factors can be seen in Table 4.5. Firstly, pattern-matching was carried out by studying lists of factors from the literature and then predicting a list of factors for this study. Subsequently, the author built more lists of factors from multiple case studies. Finally, the author adopted a logic model to compare the findings from empirical studies with existing studies.

Table 4.5 The validity assessment of this research to identify and compile relevant decision factors

Technique	How this study applied the technique	Section	Output
Pattern-matching	It compares an empirically based pattern with a predicted one before collecting the data.	4.1	21 factors were predicted before collecting data
Explanation building	It builds a general explanation from several cases.	4.2-4.3	28 factors were found from empirical studies
Use logic models	It matches empirically observed occasions to theoretically predicted occasions.	4.4	6 out of 28 factors were identified as additional factors and were validated by existing studies. 1 out of 28 factors was removed since there was no existing study addressing it and the factor was mentioned by only one company. Therefore, there were 27 factors in total in the final list.

4.6 Refining factors

Following the data analysis, some of the 27 factors were grouped, while other factors were removed. The rationale for removing factors from the list could be one of the following: 1. A factor is similar to other factors; 2. The definition of a factor is already covered by other factors' definitions; 3. Factors have been considered as case studies in this research. Table 4.6 shows the factors that were removed and the reasons why they were removed from the final lists. The factors were narrowed down from 27 to 10 as shown in Table 4.7. The final list of factors is one of the findings of this research from Chapter 4.

Table 4.6 Factors removed and reasons for removal

Factor	Why the factor was removed from the final lists
Physical life	This criterion is part of reliability which is defined as the probability of an item to perform its initial functions successfully.
Technological cycle	This criterion is already included in existing available technology/techniques. If products are obsolete or too new, there is no available technology/techniques to recover them.
Condition of component	
a. type of damage	This criterion will be used in the case studies of this research. The best recovery options will be selected depending on the type of damage. This research will focus on one type of damage which is the wear on crankshaft pins.
b. severity of damage	This criterion will be used as a measurement range in the case study. This research will focus on the amount of wear on the crankshaft from 0.1 mm to 0.5 mm.
d. completeness of products	For complex products such as engines, remanufacturers do not mind the completeness of products. Remanufacturers accept incomplete cores to recover them to the original specifications. Missing components are considered as an availability problem.
e. area of fault	This criterion will be used in the case studies of this research. The best recovery options will be selected depending on the area of the fault. This research focused on one area of fault which is the crankshaft pin.
g. number of faults	This criterion is important if there are multiple cracks. For other faults, the number of faults is less important than the area of fault and severity of the fault.
Reusability	This criterion is included in the condition of components because severely damaged components cannot be reused.
Product safety	This criterion is a part of reliability which is defined as the probability of an item to perform its initial functions successfully.
Guidelines to remanufacture components from customers	This criterion can guide remanufacturers about the available technology/techniques for recovery. Therefore, this criterion is removed because the model has already considered the available technology/techniques.
Value of components a. salvage value of used components b. value of remanufactured components	All these criteria are used to calculate profit. Therefore, the definition of profit combines the definitions of all these factors.
Energy cost	
Recovery cost	
a. purchasing cost	
b. disassembly cost	
c. cleaning cost	
d. assembly cost	
e. post-assembly, painting cost	
f. test cost	

Factor	Why the factor was removed from the final lists
h. inspection cost	
Investment cost	This criterion is a part of the technology capability of recovery options to recover components. Companies need to consider investment costs of new technology to measure the capability to recover components.
Inventory level	This criterion is similar to the availability of cores because the remanufacturer has to check all available cores in its inventory.
Compliance with laws	These criteria are combined in compliance with laws and regulations
Global markets: specific regulations	
Future policies	
Waste disposal	This criterion is known when the reusable mass of components is known.
Carbon dioxide	Not mentioned by any of the companies.

Table 4.7 Final list factors

Product/component level	Factor
P,C	1. Compliance with laws and regulations
P	2. Available techniques/technology for recovery
P,C	3. Minimum demand for components
C	4. Future demand for components
C	5. Reliability of components
C	6. Operational time to rework products/components or lead time to buy new products/components
C	7. Availability of cores
C	8. Minimum purchase number from suppliers
C	9. Profit
C	10. Reusable mass of components

4.7 Decision-making framework after refining factors

The 10 factors part of the final list outlined in table 4.7 will be used in different decision-making steps and are either qualitative or quantitative. Qualitative decision-making is used before quantitative optimisation. Figure 4.1 shows the decision-making framework to optimise remanufacture profit, remanufacture time, remanufacture reliability and reusable mass of components in the automotive remanufacturing. A decision in remanufacturing starts with a feasibility analysis on whether the product/ subassembly is remanufacturable or not. Qualitative criteria are used to consider the feasibility of remanufacturing according to the law and regulations, the techniques available for remanufacturing and also the economic incentives. If products meet these three criteria, the remanufacturers will decide to remanufacture that product. When a used product is disassembled into components, decision-makers have to consider the possibility of remanufacturing at the component level. The criteria for the remanufacture of components are physical life, completeness of the component and availability of the necessary components. If the components meet all three criteria, the decision-makers can optimise those components through two steps: selecting the best recovery option for components and finding the number of required components/products for each remanufacturing activity. The first step in the decision-making process is to select the best recovery option for the component. There are 4 objectives for this step which include the reliability of components (engineering factor), operational time (economic factor), profit (economic factor), and reusable mass of components (environmental factor). The best alternatives could be replacement, remachining or additive manufacturing. These decisions affect the number of new components and the number of reworked components since if remachining or additive manufacturing is selected, there is an increase in the required number of reworked components. If replacement is selected, there is an increase in the required number of new components.. Therefore, decision-making in Step 1 will affect Step 2, which requires finding the number of required components/products for each remanufacturing activity. These activities are core acquisition, disassembly, scrap, reworking and the purchase of new components. The required number of new components and the number of reworked components affect the number of required components/products for each of the remanufacturing activities in the decisions made in Step 2. Therefore, the percentage of the reworked components will be used in the sensitivity analysis. Moreover, reworking time, reworking cost and component commonality patterns are used in the sensitivity analysis since they affect the profits of the remanufacturing business.

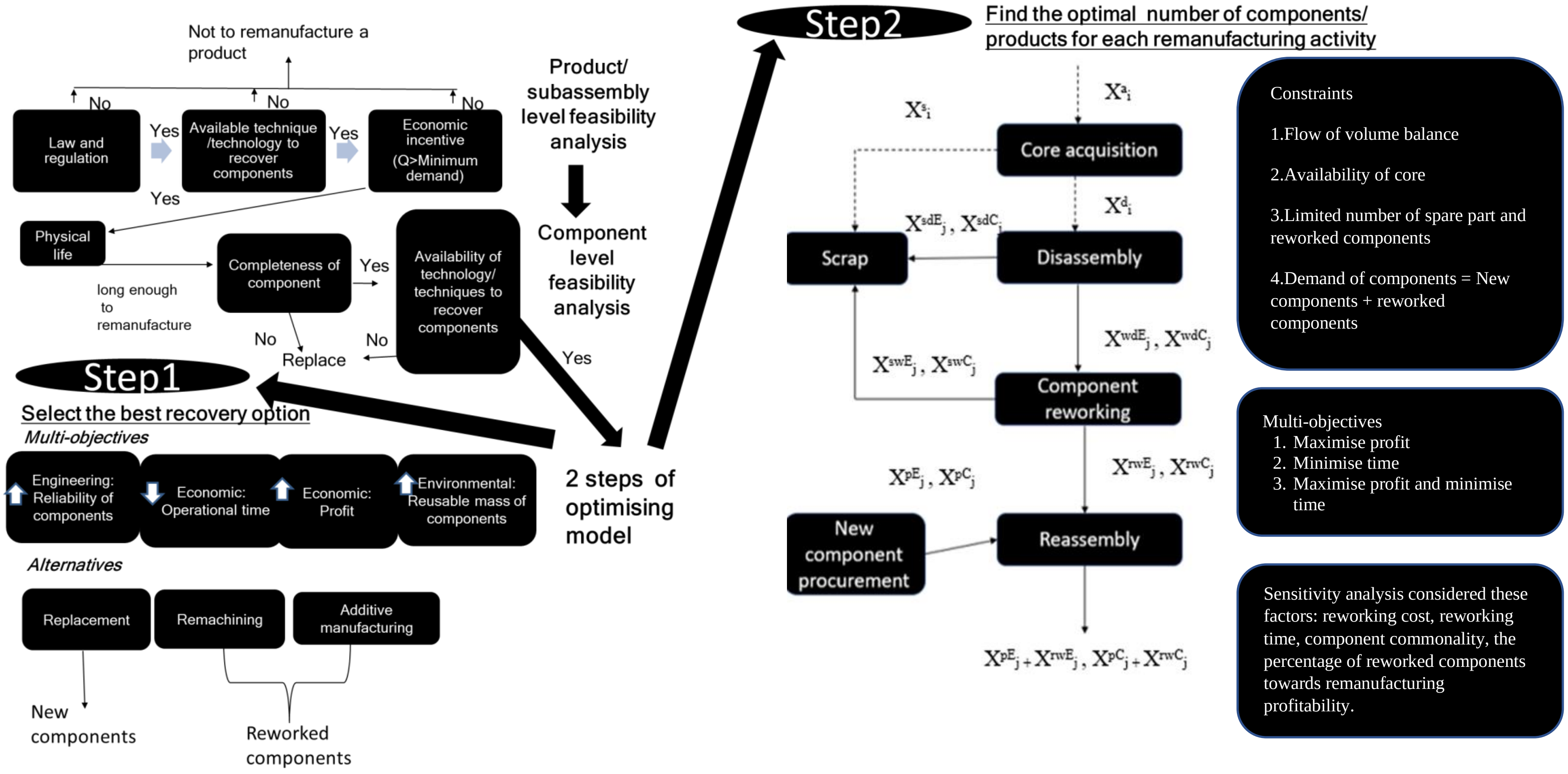


Figure 4.1 The decision-making framework to optimise the remanufacture of automotive components

4.8 Summary of Chapter 4

Chapter 4 described the research findings corresponding to research objectives 1 and 2. This research identified knowledge gaps about existing decision making in remanufacturing in the existing literatures and sourcing data from real practice. The ten final factors and their decision sequence gathered from reviewing the literature and brainstorming by experts were used to develop a 2 steps-decision making framework on how to optimise automotive remanufactured components. The first step and the second step of decision-making will be presented in chapter 5 and 6 respectively.

Chapter 5 Decision making Step 1: Select the best recovery options for components with specific faults

This research studies two steps of decision making: Step 1. Selecting the best recovery options for components with specific faults. Step 2. Determining the optimal number of components and products in each remanufacturing activity. The decision-making process of step 1 is described in this chapter while the decision making process of step 2 is described in chapter 6.

5.1 Review of recovery options for engines in real practice

Normally, components are in the waste stream because they are no longer used for two reasons (Shu and Lam, 2001). Firstly, they may fail due to loss of their intended function. Secondly, they may not be recoverable. Some of the former cases are recovered before reusing but in the latter case they are not recovered since they are not worth recovering and remanufacturers prefer to replace them. The information on the recovery options for components is collected from three engine remanufacturing companies (Companies A, B and C- see chapter 4 page 75) which are different in production volume (from 4-1500 units/month) and the number of staff (4-150 people). Therefore, the recovery options of components for each company are different. According to companies A, B and C, components which are small, cheap and connect other parts are usually replaced (such as glow plugs and bearings), while the recovery options of main components such as cylinder heads, engine blocks, crankshafts, camshafts, and connecting rods depend on their physical conditions. According to the information gathered from companies A, B, C, the recovery options of frequently remanufactured components of engines are shown in Table 5.1. The criteria used to decide on the recovery options (reuse, replace, remachine or use additive manufacturing) depend on the type of fault, severity, number of faults, area of faults, the expertise of remanufacturers and OEM specifications. The components which have severe faults (such as being burnt, too worn out, or where there is material loss), are usually replaced.

Table 5.1 The recovery options of components of engines which are usually remanufactured identified from research case studies

Component	Faulty	Area	Specification	Recovery option
Cylinder head	Crack	Glow plug bore/nearest inlet valve seat pocket	One crack	Remachine cylinder head
			Multiple cracks	Replace new cylinder head
		Valve seat area	Depth of crack is limited to chamfer area	Remachine cylinder head
			Crack occurs anywhere beyond the shortest route of the seat pocket	Replace new cylinder head
	Damaged area	Glow plug	OEM spec	Replace new cylinder head
			OEM spec	Remachine cylinder head
		Lash adjuster bores	OEM spec	Replace new cylinder head
			OEM spec	Remachine cylinder head
		Thread holes	Wall thickness <3.5 mm, not porous location	Replace new cylinder head
			wall thickness >=3.5 mm, not porous location	Remachine cylinder head
	Size dimension	Valve guides/valve seat	Gage line depth, seat width ovality, runout geometric dimension	Replace new cylinder head
			Gage line depth, seat width ovality, runout, geometric dimension	Remachine cylinder head
	Surface/flatness dimension	Head gasket surface	OEM spec	Remachine cylinder head
			OEM spec	Use additive manufacturing to improve surface
Engine block	Crack	Block bearing cap		Replace new engine block
		Inside bore: Top bore	Length< 20% of circumference	Replace new engine block
			Length< 20% of circumference	Use additive manufacturing to improve surface
		Inside bore: Bottom bore		Replace new engine block
		External engine block		Replace new engine block
				Use additive manufacturing to improve surface

Component	Faulty	Area	Specification	Recovery option
	Damage	Mounting surfaces: head gasket surface	Severe (too deep damage/dent)	Replace new engine block
			Not severe	Remachine engine block
		Cylinder wall (wear below the ridge/below the lowest ring travel)	Max.0.003 inch out of round, Max 0.005 taper, no deep scratches, min honing is 0.002"	Remachine engine block
			Out of specification	Replace new engine block
		Sealing surfaces		Replace new engine block
		Thread hole: major fixings such as bolt between cylinder head and cylinder block		Replace new engine block
		Thread hole: minor fault eg. tensioner		Replace new constant threaded hole
		Thrust washer		Replace new engine block
		Thermostat		Replace new engine block
	Size dimension	Cylinder bore (bore diameter, squareness, and position)	OEM spec	Remachine the bore and replace new liner
			OEM spec	Remachine the bore and replace bigger piston
			OEM spec	Remachine the bore and use additive manufacturing technique
	Leak	Block		Replace new engine block
	Surface warpage (level of the deck of the block)		OEM spec	Replace new engine block
			OEM spec	Remachine new engine block
Camshaft	Crack & damage	Sealing surfaces		Replace new camshaft
		Thrust surfaces		Replace new camshaft
		Thread holes		Replace new camshaft
		Mounting surfaces		Replace new camshaft
	Size dimension (three dimension, taper,outround)	Journal	OEM spec	Remachine camshaft
			OEM spec	Replace new camshaft
		Lobe	OEM spec	Remachine camshaft

Component	Faulty	Area	Specification	Recovery option
			OEM spec	Replace new camshaft
	Deformation (straightness)	Journal	OEM spec	Remachine camshaft
			OEM spec	Replace new camshaft
		Lobe	OEM spec	Remachine camshaft
			OEM spec	Replace new camshaft
Crankshaft	Crack			Replace new crankshaft
	Heat discoloration			Replace new crankshaft
	Damage	Sealing surface		Replace new crankshaft
		Mounting surfaces	Main/pin journal OEM spec: Fillet area	Replace new crankshaft
		Mounting surfaces	Main/pin journal OEM spec: Not fillet area	Remachine crankshaft
		Mounting surfaces	Main/pin journal OEM spec: Not fillet area	Replace new crankshaft
		Thrust surfaces	OEM spec	Remachine crankshaft
		Thrust surfaces	OEM spec	Replace new crankshaft
		Counting weight	OEM spec	Replace new crankshaft
		Counting weight	OEM spec	Remachine crankshaft
		Counting weight	OEM spec	Use additive manufacturing to improve surface
		Thread holes		Replace new crankshaft
	Dimension	Main Journal (size/surface furnishing)	OEM spec	Remachine crankshaft
		Main Journal (size/surface furnishing)	OEM spec	Replace new crankshaft
		Thrust Face Centre Main Journal (size/ surface furnishing)	OEM spec	Remachine crankshaft
		Thrust Face Centre Main Journal (size/ surface furnishing)	OEM spec	Replace new crankshaft
		Pin Journal (size/surface finishing)	OEM spec	Remachine crankshaft

Component	Faulty	Area	Specification	Recovery option
		Pin Journal (size/surface finishing)	OEM spec	Replace new crankshaft
		Clutch pilot bearing bore diameter	OEM spec	Remachine crankshaft
		Clutch pilot bearing bore diameter	OEM spec	Replace new crankshaft
	Alignment/twist			Replace new crankshaft
				Straighten crankshaft and detect crack
Connecting rod	Dimension	Crank End Bore Inner dimension	OEM spec	Remachine connecting rod
		Crank End Bore Inner dimension	OEM spec	Replace new connecting rod
		Crank End Bore Width	OEM spec	Remachine connecting rod
		Crank End Bore Width	OEM spec	Replace new connecting rod
		Piston pin End Bore inner dimension	OEM spec	Remachine connecting rod
		Piston pin End Bore inner dimension	OEM spec	Replace new connecting rod
		Piston pin end width	OEM spec	Remachine connecting rod
		Piston pin end width	OEM spec	Replace
		Piston end surface finish	OEM spec	Remachine connecting rod
		Piston end surface finish	OEM spec	Replace new connecting rod
		Distance between crank end bore centre to piston end bore centre	OEM spec	Replace new connecting rod
		Surface finishing between surface of rod and cap (crack cap)	OEM spec	Replace new connecting rod
		Surface finishing between surface of rod	OEM spec	Remachine connecting rod

Component	Faulty	Area	Specification	Recovery option
		and cap (smooth cap)		
	Damage	Cap underbolt head (rod and cap are not a matched pair)	OEM spec	Replace new connecting rod
		Threaded hole	OEM spec	Replace new connecting rod
		Fracture split surfaces after bolt tightening	OEM spec	Replace new connecting rod
	Crack			Replace new connecting rod
	Discoloration			Replace new connecting rod
	Bent/twist			Replace new connecting rod

This research did not study all components and all types of faults within the engine but considered the crankshaft with wear on crankpin as a case study for a decision-making in step 1. The crankshaft was selected for this since the crankshaft is a commonly remanufactured component and wear on the crankpin is the major fault that remanufacturers have to deal with in real practice (Shu and Lam, 2001). According to company B, 84% of all used crankshafts are remanufactured. Wear on crankpin is a common fault accounting for 48% of all faults of crankshafts. According to companies A, B and C, a crankshaft is one of the most expensive components in an engine. However, some companies do not remanufacture crankshafts because it requires expertise to recover the crankpin. Some companies remachine the crankpin but there are limitations to this technique since it is allowable to lose only 0.2 mm of diameter to meet the OEM specification. A fast assessment could be made for recovery options because remanufacturers will replace it with new components if the condition of a component is substandard. However, this method is not effective because when the component is near the lower limit of the specification, the remaining life of the component after recovery may not be worth recovering (Qian et al., 2015). Also, there is a development in additive manufacturing (ADM) which helps remanufacturers to succeed in removing a greater depth of the crankshaft and improve the surface (Torims et al., 2014). Due to these reasons, it would be better to increase the reusability of the used crankshaft. This benefit is especially for obsolete and hard-to-find components (Burns, 2019, Calabrese et al., 2019). Some AM techniques can reduce up to 40% of raw material waste when compared with subtractive processes (Srivastava, 2019). Therefore, the focus of this research at this stage is to select the most desirable recovery option for crankshafts with wear on crankpins. This holistic method considers multiple objectives which are maximising profit, minimising time, maximising the reuse rate of the material and maximising the reliability of components. The best recovery options are, therefore, replacement or remachining or additive manufacturing.

5.2 An overview of the decision model Step 1

The intended users of the first step of decision making are the remanufacturers who discuss recovery options for used components with different types of faults with their customers. This stage of decision making happens when the remanufacturers decide to remanufacture new types of products or when the remanufacturers or their customers want to improve their production performance and benefits. At this stage, the key objectives they need to consider are the maximum profit, minimum operational time, maximum reusable rate of material and maximum reliability of components after recovery before signing a contract to follow the specifications of a recovery option.

This model considers three recovery options: 1. Replacement 2. Remachining (Removal method) and 3. Additive manufacturing (Additive method) because remanufacturers participated in this study categorised recovery options into these three recovery options. Replacement was categorised as one of recovery options because replacing failed components with new components can extend the shelf life of products. The model was developed to optimise four objectives: maximising profit, minimising time, maximising reuse rate of material, and maximising the reliability of components. Also, this model allows remanufacturers to decide on 2 or 3 recovery options depending on whether they decide to invest in additive manufacturing or not.

5.3 Procedure on how to decide

It is recommended by the remanufacturers that if the remanufacturer decides that the demand volume of components is worth investing in additive manufacturing, then they should consider additive manufacturing in the decision regards the best recovery option of each component. The procedure on how to decide is described in the following text.

5.3.1 Consider taking a loan to buy a new machine for additive manufacturing

This procedure is important since the remanufacturers (e.g. Company B and Company G) will see how much money they need to borrow in order to invest in new additive manufacturing technology. The amounts of the monthly payments are calculated by the Excel function (1). Then the total payment is calculated by the formula below (2). This study used laser cladding as an example of additive manufacturing because it is one of the best technique to improve bonding strength which can improve durability and mitigate deterioration of components (Peng et al., 2019). The machine for laser cladding cost £301,600 (Peng et al., 2019). It is assumed by Company B that remanufacturers have to repay the loan over three years with 5% annual interest rate to invest in new additive manufacturing technology. After replacing the values in equations 1 and 2, the example calculations for taking a loan to buy a new machine for additive manufacturing are shown in Table 5.2. The information about total repayment will be used in calculation example in section 5.3.2.

Monthly payment = PMT (rate, nper, pv) (1)

rate = The interest rate for the loan

nper = The total number of repayments for the loan

pv = The present value, or total value of all current loan repayment

Total payments = Monthly payment x number of payments per year x years (2)

Table 5.2 The calculation of repayments for a loan to buy a new machine for additive manufacturing

Annual interest rate	5%
Years	3
No. of repayments per annum	12
Loan Amount*	£301,600
Monthly repayments	£9,039
Total repayments	£325,412

5.3.2 Consider whether remanufacturers should invest in additive manufacturing

This section shows how to decide on investment in additive manufacturing. Cash flow balance is used to make a comparison between new approaches (additive manufacturing, replacement and remachining) and existing approaches (replacement or remachining). The remanufacturers can make a decision by considering two questions: 1. When is the payback period of the new approach? 2. When is the profit via the new approach higher than that via the existing approach? After the remanufacturers know this information, they can decide whether remanufacturers should invest in additive manufacturing or not.

In order to calculate the cash flow balance, the number of crankshafts recovered by each recovery option, the profit of each recovery option, and the annual cash flow year are required. The number of crankshafts recovered by each recovery option is shown in equations 3 to 5. The profits from the new and existing approaches are formulated in equations 6 and 7, respectively. The formula to calculate cash flow and the balance of cash flow for year n are shown in equations 8 and 9, respectively. Formulations 10 to 13 refer to the cash flow of the new approach while formulations 14 to 15 refer to the cash flow of the existing approach.

5.3.2.1 Number of crankshafts recovered by each recovery option

$$N_a = \%_a \times D \qquad (3)$$

$$N_r = \%_r \times D \qquad (4)$$

$$N_m = \%_m \times D \qquad (5)$$

5.3.2.2 Profit via the new approach

$$Pr_n = N_a \times Pr_a + N_r \times Pr_r + N_m \times Pr_m \qquad (6)$$

5.3.2.3 Profit via the existing approach

$$Pr_e = N_r \times Pr_r + N_m \times Pr_m \qquad (7)$$

where

N_a = Number of crankshafts recovered by additive manufacturing (units)

N_r = Number of crankshafts recovered by replacement (units)

N_m = Number of crankshafts recovered by remachining (units)

$\%_a$ = percentage of required engines recovered by additive manufacturing

$\%_r$ = percentage of required engines recovered by replacement

$\%_m$ = percentage of required engines recovered by remachining

D = demand volume for engines (units)

Pr_n = Profit of new approach (£)

Pr_e = Profit of existing approach (£)

Pr_a = Profit of additive manufacturing(£)

Pr_r = Profit replacement (£)

Pr_m= Profit of remachining (£)

5.3.2.4 Cash flow and Balance of cash flow

Cash flow (£) = Total profit of a year (£) - Investment costs of a year (£) (8)

Balance of cash flow year n (£) = Cash flow year n (£) + Cash flow year n-1(£) (9)

5.3.2.4.1 Cash flow calculation of new approach

Based on the assumption from company B, remanufacturers have to repay the loan over three years to invest in new additive manufacturing technology. Therefore, the cash flow of each year from year 0 to year 2 includes loan repayments per year. Loan repayments per year are equal to the total investment cost divided by the total number of years for repayments.

L = Total repayment cost (£) / total number of years for repayments (10)

Cash flow year 0 of the new approach (£) = - L (11)

Cash flow of each year (year 1 or 2) of the new approach (£) = P_{ne} - L (12)

Cash flow of each year (from year 3 to year 12) of the new approach (£)= P_{ne} (13)

Where

L = Loan repayment per year (£)

P_{ne} = Profit of new approach per annum(£)

5.3.2.4.2 Cash flow calculation of the existing approach

Cash flow of year 0 of the existing approach (£) = 0 (14)

Cash flow of each year (from year 1 to 12) of the existing approach (£)

= Profit of existing approach per annum (15)

Table 5.3 demonstrates the calculation example for investment in additive manufacturing although in real practice the remanufacturers who are informants have not invested in additive manufacturing. It shows comparisons between new approaches (additive manufacturing, replacement and remachining) and existing approaches (replacement or remachining) to recover a crankshaft.

All following assumptions applied in the calculation are based on the information given by the remanufacturers B,G who remanufacture crankshafts**.** With the exception of assumption 1 which is based on information from remanufacturer B, other assumptions are based on information from remanufacturer G.

1. The remanufacturer has to repay the loan over three years to invest in new additive manufacturing technology.

2. The unit profit of additive manufacturing and the unit profit of remachining are the same at £ 600 per unit

3. The unit profit of replacement is £ 300 per unit.

4. The average demand for engines is 6000 units/ year.

5. 20% of all crankshafts are remanufactured. Out of these, replacement is 15% and remachining is 5% in the existing approach.

6. Additive manufacturing can increase the recovery of crankshafts by 15% because it is assumed that the percentage of components recovered by additive manufacturing is equal to the percentage of components recovered by replacement. Therefore, 35% of all crankshafts are remanufactured with the new approach.

After replacing all variables by the values from assumptions and total repayments from section 5.3.1 in equations 3 to 15, the cash flow balance for both the new and the existing approaches is shown in Table 5.3. According to Table 5.3, the payback period of the new approach is at year 1. Also, a new approach with 3 recovery options can provide more profit than that of the original approach with 2 recovery options at the end of year 2. After making a comparison between the new and the original approach, remanufacturers can decide on whether to invest in additive manufacturing or not. This information will control the model. If they invest in additive manufacturing, the model will have 3 options: additive manufacturing, remachining or replacement , otherwise, there are only 2 options: replacement or remachining.

Table 5.3 A comparison between the new and existing approaches

	Unit	Additive manufacturing	Replacement	Remachining	Replacement	Remachining
Profit	pound/unit	600	300	600	300	600
Demand volume of engine	units/year	6,000			6,000	
No. of crankshaft that should be remanufactured	% of required engines	15%	15%	5%	15%	5%
Investment cost of machine and ancillary equipment	pounds	325,412				

New approach (Replacement, remachining and additive manufacturing)			Original approach (Replacement and remachining)		
Year	Cash Flow	Balance	Year	Cash Flow	Balance
0	-108,471	-108,471	0	0	450,000
1	881,529	773,059	1	450,000	900,000
2	881,529	1,654,588	2	450,000	1,350,000
3	990,000	2,644,588	3	450,000	1,800,000
4	990,000	3,634,588	4	450,000	2,250,000
5	990,000	4,624,588	5	450,000	2,700,000
6	990,000	5,614,588	6	450,000	3,150,000
7	990,000	6,604,588	7	450,000	3,600,000
8	990,000	7,594,588	8	450,000	4,050,000
9	990,000	8,584,588	9	450,000	4,500,000
10	990,000	9,574,588	10	450,000	4,950,000
11	990,000	10,564,588	11	450,000	5,400,000
12	990,000	11,554,588	12	450,000	5,850,000

Payback period at the end of year 1

At the end of year 2, new approach (3 recovery options) can provide more profit than that of the original approach (2 recovery options)

Cash flow= Total profit of that year - Investment cost of that year

Cumulative cash flow

5.3.3 Consider the best recovery option of each component

After considering 2 or 3 recovery options, it is a suitable time to consider the best recovery option of each component.

This section describes the logic of the model to consider the best recovery option of each component by optimising the key objectives together with the input and output of the model as seen in Figure 5.1.

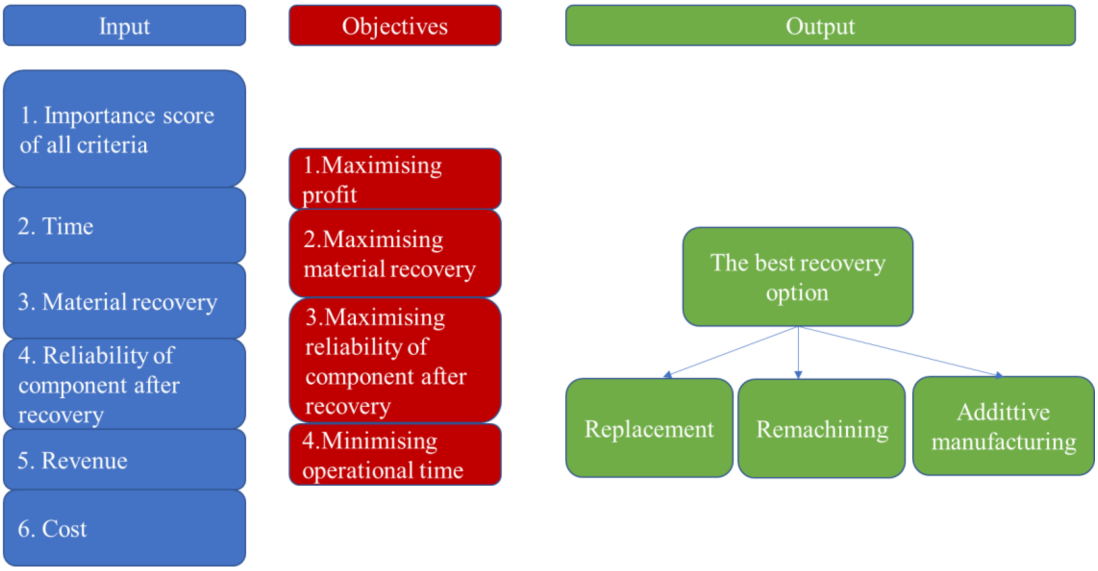
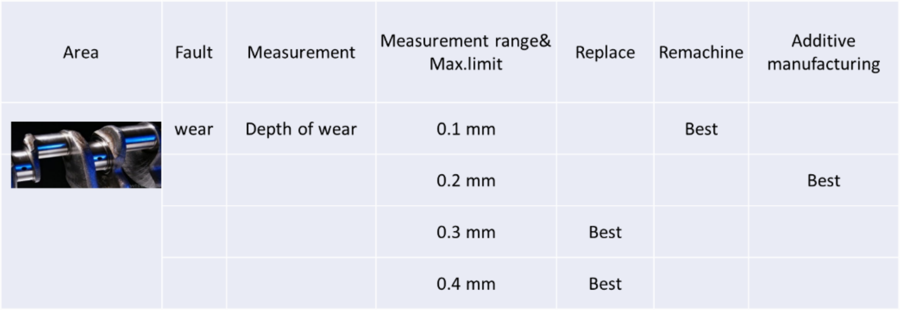


Figure 5.1 Inputs, objectives and output of the model

This model helps remanufacturers to find the most desirable recovery option for components with different levels of wear by considering multiple objectives. This model used a crankshaft with different wear depths (0.1 mm to 0.5 mm.) on crankpins as example cases and uses 'Solver' which is Excel's plug-in to run decisions. An example of the results can be seen in Figure 5.2.



Area	Fault	Measurement	Measurement range& Max.limit	Replace	Remachine	Additive manufacturing
	wear	Depth of wear	0.1 mm		Best	
			0.2 mm			Best
			0.3 mm	Best		
			0.4 mm	Best		

Figure 5.2 An example of the results from this model

5.4 Inputs of the model to consider the best recovery option of each component

The input data are from previous research papers and commercial websites. These data are based on the cases of 6-cylinder engines. Since decision makers can select 2 or 3 recovery options, they need to consider the different inputs as shown in Table 5.4.

Table 5.4 The different inputs to be considered after deciding on 2 or 3 recovery options

	Recovery options	
Main Inputs	3 recovery options (remachining, replacement, additive manufacturing)	2 recovery options (remachining, replacement)
Importance score of profit, time, material recovery and reliability after recovery.	✓	✓
Total time excluding material deposition time	✓	✓
Material deposition time	✓	
Material reusable mass of component after recovery	✓	✓
Reliability of component after recovery	✓	✓
Revenue of each recovery option	✓	✓
Total cost of replacement	✓	✓
Total cost of remachining	✓	✓
Total cost of additive manufacturing excluding material deposition cost	✓	
Material deposition cost	✓	

5.4.1 Input 1: Importance score of all 4 criteria

The importance score is subjective because it is based on the opinion of remanufacturers. Different companies gave different scores for all criteria as seen in Table 5.5. They agreed on the equal importance of profit and time at a score of 20 while the importance score of material recovery and the reliability of component were between 10-15 and 45-50, respectively. This research studied the sensitivity of the material recovery and reliability of the component after recovery which is mentioned later in sections 5.7 to 5.8.

Table 5.5 Importance score for criteria

Criteria	Importance score (out of 100)
Profit	20
Time	20
Material recovery	10-15
Reliability of component after recovery	45-50

5.4.2 Input 2: Time

Before a suitable recovery option can be decided on, the components are disassembled, cleaned and inspected. Therefore, if any recovery option is to be selected, time for disassembly, initial cleaning and inspection are considered. When replacement is selected, the time to buy new components is included. Whereas, when remachining or additive manufacturing is selected, times for grinding, polishing, cleaning and hardness measurement are included. The only difference between remachining and additive manufacturing is the time of material deposition which only occurs in the additive manufacturing process. Table 5.6 shows the activities which need to be included to calculate the total time spent on each recovery option.

Table 5.6 All activities necessary to calculate the total time for each recovery option

	Activity	**Replacement**	**Remachining**	**Additive manufacturing**
Activities before condition of used products is known	Disassembly	✓	✓	✓
	Initial cleaning	✓	✓	✓
	Inspection	✓	✓	✓
Further activities	Buying new crankshaft	✓		
	Grinding		✓	✓
	Additive Manufacturing (Material deposition)			✓
	Polishing		✓	✓
	Cleaning		✓	✓
	Hardness measurement		✓	✓

5.4.3 Input 3: Material recovery

Table 5.7 shows the material recovery of three different recovery options: replacement, remachining and additive manufacturing. Since the surface removed from components after remachining or additive manufacturing is quite thin (0.1 to 0.5 mm), the mass after recovery options is assumed to be similar to the original mass of the component. Material recovery after replacement is 0 since the remanufacturer needs to purchase new components, which means they reuse 0 kg of materials.

Table 5.7 The material recovery of three different recovery options

Original mass of component (kg)	Replacement (kg)	Remachining (kg)	Additive manufacturing (kg)
20.6	0	20.6	20.6

5.4.4 Input 4: Reliability after recovery

Remachining is a recovery option with the limitation that this method needs to remove the surface of components while the remanufacturers need to follow the OEM specification which does not allow too small dimension of components. After a discussion with remanufacturers A, B, C, they suggested that 0.2 mm is the maximum depth that remanufacturers can remachine the journal of a crankpin with an acceptable level of reliability for recovered components. Additive manufacturing can increase the recovery of components since it improves the surface of the components by adding material and then removing the material to meet the OEM specification. Remanufacturers A, B,and C recommended that additive manufacturing can recover crankpins with a wear depth of 0.1 to 0.5 mm. Replacement is the method used when a remanufacturer buys new components. Therefore, in order to assure the reliability of components after recovery, replacement and additive manufacturing can recover crankpins with 0.1 to 0.5 mm of wear depth while remachining can recover crankpins with 0.1 to 0.2 mm of wear depth. Table 5.8 demonstrates the reliability of crankpin after recovering with each recovery option.

Table 5.8 The reliability of crankpins after each recovery option.

Fault	Measurement	mm.	Reliability (1= reliable, 0 = unreliable)		
			Replace	Remachine	Additive manufacturing
Wear	Depth of wear	0.1	1	1	1
		0.2	1	1	1
		0.3	1	0	1
		0.4	1	0	1
		0.5	1	0	1

5.4.5 Input 5: Revenue

Table 5.9 shows there are two sources of revenue for each recovery option: 1. selling used components and selling remanufactured components. While the first source is only for replacement, the second source is for all recovery options.

Table 5.9 Sources of revenue for each recovery option

Revenue	Replacement	Remachining	Additive manufacturing
Revenue from selling used components	✓		
Revenue from selling remanufactured components	✓	✓	✓

5.4.6 Input 6: Total cost

The cost for each recovery option depends on the activities required. Table 5.10 shows the costs of each recovery option. The direct labour cost of each recovery option includes the cost of the activities related to the recovery options which were previously described in section 5.4.2. Direct material costs are included if replacement or additive manufacturing is selected. While direct material costs are not considered if remachining is selected because this recovery option removes the existing surface of the material. Overhead costs are included for each recovery option which is assumed to be 10 to 30% of the total direct labour cost (Abu et al., 2018b). To estimate the costs, this research adopted the principles introduced by Abu et al. (2018a) and Abu et al.(2018b).

Total cost

Total cost (£) = Direct labour costs (£) + Direct material costs (£) + Overhead costs (£)   (16)

Direct labour cost

Direct Labour cost (£) = Disassembly costs (£) + Inspection costs (£) + Purchasing new component costs (£) + Grinding costs (£) + Material deposition costs (£) + Polishing costs (£) + Cleaning costs (£) + Hardness measurement costs (£)   (17)

Table 5.10 The costs of each recovery option

Cost	Equation associated with each cost	Replacement	Remachining	Additive manufacturing
Direct labour costs				
Disassembly	*Disassembly costs* (£) = Disassembly time per crankshaft (h) x Manpower (person) x Labour costs (£/h) (18)	✓	✓	✓
Initial cleaning	*Initial cleaning costs (£)* = Initial cleaning time per crankshaft (h) x Manpower (person) x Labour costs (£/h) (19)	✓	✓	✓
Inspection	*Inspection costs* (£) = Inspection time per crankpin (h) x Number of crankpin (units) x Manpower (person) x Labour costs (£/h) (20)	✓	✓	✓
Buying new crankshaft		✓		
Grinding	*Grinding costs* (£) = Grinding time per crankpin (h) x Number of crankpin (units) x Manpower (person) x Labour costs (£/h) (21)		✓	✓
Material deposition cost	*Material deposition costs (£)* = Commercial power costs (£) + Metal powder costs (£) + Shielding gas costs (£) + Machine costs (£) + Labour costs (£) (22)			✓

Cost	**Equation associated with each cost**	**Replacement**	**Remachining**	**Additive manufacturing**
Polishing	*Polishing costs* (£) = Polishing time per crankpin (h) x Number of crankpin (units) x Manpower (person) x Labour costs (£/h) (23)		✓	✓
Cleaning	*Cleaning costs (£)* = Cleaning time per crankshaft (h) x Manpower (person) x Labour costs (£/h) (24)		✓	✓
Hardness measurement	*Hardness measurement* costs (£) = Number of crankshafts (units) x Costs per crankshafts (£) (25)		✓	✓
Direct Material costs		✓		✓
Overhead costs	*Overhead costs (£)*= The percentage of direct labour costs x total direct labour costs (£) (26)	✓	✓	✓
		10-30% of direct costs		

Material deposition cost

Material deposition costs are included when additive manufacturing is selected. This research adopted the principles introduced by Peng et al.(2019), Busachi et al.(2017) and Zhai (2012) to estimate the material deposition costs. Equation 22 demonstrates how to calculate material deposition cost.

Material deposition costs are the sum of five costs including 1. commercial power costs , 2. metal powder costs 3.Shielding gas costs 4.machine costs and 5.labour costs. The details of how these costs are calculated are shown as follow.

1. Commercial power costs (£) = Unit power costs (£/kW) x Total energy consumption (kW) (27)

1.1 Total energy consumption for all crankpins (kW) =

Total energy consumption of the machine per hour $\frac{(\text{kW})}{(\text{hour})}$ x Total time of laser cladding for all crankpins (min) x$\frac{(1\text{ hour})}{(60\text{ min})}$ (28)

2. Metal powder costs (£)

= Unit powder costs (£/kg) x Total mass of required alloy powder (kg) (29)

2.1 Total required mass of alloy powder (kg) =

Alloy powder density $\frac{(\text{kg})}{(1000\text{ cm}^3)}$ x Total volume of alloy powder required for all crankpins(1000cm^3) (30)

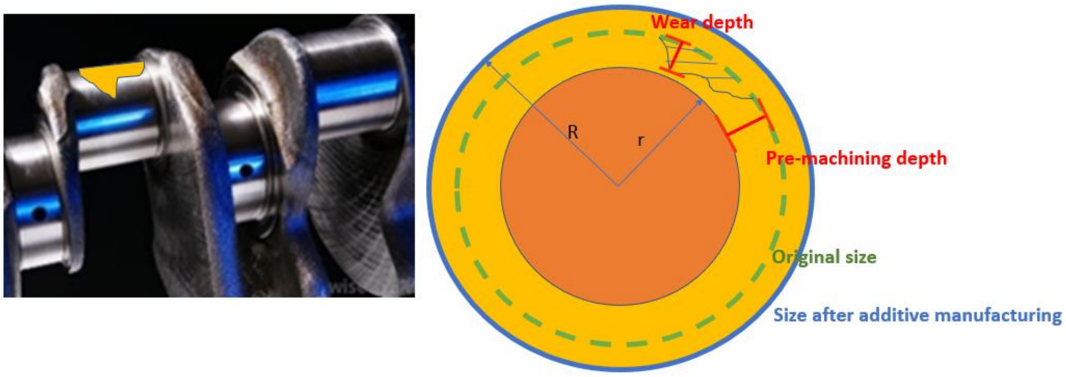


Figure 5.3 Cross-section of crankpin after additive manufacturing

It is assumed that some amount of alloy powder is wasted in the process, therefore the total volume of alloy powder required is more than the effective volume of alloy powder to be deposited (Peng et al., 2019). According to Figure 5.3, the total volume of alloy powder required for all crankpins can be calculated by the following formula.

2.1.1 Effective volume of alloy powder to be deposited for all crankpins (EV)(mm^3)

= ¶(R^2-r^2) x Length of crankpin needing a material deposit (31)

Where

R = The radius of the crankshaft after additive manufacturing

r = The radius of the crankshaft after pre-machining

2.1.2 The total volume of alloy powder required for all crankpins (TV)(mm^3)

= EV/ material deposition efficiency (32)

3. Shielding gas costs (£) = Unit gas costs(£/l) x Total gas flow (l) (33)

3.1 Total gas flow (litre)=Gas flow rate $\left(\frac{\text{litre}}{\text{min}}\right)$x Total time of gas flow (min) (34)

Assumption: Total time to feed powder = Total time of gas flow

3.1.1 Total time to feed powder

= Alloy powder density $\left(\frac{\text{kg x 1000 g}}{\text{1000cm}^3\text{ x kg}}\right)$ x Total volume of alloy powder required for all crankpins $\left(\frac{\text{mm}^3\text{x }10^6\text{cm}^3}{\text{mm}^3}\right)$ x $\frac{1}{\text{Feed rate of powder}}\left(\frac{\text{s}}{\text{g}}\right)$ (35)

4. Machine costs (£) *= Machine hourly rate (£/h) x Total working time of the machine (h)*

(36)

Table 5.11 shows how to calculate the machine hourly rate of laser cladding. All inputs were discussed with the remanufacturers (companies B, F, G) on their suitability. Based on Zhai (2012), the outputs have been calculated by equations 37 to 40.

Table 5.11 How to calculate the machine hourly rate of laser cladding

		Amount	Unit
Input	Investment cost of machine and ancillary equipment (including interest)[1]	325,412	£
	Life of machine[2]	12	Years
	Machine maintenance cost per year[2]	18,850	£
	Operational hours/day[2]	16	Hours (h)
	Operational days/year[2]	230	days
	Machine can work[2]	85.00%	of total working time without breakdown
Output	Hours per year in operation = 365*16*85% = 3128	3,128	Hours (h)
	Equipment depreciation costs per year	27,117.67	£
	Machine maintenance costs per year	18,850	£
	Total machine costs per year	45,968	£
	Machine hourly rate	14.69555	£/hour (£/h)

Source:

1 (Xu et al., 2014)

2 Assumption based on informant companies (companies B, F, G)

4.1 Hours per year in operation = days per year x operational hours per day x % of total working time without breakdown (37)

4.2 Equipment depreciation cost per year (£/ year)

= Investment cost of machine and ancillary equipment(£) / Life of machine (year) (38)

4.3 Total machine costs per year (£/ year)

= Equipment depreciation costs per year + Machine maintenance costs per year (39)

4.4 Machine hourly rate (£/h) = Total machine cost per year/ hours per year in operation (40)

5. Labour costs (£)

= Unit labour costs (£/h) x Total time of laser cladding for all crankpins (h) (41)

5.5 The numerical data in the model

Since the researcher has described the formulations used to calculate the values of the inputs in section 5.4, this section shows the numerical data calculated by those formulations. This model used Microsoft Excel as a tool. After users input any values in the yellow cells, the model will calculate other values automatically. The yellow cells are shown in Table 5.12 to 5.24. All values mentioned in section 5.5.3 will be used in the numerical example which will be described more in section 5.6.7.

5.5.1 The costs of the recovery options

Tables 5.12, 5.13, and 5.14 show the calculation sheets of replacement, remachining and additive manufacturing excluding material deposition costs, respectively. The material deposition cost calculation is only for additive manufacturing (laser cladding) as seen in Table 5.15. In order to calculate the material deposition costs, it is necessary to know the hourly rate of the machine which is shown on the calculation sheet in Table 5.16. Also, the technical data for the laser cladding, such as the volume of alloy powder, total energy consumption, total time to feed powder, total gas flow etc., are required. The calculation of these technical data is shown in Table 5.17. In order to know the technical data for laser cladding, removed depth and added material depth of the laser cladding are required. The calculation sheet is shown in Table 5.18.

Table 5.12 Total costs of replacement

	Duration per crankpin[1,3]		% of total direct labour cost[1]		Number of crankpin[1]	Duration per crankshaft[1]		Manpower[1]	Labour cost[4]	Direct Material Cost[5](£)		Cost(£)	
Cost	min. (minutes)	max. (minutes)	min.	Max.	unit	min. minutes	max. minutes	person	£ /hour	min. cost	max. cost	Min. cost	max. cost
Direct Labour cost													
Disassembly cost						6	6	1	8.46			1.25	1.25
Inspection cost	12	18			6	72	108	1	8.46			10.15	15.23
Initial Cleaning cost						18	18	1	8.46			2.61	2.61
Total direct labour cost												14.01	19.08
Direct Material Cost										50	600	50.00	600.00
Overhead cost			10%	30%								1.40	5.72
Total cost												65.41	624.81

Source:
1 Integration of Mahalanobis-Taguchi system and traditional cost accounting for remanufacturing crankshafts
2 Costing improvement of remanufacturing crankshaft by integrating Mahalanobis-Taguchi System and Activity based costing
3 Genetically optimised disassembly sequence for automotive component reuse
4 https://www.payscale.com/research/UK/Manufacturing/Hourly_Rate
5 Price list from E-bay, Remanufacturers

Table 5.13 Total cost of remachining

	Duration per crankpin[1,3]		Number of crankpin[1]	Duration per crankshaft[1]		Manpower [1]	Labour cost[4]	Number of crankshaft.[2]	Cost per unit[2] (£)	% of total direct labour costs[1]		Cost (£)	
Cost	Min. minutes	Max. minutes	unit	Min. mintes	Max. minutes	person	£ /hour					Min. cost	Max. cost
Direct Labour cost													
Disassembly cost				6	6	1	8.46					1.25	1.25
Inspection cost	12	18	6	72	108	1	8.46					10.15	15.23
Grinding cost	0	54	6	0	324	1	10.31					0	55.67
Polishing cost	48	64	6	216	288	1	10.31					37.12	49.49
Cleaning cost				60	72	1	8.46					8.46	10.15
Hardness measurement cost								1	16.07			16.07	16.07
Total direct labour cost												73.04	147.86
Overhead cost										10%	30%	7.30	44.36
Total cost												80.35	192.21

Source:
1 Integration of Mahalanobis-Taguchi system and traditional cost accounting for remanufacturing crankshafts
2 Costing improvement of remanufacturing crankshaft by integrating Mahalanobis-Taguchi System and Activity based costing
3 Genetically optimised disassembly sequence for automotive component reuse
4 https://www.payscale.com/research/UK/Manufacturing/Hourly_Rate
5 Price list from E-bay, Remanufacturers

Table 5.14 Total cost of additive manufacturing excluding material deposition costs

	Duration per crankpin[1,3]		Number of crankpin[1]	Duration per crankshaft[1]		Manpower[1]	Labour cost[4]	Number of crankshaft.[2]	Cost per unit[2] (£)	% of total direct labour costs[1]		Cost (£)	
Cost	Min. minutes	Max. minutes	unit	Min. mintes	Max. minutes	person	£ /hour			Min. minutes	Max. minutes	unit	Min. mintes
Direct Labour cost													
Disassembly cost				6	6	1	8.46					1.25	1.25
Inspection cost	12	18	6	72	108	1	8.46					10.15	15.23
Grinding cost	0	54	6	0	324	1	10.31					0.00	55.67
Polishing cost	36	48	6	216	288	1	10.31					37.12	49.49
Cleaning cost				60	72	1	8.46					8.46	10.15
Hardness measurement cost								1	16.07			16.07	16.07
Total direct labour cost												73.04	147.86
Overhead cost										10%	30%	7.30	44.36
Total cost												80.35	192.21

Source:
1 Integration of Mahalanobis-Taguchi system and traditional cost accounting for remanufacturing crankshaft
2 Costing improvement of remanufacturing crankshaft by integrating Mahalanobis-Taguchi System and Activity based costing
3 Genetically optimised disassembly sequence for automotive component reuse
4 https://www.payscale.com/research/UK/Manufacturing/Hourly_Rate
5 Price list from E-bay, Remanufacturers

Table 5.15 Material Deposition cost

Input	Unit cost					
	Commercial power cost[1]	0.14	GBP/kWh			
	Metal powder cost[2]	62.88	GBP/kg			
	Shielding gas cost[3]	5	GBP/l			
	Labour cost[4]	8.46	GBP/h			
	Machine cost[5]	14.70	GBP/h			
Output	Wear depth of the component (mm)	0.5	0.4	0.3	0.2	0.1
	Commercial power cost (GBP)	0.14	0.14	0.14	0.14	0.14
	Metal powder cost(GBP)	1.54	1.38	1.24	0.78	0.53
	Shielding gas cost (GBP)	153.24	137.59	123.45	77.29	53.07
	Labour cost (GBP)	1.69	1.69	1.69	1.69	1.69
	Machine cost (GBP)	2.94	2.94	2.94	2.94	2.94
	Total cost(GBP)	159.55	143.74	129.46	82.83	58.38

Source:

1 https://www.businessenergy.com/business-electricity/

2 https://www.alibaba.com/product-detail/Plasma-Spray-Ni-50-Nickel-Based_60809823417.html?spm=a2700.7724838.2017115.61.58b7c57bYuF1Y0

3 https://www.ebay.co.uk/itm/361207029201]

4 https://www.payscale.com/research/UK/Manufacturing/Hourly_Rate

5 Table 5.16

Table 5.16 Machine cost of Additive manufacturing (Laser cladding)

		Amount	Unit
Input	Investment cost of machine and ancillary equipment (including interest)[1]	325,412	£
	Life of machine[2]	12	Years
	Machine maintenance cost per year[2]	18, 850	£
	Operational hours/day[2]	16	Hours (h)
	Operational days/year[2]	230	days
	Machine can work[2]	85.00%	of total working time without breakdown
Output	Hours per year in operation=365*16*85% =3128	3,128	Hours (h)
	Equipment depreciation cost per year	27,117.67	£
	Machine maintenance cost per year	18,850	£
	Total machine cost per year	45,968	£
	Machine hourly rate	14.69555	£/hour (£/h)

Source:

1 (Xu et al., 2014)

2 Assumption

Table 5.17 The technical data for laser cladding

		Parameter	unit					
Input		Wear depth of the component	mm	0.5	0.4	0.3	0.2	0.1
	(Fu et al., 2016)	Removed depth of the component from pre-machining	mm	0.8	0.7	0.5	0.3	0.1
		Added material depth	mm	1.0	0.9	0.8	0.5	0.3
		Initial diameter of the crankpin (The smallest diameter that can be measured when there is wear on it)	mm	57.5	57.6	57.7	57.8	57.9
	(Randhavan and Galhe, 2017)	Desired diameter of the crankpin	mm	58	58	58	58	58
		Length of the crankpin to be deposited	mm	31	31	31	31	31
	(Abu et al., 2018b)	Number of crankpins		6	6	6	6	6
	(Cavanaugh et al., 2016)	Total energy consumption of the machine per hour	kWh	5				
	(Peng et al., 2019)	Gas flow rate (Argon)	l/min.	10				
	(Eboo and Blake, 1986)	Time of laser cladding per crankpin	Min.	2	2	2	2	2
		Total time of laser cladding for all crankpins (deposition time)	Min.	12	12	12	12	12
	Assumption	Time of gas flowing for all crankpins	Min.	3.06	2.75	2.47	1.55	1.06
	(Peng et al., 2019)	Material deposition efficiency		80%	80%	80%	80%	80%
		Feed rate of powder	g/s	0.13				
	https://www.alibaba.com/product-detail/Plasma-Spray-Ni-50-Nickel-Based_60809823417.html?spm=a2700.7724838.2017115.61.58b7c57bYuF1Y0	Alloy powder density	kg/1000 cm^3	3.5				
Output		Effective volume of alloy powder to be deposited for all crankpins	mm^3	5590.15	5019.23	4503.28	2819.42	1936.08
		Total volume of alloy powder required for all crankpins	mm^3	6987.69	6274.04	5629.11	3524.28	2420.10
		Total energy consumption for all crankpins	kW	1	1	1	1	1
		Total required alloy powder	g	24.46	21.96	19.70	12.33	8.47
		Total time to feed powder	Min.	3.06	2.75	2.47	1.55	1.06
		Total gas flow	l	30.65	27.52	24.69	15.46	10.61

In this research, removed depth and added material depth are assumed based on previous studies (Fu et al., 2016).

Since the removed depth and added material depth of laser cladding is available for the wear depth at 0.2, 0.3, 0.5, 1, 1.8 mm (Fu et al., 2016) as seen in Figure 5.4, the information for the experiment is plotted and the equations for the graph are shown. Next, this research found the removed depth and added the material depth for the wear depth at 0.1 and 0.4 mm by assuming x = 0.1 and 0.4 mm in the equation respectively. After calculation, the removed depth and added material depth is known. Table 5.18 shows the relationship between wear depth and removed depth and the relationship between wear depth and the cladding depth. The information in Table 5.18 is from the experiment and the calculation. Formulas 42 and 43 are used for the calculation as shown below.

1. Find removed depth of surface

$$y = -0.4091a^2 + 2.0485a + 0.1412 \qquad (42)$$

y= Removed depth (mm)

a= Wear depth (mm)

2. Find added material depth

$$y = -0.5275a^2 + 2.1191a - 0.1031 \qquad (43)$$

y= Added material depth (mm)

a= Wear depth (mm)

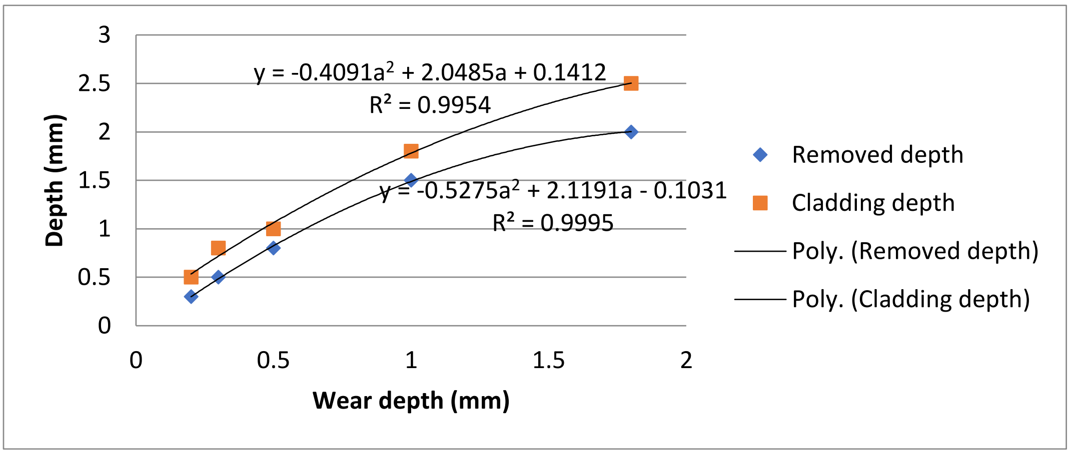


Figure 5.4 Relationship between wear depth and removed depth and cladding depth from experiment

Table 5.18 Relationship between wear depth and removed depth and cladding depth from experiment and equation

	Data from experiment (Fu et al., 2016)					Data from equation				
wear depth (mm)	0.2	0.3	0.5	1	1.8	0.1	0.2	0.3	0.4	0.5
removed depth (mm)	0.3	0.5	0.8	1.5	2	0.1	0.3	0.5	0.7	0.8
Added material depth (Cladding depth) (mm)	0.5	0.8	1	1.8	2.5	0.3	0.5	0.8	0.9	1

5.5.2 The numerical data of operational time per crankshaft

Operational time per crankshaft is shown in Table 5.19. Most of the information was gathered from existing research papers. Only the time for replacement was assumed. The time for disassembly, inspection and initial cleaning are included in the replacement option since remanufacturers stated that these activities are related to replacement. This research assumes that the time of disassembly and inspection for replacement is as same as for remachining and additive manufacturing since they are activities conducted before selecting a suitable recovery option depending on the physical condition of the components. While the initial cleaning time for replacement is shorter than the total cleaning time of remachining and additive manufacturing because the total cleaning time includes the initial cleaning time before the condition of the components is known and cleaning time after the resurfacing of the components. As shown in Table 5.19, the time for remachining is the same as the time for additive manufacturing without the material deposition time. To calculate the total time of additive manufacturing, the time of material deposition from Table 5.17 will be added to the time of additive manufacturing without the material deposition time automatically.

Table 5.19 Operational time per crankshaft

Replacement[1]			Remachining (6 cylinders)[2]			Additive manufacturing[2]		
	Time (hrs)			time(hrs)			time(hrs)	
	Min.	Max.		Min	Max		Max	Min
Disassembly cost	0.15	0.15	Disassembly cost	0.15	0.15	Disassembly cost	0.15	0.15
Inspection	1.20	1.80	Inspection	1.20	1.80	Inspection	1.20	1.80
Initial Cleaning	0.31	0.31	Grinding	0.00	5.40	Grinding	5.40	5.4
			Polishing	3.60	4.80	Polishing	4.80	4.8
			Cleaning	1.00	1.20	Cleaning	1.20	1.2
			Hardness measurement	0.002	0.002	Hardness measurement	0.002	0.002
Total time	1.66	2.26	Total time (hrs)	5.95	13.35	Total time (hrs)*	5.95	13.35

* excluding time for material deposition

1 Assumption 2 (Abu et al., 2018b)

5.5.3 The numerical data of all factors

The section shows all the values of the factors necessary for comparisons. The factors are the importance score of each criterion, total cost/profit of each recovery option, total operational time, material recovery and reliability of component after recovery of each recovery option as shown in Tables 5.20 to 5.24. The score is agreed by companies B, F, G and H. Since cost, profit and time are uncertain factors for remanufacturing, this model contributes to solving this problem by showing both the minimum value and maximum value to help make a better decision.

Table 5.20 Importance score of each criterion

Criteria	Importance score(out of 100)
Profit	20
Time	20
Material recovery rate	10-15
Reliability	45-50

Table 5.21 Cost/profit

			Cost(GBP)						Revenue(GBP)			Profit (GBP)					
Fault	Measurement	mm.	Replace		Remachining		Additive manufacturing		Revenue from remanufactured products	Revenue from selling used crankshafts (% of the revenue of remanufactured products)	Revenue from selling used crankshafts	Replace		Remachining		Additive manufacturing	
			Min.	Max.	Min.	Max.	Min.	Max.				Min.	Max.	Min.	Max.	Min.	Max.
wear	Depth of wear	0.1	65.41	624.81	80.35	192.21	138.72	250.59	900	5%	45	320.19	879.59	707.79	819.65	649.41	761.28
		0.2	65.41	624.81	80.35	192.21	163.18	275.05	900	5%	45	320.19	879.59	707.79	819.65	624.95	736.82
		0.3	65.41	624.81	80.35	192.21	209.80	321.67	900	5%	45	320.19	879.59	707.79	819.65	578.33	690.20
		0.4	65.41	624.81	80.35	192.21	224.09	335.96	900	5%	45	320.19	879.59	707.79	819.65	564.04	675.91
		0.5	65.41	624.81	80.35	192.21	239.90	351.76	900	5%	45	320.19	879.59	707.79	819.65	548.24	660.10

Table 5.22 Time

Fault	Measurement	mm.	Replace				Remachining		Additive Manufacturing	
			The demand for new crankshafts (units)	Buying new crankshafts Time (hour)	Time of Replacement (hours)		Time of Remachining (hours)		Time of Additive manufacturing (hours)	
					Min.	Max.	Min.	Max.	Min.	Max.
wear	Depth of wear	0.1	38	8	1.87	2.47	5.95	13.35	6.15	13.55
		0.2	38	8	1.87	2.47	5.95	13.35	6.15	13.55
		0.3	38	8	1.87	2.47	5.95	13.35	6.15	13.55
		0.4	38	8	1.87	2.47	5.95	13.35	6.15	13.55
		0.5	38	8	1.87	2.47	5.95	13.35	6.15	13.55

Table 5.23 Material recovery

Area	Fault	Measurement	mm.	Material recovery (kg)		
				Replace	Remachine	Additive manufacturing
	wear	Depth of wear	0.1	0	20.6	20.6
			0.2	0	20.6	20.6
			0.3	0	20.6	20.6
			0.4	0	20.6	20.6
			0.5	0	20.6	20.6

Table 5.24 Reliability of component after recovery

Area	Fault	Measurement	mm.	Reliability (1 = reliable, 0 = unreliable)		
				Replace	Remachining	Additive manufacturing
	wear	Depth of wear	0.1	1	1	1
			0.2	1	1	1
			0.3	1	0	1
			0.4	1	0	1
			0.5	1	0	1

5.6 Mathematical formulation to select the best recovery option of each component

After background information and data has been described in the earlier sections of this chapter, this section explains the mathematical formulation.

In this study, a combined point allocation-goal programming is proposed to select the best recovery option at each wear depth of a crankpin. Point allocation is used for weighting factors in this project since computation is easier than AHP and appropriate to allocate points for less than 6 criteria (Deng et al., 2000, Mustajoki et al., 2004). According to Aalaei and Davoudpour(2016),Goal programming (GP) is an effective tool for trading-off several conflicting objectives such as maximizing profit and minimizing environmental impacts in the decision-making process. GP is a practical MCDM method since it can choose an infinite number of alternatives. Also, it can be used for large scale problems such as production planning problems.

Possible recovery options for used crankshafts in remanufacturing are replacement of new components, remachining surface of components and additive manufacturing. The model formulation is given below with notations and decision variables.

5.6.1 Nomenclature

n = 1 if it is replacement, n = 2 if it is remachining, n = 3 if it is additive manufacturing

P_p = importance score of profit

P_t = importance score of time

P_m = importance score of the reusable mass of the component

P_r = importance score of reliability of components after recovery

p_n = Profit of recovery option n, Total revenue – total cost

T_n = Time of recover option n

M_n = Mass of reusable components of recovery option n

R_n = Component reliability after recovery option n

X_n = 1 if recovery option n is used, zero otherwise

d_p^-, d_p^+ = negative/positive deviation of profit

d_t^-, d_t^+ = negative/positive deviation of operational time

d_m^-, d_m^+ = negative/positive deviation of reusable mass

d_r^-, d_r^+ = negative/positive deviation of component reliability after recovery

5.6.2 Technical assumptions

In order to calculate, profit of each recovery option, time of each recovery option and reusable mass of components. The technical assumptions are given below.

1. According to the information from companies B,F,G, since the surface removed from components after remachining or additive manufacturing is quite thin (0.1 to 0.5 mm), the mass after recovery options is assumed to be similar to the original mass of the component.

2. Overhead costs are included for each recovery option which is assumed to be 10 to 30% of the total direct labour cost (Abu et al., 2018b).

3. It is assumed that some amount of alloy powder is wasted in the process, therefore the total volume of alloy powder required is more than the effective volume of alloy powder to be deposited (Peng et al., 2019).

4. According to the information from companies B,G, total time to feed powder is assumed to be equal to total time of gas flow to simplify the calculation. While the laser cladding machine runs to feed powder, gas flows all the time. In real practice total time of gas flow is longer than total time to feed powder because total time of gas flow includes setting time. However, remanufacturers suggested that the setting time is very short.

5. The information to calculate machine hourly rate of laser cladding are based on companies B, F, G who agree about these values.

5.1 Life of machine	12	Years
5.2 Machine maintenance cost per year	18850	£
5.3 Operational hours/day	16	Hours
5.4 Operational days/year	230	days
5.5 Machine can work	85%	of total working time without breakdown

6. In order to estimate the cost of additive manufacturing ,removed depth and added material depth of components are assumed based on previous studies (Fu et al., 2016).

7. Only the time for replacement was assumed. The time for disassembly, inspection and initial cleaning are included in the replacement option since remanufacturers stated that these activities are related to replacement. This research assumed that the time of disassembly and inspection for replacement is as same as for remachining and additive manufacturing since they are activities conducted before selecting a suitable recovery option depending on the physical condition of the components.

5.6.3 Objective function

When formulating goal programming to select the best recovery options, it is desirable to maximize profit, amount of material reusable, reliability of components and minimize operational time. Profit, amount of material usable and reliability of components after recovery are defined as benefit criteria (the smaller value, the smaller preference) while operational time is defined as drawback criteria(the larger value, the smaller preference). Therefore, the objectives are to minimize negative deviations of profit, reusable mass, reliability of components while minimising positive deviations of operational time.

MIN $P_p d_p^- + P_t d_t^+ + P_m d_m^- + P_r d_r^-$ (44)

5.6.4 Constraints

The first constraint is to maximize the profit of the recovery options. The mathematical expression for the first constraint is written as follows: the coefficients before X_1, X_2, X_3 are the profit of each recovery option.

$p_1X_1 + p_2X_2 + p_3X_3 + d_p^- - d_p^+ =$ Max.profit/unit (45)

The second constraint is to minimize the operational time of the recovery options. The mathematical expression for the second objective is written below. The coefficients before X_1, X_2, X_3 are the operational time of each recovery option.

$T_1X_1 + T_2X_2 + T_3X_3 + d_t^- - d_t^+ =$ Min. operational time/unit (46)

The third constraint is to maximize the reusable mass of components through the recovery options. The mathematical expression for the third objective is written below. The coefficients before X_1, X_2, X_3 are the reusable mass of components for each recovery option.

$M_1X_1+M_2X_2+M_3X_3+d_m^- -d_m^+ =$ Max. reusable mass of components/unit (47)

The fourth constraint is to maximize the reliability of components after recovery. The mathematical expression for the fourth objective is written below. The coefficients before X_1, X_2, X_3 are the reliability of the components after each recovery option.

$R_1X_1+R_2X_2+R_3X_3+d_r^- -d_r^+ =$ Max. reliability of components after recovery (48)

The fifth constraint is that the sum of X_1, X_2, X_3 is equal to 1 and X_1, X_2, X_3 are equal to 0 or 1 since only one recovery option is selected.

$X_1+X_2+X_3 = 1$, $X_1, X_2, X_3 = 0$ or 1 (49)

The sixth constraint is that $d_p^+, d_p^-, d_t^+, d_t^-, d_m^+, d_m^-, d_r^+, d_r^-$ are more than or equal to zero.

$d_p^+, d_p^-, d_t^+, d_t^-, d_m^+, d_m^-, d_r^+, d_r^- \geq 0$ (50)

5.6.5 Decision variables

1. $X_1 = 1$ if replacement is selected, otherwise $X_1 = 0$
2. $X_2 = 1$ if remachining is selected, otherwise $X_2 = 0$
3. $X_3 = 1$ if additive manufacturing is selected, otherwise $X_3 = 0$

5.6.6 Normalisation

Since four different objectives are shown in different units, normalisation is required to change the values to comparable scales. The scale of measurement varies from 0 to 1 for each criterion. The lowest value of $r_{ij} = 0$ while the highest value $r_{ij} = 1$.

According to White (1982), since profit, reusable mass of components and reliability of components after recovery are defined as benefit criteria (the larger the value, the greater the preference), therefore equation 51 is used. When operational time is defined as drawback criteria, the equation is transformed to equation 52.

$$\frac{x_{ij}-x_j^{min}}{x_j^{*}-x_j^{min}} = r_{ij} \tag{51}$$

$$\frac{x_j^{*}-x_{ij}}{x_j^{*}-x_j^{min}} = r_{ij} \tag{52}$$

x_j^{*} is the maximum value of the different alternatives

x_j^{min} is the min value of the different alternatives

x_{ij} is the value of each alternative

r_{ij} is the normalised value of each alternative, $0 \leq r_{ij} \leq 1$

Therefore, the final equations have been changed to

Objective function $\quad$ MIN $P_p d_p^- + P_t d_t^+ + P_m d_m^- + P_r d_r^-$ (53)

Goal constraints

1. Maximise profit

$$\frac{P_1-P_j^{min}}{P_j^{max}-P_j^{min}} X1 + \frac{P_2-P_j^{min}}{P_j^{max}-P_j^{min}} X2 + \frac{P_3-P_j^{min}}{P_j^{max}-P_j^{min}} X3 + d_p^- - d_p^+ = 1 \tag{54}$$

2. Minimise time

$$\frac{T_j^{max}-T_1}{T_j^{max}-T_j^{min}} X1 + \frac{T_j^{max}-T_1}{T_j^{max}-T_j^{min}} X2 + \frac{T_j^{max}-T_1}{T_j^{max}-T_j^{min}} X3 + d_t^- - d_t^+ = 1 \tag{55}$$

3. Maximise reusable mass

$$\frac{M_1-M_j^{min}}{M_j^{max}-M_j^{min}} X1 + \frac{M_2-M_j^{min}}{M_j^{max}-M_j^{min}} X2 + \frac{M_3-M_j^{min}}{M_j^{max}-M_j^{min}} X3 + d_m^- - d_m^+ = 1 \tag{56}$$

4. Maximise reliability after recovery

$$R_1X_1 + R_2X_2 + R_3X_3 - d_r^+ + d_r^- = 1 \tag{57}$$

5. Only one recovery option is selected and X_1, X_2, X_3 are either 1 or 0

$$X_1 + X_2 + X_3 = 1 \text{ and } X_1, X_2, X_3 = 1 \text{ or } 0 \tag{58}$$

6. All deviations of profit, reusable mass, reliability of components and operational time are more than or equal to 0

$$d_p^+, d_p^-, d_t^+, d_t^-, d_m^+, d_m^-, d_r^+, d_r^- \geq 0 \tag{59}$$

Nomenclature

n = 1 if it is replacement, n = 2 if it is remachining, n = 3 if it is additive manufacturing

P_p = importance score of profit

P_t = importance score of time

P_m = importance score of the reusable mass of the component

P_r = importance score of the reliability of components after recovery

p_n = Profit of recovery option n, Total revenue – total cost

p_j^{max} = Maximum profit among different recovery options

p_j^{min} = Minimum profit among different recovery options

T_n= Time of recover option n

T_j^{max} = Maximum time among different recovery options

T_j^{min} = Minimum time among different recovery options

M_n= Mass of the reusable component of recovery option n

M_j^{max} = Maximum reusable mass among different recovery options

M_j^{min} = Minimum reusable mass among different recovery options

R_n = Component reliability after recovery option n

X_n = 1 if recovery option n is used, zero otherwise

d_p^-, d_p^+ = negative/positive deviation of profit

d_t^-, d_t^+ = negative/positive deviation of operational time

d_m^-, d_m^+ = negative/positive deviation of reusable mass

d_r^-, d_r^+ = negative/positive deviation of component reliability after recovery

5.6.7 Numerical example

The objective function is to minimise unwanted deviations in each of the goal constraints. The goal constraints include maximising profit, reusable mass, reliability after recovery and minimising operation time. Therefore, the objective function is to minimise negative deviations of profit, reusable mass and reliability after recovery and to minimise positive deviation of operational times. The importance score of profit, operational time, reusable mass and reliability are 0.2, 0.2, 0.1 and 0.5, respectively. These importance scores are seen as the coefficients of d_p^-, d_t^+, d_m^- and d_r^-. Profit, time, reusable mass and reliability after recovery vary for each recovery option. All data are given in Table 5.25.

Table 5.25 All input data for modelling

Wear depth (mm)	Profit (GBP)						Time (hrs)						Reusable mass (kg)			Reliability after recovery (1= Reliable , 0 = Unreliable)		
	Replacement		Remachining		Additive manufacturing		Replacement		Remachining		Additive manufacturing		Replacement	Remachining	Additive manufacturing	Replacement	Remachining	Additive manufacturing
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.						
0.1	320.19	879.59	707.79	819.65	649.41	761.28	1.87	2.47	5.95	13.35	6.15	13.55	0	20.6	20.6	1	1	1
0.2	320.19	879.59	707.79	819.65	624.95	736.82	1.87	2.47	5.95	13.35	6.15	13.55	0	20.6	20.6	1	1	1
0.3	320.19	879.59	707.79	819.65	578.33	690.2	1.87	2.47	5.95	13.35	6.15	13.55	0	20.6	20.6	1	0	1
0.4	320.19	879.59	707.79	819.65	564.04	675.91	1.87	2.47	5.95	13.35	6.15	13.55	0	20.6	20.6	1	0	1
0.5	320.19	879.59	707.79	819.65	548.24	660.1	1.87	2.47	5.95	13.35	6.15	13.55	0	20.6	20.6	1	0	1

The calculations below use a case with 0.1 mm wear depth as an example. The maximum value of profit and the minimum value of time are used. According to equations 53 to 59, after replacing variables with values from Table 5.25, the new equations 60 to 66 are as follow:

Objective function Min $0.2d_p^- + 0.2d_t^+ + 0.1d_m^- + 0.5d_r^-$ (60)

Goal constraints

1. To maximise profit

$$\frac{879.59-761.28}{879.59-761.78} X_1 + \frac{819.65-761.28}{879.59-761.78} X_2 + \frac{761.28-761.28}{879.59-761.78} X_3 - d_p^+ + d_p^- = 1 \tag{61}$$

2. To minimise operational time

$$\frac{13.55-1.87}{13.55-1.87} X_1 + \frac{13.55-13.35}{13.55-1.87} X_2 + \frac{13.55-13.55}{13.55-1.87} X_3 - d_t^+ + d_t^- = 1 \tag{62}$$

3. To maximise reusable mass

$$\frac{0-0}{20.6-0} X_1 + \frac{20.6-0}{20.6-0} X_2 + \frac{20.6-0}{20.6-0} X_3 - d_m^+ + d_m^- = 1 \tag{63}$$

4. To maximise reliability after recovery

$$1 X_1 + 1 X_2 + 1X_3 - d_r^+ + d_r^- = 1 \tag{64}$$

5. Only one recovery option is selected and X_1 , X_2 ,X_3 are either 1 or 0

$$X_1 + X_2 + X_3 = 1 \tag{65}$$

6. All deviations of profit, reusable mass, reliability of components and operational time are more than or equal to 0

$$d_p^+, d_p^-, d_t^+, d_t^-, d_m^+, d_m^-, d_r^+, d_r^- \geq 0 \tag{66}$$

5.7 Sensitivity analysis setting

Since this model considers the maximum and minimum values of factors, a sensitivity analysis was conducted to gain useful insights from the proposed model. Sensitivity analysis was conducted to study the effects of changing the values of profit of each recovery option, operational time of recovery option, and reliability of component after recovery. These criteria are significant to select the best recovery for each component. Using the data from Table 5.26, for each depth of wear on a crankpin from 0.1 mm to 0.5 mm, this model tested a total of 20 cases (4 main cases x 5 subcases = 20 total cases). Therefore, this research studied 100 cases in total as seen in Table 5.26. Main case 1 to main case 4 studied the different values of profit, time and material recovery for each of the recovery options as shown in Table 5.27. Subcases A to E studied the different values for reliability of each recovery option as shown in Table

5.28. Subcases A to C are with the assumption that the reliability of a component after replacement is as same as or better than the reliability of a component after additive manufacturing. While, subcases D to E are with the assumption that the reliability of a component after replacement is worse than the reliability of a component after additive manufacturing. The reliability of a component after remachining should be as same as or worse than the reliability of a component after replacement since remachining removes surface of components which can reduce the physical structure of the components. According to Table 5.28, the reliability of the components can be 0, 70, 90 or 100% for each recovery option. This research studied this range of values since the reliability of components can vary between 0 to 100% and the results showing different best recovery option when the reliability of the components is 0, 70, 90 and 100%. Also, this study considered the importance of the criteria which depended on the different opinions of the various companies. For example, the importance score for reusable mass is from 10 to15 and the importance score for reliability is from 45 to 50.

Table 5.26 The total number of cases for each wear depth of a crankpin

Wear Depth	Main Case	Sub case A	Subcase B	Subcase C	Subcase D	Subcase E
0.1 mm	Case 1	✓	✓	✓	✓	✓
	Case 2	✓	✓	✓	✓	✓
	Case 3	✓	✓	✓	✓	✓
	Case 4	✓	✓	✓	✓	✓
0.2 mm	Case 1	✓	✓	✓	✓	✓
	Case 2	✓	✓	✓	✓	✓
	Case 3	✓	✓	✓	✓	✓
	Case 4	✓	✓	✓	✓	✓
0.3 mm	Case 1	✓	✓	✓	✓	✓
	Case 2	✓	✓	✓	✓	✓
	Case 3	✓	✓	✓	✓	✓
	Case 4	✓	✓	✓	✓	✓
0.4 mm	Case 1	✓	✓	✓	✓	✓
	Case 2	✓	✓	✓	✓	✓
	Case 3	✓	✓	✓	✓	✓
	Case 4	✓	✓	✓	✓	✓
0.5 mm	Case 1	✓	✓	✓	✓	✓
	Case 2	✓	✓	✓	✓	✓
	Case 3	✓	✓	✓	✓	✓
	Case 4	✓	✓	✓	✓	✓

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Table 5.27 The different values for profit, time and material recovery for each recovery option studied in 4 main cases

REP = replacement, REM = remachining, ADM = additive manufacturing

	Main case 1			Main case 2			Main case 3			Main case 4		
	REP	REM	ADM	REP	REM	ADM	REP	REM	ADM	REP	REM	ADM
Profit	Max.	Max.	Max.	Max	Min	Min	Min	Max	Max	Min	Min	Min
Time	Min.	Min.	Min.	Min	Max	Max	Max	Min	Min	Max	Max	Max
Material recovery (kg)	0	20.6	20.6	0	20.6	20.6	0	20.6	20.6	0	20.6	20.6

Table 5.28 The different reliability values for each recovery option studied in 4 subcases

	Reliability (%)														
Wear depth	0.1 mm			0.2 mm			0.3 mm			0.4 mm			0.5 mm		
Sub-Cases	REP	REM	ADM	REP	REM	ADM	REP	REM	ADM	REP	REM	ADM	REP	REM	ADM
A	100	100	100	100	100	100	100	0	100	100	0	100	100	0	100
B	100	70	70	100	70	70	100	0	70	100	0	70	100	0	70
C	100	90	90	100	90	90	100	0	90	100	0	90	100	0	90
D	70	70	100	70	70	100	70	0	100	70	0	100	70	0	100
E	90	90	100	90	90	100	90	0	100	90	0	100	90	0	100

5.8 Results of the decision making on the best recovery options from goal programming

The results of the sensitivity analysis in section 5.7 yield 100 results as shown in Table 5.29. The importance score for each criterion makes the model prioritise each criterion from the most important criterion to the least important criterion. The reliability of components after recovery is considered first because it is the most important factor with a score of 50, the second considers the factors of profit and operational time for which the importance score is 20 each and the least important factor is reusable mass with a score of 10. The results from the model are also in accordance with this concept of priority according to importance. Since the reliability of components after recovery is the most important factor for subcases D and E, additive manufacturing is the best recovery option when additive manufacturing is the best recovery option in terms of the reliability of components after recovery. Likewise, replacement will be the best recovery option for each level of wear depth (0.1 mm - 0.5 mm) as seen in subcases B and C because replacement is the best recovery option in terms of the reliability of components after recovery. In subcase A for which all recovery options give the same percentage for reliability of the components, the next factor to consider is operational time and profit. Replacement is selected as the best recovery option since its operational time is the lowest and profit is higher than that of remachining or additive manufacturing. Since some companies give different importance score for reusable mass and reliability, this research studied the results when the importance score for the criteria were changed. It was found that the results in table 5.29 do not change although the importance score for reusable mass was changed from 10 to 15 and the importance score for reliability from 45 to 50.

Table 5.29 Results of the decision making on the best recovery options by goal programming

Wear depth	0.1 mm					0.2 mm					0.3 mm					0.4 mm					0.5 mm				
	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
Case 1	REP	REP	REP	ADM	ADM	REP	REP	REP	ADM	ADM	REP	REP	REP	ADM	ADM	REP	REP	REP	ADM	ADM	REP	REP	REP	ADM	ADM
Case 2	REP	REP	REP	ADM	ADM	REP	REP	REP	ADM	ADM	REP	REP	REP	ADM	ADM	REP	REP	REP	ADM	ADM	REP	REP	REP	ADM	ADM
Case 3	REM	REP	REP	ADM	ADM	REM	REP	REP	ADM	ADM	ADM	REP	REP	ADM	ADM	ADM	REP	REP	ADM	ADM	ADM	REP	REP	ADM	ADM
Case 4	REM	REP	REP	ADM	ADM	REM	REP	REP	ADM	ADM	ADM	REP	REP	ADM	ADM	ADM	REP	REP	ADM	ADM	ADM	REP	REP	ADM	ADM

REP = Replacement, ADM = Additive manufacturing, REM = Remachining

5.9 Validating the model

Testing the model with real data can bring real practice into the simulated situation, but not all the data is accessible (Beisbart and Saam, 2019, Law and Kelton, 1991, Louloudi, 2012). It is therefore recommended to use an expert review to validate the model (Beisbart and Saam, 2019, Law and Kelton, 1991, Ijomah, 2002) because this method can gather the views of experts who have extensive and comprehensive expertise of the system in both normal and unusual situations. All results reported in this paper were obtained after adjustments were made as recommended by academic and industrial participants.

5.9.1 The validating panel

In the validation process, the participants were either automotive remanufacturing industry representatives or academics involved in remanufacturing optimisation as shown in Table 5.30. Case study companies and non-case study companies were used for the validation. The non-case study companies were used for external validation of the results which were obtained from the case studies. Academics involved in remanufacturing optimisation were also included on the validating panel since they are working in the remanufacturing industry and are specialised in optimisation techniques. Therefore, they had an adequate knowledge of the remanufacturing processes which were necessary to assess the model.

Table 5.30 The participants involved in the validation of decision-making Step 1

Company/Institution	**Products**	**Type of remanufacturer**	**Position**
Industrial representatives			
Case study company			
Company B	Engine	IR, Contract	Senior production manager
Company B	Engine	IR, Contract	Production Engineer
Non-case study companies			
Company F	Engine	OEM	Production engineer
Company G	Engine	IR, Contract	Director
Company H	Engine (Marine)	IR, Contract	Quality Manager

Company/Institution	Products	Type of remanufacturer	Position
Academics			
Linkoping University (Academic A)			Remanufacturing academic
Linkoping University (Academic B)			Professor with focus on industry-led remanufacturing research as well as knowledge of the transfer to the remanufacturing industry
University of Brighton (Academic C)			Principal lecturer specializing in remanufacturing research and knowledge transfer
Hochschule Trier, Umwelt-Campus Birkenfeld (Academic D)			Remanufacturing researcher
Universidad de la República (Academic E)			Assistant Professor / remanufacturing academic

5.9.2 The validation process

Before the validation, the author contacted participants via e-mail so that the validation would be conducted and all the participants were sent information about the research and what the author required from them for the validation.

The researcher presented the model before the validation process. During the interviews, the author took notes on the information from the interviewees and provided them with feedback sheets.

5.9.3 The validation documents

On the day of the validation, participants were given two documents: a presentation of the model and a feedback sheet.

1. A presentation of the model including research significance, decision making, input and output of the model, assumptions and formulae in the model,

2. A feedback sheet with questions in two sections. This document was used by the participants to assess the validity of the model in general. The first section is about the main criteria assessed by participants: clarity (C), sufficiency (SF) and suitability (ST). The other section consisted of two questions:

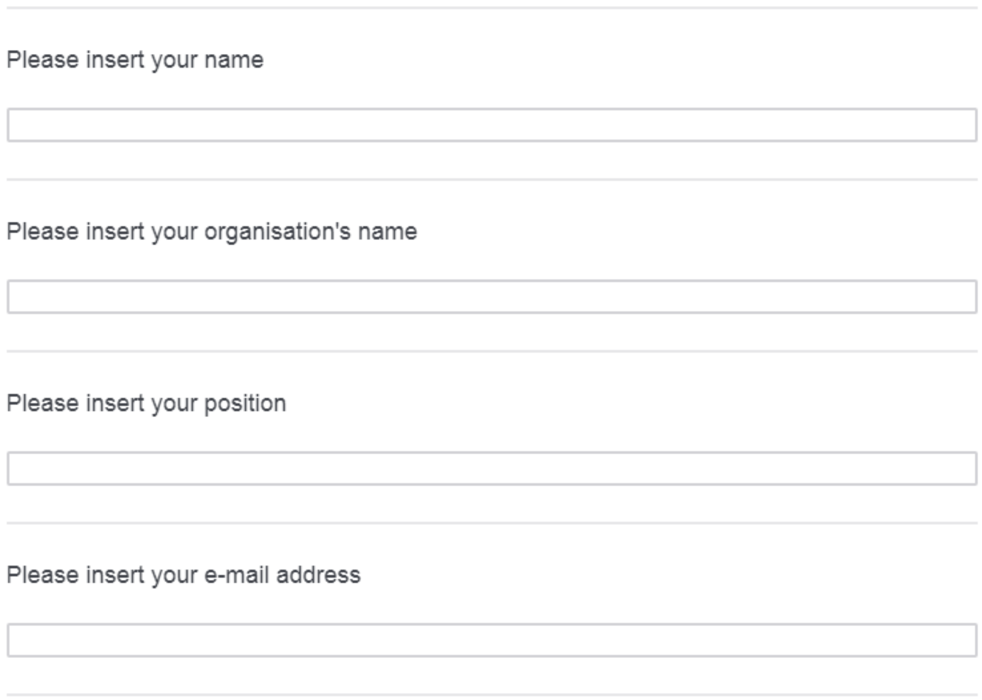
   1. Additional suggestions for the model if it was not complete.
   2. Any additional comments that the participants wanted to make.

   An example of the feedback sheet is illustrated in Figure 5.5.

Purpose:
The purpose of this questionnaire is to validate a decision model about selecting the best recovery option of used automotive components

Pledge of confidentiality:
Any information contributed by you will be kept with strict confidentiality. The data will be published or presented without revealing the name of your organisation.

Questions about the Research
If you have questions regarding this study, you may contact Ms. Sakraan Sitcharangsie at
E-mail : sakraan.sitcharangsie@strath.ac.uk



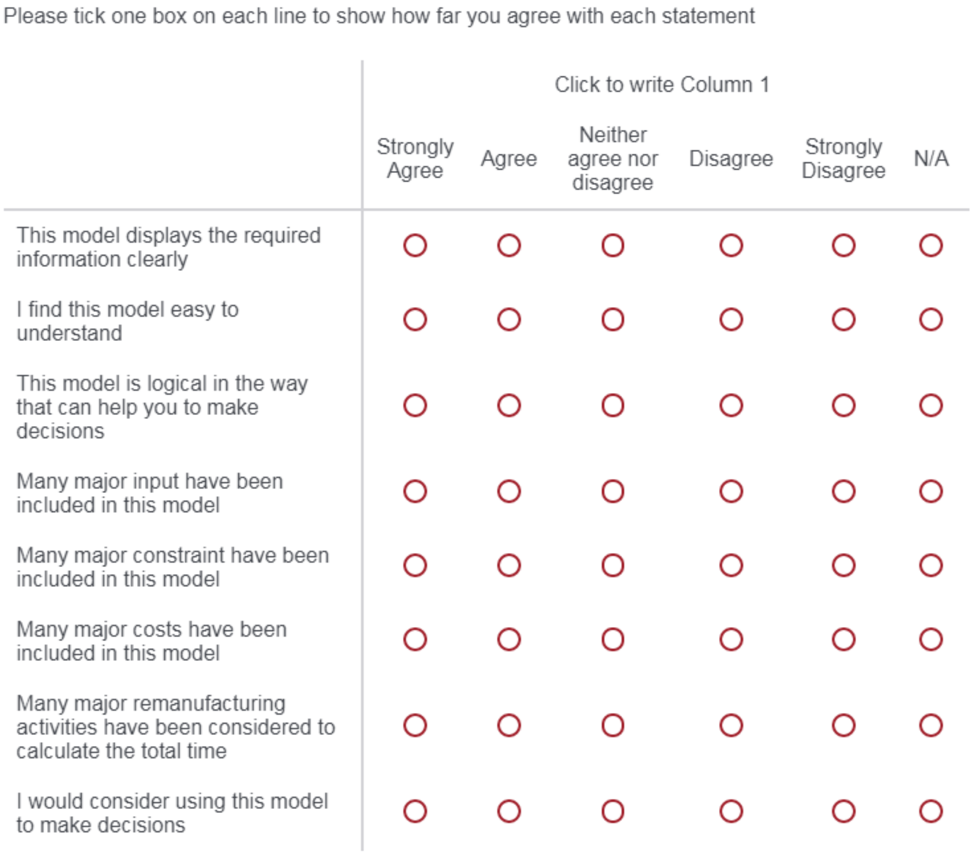
Please insert your name

Please insert your organisation's name

Please insert your position

Please insert your e-mail address

Figure 5.5 The feedback sheet



Please tick one box on each line to show how far you agree with each statement

	Click to write Column 1					
	Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree	N/A
This model displays the required information clearly	○	○	○	○	○	○
I find this model easy to understand	○	○	○	○	○	○
This model is logical in the way that can help you to make decisions	○	○	○	○	○	○
Many major input have been included in this model	○	○	○	○	○	○
Many major constraint have been included in this model	○	○	○	○	○	○
Many major costs have been included in this model	○	○	○	○	○	○
Many major remanufacturing activities have been considered to calculate the total time	○	○	○	○	○	○
I would consider using this model to make decisions	○	○	○	○	○	○

Validation Feedback Sheet
If the model is not complete, what do you suggest?

Any additional comments?

Figure 5.5. The feedback sheet (continued)

After all the feedback sheets had been returned, the author collected the information from the validation and used it to enhance the model. The next sections show the results for the panel’s opinions of the model.

5.9.4 The results of the validating panel's assessments of the model

As shown in Tables 5.31, all the industrial members of the validation panel either 'strongly agreed' or 'agreed' on the clarity, suitability and sufficiency of the model.

The majority of the academic participants agreed on the clarity, suitability and sufficiency of the model with the exceptions of these opinions: 'Many major constraints have been included in this model' and 'I would consider using this model to make decisions'. They gave suggestions regarding the constraints as shown in Table 5.32. Although some academics neither agreed or disagreed on 'I would consider using this model to make decisions', all the industrial participants 'strongly agreed' or 'agreed' on it and the industrial participants were the more important group in validating the model.

Table 5.31 The results of the validating panel's assessment of the model

Academics							
Criteria	Detail	Opinion					
		Strongly agree	Agree	Neither agree or disagree	Disagree	Strongly disagree	N/A
Clarity	This model displays the required information clearly	1	4				
Clarity	I find this model easy to understand		4	1			
Suitability	This model is logical in a way that can help you to make decisions		4	1			
Sufficiency	Many major inputs have been included in this model		4	1			
Sufficiency	Many major constraints have been included in this model		2	3			
Sufficiency	Many major costs have been included in this model		3	2			
Sufficiency	Many major remanufacturing activities have been considered to calculate the total time		4	1			
Suitability	I would consider using this model to make decisions		2	2			1
Industrial Representatives							

Criteria	Detail	Opinion					
		Strongly agree	Agree	Neither agree or disagree	Disagree	Strongly disagree	N/A
Clarity	This model displays the required information clearly		5				
Clarity	I find this model easy to understand	1	4				
Suitability	This model is logical in a way that can help you to make decisions		5				
Sufficiency	Many major inputs has been included in this model	3	2				
Sufficiency	Many major constraints have been included in this model		5				
Sufficiency	Many major costs have been included in this model	2	3				
Sufficiency	Many major remanufacturing activities have been considered to calculate the total time	3	2				
Suitability	I would consider using this model to make decisions	1	4				

The amendments that the participants suggested on the feedback sheets and the actions taken by the author, are summarised in Table 5.32. All the changes are related to the sufficiency of the model, the major costs, major remanufacturing activities, and major constraints. The additional comments are related to the value of the input data. However, some of the comments have not resulted in any changes since the majority of the participants agreed on the existing model.

Table 5.32 Comments from 5 academics and 5 industrial representatives

Proposed improvements	Proposed by	Action taken	Why the researcher did not take action	How the researcher took action
Major costs				
Coating may be considered for both machining and additive manufacturing	Academic C	x	Major costs in the model are already included in the model guaranteed by the automotive remanufacturers	
Bearings for crankshaft should be considered for both remachining and additive manufacturing	Company F	x	Different sizes of bearing do not affect the bearing costs	
Major remanufacturing activities				
Coating may be considered for both machining and additive manufacturing	Academic C	x	Major remanufacturing activities in the model are already included in the model guaranteed by the automotive remanufacturers	
No leak testing	Company B	✓		Leak testing cost has already been removed
Major constraints				
The concept of reliability is currently binary. Statistical data and distributional characteristics should be considered	Academic B	✓		This research conducted a the sensitivity analysis for reliability
The concept of reliability is currently binary, it should be reusability rather than reliability	Academic D	x	The access to information is limited. The binary concept of reliability is accepted by remanufacturers	
The reliability could be represented as a percentage. For example, values vary from 0-100%	Academic E	✓		This research conducted a sensitivity analysis of reliability.

Proposed improvements	**Proposed by**	**Action taken**	**Why the researcher did not take action**	**How the researcher took action**
Please make sure how the weight of components could be measured. For example, weight after or before machining.	Academics B, C, D	✓		For remachining and additive manufacturing options, the weight of the component after machining is measured. After calculation, the weight of component after machining is almost equal to the original mass of new crankshaft. Also, the weight of the component after machining, remachining and additive manufacturing is similar.
Weight of component for remachining and additive manufacturing should be similar.	Company B	✓		
Weight of component for remachining and additive manufacturing should be similar but less than the original mass.	Company B	✓		
Additional comments				
Assumptions:				
Machine investment cost:				
Working days: 46 weeks x 5 days = 230 days	Company B	✓		These data are already included.
Should include 5% interest rate of investment cost	Company B	✓		
Call machine supplier to know more about the total working time before breaking down	Company F	✓		
A machine can work 80-95% of total working time before breaking down	Company B	✓		
Replacement cost:				
New crankshaft costs around £50 - 600	Company G	✓		
Selling scrap:				
They cannot sell used crankshafts because of intellectual property protection	Company G	x		Some companies can earn money from scrap
Demand volume:				
This model should consider the optimum demand volume of	Companies B and G	✓		This model considered whether remanufacturers

Proposed improvements	Proposed by	Action taken	Why the researcher did not take action	How the researcher took action
components which is worth investing in additive manufacturing before considering recovery options for individual pieces of components				should invest in additive manufacturing in 5.3.1 and 5.3.2.
Demand volume of engines per year is around 6000 engines	Company G	✓		These data are already included.
20% of engines are required for remanufactured crankshafts	Company G	✓		
Importance score of factor				
Increase importance score of the reusable mass of components from 10 to 15 and reduce the importance score of reliability of components after recovery from 50 to 45 because companies consider the possibility of repeat business. If the importance score of the reusable mass of the component is high, it is better to recover used components than replace them with new components.	Company H	✓		This research conducted a sensitivity analysis by increasing the importance score of the reusable mass of components from 10 to 15 and reducing the importance score of reliability of components after recovery from 50 to 45%

5.10 Discussion

This research studied the research gaps which have never been studied by other previous studies before. This step of decision-making framework is a systematic and holistic tool for selecting the best recovery options for components at each level of failure by considering profit and operational time of each recovery option, reusable mass of components and reliability of components simultaneously. The decision-making framework was developed after validation. The validation methods included qualitative and quantitative data which can capture data-driven decision making of remanufacturing in real practice. This decision compared current recovery options (e.g. replacement and re-machining) and new recovery options (e.g. additive manufacturing) for a crankshaft which is a common and costly component of an engine.

For managerial implication, this model is practical since it helps remanufacturer to decide whether the demand volume of components is worth investing in additive manufacturing before considering recovery options for individual pieces of components. This decision question is important because the remanufacturer can ignore other subsequent decision processes which can save time of decision. After the remanufacturer decides that the demand volume of components is worth investing in additive manufacturing, it is suitable to consider the best recovery option of each components in different scenarios.

According to the information given by remanufacturing experts, reliability was the most important among other factors (profit, operational time and reusable mass) as its importance was informed by remanufacturing participants. Additive manufacturing which is a new and popular method in the industry could be the best recovery option for used components. In this study, a crankshaft was used as example, so the results were related to a crankshaft. Additive manufacturing could be the best recovery option for a used crankshaft for two scenarios as follows.

1. A crankshaft after additive manufacturing has higher percentage of reliability than that of a crankshaft after other recovery options.

2. When crankpins of a crankshaft have the wear depth from 0.3 to 0.5 mm, replacement or additive manufacturing is the best recovery option since remachining can no longer recover crankpins of the crankshaft when the wear depth is beyond 0.2 mm. If additive manufacturing is more profitable than replacement to recover the wear depth from 0.3 to 0.5 mm, additive manufacturing is the most suitable recovery option. Therefore, it can conclude that additive manufacturing can exceed the current recoverability of crankshafts which only allows replacement when the wear depth is more than 0.2 mm. If the additive manufacturing technique is cheaper than replacement, remanufacturer who recover crankshafts by additive manufacturing can earn more profit than replacing them with new crankshafts.

5.11 Summary of chapter 5

This study compared current recovery options (replacement and remachining) and new recovery options (additive manufacturing). Additive manufacturing is a new trend in the industry and may exceed the recovery potential of the crankshaft. In this study, a generalised framework was proposed to select the best recovery options to optimise the components for each severity degree of their failure. A case study focused on a crankshaft which is a common and costly component of the automotive remanufacturing industry. This study showed that this framework can provide advice on the premise of profit, time, recovered mass and reliability after each recovery option. The model helps to show whether or not the additive manufacturing is the most suitable recovery choice within different situations.

The next chapter will describe the step two of the decision-making framework. The next chapter is about a model to find the number of required components/ products for each remanufacturing activity. Chapter 6 shows the model description, mathematical formulations and optimisation results. Also, it shows a sensitivity analysis about reworking costs, reworking time, the percentage of reworked components and component commonality patterns which affect the profit of remanufacturing business.

Chapter 6 Decision making step 2: Find number of required components/ products in each activity of remanufacturing

6.1 Problem description

The process of remanufacturing is driven mainly by market demand for remanufactured items. Since either used or new components can be chosen to remanufacture products, deciding various choices of components and the associated impact on the choice outcomes at the same time becomes more difficult. Moreover, every decision taken in one remanufacturing activity will have a significant impact on the decisions taken in subsequent activities that affect the remanufacturing outcome. Furthermore, each product in the same product family may share the same components. Therefore, considering component commonality in the planning decision may increase the profit by obtaining the same component from a cheaper source (used product). However, it remains unknown if component commonality can always benefit remanufactures. Therefore, this research developed a decision-making model to uncover how component commonality can affect the remanufacturing outcomes under different remanufacturing scenarios defined by the percentage of reworked components, reworking time, and reworking costs.

The proposed model considers the research problem using high-value engines as an illustrative example. Each engine assembly structure has two levels: core (product) and component. A core refers to a whole used engine which consists of an engine block, a crankshaft and other subassemblies as shown in Figure 6.1. Disassembly separates a core into components which are any decomposable element of a product. In this study, cores (products) mean engines while only two components, engine blocks and crankshafts, are examined since they are of high-value and often remanufactured in the automotive sector. Component commonality allows that each engine may share the same type of engine block or crankshaft with other engines. As the first study in examining the impact of component commonality under different remanufacturing scenarios, an illustrative example is used although it is on a small-scale which only considers two types of engine blocks and two types of crankshafts. It is assumed that each engine must share either one of two types of engine blocks and either one of two types of crankshafts. Table 6.1 shows a pattern of component commonality. Using 0011_1100 as an example, it states that engine 1 and engine 2 do not share engine block 1 (but share engine block 2), and engine 3 and engine 4 share engine block 1 while Engine 1 and Engine 2 share crankshaft 1, and Engine 3 and Engine 4 do not share crankshaft 1 (but share crankshaft 2). Table 6.2 shows the characteristics of four products (engines 1-4) and four components

(Engine block 1, Engine block 2, crankshaft 1, and crankshaft 2). This differentiation can help define different combinations of products and components. The characteristics of each product and component in the model are differentiated by cost, selling price and operational time. For example, the total cost of Engine 2 is the lowest, while that of Engine 3 is the highest. The same procedure is used with components. The cost, selling price and operational time of each type of product and component vary greatly in real practice which can be simulated on a random basis, e.g. the product with the longest (shortest) operational time does not always have the highest (lowest) cost. The proposed model aims to support decision making for each remanufacturing activity under different remanufacturing scenarios. It covers both common and rarely seen cases by examining the extreme values (maximum or minimum) of factors in scenarios. The scenario setting is mainly based on the data from companies and the literature.

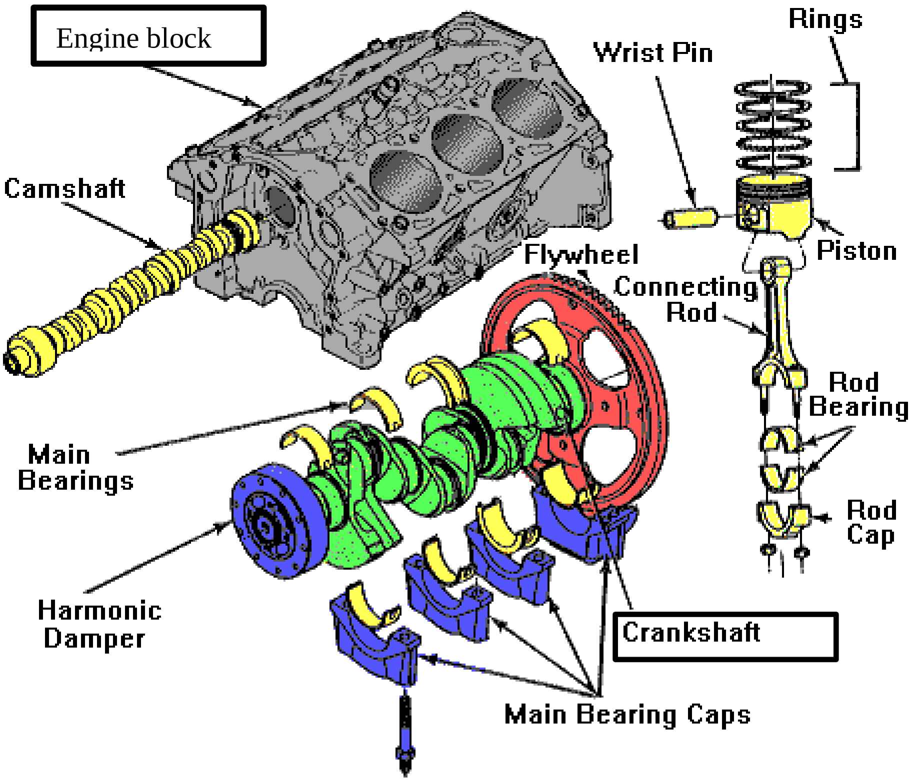


Figure 6.1 Engine assembly structure (Source: www.ukcar.com)

Table 6.1 Example of component commonality pattern (0011_1100)

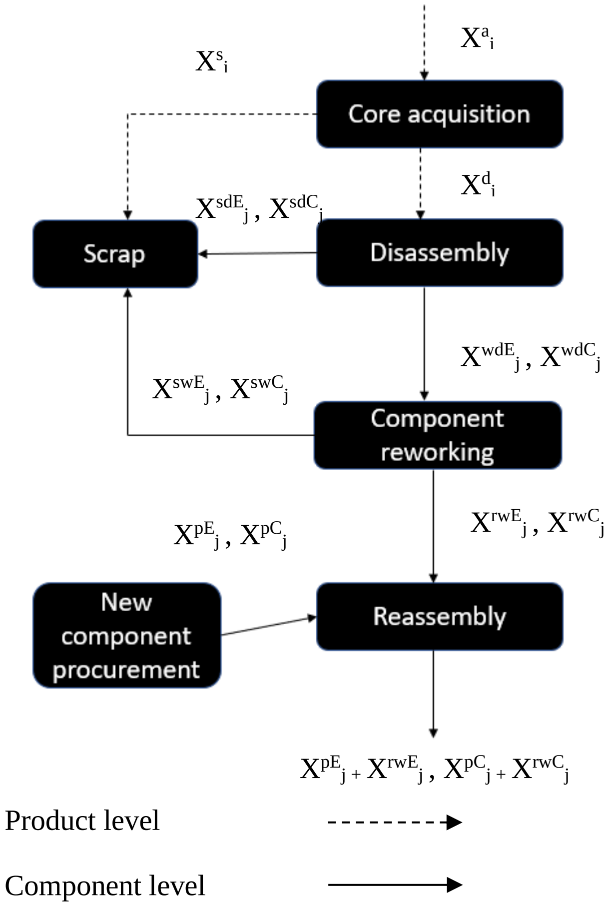
Component	Engine 1	Engine 2	Engine 3	Engine 4	Component	Engine 1	Engine 2	Engine 3	Engine 4
Engine block 1	0	0	1	1	Crankshaft 1	1	1	0	0
Engine block 2	1	1	0	0	Crankshaft 2	0	0	1	1

1 = share the components in common

Table 6.2 Characteristics of four engines and four components

Product Level				
Engine	1	2	3	4
labour cost	lowest	2nd lowest	highest	2nd highest
total cost	2nd highest	lowest	highest	2nd highest
time	fastest	2nd fastest	slowest	2nd slowest
Selling price	2nd lowest	2nd highest	highest	lowest
Profit	2nd lowest	highest	2nd highest	lowest
Component Level				
Component	Engine block 1	Engine block 2	Crankshaft 1	Crankshaft 2
cost	high	low	high	low
time	high	low	high	low

Figure 6.2 demonstrates the six key remanufacturing activities relevant to component planning, including core acquisition, disassembly, component reworking, reassembly, scrap and new component procurement (Sitcharangsie et al., 2019). Figure 6.2 shows the flow balance of components/products, which allows the output components/products to be equal to the input components/products in remanufacturing activities. All the variables are defined in Tables 6.7 and 6.8. Inspection and testing were not considered as decision variables in this study as remanufacturers have to comply with OEMs specifications when operating inspection and testing in order to achieve quality assurance for remanufactured products. Remanufacturers can use both new components and reworked components, by re-machining or additive manufacturing (Rahito et al., 2019, Matsumoto and Ijomah, 2013), to meet the demand of remanufactured products. Also, if the components are not reusable, remanufacturers will scrap both used products and components.



$$X^a{}_i = X^s{}_i + X^d{}_i$$

$$nX^d{}_i = X^{sdE}{}_j + X^{wdE}{}_j$$

$$nX^d{}_i = X^{sdC}{}_j + X^{wdC}{}_j$$

Where n= number of components can be generated from one core

$$X^{wdE}{}_j = X^{swE}{}_j + X^{rwE}{}_j$$

$$X^{wdC}{}_j = X^{swC}{}_j + X^{rwC}{}_j$$

Figure 6.2 The flow of volume balance of products and components in remanufacturing

6.2 Methodology

This stage of decision making used mixed-integer linear programming (MILP) which is part of goal programming to solve the mathematical optimisation problem. Moreover, this research used sensitivity analysis to uncover the impact of the component commonality pattern on remanufacturing outcomes and high face validation to justify the quality of the research findings.

6.2.1 Mixed-integer linear programming

Mixed-integer linear programming (MILP) is used as the current problem, although not considered as NP-hard or NP-complete, which involves 53 variables (11 out of 53 are decision variables) in which each decision variable can be any integer number more than or equal to 0. This means there is an infinite number of solutions and at least one optimum solution can be obtained using exhaustive searching. Compared with most previous studies of similar complexity, Kwak (2015) which considered 43 variables (13 out of 43 are decision variables) and Xanthopoulos and Iakovou (2009) which considered 67 variables (19 out of 67 are decision variables) used MILP to solve the problem.

The output of MILP is the optimal solution (Bian et al., 2019, Yang et al., 2019, Shao et al., 2017) which is better than the output of heuristics and metaheuristics. Although heuristics and metaheuristics are effective alternatives to solve multi-criteria decision making, these two methods can find only near- optimal solutions (Ma et al., 2011, Liu et al., 2016, Song et al., 2016) given the complexity of the current problem.

6.2.2 Sensitivity analysis

To get useful insights from the proposed model, a sensitivity analysis was conducted to study the effects of changing the values of reworking costs, reworking time, and percentage of reworked components, which are the significant decision factors towards remanufacturing outcomes in consideration of component commonality. According to Saltelli (2002), a sensitivity analysis can help to quantify the uncertainty which is one of the remanufacturing challenges. This analysis aims to study the effects of changing inputs on the model behaviours and its output (Landry et al., 1983, Beisbart and Saam, 2019, Saltelli, 2002), which would drive a greater understanding of the underlying model. This analysis is deemed effective to obtain reliable information for examining the credibility of the underlying model (Saltelli et al., 2008, Campolongo et al., 2007, Law and Kelton, 1991) because the extreme values of the factors would be considered.

To be specific, the sensitivity of reworking time and reworking costs to optimise the remanufacturing benefits according to the different percentages of reworked components were examined. Table 6.3 shows a total of six cases by varying the reworking time and reworking costs where HT = High time, MT= Medium time, LT= Low time, HC = High cost, LC = Low cost, and eLC= Extremely low cost.

Each case was tested with 42 different patterns of component commonality (as shown in Table 6.4) and the baseline case without component commonality. With three different optimisation options (i.e. maximising profit only, minimising time only and both), each component commonality pattern was tested. Furthermore, this study compared the optimisation results of different component commonality patterns against the baseline case to uncover the potential of increasing the remanufacturing profit from sharing components. This research studied the effect of component costs, therefore it used both expensive crankshafts and cheap crankshafts as examples. The 42 commonality patterns of the components can be categorised into three main groups: 1. sharing the same cheapest crankshafts for all engines, 2. sharing the same costliest crankshafts for all engines and 3. other cases as shown in Table 6.4. There are 16 possible cases for each group, except for the last group whose cases were selected randomly. The profits of cases in the last group is between the profits of the first and the second group. Therefore, 10 cases of the last group were chosen to represent other cases which do not belong to the first or the second group. Thus, a total of 6 x 43 x 3 = 774 scenarios were examined. Although these scenarios do not cover all possible instances, the extreme values of all decision factors were covered. Therefore, the results of the sensitivity analysis are deemed as reliable.

Table 6.3 Six Cases defined by two decision factors

	Core acquisition	Time to rework crankshaft (hour)						Cost of reworking crankshaft **(£)**						Can sell scrap	Optimisation objective		
	material cost for engine 1 only	C1 =8	C2 =1	C1 =1.2	C2 =1	C1 =1	C2= 0.3	C1= 120	C2= 50	C1 =50	C2 =15	C1 =10	C2 =3		Profit only	Time only	Profit50%,
HT, HC	✓	✓	✓					✓	✓					✓	✓ *	✓ *	✓ *
HT, LC	✓	✓	✓							✓	✓			✓	✓ *	✓ *	✓ *
MT, HC	✓			✓	✓			✓	✓					✓	✓ *	✓ *	✓ *
MT, eLC	✓			✓	✓							✓	✓	✓	✓ *	✓ *	✓ *
LT, HC	✓					✓	✓	✓	✓					✓	✓ *	✓ *	✓ *
LT,e LC	✓					✓	✓					✓	✓	✓	✓ *	✓ *	✓ *

* = 42 cases of a combination of component commonality C1= crankshaft 1, C2= crankshaft 2

HT = High Time, MT= Medium time, LT= Low time, HC = High cost, LC = Low cost, eLC= Extremely low cost

Table 6.4 Three groups of component commonality pattern (List of materials)

Share the same cheapest crankshafts for all engines	Share the same most expensive crankshafts for all engines	Other cases
0011_0000	0011_1111	0011_0011
0101_0000	0101_1111	0011_0111
0110_0000	0110_1111	0011_1110
0111_0000	0111_1111	0101_0111
1011_0000	1011_1111	0110_0011
1101_0000	1101_1111	0110_0111
1110_0000	1110_1111	1110_1001
0000_0000	0000_1111	1110_1101
1111_0000	1111_1111	1111_0011
1100_0000	1100_1111	1111_0111
1010_0000	1010_1111	
1001_0000	1001_1111	
1000_0000	1000_1111	
0100_0000	0100_1111	
0010_0000	0010_1111	
0001_0000	0001_1111	

6.2.3 High face validation

According to (Beisbart and Saam, 2019, Law and Kelton, 1991, Louloudi, 2012), testing the model with real data can bring the simulated situation close to real practice, but not all information is always available. Furthermore, in the early stage, the proposed model is not similar to the existing system (Beisbart and Saam, 2019, Law and Kelton, 1991). Therefore, it is recommended to use high face validation to validate the model. Face validation requires the opinions of experts who have broad and detailed knowledge of the system in both normal and unusual situations.

As shown in Table 6.5, this research involved participants from four companies in which two of them (company B and company G) gave their data to be used in the decision-making model. Since the validation was done by practitioners working at different companies with regard to four aspects, namely, clarity of the model, sufficiency of data used in the model, the reasonableness of the experimental results and the applicability of the model (Ijomah, 2002, Law and Kelton, 1991, Beisbart and Saam, 2019), the robustness of validation was secured with evidence through data triangulation from multiple sources and perspectives.

In this research, all the experimental results were assessed by field experts using an effective validation criterion "reasonableness" (e.g. Boisvert et al.(2010) and Zhuang et al.(2018)) where the problem was at an early-stage and real data was limited.

Table 6.5 Case companies involved in the model validation

Cases	How each company was involved in this study	Products	Type of remanufacturer	Position
Company B	Gave data, Validated the model	High-value engine	IR, Contract	Production Engineer
Company G		High-value engine	IR, Contract	Director
Company H	Validated the model	High-value engine	IR, contract	Quality Manager
Company I		High-value engine cooling system	IR, Contract	Sales Director

6.3 Decision making model

To find the optimal number of components/products for each remanufacturing activity in order to maximise profit or minimise operational time, the following assumptions were applied when formulating the decision-making model. The notations of indices, decision variables and parameters are listed in Tables 6.6 to 6.8, respectively.

1) It is single-period planning (Franke et al., 2006, Kwak, 2015).

2) Operation costs, time and revenues are known and deterministic (Franke et al., 2006, Kwak, 2015).

3) Each engine has a two-level assembly structure consisting of a product and component level (Franke et al., 2006, Kwak, 2015).

4) The procurement of spare components is bound by the upper limits (Engel and Al-Maeeni, 2020).

5) There is a limited number of reworked components due to capacity limitation (Kim et al., 2006, Xanthopoulos and Iakovou, 2009).

6) Remanufacturers can salvage the value from selling scrapped engines and components (Scottish Government, 2013)

7) Remanufacturers need to pay for material costs when acquiring the cores of engine 1. In contrast, they do not need to pay for the material costs for other types of cores because this model is based on real practice so the remanufacturers may or may not pay for the material costs of the cores (Lind et al., 2014, Wei et al., 2015).

8) Labour cost depends on time (Franke et al., 2006, Abu et al., 2018b). The formula showing how to calculate labour costs are shown in eq.7 to eq.14.

Table 6.6 The description of the indices

I	Index set for product, $i \in I$
J	Index set for component, $j \in J$

Table 6.7 The description of the decision variables

X^s_i	No. of scrapped engine model i
X^{sdE}_j	No. of scrapped engine block model j after disassembly
X^{sdC}_j	No. of scrapped crankshaft model j after disassembly
X^a_i	No. of cores from Engine model i that should be acquired
X^d_i	No. of cores from Engine model i that should be disassembled

X^{wdE}_j	No. of common engine block model j that should be reworked after disassembly
X^{wdC}_j	No. of common crankshaft model j that should be reworked after disassembly
X^{swE}_j	No. of engine block model j that should be scrapped after reworking
X^{swC}_j	No. of crankshaft model j that should be scrapped after reworking
X^{pE}_j	No. of new engine block model j that should be reassembled
X^{pC}_j	No. of new crankshaft model j that should be reassembled

Table 6.8 The description of parameters

Revenue	r^P_i	Revenue from selling a unit of engine model i
	r^s	Revenue from selling a unit of scrapped engine
	r^{sdE}_j	Revenue from selling a unit of scrapped engine block model j after disassembly
	r^{sdC}_j	Revenue from selling a unit of scrapped crankshaft model j after disassembly
Cost	C^L	Unit labour cost
	C^P	Unit cost of used engine
	C^{cE}	Unit material cost for reworking engine block
	C^{cC}	Unit material cost for reworking crankshaft
	C^a_i	Core acquisition cost of engine model i
	C^d_i	Disassembly cost of engine model i
	C^r_i	Reassembly cost of engine model i
	C^s_i	Scrap cost of engine model i
	C^{wE}_j	Reworking cost of engine block model j
	C^{wC}_j	Reworking cost of crankshaft model j
	C^{sE}_j	Scrap cost of engine block model j
	C^{sC}_j	Scrap cost of crankshaft model j
	C^{pE}_j	Purchasing cost of new engine block model j
	C^{pC}_j	Purchasing cost of new crankshaft model j
Time	t^a_i	Core acquisition time of engine model i
	t^d_i	Disassembly time of engine model i
	t^r_i	Reassembly time of engine model i
	t^s_i	Scrap time of engine model i
	t^{wE}_j	Reworking time of engine block model j

	t^{wC}_j	Reworking time of crankshaft model j
	t^{sE}_j	Scrap time of engine block model j
	t^{sC}_j	Scrap time of crankshaft model j
	t^{pE}_j	Time to purchase new engine block model j
	t^{pC}_j	Time to purchase new crankshaft model j
Quantity	Z_i	Demand of engine model i
	X^{pE}_j	No. of new engine block model j that should be reassembled
	X^{pC}_j	No. of new crankshaft model j that should be reassembled
	X^{rWE}_j	No. of reworked engine block model j that should be reassembled
	X^{rWC}_j	No. of reworked crankshaft model j that should be reassembled
	n	No. of component q that can be disassembled from engine i; q=E1 for engine block1, E2 for engine block 2, C1 for crankshaft 1, C2 for crankshaft 2
	k	Types of component; k = E for engine block, C for crankshaft
	z^k_{ji}	Demand of remanufactured component k model j that can be disassembled from engine i
	X^{wdk}_j	No. of component k model j that should be reworked after disassembly
	X^{swk}_j	No. of component k model j that should be scrapped after reworking
	X^{wk}_j	No. of reworked component k model j that should be reassembled
	X^{wdk}_j	No. of component k model j that should be reworked after disassembly
	X^{swk}_j	No. of component k model j that should be scrapped after reworking
	P^{nk}_j	No.of new component k model j that should be reassembled

All model formulations can be stated as follows.

Objective 1: Maximise $f_{profit} = \sum_{b=1}^{3} R_b - \sum_{b=1}^{2} C_b$ (1)

Where

$$R_1 = \sum_{i=1}^{4} r^{P}_{i} \cdot Z_i \qquad (2)$$

$$R_2 = \sum_{i=1}^{4} r^{s} \cdot X^{s}_{i} \qquad (3)$$

$$R_3 = \sum_{j=1}^{2} r^{sdE}_{j} \cdot X^{sdE}_{j} + r^{sdC}_{j} \cdot X^{sdC}_{j} \qquad (4)$$

$$C_1 = \sum_{i=1}^{4} C^{a}_{i} \cdot X^{a}_{i} + C^{d}_{i} \cdot X^{d}_{i} + C^{r}_{i} \cdot Z_i + C^{s}_{i} \cdot X^{s}_{i} \qquad (5)$$

$$C_2 = \sum_{j=1}^{2} C^{wE}_{j} \cdot X^{wdE}_{j} + C^{wC}_{j} \cdot X^{wdC}_{j} + C^{sE}_{j} \cdot (X^{swE}_{j} + X^{sdE}_{j}) + C^{sC}_{j} \cdot (X^{swC}_{j} + X^{sdC}_{j}) + C^{pE}_{j} \cdot X^{pE}_{j} +$$

$C^{pC}_j \cdot X^{pC}_j$ (6)

$C^a_i = t^a_i \cdot C^L + C^P$ (7)

$C^d_i = t^d_i \cdot C^L$ (8)

$C^r_i = t^r_i \cdot C^L$ (9)

$C^s_i = t^s_i \cdot C^L$ (10)

$C^{wE}_j = t^{wE}_j \cdot C^L + C^{cE}$ (11)

$C^{wC}_j = t^{wC}_j \cdot C^L + C^{cC}$ (12)

$C^{sE}_j = t^{sE}_j \cdot C^L$ (13)

$C^{sC}_j = t^{sC}_j \cdot C^L$ (14)

Objective 2: Minimize $f_{time} = \sum_{b=1}^{2} t_b$ (15)

where $t_1 = \sum_{i=1}^{4} t^a_i \cdot X^a_i + t^d_i \cdot X^d_i + t^r_i \cdot Z_i + t^s_i \cdot X^s_i$ (16)

$t_2 = \sum_{j=1}^{2} t^{wE}_j \cdot X^{wdE}_j + t^{wC}_j \cdot X^{wdC}_j + t^{sE}_j \cdot (X^{swE}_j + X^{sdE}_j) + t^{sC}_j \cdot (X^{swC}_j + X^{sdC}_j) + t^{pE}_j \cdot X^{pE}_j + t^{pC}_j \cdot X^{pC}_j$

(17)

Subject to

$\sum_{i=1}^{4} z^k_{ji} = \sum_{i=1}^{4} nZ_i$ for all i∈I, j∈J (18)

$nX^d_i = X^{sdk}_j + X^{wdk}_j$ for all i∈I, j∈J (19)

$X^a_i = X^d_i + X^s_i$ for all i∈I (20)

$X^{ak}_j = X^{wdk}_j - X^{swk}_j$ for all j∈J (21)

$X^a_i \leq Z_i$ for all i∈I (22)

$Z^k_i = X^{wk}_i + P^{nk}_i$ for all i∈I (23)

This research examines three different optimising objectives which can be selected by users as follows.

1. Maximising total profit

2. Minimising total time

3. Maximising total profit and minimising total time

The first objective function in Eq.1 is to maximise total net profit. Eqs.2 to 4 show the revenue is from three sources: selling remanufactured engines, selling scrapped engines, selling scrapped components (engine blocks and crankshafts). This research used activity-based costing to calculate the costs from remanufacturing activities by using Eqs. 5 to 14. Eq. 5 shows the relevant costs at the product level are core acquisition cost, disassembly cost, reassembly cost and scrap cost. Each unit cost of these four activities is the product of the unit time spent on each activity multiplied by the labour cost per hour as shown in Eqs.7 to 10. Core acquisition cost is the only cost which also includes the cost of cores as shown in Eq.7. Eq. 6 shows the relevant costs at the component level are reworking costs, spare purchasing costs, and scrap costs. The unit reworking cost is the sum of labour cost per unit and the material cost per unit as shown in Eqs. 11 to 12. The unit scrap cost is the product of scrap time per unit multiplied by labour cost per hour as shown in Eqs. 13 to 14.

The second objective function in Eq.15 is to minimise total time. Eqs. 16 and 17 present the calculation of time spent on remanufacturing activities.

Eqs.18 to 23 show all the constraints considered in the model. Constraints Eqs.18 to 21 ensure the flow of volume balance for products and components in remanufacturing activities (core acquisition, disassembly, component reworking, and reassembly, scrap and new component procurement). The volume balance between the number of input products/components and the number of output products/components should be the same. Constraint Eq.22 represents the core acquisition availability. The amount of used engines available for acquisition should be less or equal to the demand for remanufactured products (engines). Constraint Eq.23 shows that the supply of reworked components and new components cannot exceed the demand for components because the model intends to find the least number of components the company should hold in order to save money.

The third optimisation option considered both objectives 1 and 2 simultaneously because the lowest operational time and the highest profit are the goal of all companies. However, there are tradeoffs between these two objectives in real practice. For example, some of the remanufacturing techniques are expensive but require a short time to recover components. Some types of cores are cheap but remanufacturers need more time to acquire them. To consider the combination of two objectives, this research adopted the Pareto optimal by using the ε-constraint approach because it was appropriate to meet the two optimising objectives simultaneously (Mavrotas, (2009) Kwak, (2015); and Kwak and Kim, (2015). The ε-constraint approach uses one optimised objective function while the optimised value of a variable by another objective function is a constraint.

First, the problem with maximising profit is solved by using Eq. 1 under constraints from Eqs. 2 to 14 and Eqs.18 to 23. Therefore, operational time when maximising profit ($f_{time}(a2^*)$ is known. After that, the problem is to minimise operational time by using Eq.15 under constraints from Eqs.16 to 23. As a result, operational time when minimising operational time ($f_{time}(a1^*)$ is known. Then, to consider the combination of the two objectives, Eg. 1 is used to calculate the maximum profit while Eqs. 2 to 14 , Eqs.18 to 23 and the additional constraint in Eq. 24 are constraints. Eq. 24 shows that the operational time should not exceed the expected operational time (ε). As shown in Eq. 25, the range of ε can be given i.e. the lower bound is $f\text{time}(a1^*)$ and the upper bound is $f\text{time}(a1^*) + (f\text{time}(a2^*) - f\text{time}(a1^*))$. By increasing the value of μ, the point of ε is different. According to Eq. 26, μ can be any value from 0 to 1. *If* $\mu = 0$, the optimum result of Eq. 1 is the same as the value of profit when minimising operational time. *If* $\mu =1$, the optimum result is the same as the value of profit when the profit is maximised. The pareto optimal was adopted in the model by considering that the two objectives are equally important by setting $\mu = 0.5$.

$$f_{time}(a) \leq \varepsilon \tag{24}$$

$$\varepsilon = f_{time}(a1^*) + (f_{time}(a2^*) - f_{time}(a1^*)) \cdot \mu \tag{25}$$

$$0 \leq \mu \leq 1 \tag{26}$$

Where

$f_{time}(a)$= operational time when optimising objectives minimise operational time and maximise profit

$f_{time}(a1^*)$= operational time when optimising objectives minimises operational time

$f_{time}(a2^*)$=operational time when optimising objectives maximises profit

μ = the importance of operational time, if μ = 0.5 it means the importance of time is equal to the importance of profit

ε = the expected operational time

6.4 An illustrative example

6.4.1 Background

The purpose of this example is to show how the proposed model can determine the optimal number of components and products for each remanufacturing activity of high-value engine remanufacturers. The proposed model can generate an infinite number of remanufacturing plans covering all the important decisions in order to maximise profit, minimise time or both. Remanufacturers can then choose a plan that conforms to their business goals. This model was programmed using the solver add-in of Microsoft Excel. The inputs were sourced from engine remanufacturers, the literature and commercial websites such as Alibaba and eBay. As shown in Table 6.9, those engine remanufacturers have been operating independently with a long history in the UK. They have different production volumes (from 16 -1500 units/month) and number of staff (4 -150 people). Tables 6.10 – 6.12 provide all the information needed to drive the model which are:

- Component commonality pattern which shows shared components
- Demand for remanufactured products
- Demand for remanufactured crankshafts and engine blocks
- Costs, time and revenue for each remanufacturing activity
- Percentage of reworked components/new components that need to be reassembled

Firstly, this study proved the optimal solution through the model. Then it used the sensitivity analysis to extract new information from the model. The changing factors used for the sensitivity analysis are the component commonality pattern, unit reworking cost and unit reworking time at the component level, the demand for reworked components and the demand for new components, while other factors remain fixed.

Table 6.9. **Background of the benchmarked engine remanufacturers**

Company	Country	Years of experience	Products	Type of remanufacturers	Production volume	Number of employees
B	UK	More than 40 years	Engine	Contract remanufacturers, independent remanufacturers	1500 units/ months	150 people
C	UK	39 years	Engine	Contract remanufacturers, independent remanufacturers	16 units/ month	4 people
G	UK	More than 40 years	Transmission, Engine	Contract remanufacturers, independent remanufacturers	500 units/ months (engines)	52 people

Table 6.10 Given information about the component commonality pattern and the demand for remanufactured products

		Engine 1	Engine 2	Engine 3	Engine 4		
Demand[1]		125	125	125	125		
Component commonality pattern						**Demand of remanufactured component**	
Component	Engine 1	Engine 2	Engine 3	Engin e4		Component	Demand
Engine block 1	1	1	0	0		Engine block 1	250
Engine block 2	0	0	1	1		Engine block 2	250
Crankshaft 1	0	0	0	0		Crankshaft 1	0
Crankshaft 2	1	1	1	1		Crankshaft 2	500

1 = share the same component in common

The total demand for all engines is 500 units which is the median value from the real information of the companies as seen in Table 6.9. Since it is assumed that the company requires each engine equally, the demand for each engine is 125 units (500 units/4 types of engines) as shown in Table 6.10.

The total demand for remanufactured component k that can be disassembled from all engines is equal to the sum of the demand for engine model i multiplied by the number of components k that can be disassembled from Engine i , where k =E for engine block, C for crankshaft. According to the component commonality pattern in Table 6.10, Engine 1 and Engine 2 share Engine block 1, Engine 3 and Engine 4 share Engine block 2 and all the engines share crankshaft 2. Given the demand for engines, Eq.18 defines that the demand for remanufactured engine block 1 is equal to the demand for Engine 1 multiplied by the number of Engine block 1 that can be disassembled from Engine 1 plus the demand for Engine 2 multiplied by the number of Engine blocks 1 that can be disassembled from Engine 2 (125 x 1 + 125 x 1 = 250 units).

Table 6.11 Cost and revenue for each remanufacturing activity

Unit cost of remanufacturing at product level (£)[7]				
Cost	Engine 1	Engine 2	Engine 3	Engine 4
Core acquisition	195.423	10.998	67.68	0.423
Disassembly	6.768	10.152	109.98	109.98
Reassembly	15.228	19.458	27.072	27.072
Scrap	0.02538	0.3384	25.38	0.2538
Total cost	217.44438	40.9464	230.11	137.73
Unit selling price of remanufactured products (£)[8]	456	500	585	320
Unit selling price of scrapped engines (£)[9]	30			

Unit cost of remanufacturing at component level (£)[1,2,3,7,8]				
Cost	Reworking (inc. material cost)	Spare purchase	Scrap	
Engine block 1	91	312	1.692	
Engine block 2	50	296	2.538	
Crankshaft 1	120	56	8.46	
Crankshaft 2	50	54	0.846	
Unit price of scrapped engine	3			
Unit price of scrapped crankshaft	3			

Source: [1] Company B, [2] Company C, [3] Company G, [4] (Meng et al., 2017a), [5] (Abu et al., 2018b), [6] (Abu et al., 2018a), [7] Activity-based costing calculation, [8] Commercial websites such as Alibaba, eBay, [9] Assumption

Table 6.12 Given information about the time for each remanufacturing activity

Operational time (hour) (product level) [1,2,3,4]				
	Engine 1	Engine 2	Engine 3	Engine 4
Core acquisition	0.05	1.3	8	0.05
Disassembly	0.8	1.2	13	13
Reassembly	1.8	2.3	3.2	3.2
Scrap	0.003	0.04	3	0.03
Total time	2.653	4.84	27.2	16.28
Operational time (hour) (component level) [1,2,3,5,6]				
Cost	Reworking	Spare purchase	Scrap	
Engine block 1	1	0.7	0.2	
Engine block 2	0.6	0.6	0.3	
Crankshaft 1	8	0.8	1	
Crankshaft 2	1	0.5	0.1	

Source: [1] Company B, [2] Company C, [3] Company G, [4] (Meng et al., 2017a), [5] (Abu et al., 2018b), [6] (Abu et al., 2018a), [7] Activity-based costing calculation, [8] Commercial websites such as Alibaba, eBay, [9] Assumption

Some examples of the cost calculations are also shown. From Eq.7 to Eq.10, the remanufacturing costs of Engine 1 and Engine 2 at product level can be derived as shown in Table 6.13.

Table 6.13 Calculation examples of remanufacturing costs at product level

	Engine 1:	Engine 2:
Core acquisition cost	195 + 0.05 x 8.46 = £195.423 (Core 1 is the only core which has material cost. Core 1 cost £195)	0 + 1.3 x 8.46 = £10.998 (Core 2 has no material cost.)
Disassembly cost	0.8 x 8.46 = £6.768	1.2 x 8.46 = £10.152
Reassembly cost	1.8 x 8.46 = £15.228	2.3 x 8.46 = £19.458
Scrap cost	0.03 x 8.46 = £0.025	0.04 x 8.46 = £0.338

Replacing Eqs. 11 - 14 with numbers shows how the reworking costs and scrap costs of components are derived as shown in Table 6.14.

Table 6.14 Calculation examples of remanufacturing costs at component level

	Engine block 1	Crankshaft 2
Reworking costs	(1 x 8.46) + 82.54= £91	(1 x 8.46) + 41.54 = £50
Scrap costs	0.2 x 8.46 = £1.692	0.1 x 8.46 = £0. 846

6.4.2 Optimisation results

The model was applied with three optimisation options (maximising profit, minimising time and both). Table 6.15 shows examples of the optimisation results. Three different percentages of reworked components (100%, 50%, and 0%) are shown in the example to demonstrate the overall trend covering the effects of changing minimum, median and maximum values.

Table 6.15 Examples of optimal results with component commonality

Decision variables	100% of demand is for reworked components			50% of demand is for reworked components			0% of demand is for reworked components		
	Objective 1: Maximise profit	Objective 2: Minimise time	Both	Objective 1: Maximise profit	Objective 2: Minimise time	Both	Objective 1: Maximise profit	Objective 2: Minimise time	Both
No. of cores from Engine1 that should be acquired	125	125	125	0	125	63	0	0	0
No. of cores from Engine 2 that should be acquired	125	125	125	125	0	62	125	0	58
No. of cores from Engine 3 that should be acquired	125	125	125	0	0	0	0	0	0
No. of cores from Engine 4 that should be acquired	125	125	125	125	125	125	125	0	125
Total no. of common engine block 1 that should be reworked after disassembly	250	250	250	125	125	125	0	0	0
Total no. of common crankshaft 1 that should be reworked after disassembly	0	0	0	0	0	0	0	0	0
Total no. of common engine block 2 that should be reworked after disassembly	250	250	250	125	125	125	0	0	0
Total no. of common crankshaft 2 that should be reworked after disassembly	500	500	500	250	250	250	0	0	0
No. of cores from Engine 1 that should be disassembled	125	125	125	0	125	63	0	0	0
No. of cores from Engine 2 that should be disassembled	125	125	125	125	0	62	0	0	0
No. of cores from Engine 3 that should be disassembled	125	125	125	0	0	0	0	0	0
No. of cores from Engine 4 that should be disassembled	125	125	125	125	125	125	0	0	0
No. of cores from Engine 1 that should be scrapped	0	0	0	0	0	0	0	0	0
No. of cores from Engine 2 that should be scrapped	0	0	0	0	0	0	125	0	58

Decision variables	100% of demand is for reworked components			50% of demand is for reworked components			0% of demand is for reworked components		
	Objective 1: Maximise profit	Objective 2: Minimise time	Both	Objective 1: Maximise profit	Objective 2: Minimise time	Both	Objective 1: Maximise profit	Objective 2: Minimise time	Both
No. of cores from Engine 3 that should be scrapped	0	0	0	0	0	0	0	0	0
No. of cores from Engine 4 that should be scrapped	0	0	0	0	0	0	125	0	125
Total no. of engines block 1 that should be scrapped after disassembly	0	0	0	0	0	0	0	0	0
Total no. of engines block 2 that should be scrapped after disassembly	0	0	0	0	0	0	0	0	0
Total no. of crankshafts 1 that should be scrapped after disassembly	0	0	0	0	0	0	0	0	0
Total no. of crankshafts 2 that should be scrapped after disassembly	0	0	0	0	0	0	0	0	0
Total no. of engine blocks 1 that should be scrapped after reworking	0	0	0	0	0	0	0	0	0
Total no. of engine blocks 2 that should be scrapped after reworking	0	0	0	0	0	0	0	0	0
Total no. of crankshafts 1 that should be scrapped after reworking	0	0	0	0	0	0	0	0	0
Total no. of crankshafts 2 that should be scrapped after reworking	0	0	0	0	0	0	0	0	0
No. of reworked engine blocks 1 that should be reassembled	250	250	250	125	125	125	0	0	0
No. of reworked engine blocks that 2 should be reassembled	250	250	250	125	125	125	0	0	0
No. of reworked crankshafts 1 that should be reassembled	0	0	0	0	0	0	0	0	0
No. of reworked crankshafts 2 that should be reassembled	500	500	500	250	250	250	0	0	0
No. of new engine blocks 1 that should be reassembled	0	0	0	125	125	125	250	250	250
No. of new engine blocks 2 that should be reassembled	0	0	0	125	125	125	250	250	250
No. of new crankshafts 1 that should be reassembled	0	0	0	0	0	0	0	0	0
No. of new crankshafts 2 that should be reassembled	0	0	0	250	250	250	500	500	500
Demand for remanufactured engine blocks 1	250	250	250	250	250	250	250	250	250
Demand for remanufactured engine blocks 2	250	250	250	250	250	250	250	250	250
Demand for remanufactured crankshafts 1	0	0	0	0	0	0	0	0	0
Demand for remanufactured crankshafts 2	500	500	500	500	500	500	500	500	500
Profit (£)	97,346	97,346	97,346	85,452	62,822	74,047	48,520	42,521	47,269
Time (hours)	6,888	6,888	6,888	3,994	3,788	3,890	2,065	1,888	1,975

According to Table 6.15, when 100% of demand is for reworked components, the number of required components/products for each remanufacturing activity is the same for the three optimisation options.

Although 50% of the demand is for reworked components, the number of required components/products for each remanufacturing activity varies depending on the optimisation objectives. When maximising profit, the number of cores 1 acquired or disassembled is less than the number of cores 1 acquired or disassembled when other optimisation objectives are considered. The explanation is that core 1 is the most costly core which can result in the lowest profit, so the model recommended that core 1 be used as little as possible. When the objective is minimising time, the number of acquired or disassembled cores 1 is larger than the number of acquired or disassembled cores 1when the other optimisation objectives are achieved. The reason is that core 1 is the core which consumes the least operational time. Therefore, the model suggested using core 1 as much as possible.

If 0 percent of the demand is for reworked components, cores 2 and cores 4 will be acquired and scrapped to maximise profit. Although 100 percent of the demand is for new components, it can generate revenue if some components are scrapped. In considering the combination of two objectives: maximising profit and minimising time, a compromise exists between the two objectives. Therefore, the number of components/products needed for each remanufacturing activity is between the values for maximising profit and minimising time.

This research adopted the Pareto optimal method to consider trade-offs between profit and time. As shown in Table 6.15, when considering both objectives, the profit is always between that of objective 1 (maximising profit) and that of objective 2 (minimising time). For example, if 0% of the demand is for reworked components, the profit when considering both objectives is £47,269 which is between £48,520 (objective 1) and £42,521 (objective 2). When considering both objectives, the operational time is between that of objective 1 (maximising profit) and that of objective 2 (minimising time). For example, if 0% of the demand is for reworked components, the optimum operational time for both objectives is 1,975 hours which is between 1,888 hours (objective 2) and 2,065 hours (objective 1).

This model is deemed to be efficient as it can always find the optimal solutions and satisfy all the constraints. Also, the computation time was insignificant as each of the 774 scenarios required only 33 seconds on average. Although this illustrative example does not cover all possible scenarios, the proposed model is able to generate infinite numbers of component planning with respect to the optimisation option chosen by the users. All 774 remanufacturing scenarios can give an overall picture of the best possible solutions and remanufacturers need only select those which are feasible.

6.5 Results from sensitivity analysis

A sensitivity analysis was conducted to study the correlation between the different model variables as specified in Table 6.3. The model settings show that cases with the same operational time may not have the same operational costs that are usually be seen in the real practice. Figure II.1 to figure II.18 in Appendix II show the relationship between total profit and the percentage of reworked components for cases with component commonality (cc) and cases without component commonality (ncc) after optimisation under different scenarios of reworking time and reworking costs**.** The analysed results are shown in Tables 6.16 to 6.18**.** The changing value of reworking time has no effect on the optimised result of the model (the profit after different objective optimisation) if the reworking cost is not changed as seen in figure II.1 to figure II.18. However, the optimised result varies depending on the reworking cost. This result is true for all cases with commonality (cc) and all cases without commonality(ncc). Component commonality can increase or decrease profit if reworking costs are changed when compared with cases without component commonality. The result applies to all optimisation objectives (maximising profit, minimising time and both). When reworking costs are lower, planning with component commonality has a greater effect on increasing the chances that profit of cc will be higher than the profit of ncc while changing the reworking time will not have any impact on the optimised results. Moreover, the results from Tables 6.16 to 6.18 show that the gap between the highest and lowest profit of different component commonality patterns is larger when reworking costs are higher.

Table 6.16 Results when optimization objective is maximising profit

Comparison	Condition	Result
Figure II.4 and Figure II.6	At extremely low reworking costs and higher reworking time	There is no impact on optimised result
Figure II.1 and Figure II.3	At high reworking costs and higher reworking time from medium to high	There is no impact on optimised result
Figure II.1 and Figure II.5, Figure II.3 and Figure II.5	At high reworking costs and higher reworking time from low to medium and from low to high	There is no impact on optimised result
Figure II.1 and Figure II.2, Figure II.3 and Figure II.4, Figure II.5 and Figure II.6	At high or medium or low reworking time and lower reworking costs	There is an increased chance that profit of cc will be higher than the profit of ncc (see discussion in paragraph 6.6.2)
	At high or medium or low reworking time and higher reworking costs	There is a greater size in the gap between the highest profit and the lowest profit for different component commonality patterns (see discussion in paragraph 6.6.1)

cc= cases with component commonality, ncc = cases without component commonality

Table 6.17 Results when optimization objective is minimising time

Comparison	Condition	Result
Figure II.10 and Figure II.12	At extremely low reworking costs and higher reworking time	There is no impact on optimised result
Figure II.7 and Figure II.9	At high reworking costs and higher reworking time from medium to high	There is no impact on optimised result
Figure II.7 and Figure II.11, Figure II.9 and Figure II.11	At high reworking cost and higher reworking time from low to high and from low to medium	There is no impact on optimised result
Figure II.7 and Figure II.8, Figure II.9 and Figure II.10, Figure II.11 and Figure II.12	At high or medium or low reworking time and lower reworking costs	There is an increased chance that profit of cc will be higher than the profit of ncc (see discussion in paragraph 6.6.2)
	At high or medium or low reworking time and higher reworking costs	There is a larger gap between the highest profit and the lowest profit for different component commonality patterns (see discussion in paragraph 6.6.1)

Table 6.18 Results when optimization objectives are maximising profit and minimising time

Comparison	Condition	Result
Figures II.16 and Figure II.18	At extremely low reworking costs and higher reworking time	There is no impact on optimised result
Figures II.13 and Figure II.15	At high reworking costs and higher reworking time from medium to high	There is no impact on optimised result
Figures II.13 and Figure II.17, Figures II.15 and Figure II.17	At high reworking costs and higher reworking time from low to high and from low to medium	There is no impact on optimised result
Figures II.13 and Figure II.14, Figures II.15 and Figure II.16, Figures II.17 and Figure II.18	At high or medium or low reworking time, lower reworking cost	There is an increased chance that profit of cc will be higher than the profit of ncc (see discussion in paragraph 6.6.2)
	At high or medium or low reworking time and higher reworking costs	There is a larger gap between the highest profit and the lowest profit for different component commonality patterns (see discussion in paragraph 6.6.1)

6.6. Discussion

After proving the model optimality, a sensitivity analysis was conducted to study the correlation between the different model variables as specified in Table 6.3. Some of the findings of this model are the same as the findings of previous studies or reinforce real practice. Moreover, this study also uncovered new findings. Table 6.19 shows what new knowledge has been created from this study and what knowledge reinforce existing knowledge. Paragraph 6.6.1 is partially new knowledge. Paragraphs 6.6.2 and 6.6.3 are purely new knowledge. While paragraphs 6.6.4 to 6.6.5 reinforce existing knowledge.

Table 6.19 New knowledge and knowledge reinforce existing knowledge

Paragraph	New knowledge created from this study	Knowledge reinforce existing knowledge
6.6.1 Controlling profit fluctuation in remanufacturing	There is a larger gap between the highest profit and the lowest profit of the different component commonality patterns when increasing reworking costs	To improve profit, remanufacturers should reduce reworking costs.
	There is a larger gap between the highest profit and the lowest profit for the different component commonality patterns when there is a higher percentage of reworked components	
	Remanufacturers should consider component commonality patterns when they remanufacture products with high reworking costs or a high percentage of reworked components to avoid profit fluctuation.	
	To improve control over profit fluctuations, remanufacturers should select some specific component commonality patterns or select a suitable percentage of reworked components. This model can run infinite scenarios and suggests which pattern of component commonality or percentage of reworked components is the best depending on different scenarios	
6.6.2 Cases with component commonality are preferable to cases without component commonality in situations	There are 73% to 91% of total occasions categorised by the percentage of reworked components showing higher profits in cases with	

Paragraph	New knowledge created from this study	Knowledge reinforce existing knowledge
with low remanufacturing costs	component commonality than cases without component commonality in the scenario with lower remanufacturing costs	
6.6.3 Correlation of the profit and the percentage of reworked components	This study revealed that a higher percentage of reworked components does not always lead to higher profitability. The correlation between the profit and the percentage of reworked components is strongly positive for all cases (with/without component commonality) except for the cases with component commonality and high reworking costs	
6.6.4 Sharing components for products within the same product family		Greater sharing will lead to greater profit.
6.6.5 Finding the optimal number of components for each remanufacturing activity		Given the same demand for components, the same optimisation objectives and the same percentage of reworked components, the optimal number of components/products needed for each remanufacturing activity remains the same for different remanufacturing scenarios with or without component commonality
		Changing component commonality patterns between engines affects the optimal number of components required for each remanufacturing activity
		If remanufacturers want a faster operation, they should remanufacture the products that take the least time to produce.
		If operating costs are to be optimised, it is best to use cheaper products

Paragraph	New knowledge created from this study	Knowledge reinforce existing knowledge
		rather than those products which are expensive.
		The optimal number of reassembled components after reworking should be the same as the number of components that should be reworked after disassembly.
		If remanufacturers want higher returns but do not consider component commonality when the percentage of reworked components is smaller, they need to continue to buy the same quantities of cheap cores regardless of the percentages of reworked components

6.6.1 Controlling the risk of profit fluctuation in remanufacturing

As seen in Figure 6.3, this study reinforced the existing knowledge that profit increases when the reworking cost is reduced. However, this research also revealed new knowledge about profit fluctuation increases when reworking costs and percentage of reworked components increases. Remanufacturing products with high cost may have either a higher or lower risk of profit fluctuation than remanufacturing products with low cost. Moreover, remanufacturing products with a high percentage of components may have either a higher or lower risk of profit fluctuation than remanufacturing products with a low percentage of reworked components. This is because the range of profit varies depending on different component commonality patterns, unit reworking cost and percentage of reworked components which are considered as important factors in the real practice of remanufacturing. The knowledge of this model can provide industry with new perspectives because this model considered component commonality patterns, unit reworking cost and percentage of reworked components simultaneously, because these factors are important in real decision-making while the traditional model may lack component commonality patterns. After considering all 774 representatives of components commonality patterns, the results from this study were acknowledged by remanufacturing experts to show that the profit fluctuation increases when the reworking costs increase or the percentage of reworked components increases. Examples of the results are shown in Figure 6.3. From the two charts (graphs of HT, HC and HT, LC), the graph of HT, HC shows a larger gap between the highest profit and the lowest profit of the different component commonality patterns when compared to that of HT, LC for the same percentage of reworked components. Also, there is a larger gap between the highest profit and the lowest profit for the different component commonality patterns when there is a higher percentage of reworked components.

This research has also revealed two new implications from the results above. Firstly, it is necessary for remanufacturers to consider component commonality patterns when they remanufacture products with a high reworking cost or a high percentage of reworked components to avoid profit fluctuation because the impact of component commonality on profit fluctuation increases when the reworking costs or percentage of reworked components increases. Secondly, remanufacturers should reduce reworking costs or select some specific component commonality pattern or select a suitable percentage of reworked components to improve control over profit fluctuations. Although a pattern of component commonality and a percentage of reworked components itself cannot guarantee profitability, this model can run infinite scenarios and suggests which pattern of component commonality or percentage of reworked components is the best depending on different scenarios (e.g. a different percentage of reworked components on the same pattern of component commonality or a different pattern of component commonality on the same percentage of reworked components).

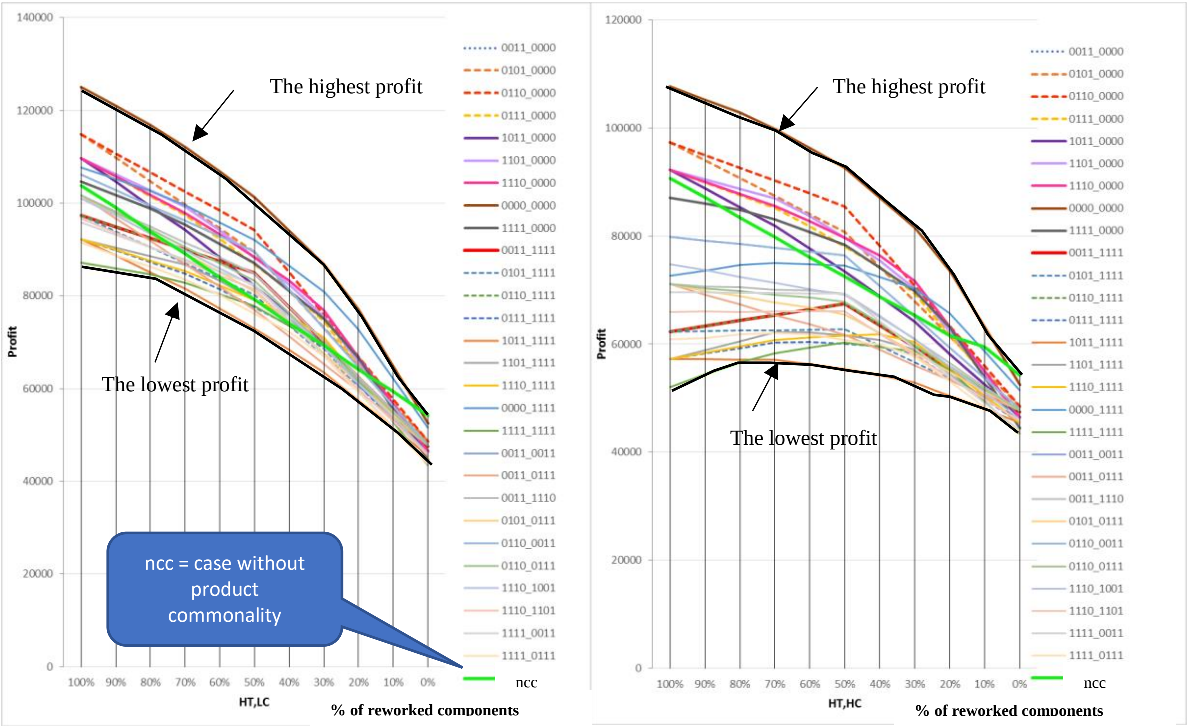
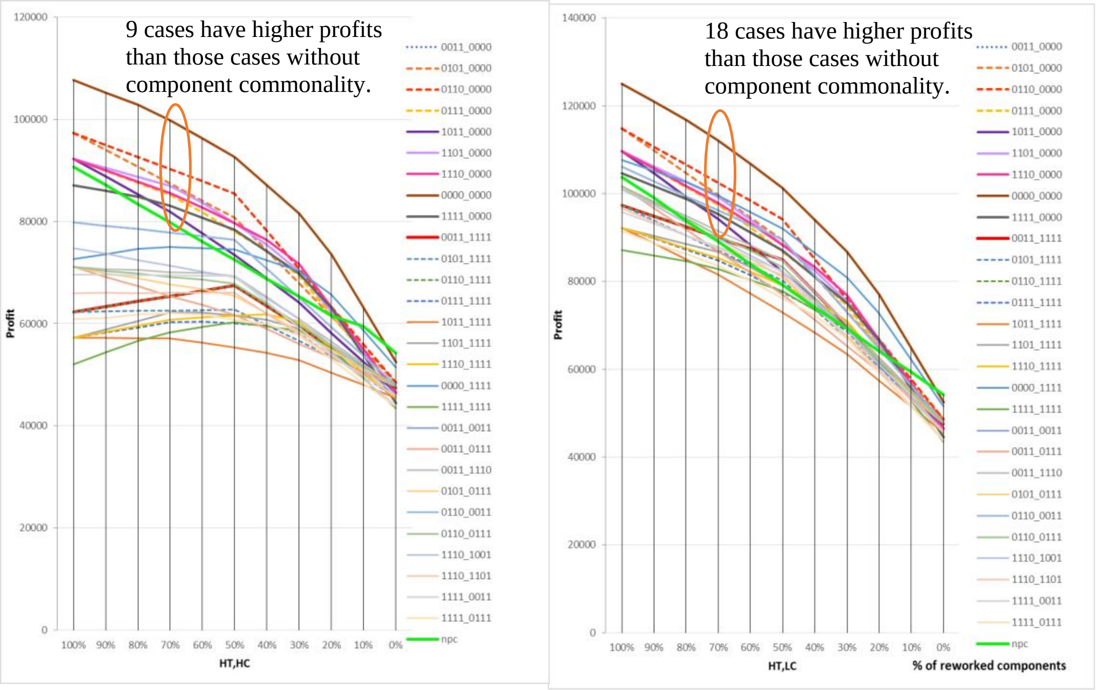


Figure 6.3 Examples of results from paragraph 6.6.1

6.6.2 Cases with component commonality are preferable to cases without component commonality for situations with low remanufacturing cost.

When comparing two remanufacturing scenarios having the same operational time but different remanufacturing costs, there are 73% to 91% of total occasions categorised by the percentage of reworked components showing higher profits in cases with component commonality than cases without component commonality in the scenario with lower remanufacturing costs as shown in Table 6.20. Also, Table 6.20 shows that if the objective function involves profit maximisation (e.g. maximising profit or both objectives), the number of occasions tends to be higher than that for minimising time. Examples of the results are shown in Figure 6.4. Comparing the two charts (graphs of HT, HC and HT, LC) at 70% of reworked components, the low reworking cost (LC) graph has up to 2 times higher chances of having higher profit cases with component commonality than the graph with high reworking cost (HC). In other words, if remanufacturing costs are low, remanufacturers tend to benefit more from cases with component commonality than from cases without component commonality. The effect of component commonality remains significant across all the optimisation options and this effect remains true from low to high percentages of reworked components.


9 cases have higher profits than those cases without component commonality.

18 cases have higher profits than those cases without component commonality.

Figure 6.4 Examples of results comparing the two scenarios

Table 6.20 No. of cases categorised by percentage of reworked components which have a higher profit than cases without component commonality

Optimising objectives	Scenarios	Occasion											% of total occasions (The total no. of occasions is 11)
		1	2	3	4	5	6	7	8	9	10	11	
		percentage of reworked components											
		100%	90%	80%	70%	60%	50%	40%	30%	20%	10%	0%	
		Number of cases with component commonality that has a higher profit than the cases without component commonality											
Maximising profit	HT, HC	8	8	9	9	11	12	12	9	8	1	0	10/11 = 91%
	HT, LC	12	12	14	18	20	21	22	17	11	2	0	
	MT, HC	8	8	9	9	11	12	12	9	8	1	0	10/11 = 91%
	MT, eLC	25	26	28	28	28	28	27	24	16	2	0	
	LT, HC	8	8	9	9	11	12	12	9	8	1	0	10/11 = 91%
	LT, eLC	25	26	28	28	28	28	27	24	16	2	0	
Minimising time	HT, HC	8	8	8	7	6	5	5	4	1	0	0	8/11 = 73%
	HT, LC	12	11	13	13	11	8	8	4	2	0	0	
	MT, HC	8	8	8	7	6	5	5	4	1	0	0	9/11 = 82%
	MT, eLC	25	24	25	22	18	13	13	8	2	0	0	
	LT, HC	8	8	8	7	6	5	5	4	1	0	0	9/11 = 82%
	LT, eLC	25	24	25	22	18	13	13	8	2	0	0	
Maximising profit and minimising time	HT, HC	8	8	9	9	10	10	10	8	5	1	0	10/11 = 91%
	HT, LC	12	12	13	14	15	16	17	9	8	2	0	
	MT, HC	8	8	9	9	10	10	10	8	5	1	0	10/11 = 91%
	MT, eLC	25	25	27	26	26	25	24	18	10	2	0	
	LT, HC	8	8	9	9	10	10	10	8	5	1	0	10/11 = 91%
	LT, eLC	25	25	27	26	26	25	24	18	10	2	0	

6.6.3 Study of correlation of the profit vs. the percentage of reworked components

This study revealed that a higher percentage of reworked components does not always lead to higher profitability but the correlation of the profit and the percentage of reworked depends on cases as following.

6.6.3.1 The correlation between the profit and the percentage of reworked components is strongly positive for cases without component commonality. As seen in Figure 6.5, a strong positive correlation ($r = 1$, $p < 0.05$) can be described by a straight line. This demonstrates the fact that using reworked components helps save costs as compared to purchasing new components.

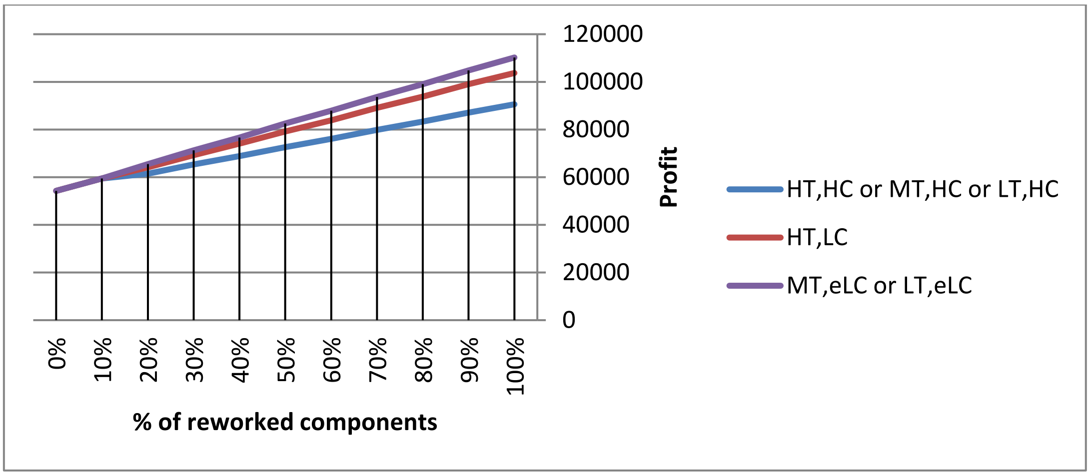


Figure 6.5 The correlation between the profit and the percentage of reworked components for cases without component commonality

6.6.3.2 The correlation between the profit and the percentage of reworked components for cases with component commonality can be examined under two groups as follows.

- At HT, LC , MT, eLC , LT, eLC (group of low reworking cost scenarios), there is a significantly strong positive correlation ($r = 0.94 – 1$, $p < 0.05$) between the profit and the percentage of reworked components. This reinforces the fact that more remanufactured components would increase the profit when remanufacturing costs are lower if component sharing is considered, which is similar to the case without component commonality.
- At HT, HC , MT, HC , LT, HC (group of high reworking cost scenarios), component sharing has a mixed effect which can be explained by three classifications: Unknown effect, Strong effect and Medium effect as shown in Figures 6.6 – 6.8, respectively.

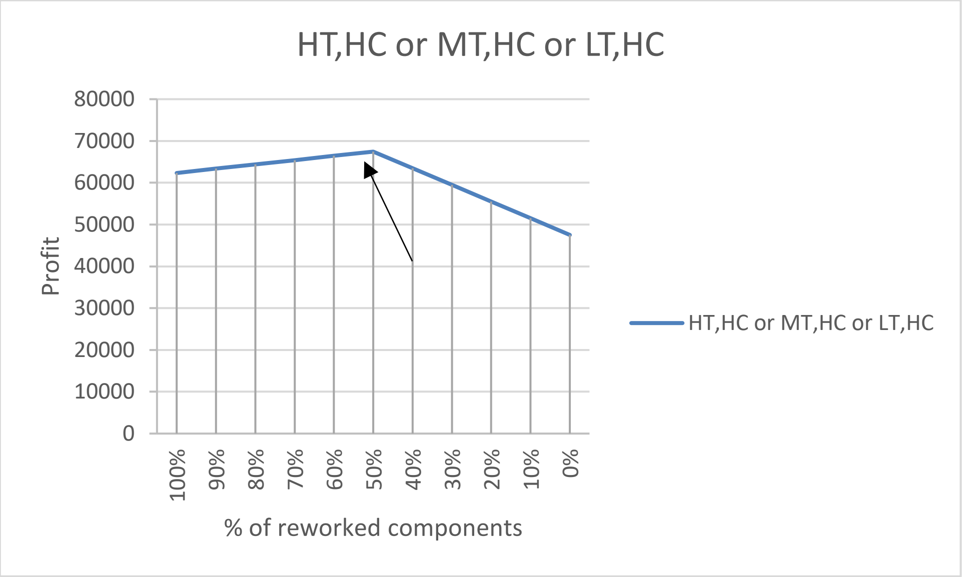


Figure 6.6 The results between the profit and the percentage of reworked components for the cases in which all 4 engines share the same costly crankshafts

Unknown effect is the worst case: if all 4 engines share the same costly components such as crankshafts in this study, there is no correlation between the profit and the percentage of reworked components. The profit would decrease or increase when the percentage of reworked components increases as seen in Figure 6.6. In other words, if the remanufacturing costs are high, it is not clear whether more reworked components should be used as there exists a balance point to maximise the profit. However, this balance point is not well-understood in this study so further research will be needed.

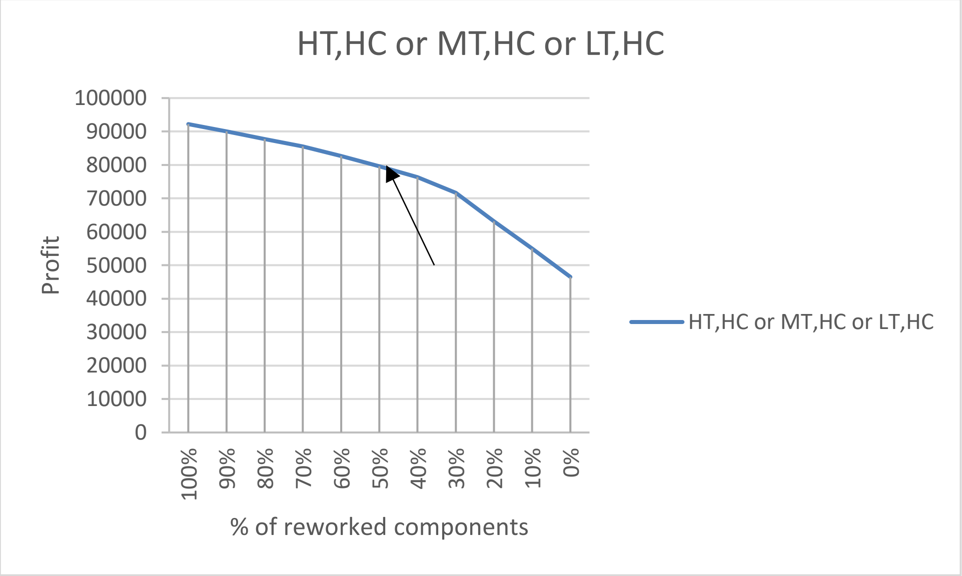


Figure 6.7 The correlation between the profit and the percentage of reworked components for the cases in which all 4 engines share the same cheapest crankshafts

The strong effect is produced if all 4 engines share the same cheap components in common, there is a significantly strong positive correlation (r = 0.94 – 1, $p < 0.05$) between the profit and the percentage of reworked components as seen in Figure 6.7. This clearly shows that more reworked components should be used to increase the profit, which is similar to low cost remanufacturing situations.

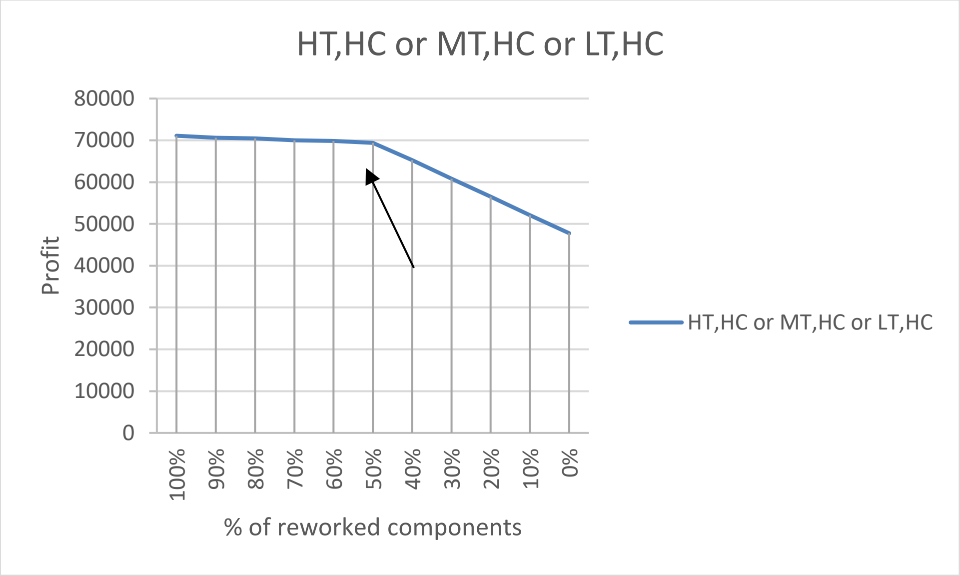


Figure 6.8 The correlation between the profit and the percentage of reworked components for other cases

A medium effect is produced if all 4 engines do not share the same costly or the same cheap components, so profit increases or almost remains steady when the percentage of reworked components increases. As seen in Figure 6.8, there is a significantly positive correlation (r = 0.84 – 1, $p < 0.05$) between the profit and the percentage of reworked components, however, such correlation diminishes if more reworked components are used.

In conclusion, a greater number of reworked components improves profit for all cases except for the cases with component commonality and high reworking costs. The profit of these exceptional cases can increase or decrease when the percentage of reworked components is increased. The component commonality pattern can be controlled to support more reworked components to increase profit. For example, if remanufacturers want to increase their profit, it is recommended that they should avoid a component commonality pattern when all the engines share the same costly components.

6.6.4 Sharing components for products within the same product family

Greater sharing will lead to greater profit. This is consistent with the findings of Kwak and Kim (2015). In addition, the results of this research suggest that if 100% of reworked components is needed, a greater sharing of the cheapest components will result in greater profit for the remanufacturer. If 2 types of engines share the cheapest components, the profit increases by 12-20% as compared to the case in which there is no sharing of the cheapest components. If all 4 types of engines share the cheapest components, the profit increases by 24-39% as compared to the case in which there is no sharing of the cheapest components.

6.6.5 Finding optimal number of components for each remanufacturing activity

This topic purely reinforces existing knowledge and current practice which can validate the model.

6.6.5.1 Given the same demand for components, the same optimisation objective and the same percentage of reworked components, , the optimal number of components/products needed for each remanufacturing activity remains the same for different remanufacturing scenarios with or without component commonality. For example, as shown in Figure 6.9, when considering maximising profit (objective 1) with 70% of reworked components, the optimal number of components/products required for each remanufacturing activity does not change with varying reworking times and reworking costs.

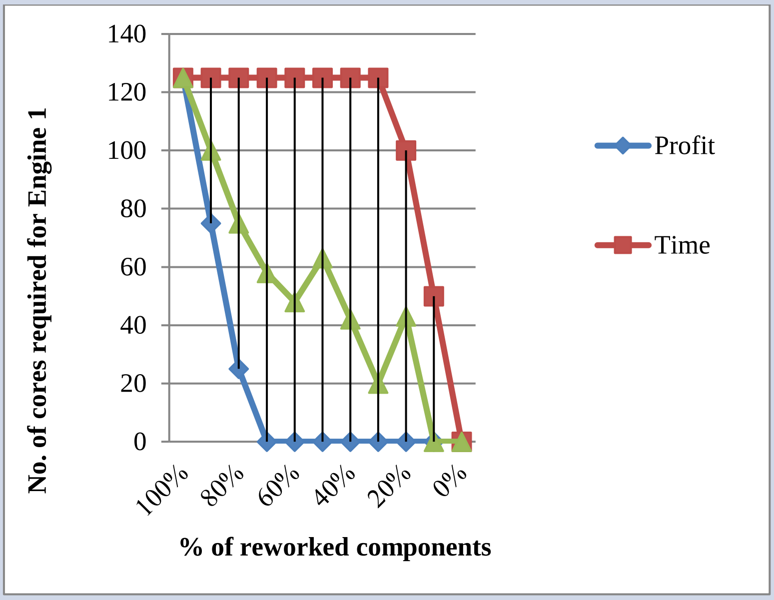
Factors		The optimal number of cores required for Engine 1
Reworking costs	**Reworking times**	
high	high	
high	medium	
high	low	
low	high	
extremely low	medium	
extremely low	low	

Figure 6.9 Examples of results for number 6.6.5.1

6.6.5.2 Changing component commonality patterns between engines affects the optimal number of components required for each remanufacturing activity. As seen in Figure 6.10, when the aim is to minimise time only, the number of core 1 required remains at 120 units when the percentage of reworked components is reduced from 100 % to 40%, and then the number sharply drops to 0 units when the percentage of reworked components is further reduced from 30% to 0% as in the case 0011_1110. According to Figure 6.11, the number of core 1 required remains at 120 units when the percentage of reworked components is reduced from 100 % to 50% and then the number sharply falls to 0 units when the percentage of reworked components is reduced from 50% to 0% for case 0011_0011.

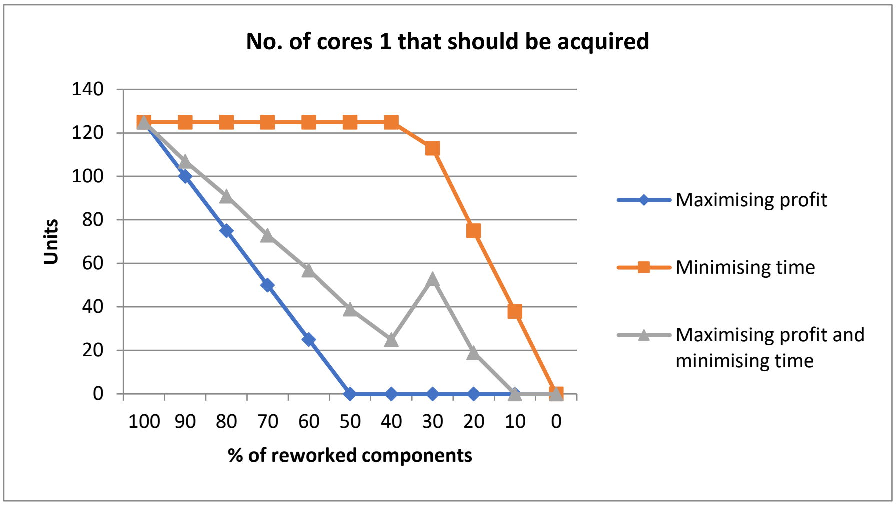


Figure 6.10 Optimisation results for case 0011_1110

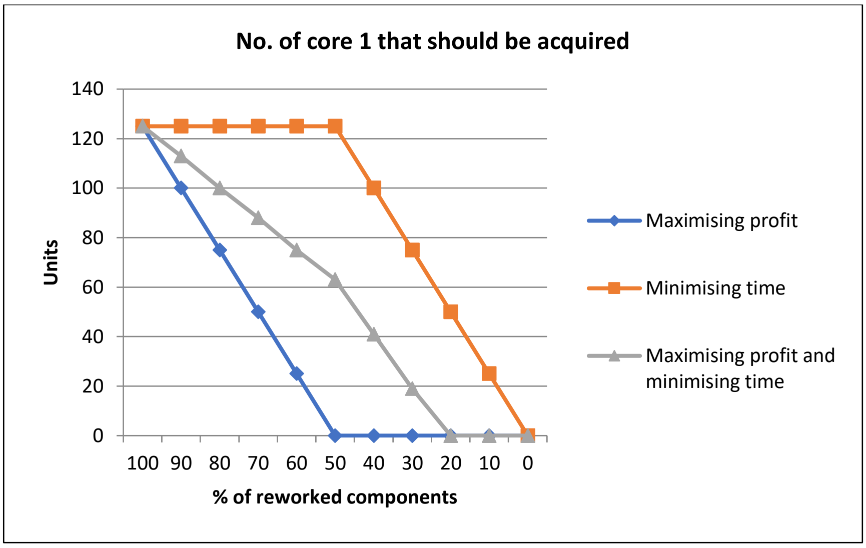


Figure 6.11 Optimisation results for case 0011_0011

In addition to a component commonality pattern, the optimal number of components and products in each remanufacturing activity also varies according to the selected optimisation option (objective).

6.6.5.3 If minimising time is selected, the number of the least time-consuming cores acquired is higher than that of maximising profit and both objectives combined as seen in figure 6.10 and 6.11. Engine 1, which requires the least remanufacturing time, is required in a larger quantity. Therefore, if remanufacturing speed is the main concern, remanufacturers should acquire more cores with a short process time and acquire fewer cores with a high process time if the two types of cores share the same components.

6.6.5.4 If maximising profit is the objective, the number of expensive cores acquired is smaller than that of minimising time and also for both objectives combined as seen in figure 6.10 and 6.11. The acquisition cost of Engine 1 is the highest, hence, it will be acquired in smaller quantities. This result shows that if remanufacturers want to keep their profits high, they should avoid the acquisition of expensive cores and acquire high profit cores, if the ones with high profits and the ones with the highest acquisition costs share the same components in common.

6.6.5.5 The optimal number of reassembled components after reworking should be the same as the number of components that should be reworked after disassembly. This is consistent with the findings of Kwak (2015). Remanufacturers should not scrap components after reworking in order to optimise the system objectives such as profit and time.

6.6.5.6 If remanufacturers want higher returns but do not consider component commonality when the percentage of reworked components is smaller, they need to continue to buy the same quantities of cheap cores regardless of the percentages of reworked components. For example, the remanufacturers should buy 120 units of core 2 when the percentage of reworked components is 100 or 0 when the objective is maximising profit. Also, they need to scrap more cores with low scrap costs when the percentage of reworked components is lower. As shown in Figure 6.12, to maximise profit, the model suggests acquiring the same amounts of Engines 2 and 4 at approximately 120 units for each and increasing the number of scrapped Engines 2 and scrapped Engines 4 if there is a lower requirement of reworked components. This is because these two types of engines have the lowest core acquisition costs and the remanufacturers will not be able to recover their value by scrapping their products.

Figure 6.12 The results in detail from paragraph 6.6.5.6

In summary, the findings referred to in paragraphs 6.6.5 reinforce the practicality of the proposed model since all of them are sensible. For example, if remanufacturers want a faster operation, then they should remanufacture the products that take the least time to produce. If operating costs are to be minimised, it is best to use cheaper products rather than products those which are expensive, if they share the same components. Moreover, the findings show some new insights, such as the fact that sharing the cheapest components can increase 12-39 % of the profit of the cases which do not use the cheapest components.

6.7 Validation of decision making Step 2

Although testing the model with real data can simulate situations closer to real practice, all required information is not always available. Furthermore, in the early stage, the proposed system is not similar to the existing system. Therefore, the author used face validation to validate the decision model Step 2. Face validation is a qualitative technique that can be used to gather opinions about the reasonableness of the model from specialists who are familiar with the system. An assessment of the reasonableness of the simulation results is an appropriate way to review how well the simulation result represents the reality/ real system (Law and Kelton, 1991, Beisbart and Saam, 2019, Cohen et al., 1998) especially for situations where there is a lack of data because the reasonableness of the simulation results is more important than their accuracy in these circumstances (Beisbart and Saam, 2019). Reasonableness is defined by Cambridge dictionary as “ The fact of being based on or using good judgment and therefore being fair and practical”. Accuracy is a measurement demonstrating how close the forecast result of the simulation to the true experimental result (Beisbart and Saam, 2019). Since there are no true experimental data to validate the forecasts of the simulation model, reasonableness which is more open definition than accuracy is properly used to validate the model.

6.7.1 The validating panel

The second phase of the decision-making process was validated by four representatives from various companies and different positions in the automotive industry. The industry validators were all satisfied with the reasonableness of the simulation results. This similarity of validation outcome from a range of relevant cases and validators can be taken as demonstration of the validity of the model. Table 6.21 shows the cases involved in the validation of Step 2 of the decision-making process. The validation used case studies of two companies (Companies B and G) to validate the results because some of the inputs were from these particular companies. Moreover, two companies which were not used in the 4 case studies (Companies H and I) were used for the external validation of the results. Since the sources of the validation information were from representatives of the industry in different positions, for example, production engineer, quality manager, sales director and director, the evidence provided from these multiple sources enabled the reseacher to use the data for triangulation.

Table 6.21 Case studies involved in the validation of the Step 2 of decision-making

Cases	Products	Type of remanufacturer	Position
Company B	Engine	IR, Contract	Production Engineer
Company G	Engine	IR, Contract	Director
Company H	Engine(Marine)	IR, contract	Quality Manager
Company I	Engine cooling system	IR, Contract	Sales Director

6.7.2 The validation process

Before the validation, the author contacted the participant companies via e-mail and informed them when the validation would be held and asked them to send their representatives to participate in the validation process.

The author presented the validation model to Companies B and H before the validation took place. During the interview on the validation results, the author made notes on the information from the interviewees and then provided them with questionnaires to assess the model.

With regard to Companies G and I, the author sent a presentation of the model to them via e-mail. This presentation was later updated based on suggestions from Companies B and H. Subsequently, the author provided the participants with any additional information needed by the participants through a telephone call. E-mail and telephone calls were used for contact between the author and the participant companies. The author also discussed the model with Companies G and I and asked them for their opinions on the validity of the model.

6.7.3 The validation documents

Two documents were used for the validation: a report on the model and a feedback sheet.

1. The report included a copy of the model and its benefits, a description, and the logic of the model and its findings.

2. The questionnaires is illustrated in Figure 6.13.

Questionnaires

On a scale from 1-10 how would you rate the reasonableness of each result from the model (1 = the lowest, 10 = the highest)

The results from the model	Score
1.	
2.	
3.	
4.	
5.1	
5.2	
5.3	
5.4	
5.5	
5.6	
5.7	

Please recommend how this model can be improved in terms of clarity, sufficiency and applicability

Figure 6.13 The format of the questionnaires

6.7.4 The results of the validating panel's assessment of the model

According to Landry et al.(1983), Ijomah(2002), Beisbart (2019)and Law and Kelton(1991), there were 4 recommended criteria: clarity of the model, sufficiency of data used in the model, reasonableness of the simulation results and the applicability of the model, were selected for the validation. Therefore, all the suggestions from the companies were related to these.

6.7.4.1 Clarity and sufficiency of the model

The proposed improvements on the clarity and the sufficiency of the model are shown in Table 6.22. Appendix III shows the updated version of the model.

Firstly, Companies B and H were the first to validate the model. They suggested some improvements with regard to clarity (proposed improvements: numbers 1.1 to 1.3) and sufficiency (proposed improvements: number 2.1) of the model. After the author modified the model according to the companies' suggestions , the author checked that they were satisfied with the changes. Next, the author used the updated version of the model to ask Companies G and I for their assessment of the model. They were both satisfied with these improvements (improvement numbers: 1.1 to 1.3 and number 2.1).

However, proposed improvements numbers 2.2 and 2.3 suggested by the companies have not been included in this research because they require a real-time model which would be impossible within the resource constraints (time, cost) of this research and furthermore outside the scope of this research. Given the time and costs of PhD research the work described in this PhD thesis was designed to specifically focus on small-scale problems with determined variables. This research studied specifically the changes in reworking costs while the unit selling price of the product remained the same for all cases. Therefore, it considered results for when the profit is low or when the profit is high. The limitation of this study is that it focuses on high-value products with low production volumes. This model considered 4 different types of engines, shown in Table 6.2 in order to mimic reality. The reason here is that in real life different engines types will vary greatly regards their remanufacturing costs, operational time and the selling prices of finished products. This model selected these characteristics randomly for each type of engine to study the behavior of scenarios. The demand for each type of engine was 125 units and the monthly production volume of all types of engines was 500 units.

Although there are some limitations to the model settings which cannot consider all possible cases, the model itself can simulate an unlimited number of cases depending on the values of the inputs. Also, the proposed improvement suggestions 2.2 and 2.3 could be investigated as a line of interesting future research. In order to implement improvement the proposed improvement numbers 2.2 and 2.3, the modeler may consider using the internet of things to develop real-time decision-making and use another computation program such as Cplex to manage the multiple variables that will arise in a more complex problem.

Table 6.22 The proposed improvements on the clarity and the sufficiency of the model

Proposed improvements	**Proposed by companies**	**Action Taken**	**Action details**	**Proposed improvements agreed by companies**
1.Clarity				
1.1 They suggested that the logic of the model was poorly presented because they were not familiar with mathematical modelling	B, H	✓	The logic of the model is presented visually by mindmapping demonstrating input, output, objectives and constraints (see Appendix III page 294)	B, G , H, I
1.2 They criticised the sentences describing the results of the model as difficult to understand because they were very long.	B, H	✓	The sentences were rewritten to be more concise (see Appendix III page 297-300)	B, G, H, I
1.3 The component commonality concept should be described clearly.	B, H	✓	The concept of component commonality was described more clearly and visually (see Appendix III page 293)	B, G, H, I
2. Sufficiency of the model				
2.1. The model did not cover all possible cases with component commonality	B, H	✓	The model was revised to show all possible cases with component commonality. (see Appendix III page 296)	B, G, H, I
2.2 The model should include the problems of the latest design index for remanufacturing.	I	X	Further research is necessary	

Proposed improvements	**Proposed by companies**	**Action Taken**	**Action details**	**Proposed improvements agreed by companies**
Therefore, real-time decision making should be considered				
2.3 The results of the simulation were observed by the remanufacturers. However, an important factor is the scale of the remanufactured components vs labour costs per unit i.e. it may not be the same when remanufacturing a small engine or a large diesel engine.	I	X		

6.7.4.2 The reasonableness of the simulation results

The results from the model were discussed in section 6.6. As a result, there are findings 6.6.1 to 6.6.5.6. This research used ‘reasonableness’ as an acceptable criterion to assess the representativeness of all the findings from the model. As shown in Table 6.23, the average score given by all participants is greater than or equal to 9 with standard deviation of 0 to 0.82. thus, it is concluded that all the research findings are deemed as reasonable which proves the model’s usefulness.

Table 6.23 The score showing the reasonableness of the findings from the model on a scale from 1-10 (1= the lowest, 10= the highest)

The findings from the model	Score				Average score	Standard deviation
	Company B	Company G	Company H	Company I		
6.6.1	9	9	9	9	9	0.00
6.6.2	9	9	10	9	9.25	0.50
6.6.3.1	9	9	9	9	9	0.00
6.6.3.2	9	9	9	9	9	0.00
6.6.4	9	10	9	9	9	0.50
6.6.5.1	9	9	10	9	9.25	0.50
6.6.5.2	8	10	9	9	9.5	0.82
6.6.5.3	10	9	10	10	10	0.50
6.6.5.4	10	10	10	10	10	0.00
6.6.5.5	10	9	9	10	9.75	0.58
6.6.5.6	10	10	10	10	10	0.00

6.7.4.3 Applicability of the model

Although the findings from this model are deemed as highly reasonable, according to the companies involved, this model might not be applicable in some situations where:

1. Remanufacturers (e.g. Company I) cannot control the level of component commonality which is usually determined by OEMs (i.e. car manufacturers) as engine design decisions.
2. Cores are more often freely issued by the OEMs on a high-volume business model of remanufacturers (e.g. Company G), and if remanufacturers do not build for stock, there is no risk of resulting scrap from finished units.

This model offers some various opportunities. For example, remanufacturers who cannot decide on the component commonality by themselves can use the model's results to discuss an appropriate level of component commonality with the OEMs in order to improve profitability of both OEMs and remanufacturers. This is supported by Hatcher et al.(2013) who stated that remanufacturers and OEMs need supply chain collaboration to improve the design of products. The model in this thesis suggests that the pattern of component commonality 0110_0000 can generate a higher profit than the pattern 0000_1111 with 50% of reworked components while 0000_1111 can generate a higher profit than that of 0110_0000 with 30% of reworked components as seen in graph HT, LC of Figure 6.3.

Also, remanufacturers who validated the model indicated that the model would be useful for small companies. This is because they always face uncertainties over the number of cores needed whilst reducing risk (stoppage due to lack of appropriate core/component, or unnecessary cost from overstocking of core/ component). Moreover, validators further indicate that companies will appreciate the fact that this model can help in making decisions which a conventional planning system cannot do because:

1. This model adopted the Pareto optimal which supports bi-objective optimisation which saves companies from determining the importance of each objective.
2. This model provides a useful means to quantify the impact of component commonality and control it under different scenarios as defined by the percentage of reworked components, reworking costs and reworking time. When the reworking costs and the percentage of reworked components increase, the impact of component commonality on the profit fluctuation increases. The remanufacturers can gain more control over profit by reducing reworking costs or choosing some specific patterns of component commonalities. This will generate higher profits even with high remanufacturing costs. This knowledge is applicable in real practice. For example, if there are 10 possible component commonality patterns to use, the decision model may suggest that the remanufacturers use only 2 patterns of component commonality to improve the company profit. If remanufacturers cannot avoid using expensive components, the proposed model suggests an appropriate percentage of reworked components for different scenarios in order to minimise costs. An optimal percentage of reworked components can then be determined to increase the likelihood of maintaining a higher profit under a remanufacturing scenario defined by specific remanufacturing costs and time. Unlike the level of component commonality, this particular function of the model will be useful for most remanufacturers because, previously, they have been managing their operations through controlling the percentage of reworked components.
3. With this model, remanufacturers can define the different remanufacturing scenarios and examine the associated effects of component commonality. This will make remanufacturers more proactive in decision-making, such as adjusting remanufacturing time/costs of certain components to optimise the overall remanufacturing outcomes.

6.8 Summary of chapter 6

The chapter 6 has proposed a decision-making model to support businesses in each remanufacturing activity by optimising profit and operational time. The findings contributes to the knowledge by quantifying and controlling the impact of component commonality on the objectives (maximising profit, minimising operational time or both) under different reworking scenarios (percentage of reworked components, reworking time, and reworking cost), which is a research gap. The proposed model can give managerial suggestions for profit enhancement as well as addressing the variability and uncertainty. When reworking costs and the percentage of reworked components are higher, the effect of component commonality on profit fluctuation increases. The remanufacturer can control these situations by reducing reworking costs, selecting specific patterns of component commonality that generate high profits or choosing the appropriate percentage of reworked components depending on various scenarios.

Next chapter will summarise the key findings of this thesis and showed how this research achieved its goal. Also, it will discuss the limitations of the research and further research in the future.

Chapter 7 Conclusion

In this last chapter, several topics are discussed including the research rationale, the research achievement, contribution to knowledge and practice, the research limitations and possible areas for further research.

7.1. The research rationale

This study is motivated by two new remanufacturing problems:

1. There is a lack of research on integrated decision making over multiple remanufacturing activities.

2. Tacit knowledge is not enough to consider new remanufacturing technology.

The first problem considered by this study is a lack of research to study integrated decision making over multiple remanufacturing activities. Decision making in the remanufacturing industry is more complex than traditional manufacturing because of the uncertainties of quality, quantities and the return time of used components. Previous studies have developed various method to optimise remanufacturing outcomes through making different decisions: identifying the best recovery options, acquiring the right amount of cores, and considering component commonality across different product families. However, there is a lack of research on integrated decision making over multiple remanufacturing activities which is an important topic. A decision being made for one remanufacturing activity will greatly affect the decisions for subsequent activities, which will affect remanufacturing outcomes, i.e. productivity, economic performance, and the proportion of core that can be salvaged.

The second problem which motivates this study is that tacit knowledge is not enough to decide on new remanufacturing technology. Although the remanufacturers can make decisions based on their tacit knowledge, this method is not accurate enough because there are always new threats or opportunities in their business. For example, this research considers additive manufacturing which is a new technology which may increase the ability to remanufacture beyond the existing capability. Since remanufacturers may not consider all the relevant factors to adopt this new technology, this study will consider the following factors: profit, operational time, reusable mass and reliability after recovery.

Therefore, this research studied a systematic and holistic way of integrating different decisions over multiple remanufacturing activities to make better decisions and improve remanufacturing outcomes. It adopted a 2-step decision making procedure of selecting the best recovery options and then finding the optimal number of components/products for each remanufacturing activity.

7.2. Assessing the quality of the research

This research meets all the criteria needed to guarantee the validity and reliability of the research findings. The criteria used in assessing the quality of the research are presented in Table 3.7 in Chapter 3.

Chapter 3 discussed how this research is able to guarantee research quality through its methods and techniques. The quality measurement in this research includes construct validity, internal validity, external validity and reliability.

Validation was conducted during several phases of the research including data collection and analysis. The researcher ensured the validity of the data at the point of collection. However, some questions arose after the in-depth analysis. When this occurred, the researcher communicated with the relevant participants via e-mail, telephone or at the next interview with their companies. Other validation methods used are the triangulation of data sources in the data collection phase. Moreover, the informants were from operational level to managerial level to obtain a wide range of perspective. Details of how this study ensured the validity and reliability of its result are shown in Table 7.1.

Table 7.1 Techniques to achieve research validity and reliability

Criteria	Techniques	How this study applied various techniques	Phase of research at which a technique is applied	Reference to the research
Construct validity	Use of multiple sources of evidence	Use of multiple sources of information including observation, interviews and documents review	Data collection	Chapters: 4, 5, 6
Internal validity	Use of pattern matching	Compared an empirically based pattern with a predicted one before collecting the data	Data analysis	Chapter 4

Criteria	Techniques	How this study applied various techniques	Phase of research at which a technique is applied	Reference to the research
	Explain the building process	Building the general explanation from several cases	Data analysis	Chapters: 4, 5, 6
	Use of logic models	Match empirically observed events to theoretically predicted occasions	Data analysis	Chapter 4
External validity	Use of replication logic in multiple case studies	The findings were tested by comparing them to new cases (as required for multiple case study approach)and similar results were obtained	Research design	Chapters: 5 & 6
Reliability	Use of case study protocol	This research follows the rule in section 3.3.4 for the research questions, research objectives, the number of case studies, criteria to select case studies and data collection	Data collection	Chapters: 4, 5, 6

7.3 Research questions and objectives revisited

Six research questions were proposed. These are, first, to explore the factors affecting the recovery options in remanufacturing; second, to explore the decision-making sequences in remanufacturing; third, to investigate the possible recovery options for components from different automotive remanufacturing companies. The first three questions are answered by following Objective 1 which is to review existing decision making in remanufacturing from existing research papers and the real life industry practise and find the knowledge gaps between the existing models and real practice. The findings from questions 1 to 3 were used to develop the decision-making framework on how to optimise automotive remanufactured components which is the second objective of this study. Next, this research developed a mathematical model for decision making. By following objectives 3 and 4, the fourth and the fifth questions were answered, respectively. The fourth question is how to select the best recovery options for components with specific faults. The fifth question is how to find the number of required components/ products for each remanufacturing activity. Then, objective 5 was accomplished by answering the last question about how reworking costs, reworking time, percentageof reworked components and component commonality patterns affect the profits of the remanufacturing business. Finally, this study achieved objective 6 by validating the proposed model with expert reviews of the findings.

The objectives and how this study achieved them are described as follows.

Objective 1. To review existing decision making in remanufacturing from existing research papers and the industry and to find the knowledge gaps between existing models and real practice.

The possible recovery options for components gathered from different automotive remanufacturing companies are presented in Table 5.1. The factors affecting decision making and decision sequences in remanufacturing were originally gathered from literature reviews and brainstorming with experts who make such decisions. A total of 38 factors were identified as the factors used in decision making based on the existing literature and real practice; 7 of these factors are new findings which emerged from the empirical study shown in Table 4.3.
The factors were narrowed down from 36 to 10 since some factors were similar or already covered by other factors. Also, type of damage, severity of damage and area of fault were factors removed because they were used as a case study. For example, wear on crankpins of crankshafts at different level of severity was used as a case study in the decision making step 1. Moreover, carbon dioxide emission was removed from the list since it was not considered of sufficient importance by any of the experts. The final list of factors are as follows.

1. Compliance with laws and regulations

2. Available techniques/technology for recovery

3. Minimum demand for components

4. Future demand for components

5. Reliability of components

6. Operational time to rework products/components or lead time to buy new products/components

7. Availability of cores

8. Minimum purchasing amounts from suppliers

9. Profit

10. Reusable mass of components

Objective 2. To develop the decision-making framework on how to optimise automotive remanufactured components.

This research focused on the optimisation of automotive remanufactured component by 2 steps of decisions: 1. selecting the best recovery options for used products and components 2. finding the optimal number of components/products for each remanufacturing activity. The final lists of ten factors and their decision making sequence were used to develop a 2 step decision making framework which is presented in Figure 4.1.

Objective 3. To develop a mathematical model to select the best recovery options for used products and components

Chapter 5 deals with how objective 3 was achieved. The logic of the model described is shown in figure 5.1. The details of the inputs are given in section 5.4. Then, a combined point allocation goal programme is proposed to select the best recovery option for the components as shown in section 5.6 As a result of the sensitivity analysis setting in section 5.7, the model has 100 different results as shown in Table 5.29.

Objective 4. To develop a mathematical model to find the optimal number of components/products for each remanufacturing activity.

Chapter 6 deals with how to achieve objective 4. The logic of the model described is shown in Appendix III page 294. Then, the construction of the model is described in section 6.3. This proposed model can provide a company with an infinite number of material planning for remanufacturing by maximising profit, minimising time or a combination of these two objectives. An example of the optimal results is shown in Table 6.15.

Objective 5. To study a sensitivity analysis about reworking costs, reworking time, percentage of reworked components and component commonality patterns which affect the profits of the remanufacturing business.

Since the result of decision-making step 2 can vary on different inputs and a sensitivity analysis is a reliable validation method, section 6.5 of this research examines the sensitivity of reworking time and reworking costs towards achieving an optimal profit from the remanufacturing of reworked components from 0% to 100%.

Objective 6. To validate the model by expert reviews

The expert participants validated the model by checking whether the model had reached a set benchmark or not. The validation of decision-making Step 1 and decision-making Step 2 are described in sections 5.9 and 6.7, respectively.

7.4 Contribution to knowledge

The outputs of this study were achieved by following the 6 objectives which resulted in contributions to current knowledge in the field as follows

7.4.1 The novelty of the research

- This research studied and developed, for the first time showing how to integrate different decisions over multiple remanufacturing activities to improve remanufacturing outcomes. This study considered how to select the best recovery option for components and how to find the optimal number of components/products for each remanufacturing activity. The integrated decision making considers economic, engineering and environmental objectives while two of these objectives have been considered by previous studies (Kwak, 2015). However, the holistic, enhanced framework proposed here considered under-studied factors in the decision-making of remanufacturing. The under-studied factors considered are availability, demand, quantity of components/products, component commonality and reusable mass of components. The framework developed here and shown in Figure 7.1 is a vehicle making the new knowledge obtained from this research easy to understand and use by others.

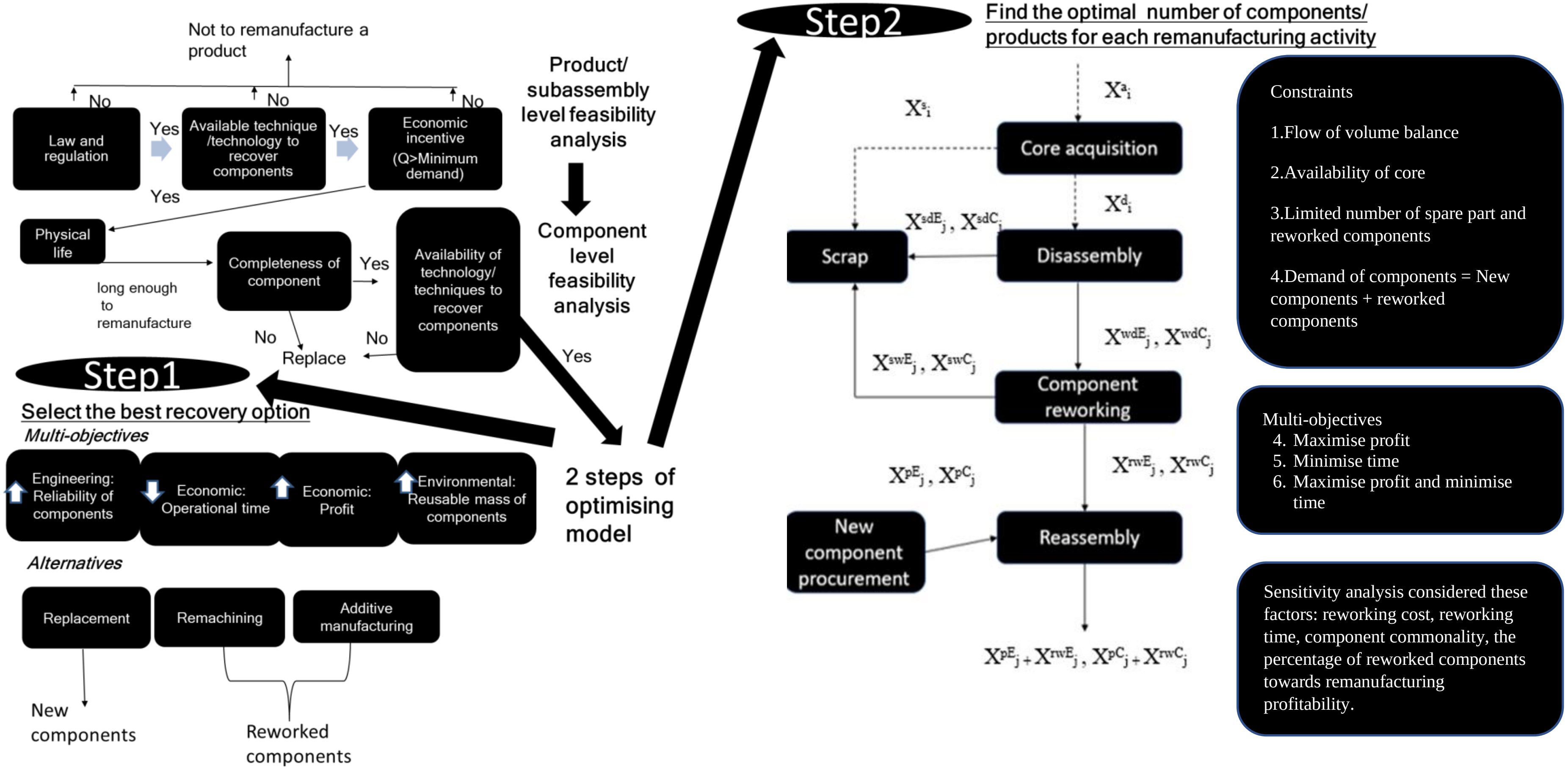


Figure 7.1 The decision -making framework of this research

- This first step of decision model developed by this research addressed current issues whether additive manufacturing is the best recovery option for crankshafts by comparing it with replacement and remachining which are the current recovery options. Also, this study used crankshafts with worn crankpins as example since this component is common and expensive and also its failure is common. Typically, companies always miss the opportunity to recover this component due to their reliance on tacit knowledge only. This model revealed whether additive manufacturing is a suitable recovery option in several scenarios. This enhanced effectiveness of decision making due to the ability to properly evaluate a greater number of options. Moreover, findings from this research will help remanufacturers to find new business opportunities through enhanced capability to recover crankshafts.
- The knowledge from the sensitivity analysis of the second step of the decision model contributes to the literature by quantifying and controlling the impact of component commonality on the objectives under different reworking scenarios characterised by the percentage of reworked components, reworking time, and reworking cost. When reworking costs and the percentage of reworked components are higher, the effect of component commonality on profit fluctuation increases. The remanufacturer can control these situations by reducing reworking costs, selecting specific patterns of component commonality that generate high profits or choosing the appropriate percentage of reworked components depending on various scenarios.

7.4.2. Uniqueness of the research

The research uniqueness is the use of different data collection and analysis approach in comparison to previous similar work as follows.

- This research was conducted by a mixed-method approach (qualitative and quantitative) to solve the problems while other existing studies conducted either qualitative or quantitative research methods.
- This research adopted mixed-integer linear programming to a material planning in remanufacturing and to use a sensitivity analysis of percentage of reworked components, reworking time, reworking costs and component commonality all of which have impacts on remanufacturing profits while other research studies in the

field usually used mixed-integer linear programming to a material planning in remanufacturing.

7.5 Contributions to practice

As well as making new contributions to academic knowledge, this research is also important because it offers benefits to practitioners:

- Practitioners will benefit from some basic guidance on what steps can be taken to optimise returned products in the automotive remanufacturing industry. In the past, the remanufacturer only used tacit knowledge which is not effective because there are now new technologies for recovering components, for example as additive manufacturing. These can increase the scope of remanufacturing by enabling the recovery of components that currently cannot be remanufactured. This benefit applies especially to obsolete and hard-to-find components. This new knowledge will help remanufacturers to select the most desirable recovery options for components with specific faults that they may not have been aware of previously. Since a crankshaft is an expensive component with limited recovery options and wear of crankshaft is a common problem. This systematic and holistic decision-making process can help them consider more recovery options with multiple criteria. Therefore, it can potentially enable them to enhance the scope of their product recovery operation and therefore increase the profits of the remanufacturing industry.
- This study conducted a sensitivity analysis on recovery time, recovery cost, percentage of reworked components and component commonality patterns which all affect the profit of the remanufacturing industry because the factors are common in the planning of the materials in the real practice of the remanufacturing industry.
- Some of the factors have not been considered previously by some companies. Therefore, this research gathered a more complete lists of factors from engagement with a range of automotive remanufacturing companies. Knowledge of these factors and the decision making sequence can help remanufacturers to make decisions more holistically which can lead to better remanufacturing outcomes in terms of productivity, economic performance effectiveness, and the proportion of cores that can be salvaged. Understanding these factors and the

sequence of decision making can help remanufacturers to select the best options available at present and also other options that may become available to them in the future.

- The holistic and systematic framework developed by this research can be applied in other sectors such as medical sectors, aerospace sectors and electronic sectors. If the products are metal based, the common failures of the products in these sectors are as same as those of automotive sectors mentioned in this study. However, what needs to be considered is that nowadays new products have more electronic parts. It may need additional information such as the economic value of electronic parts and the hazardous waste generated after recovering products. Electronic parts usually have a shorter life cycle than that of metal parts. Also, the technique to recover electronic parts are different from metal parts. These reasons lead to different results of future studies.

7.6 Research limitations

- Resource (e.g. time and cost constraints of PhD study and inability to access companies' confidential data), were a major constraint in determining the detail of the model. The input in this new model is generally less detailed than ones used to fine-tune an existing system since little data is available for the proposed system. Some of the data has been assumed, which may reduce the accuracy of the model.
- Although the researcher tried to input real quantitative data as much as possible, the use of some confidential data was not allowed by companies to be used for quantitative validation. High face validation was an acceptable alternative method to use in this study. Therefore, in further research, when using quantitative data to validate the model, the results may be different from those in this study.
- The number of factors for the study is large, therefore, this model considered only the main remanufacturing activities, 2 engine components and a limited number of shared components. This was due to the time and cost constraints of the typical PhD research.
- Solver in Microsoft Excel which was used in this study is limited to handling a maximum of 200 decision variables. If the problem is more complex, it requires a more powerful program.

7.7 Areas of future research

- Real quantitative data could be input into the model as much as possible for quantitative validation
- Further study may consider a model which can consider making 2 decisions simultaneously. Since the output of the first step in decision making is the best alternative which could be replacement, remachining or additive manufacturing. This decision making affects the number of new components and the number of reworked components which is required information for making the Step 2 decision .
- The new research can consider more complex problems by considering all remanufacturing activities, more components in the engine and a higher number of shared components
- Future research may consider using the internet of things to develop real-time decision making.

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Appendices

Appendix I: Interview results

Appendix I A: Interview with Company A

Interview in March 2017

Optimising the core in the automotive remanufacturing industry

1. Do your company remanufacture, recondition or repair products? / Do you provide remanufacturing services and also other services? / What percentages of your work is on Remanufacturing / Reconditioning / and Repairing?

   The company is a subsidiary of OEM remanufacturer. In the plant 95 % of our activities are remanufacturing while the rest is manufacturing new automotive parts for spares.

2. What are the main challenges to the management of the cores?

   The main challenge is the availability of cores. The company provides various models of cores. It may be hard or expensive to source the right parts at the right time because those parts might be obsolete or produced in low volumes. Moreover, not all customers return cores to the remanufacturer.

   In inventory management, we do not know what new parts we need until we strip and recover the parts. One core might give 50-90% usable parts. We have to offer the right parts available to replace faulty parts to keep up with demand.
   When the whole engines arrive, we disassemble engines into smaller parts. Therefore, the challenge is to find the right combination of materials because we have to manage both remanufactured parts and new parts to replace faulty products. Moreover, we have to deal with both oversized and undersized parts. For example, a shaft will be remanufactured to be undersized so we have to compensate by fitting oversized parts.

   In summary, when remanufacturing an engine, some parts are new, or remanufactured or some parts need to have their dimensions changed. Although it is quite a complicated process, we deal with this problem by ordering parts based on historical data.

   Operational strategy

3. Please allocate a total of 100 points for your objectives according to how important it is to your strategy to manage cores.

   ___ 40___ Assemble a certain number of remanufactured parts.
   Our distribution centre will tell us the number of products we have to produce per day.
   ____20___ Neglect unnecessary jobs/tasks because they consume time, labour and money.
   We believe the availability of parts is essential. We will not wait for the parts to be returned or found in a limited time. We will buy new parts if it is necessary and cost-effective.

____40___ Make a return on your investment on cores. (e.g. You want to utilise every core you acquire)

Making a decision

4. How do you decide on remanufacturing or other end of life options?

We will remanufacture whatever products the customers want. We order the core we need based on demand and keep it in the warehouse. Our marketing department will see the trend of required cores. If the part is repairable, the remanufacturer will use it for remanufacturing and will scrap the unrepairable ones. If the parts require too much reworking, the company will buy new parts instead of using them. Sometimes we need new parts or cores which we can source via our mother company or our suppliers. Sometimes we use welding to rework products. We will then test the characteristics of those parts, do welding, and inspect the quality of the parts again. If the welding works, they will keep a record of that procedure as a salvageable process and carry out the same task again when they find another core in the same condition.

5. What are the factors/criteria that you consider? Which are more or less important, and why?

Please allocate a total of 100 points for all the factors according to how important it is to your decision making on remanufacturing.

The operators in the local site do not take market trends into account because the marketing staff of our mother company are responsible for this. A remanufacturing cycle is not considered as essential since we decide after an inspection on how good the condition of a core is. Recycling is not a major factor in decision making on remanufacturing. However, we are a large company which considers minimising waste by sending metallic material to be recycled.

__5___Age of Parts

We focus more on the condition of parts to decide whether the parts are good or bad. However, we think the age of the parts can affect decision making if some parts are obsolete.

__5____Historical price and cost

When the parts are older, the demand and the volume are lower, and the cost of new parts tends to increase.

__20____Projected price and cost

When we project the costs, we consider if the parts are cost-effective to remanufacture. For example, the parts might not have been cost-effective three years ago, but today they might be worth remanufacturing because the parts are available and cheaper.

__5____Complexity of components

We also consider this factor since it is difficult to remanufacture complex components; however, sometimes we can repair it.

__5____Fasteners/parts availability

This is certainly a factor. Occasionally, you can buy only a complete assembly of parts. The individual parts are difficult to find because they come from sub-suppliers. We can buy completely assembled parts from our parent company or we can buy some smaller parts from subcontractors. Although the smaller parts are cheap per unit, the suppliers allow us to buy in high volumes. Therefore, we will purchase smaller parts in larger amounts when we need them. If it is not possible to buy smaller parts, we will buy the completely assembled parts.

__30____Condition of cores (condition investigated by visual inspection)

__30____Condition of cores (internal condition e.g. cracks)

We think both the internal and external condition of cores are equally important because we have to investigate cracks, wear and damage to make a decision on repair, reuse or remanufacture of the parts.

6. Do you consider environmental factors to optimise the reuse of cores? If so, what are those factors?

   Although we do not focus on environmental factors to optimise our use of cores directly, our mother company provides competitive technology to reduce emissions and save energy. We are a subsidiary of our parent company, so our remanufactured products follow their specifications in term of reducing carbon dioxide and cleaner combustion. The remanufacturers help the environment by making old machines run more efficiently and utilizing more environmentally friendly chemical agents in their cleaning process. We understand that the most effective agent is not necessarily the cleanest chemical agent.

7. What factors are known and recorded

   The marketing department is responsible for monitoring market trends, the age of parts, historical/projected prices and costs of the remanufacturing cycle. The condition of cores is recorded to give customers credit depending on the amount of damage or if there are missing parts in returned products. We do not consider the incompleteness of a core. We decide to remanufacture products case by case after inspection.
   The main thing that we record are replacement parts: we record what parts have failed so we have the statistics for the requirements of new parts.
   Our parent company will take care of the availability of parts/fasteners. We can usually find parts; therefore, it is not necessary to track them. The only point is that the costs can change over time.

8. How long does it take to decide on how to remanufacture returned products?

   It takes one month to introduce new remanufactured products because we need to see the availability of the parts and consider the procedures for remanufacturing. In terms of remanufacturing, when the cores arrive, we spend a few minutes to consider whether they are good or bad. We remanufacture 200 parts or five engines per day. We know the approximate data for a year. This data may change depending on the market; however, we try to keep a constant production rate to control the quality.

9. What are the inspection methods? How do inspection results decide on the suitability of remanufacturing or other end of life options?

Normally, we measure the critical features of the parts e.g. surface finishing measurement, radius check, crack check, penetration, microparticle check. It is unusual to reject cores before disassembling them. The only occasions when we reject remanufacturing them immediately is when the cores are severely damaged or they have been stored outdoors for a long time or they are full of water.

10. What is the condition of the cores that you reject immediately for remanufacturing? Which cores are more or less important and why?

Please allocate a total of 100 points among factors according to how important it is to your decision making.

__20___No. of parts damaged.
__20__Severity of damage

If all the expensive parts of a core are severely damaged, we will not remanufacture it. For example, we cannot remanufacture parts if that engine has been run without oil as this results in severely damaged parts.

__30___Types of damage e.g. deformation, burnt, wear, cracks, corrosion, holes, fractures, fastener failure, dents, looseness, and design flaws

Generally, we try to carry out fixing it first. If it is not worth remanufacturing any parts, we will replace those faulty parts with new parts.
If a specific part in a crankshaft is burnt, we cannot replace it because it is too risky to remanufacture it. We remanufacture premium products and we want to give its life to cover its warranty.
It is impossible to remanufacture parts with cracks. Corrosion, holes, and fractures are the most important factors. If the core has some design flaws, we will try to modify it first, if we cannot do this properly, we will scrap it. If the cores have some dents, we will recover them by welding and machining. If the components are loose, we will replace or repair them to meet the specifications

__30___Obsolete

If we find the parts that cause a failure, we will record the data in our system and reject those obsolete parts for the next round of remanufacturing to make sure we can guarantee the warranty.

11. What types of core failure are commonly found?

wear, cracks, corrosion, missing parts, availability of cores, non-genuine parts (parts using mixed brands), unknown condition

12. Why are some parts scrap?

Ranking by the most commonly found
____1_____Undersized __________Oversized
____5_____Overstocked ___6______Mating part lost
__________Obsolete (cannot find tools, material to repair it)
____2____Weakened parts (Further process can weaken parts)
____4_____Cosmetic flaw
____3_____Material loss

13. What do you do with scrap?

We send scrap to the recycling centre to be melted down as raw material. We do not want our unused components in to get into our competitors' hands. We have an agreement with the recyclers not to sell any of our components to our competitors.

14. How much do you agree with this statement

"If you know the failures/scrap history, you can predict the number of failures/scrap in the future."
[✓ Strongly agree]/ agree/ moderate/disagree/strongly disagree

"If you know the failures/scrap history, you can develop design strategies."
Strongly agree/ [✓ agree]/ moderate/disagree/strongly disagree

Few people consider remanufacturing when they design new products. We are starting to do this but it takes time.

"If you know the failure/scrap history, you can remanufacture products more efficiently."
[✓ Strongly agree]/ agree/ moderate/disagree/strongly disagree

We sustain the process with the right parts of stock our customers require.
"If you can predict the failures/scrap, you can predict the number and characteristics of the parts you should acquire."
[✓ Strongly agree]/ agree/ moderate/disagree/strongly disagree

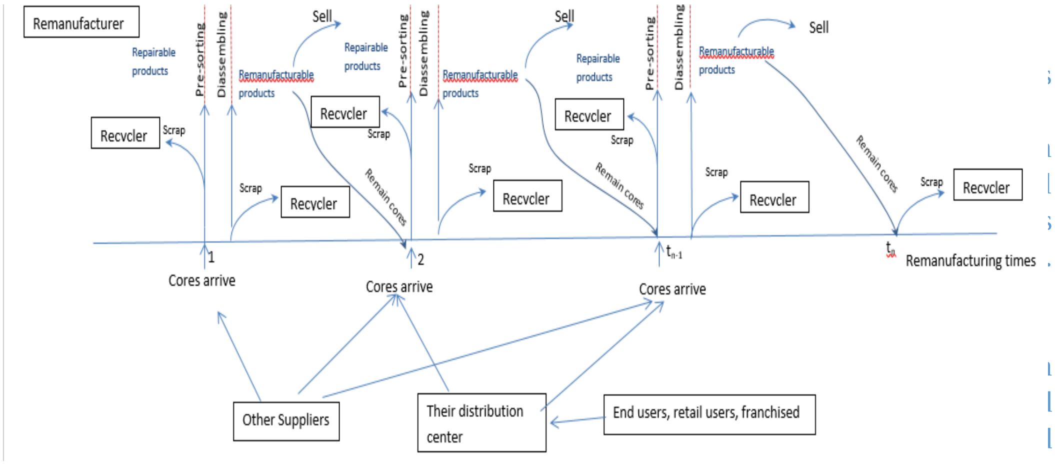
"If you can predict the number and characteristics of parts you should acquire, it can help increase product recovery rate and profit."

Strongly agree/ [✓ agree]/ moderate/disagree/strongly disagree

If we know the parts with one particular failure, we can introduce a new salvage process to repair it.

Business model

15. Could you tell me about your business model?

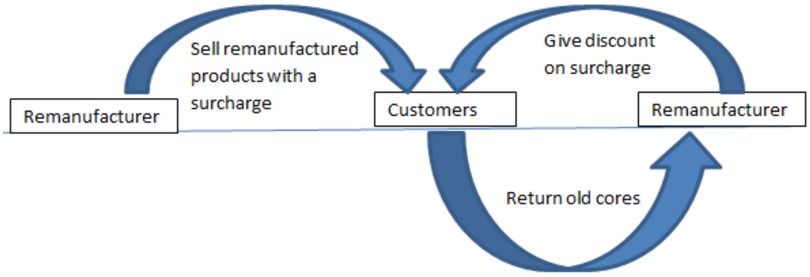


the faults of the parts. There is a step by step investigation to value the old cores. If a core does not meet some of our criteria, the core's value is reduced. For example, in the case of a turbocharger, we will check how well it rotates and how many parts are missing before giving the customer any credit.

Our suppliers are not our customers. Our customer is a part distribution warehouse which serves the European market. So the distribution centre sells products to end customers, retail customers, or a local franchise.

Our suppliers for the components are our parent company which has many branches around the world and other subcontractors. We do not know the exact percentage of our cores which have not been returned to our plant because it varies according to the region. The reason why customers do not return cores to the remanufacturers is because the customers think it is worth keeping cores for their spare parts. We keep track of the return of cores in our distribution centre.

16. How do you take cores back?



We add a surcharge when we sell remanufactured products to customers to persuade them to return the old cores to the remanufacturer within 12 months and clients will get a discount on their surcharge in their customer account. The company will give credits to customers depending on the completeness of the cores.

How can you manage your stock?

After a brand-new product has been launched for 3-4 years, we introduce remanufactured products because by that time the warranty period has ended. Up to five years after a new product is launched, there is quite a low demand for remanufactured products since the new products are of high quality. However, if there are any problems with new products, we will replace them with remanufactured products. After five years, the demand for genuine remanufactured products increases because the engines start wearing out. In this period we receive more cores because the old cores are returned. The shelf life of our products is 5 years or more. Good cores are available and there is a high demand for remanufactured products after the brand-new product has been launched from 0-10 years. After a new product has been launched for ten years, it is challenging to supply cores. However, the company will look after customers with a genuine and cost-effective remanufactured product to ensure that they will repurchase our products.

How can you maintain your inventory and buy new cores?
Our marketing department is responsible for tracking the data about the trends in the requirements for cores. The distribution centre will order several products that this plant produces and it will supply the required components. The plant tracks the number of components we want and sources parts from their distributors or their subcontractors. Then, the cores are collected in our inventory. We try to keep cores for a maximum period of 12 months in our inventory. Sometimes the cores will stay in the inventory for 2 years. How many cores are required depends on the market. The volume of required products is quite volatile, especially in the oil and gas industries. Obsolete products with no demand will be no longer be kept in our inventory and will be used as scrap.

Other considerations
The lifecycle of products seems to last a long time, however, technology changes and new regulations can reduce the lifecycle. For example, in London, old diesel engines are no longer used. The life cycle of a bus has been reduced from 10 to 5 years. Although it is possible that a newly acquired core might become obsolete due to a change in the regulations, we can launch our remanufactured products in other places which do not have such strict rules. We aware of the possible problems with this issue and may change our strategy if it is necessary.

Interview in October 2017

Description

A product family is a group of related products that share common components

According to my study, planning for components by considering common components of different products within the same product family can improve profitability and environmental sustainability. It can increase the reusability of components from used products. However, there are different amounts of demand, various types of returns, and timing uncertainty in the remanufacturing industry. Moreover, to know the total volume of components required means a full disassembly. Therefore, it might sometimes be difficult to reuse parts from the same product family. To clarify my assumption, I ask the following questions.

Question

1. Which option do you apply to manage components in your remanufacturing system?

▣Option 1 Sum up all required components from all products in the same product family before ordering the required components

Product / Component	▲	■	●	Total component required
	No. of components	No. of components	No. of components	
A	2	3		5
B	1	2	3	6
C		4	1	5
D	1		5	6

1. We group cores into similar categories. There might be ten potential cores which need to be considered. If we cannot find core number 1, we will use number 2 instead. Usually, cylinder blocks, crankshafts, conrods are shared parts of the products within the same family. However, some components cannot be remanufactured. For example, if a piston is already worn, it is difficult to investigate its condition. Therefore, the remanufacturer will not remanufacture this component.

Once we know the approximate number of remanufactured components required in the next months, we strip the engines to make parts for stock before receiving an order. We use a computer for MRP planning to match the part number required with the available parts of the core (crankshaft, cylinder head, block) in stock. If we cannot find any used components, we will find components in the new component stock. If we cannot find any new component in stock, we will buy new/used components globally from core brokers/suppliers.

Approximately 40% of the components are new components that we have to find.

☐ Option 2 Use BOM (Bill of Materials) to plan each product individually before ordering the required components

Product / Component	▲
	No. of components
A	2
B	1
C	
D	1

2. Do you need to disassemble products fully before ordering the required components?

We need to disassemble products fully before ordering the required components since the lead time of components may be long. We usually plan 4-6 weeks before we need the components.

3. Do the different brands of products share the same common parts?

We do not use other brand components since we do not know the materials used by other brands. We use genuine parts because we know the material the components are made from, so we can be sure of the reliability of the components and we can offer a warranty to the customer. We can use cores from different products. For example, we can use cores from trucks to remanufacture the cores for buses. We can rework cores to the shape we require. Also, we can use the same old components to remanufacture more modern components. For example, we can use the old ECM and reprogramme the engine to produce a new model.

4. How much percentage of commonality for products is there in the same product family?

Probably 40 %

5. What are the advantages and disadvantages of the existing methods?

The existing method is cheap and can increase remanufacturability.

The disadvantage of the existing method is its complexity. It takes lots of different parts from different locations and puts them together at the same time. Some parts are stocked, some are reworked in factories in India or the UK. Their lead time is up to 4 weeks.

6. What do you think about option 1?

☒It might be applicable in the production because

  ☒ It can increase the reusability rate

  ☒ It can increase available components from cannibalized cores

  ☒ It can reduce costs

☒Others, please specify When there is a shortage of cores, stripping more units of cores can increase the availability of cores

☒It might not be applicable in the production because

  ☒ Buying new components is cheaper than waiting for full disassembly and finding recoverable components. This is true, but labour costs are at a fixed rate.

  ☒ Buying other cores is cheaper than waiting for full disassembly and finding recoverable components. This is possible but it is difficult to find the right cores

  ☐ There are very few products which share the same parts

  ☒ This method is time-consuming

  ☐ Others

  Please specify____

7. Not all products can be remanufactured. What are the recovery options applicable to your business

☒Reuse ☒Recycle ☒Remanufacture ☒ Repair ☐ Cannibalize

8. Do you think ta policy on how to decide on when you should repair or remanufacture products is beneficial?

☐ Yes, because

☐ You can offer repairs when there is a lack of component supply

☐ You know whether it is economical or not to treat the products under the warranty period

☐ Others

Please specify____

☒No, because customers prefer to buy remanufactured products since the repaired parts might not be in stock. The remanufacturer can provide reliable remanufactured products with a warranty because remanufactured products are in stock and remanufacturers can distribute them when the customers need them.

9. What environmental impacts do you have to control in your operation because of regulations

☒Material consumption ☒ Energy consumption

☒Carbon Dioxide ☒ Other emissions (i.e. sulfur dioxide)

Please specify_chemical agents

10. What environmental impacts do you need to control in your operation

☒Material consumption ☒Energy consumption

☒Carbon Dioxide ☒Other air emissions (i.e. sulfur dioxide)

Please specify_chemical agent

Chemicals and materials should not harm the environment or workers.

Energy consumption - We can track equipment performance so we can change the equipment that consumes too much energy.

Carbon dioxide - We have to prove the engine’s emission performance.

Chemical tank to treat water - Subcontractors are responsible for this.

Regulations - We (our Department of Health and Safety) follow the local council’s regulations, which are less strict than our manufacturing specifications. Therefore, there is no conflict.

Environmental criteria to follow - All of the operations have to meet European emission standards. The criteria are the solvents in paint, fuel combustion, engine - speed, fuel consumption, load, and carbon dioxide emissions

11. How are you planning to disassemble/reassemble complex products?

We disassemble, stock products and let the computer find the bill of materials, then reassemble the components.

We divide facilities into 2 stages: A disassembly facility and a reassembly facility because disassembly is a dirty process. The challenge is to find the same building to use for disassembly, stock and reassembly.

12. To what extent do you think these methods could help you to plan complex products?

- Bill of materials

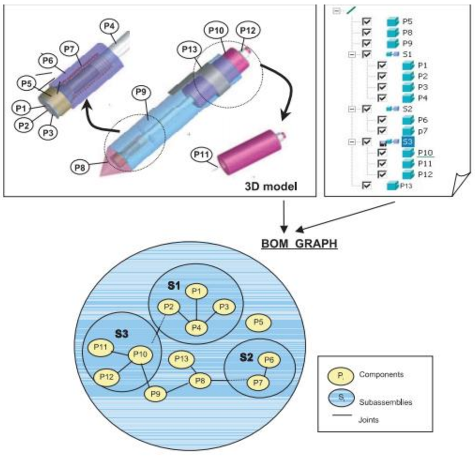


Figure 3. Translating the BOM into the BOM graph, for the example of a mechanical pencil.

☒ Very high ☐ High ☐ Medium ☐ Low ☐ Very low

- And/or graph (to show alternatives how to disassemble/reassemble products)

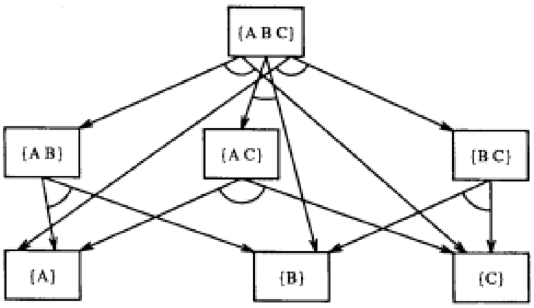


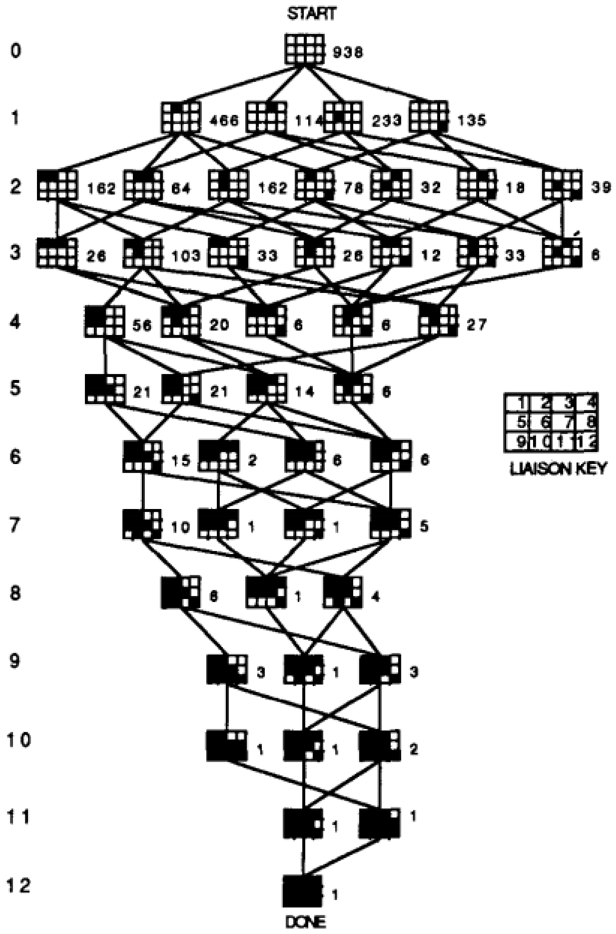
Fig. 2. The AND/OR graph for a three-part assembly.

☒ Very high ☐ High ☐ Medium ☐ Low ☐ Very low

- Disassembly possibilities (to show the angular ranges of removal of components or subassembly)

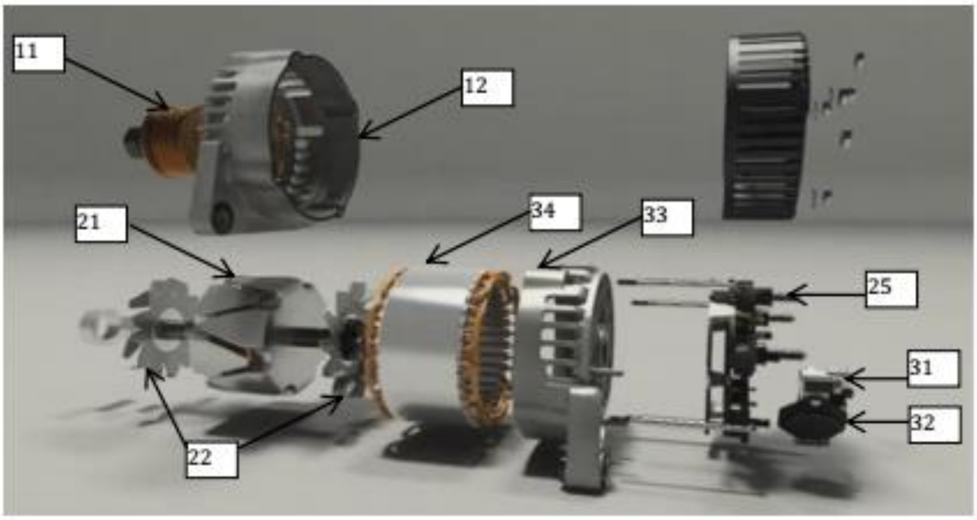
☒ Very high ☐ High ☐ Medium ☐ Low ☐ Very low

- Show diagram (to show what is the current state in the production progress)



☑ Very high (for assembly) ☐ High ☐ Medium ☐ Low ☐ Very low

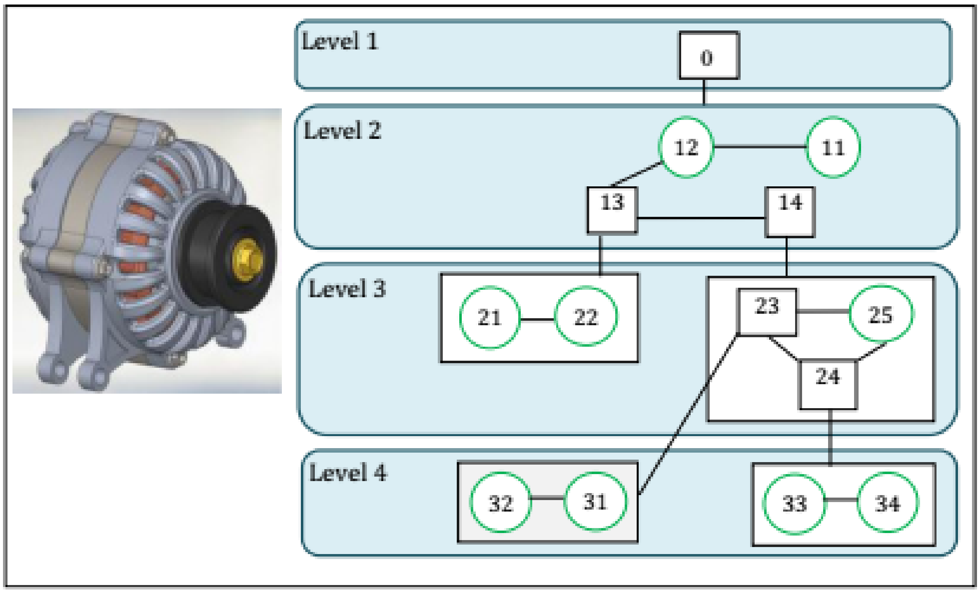
- 3D product representation



☑ Very high (It is a standard) ☐ High ☐ Medium ☐ Low

☐ Very low

- Liaison graph (to show subassemblies or components for each level of disassembly)



☐ Very high ☑ High ☐ Medium ☐ Low ☐ Very low

9.What percentage of your operation is

MTS (Made to stock)_30__%, MTO (Made to order)___%, ATO (Assemble to order)_70___%

10. How stable or predictable is the recovery rate of used products?

☐ Unpredictable and unstable

☐ Predictable and unstable

☑ Predictable and stable (avg. 3 months for each single product)

11. How stable or predictable is the demand rate

☑ Unpredictable and unstable (longer than three months)

☐ Predictable and unstable

☑ Predictable and stable (monthly, quarterly)

12. How stable or predictable is the return rate of used products

☑ Unpredictable and unstable

☐ Predictable and unstable

☐ Predictable and stable

13. In the disassembly of products, how stable or predictable are the processing times?

☑ Unpredictable and unstable

☐ Predictable and unstable

☐ Predictable and stable

14. In the reassembly of products, how stable or predictable are the processing times?

☐ Unpredictable and unstable

☐ Predictable and unstable

☒ Predictable and stable

15. How long a period does your purchasing plan cover?

Our purchasing plan covers 6 months ahead due to the different lead times of each product / component. The lead time of 80% of required products is 4 weeks. It can also be up to 10 weeks ahead, depending on the lead time of products.

16. How long does it take to disassemble one product?

Small engines: 2 hours, Large engines: 4-5 hours

17. How long does it take to dispatch products after receiving an order?

If we have items in stock, we can dispatch them within 2 days

18. How long does it take to remanufacture an engine

It might take about 4-10 weeks to carry out all the procedures for one engine.

Appendix I B: Interview with Company B

Interview in January 2018

1. What percentages of your work is on Remanufacturing / Reconditioning / and Repairing?

Remanufacturing (50%) / Reconditioning / Repairing (30%)/ Producing new products (20%)

2. What types of product do you remanufacture?

Commercial engines

3. What are the main challenges to the management of cores?

Cores deteriorate over time

4. Please draw a flow chart of core acquisition

While we get cores from B2B customers for free, we only charge customers for service and the necessary components we have to buy. This method helps both customers and remanufacturers to reduce tax costs. Company B's customers are only OEMs. The customers also return cores to company B. 90% of cores are from customers and the rest is from other third-party suppliers.

Non-wearable and non-degradable parts such as housing and casing of diesel injection systems are inspected for wear by using non-destructive testing (NDT) methods. Company B has no pre-sorting process in general. It is unusual for company B to reject cores without disassembling them since the engines are more complex and expensive than diesel injection components. The only circumstances in which company B rejects remanufacturing them immediately is when the cores are severely damaged or they have been stored outdoors for a long time or they are full of water. Company B measures the critical features of the parts e.g. surface finishing measurement, radius check, check for cracks, penetration, micro-particle check to decide on suitability for remanufacturing.

After the inspection process, company B remanufactures products to OEM's standards using OEM's parts and OEM's test equipment/data. Core acquisition in the remanufacturing industry is a multiple-period operation since remaining cores are often utilised in the next batch. The flow charts of core acquisition for company B are shown in Figure 1.

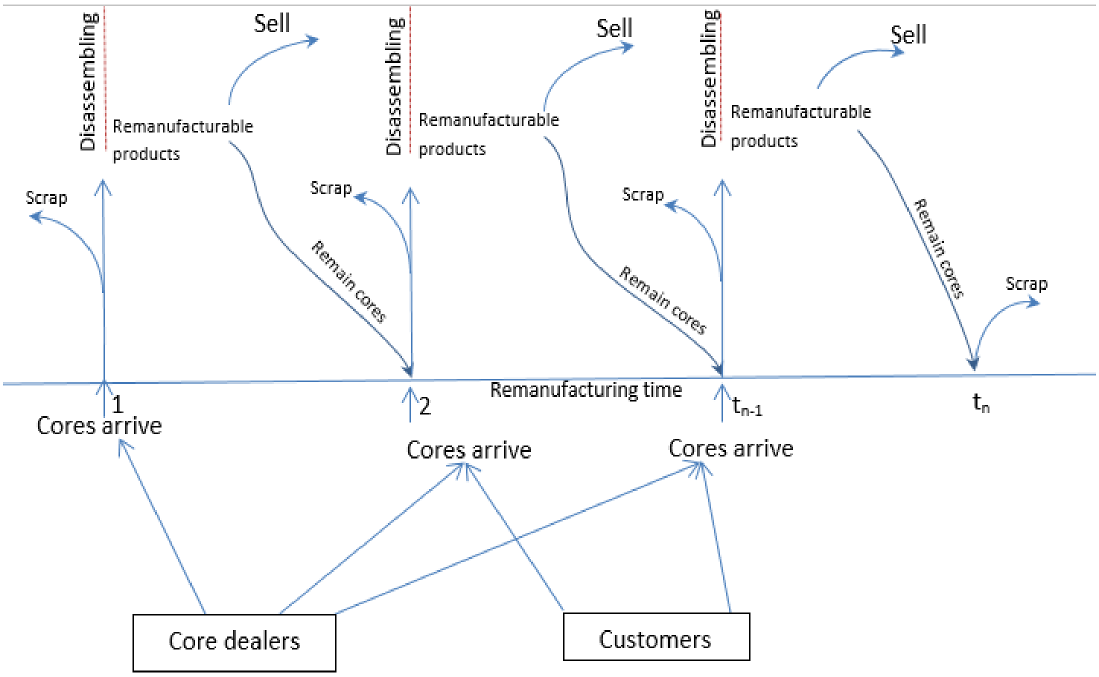


Figure 1. The flow chart of Company B (Contract Remanufacturer's core acquisition)

5. Could you tell me how long remanufacturing requires?

	Company B
The physical life of products	120-180 miles for transportation vehicles, 50,000-75,000 for private cars
The length of time remanufacturers allow customers to return old cores after purchasing remanufactured products	N/A
When remanufacturers start to remanufacture products	After the launching of a brand-new product
The right time to remanufacture	After five years of offering brand new products
The period between remanufacturing cycles	15 years
The maximum time allowed for remanufactured products in their inventory	22 years

Operational strategy

6. Please allocate a total of 100 points between the objectives according to how important it is to your strategy for the management of cores.

___ 70___ Assemble a certain number of remanufactured parts

This objective was the most important one for company B. We set the target for a certain number of remanufactured parts we produce per day. The amount of production is based on the sales information we have.

____20___ Neglect unnecessary jobs/tasks because it consumes time, labour and money

We give this criterion less priority since we get most of the cores (90%) free of charge.

____10___ Make a return on your investment on cores. (e.g. You want to utilise every core you acquire)

We do not do any pre-sorting since we have no policy to scrap the whole core, and it would require full disassembly for further core inspection.

Making a decision

7. What are the factors/criteria considered? Which are more or less important and why?

Please allocate a total of 100 points between factors according to how important it is to your decision making on remanufacturing.

__8_____Age of parts

__15____Fasteners/parts availability

__3____Historical price and cost

__5____Projected price and cost

__8____Remanufacturing cycle

__8____Complexity of components

__23___Condition of cores (condition investigated by visual inspection)

__31____Condition of cores (internal condition e.g. cracks)

8. How long does it take to make a decision on how to remanufacture returned products?

It depends on the customer introducing the remanufactured products to the market. It takes 1-5 days to remanufacture products in actual practice.

9. What are the inspection methods? How do inspection results decide on the suitability for remanufacturing or other end of life options?

Normally, we measure the critical features of the parts e.g. surface finishing measurement, radius check, check for cracks, penetration, and a microparticle check.

10. What are the conditions of cores that you can reject immediately? Which one is more or less important and why?

Please allocate a total of 100 points between factors according to how important it is to your decision making.

__20___No. of parts damaged.
__30__Severity of damage
If all the expensive parts are severely damaged, we will not remanufacture it. For example, we cannot remanufacture parts if an engine has been run without oil which severely damages parts.
__20___Types of damage e.g. deformation, burnt, wear, cracks, corrosion, holes, fractures, fastener failure, dents, looseness, design flaws
__30___Obsolete– warranty problem

We get cores for free from customers, therefore we do not have to accept cores. We will not reject whole cores at the beginning of the process. We will keep cores in the inventory when cores arrive and we will inspect the parts after we find out our customers' requirements. We will reject parts when we find out that the cores are in poor condition.

Obsolescence is important. We can always access parts from OEMs, so we do not have a pre-sorting process. Obsolescence and severity of damage outweigh the two remaining factors since we can handle various types of damage for several parts in our daily operation. The severity of damage can affect the decision on how to recover cores and keeping obsolete cores can cause higher acquisition costs.

11. What types of core failure are commonly found?

deformation, burnt, wear, cracks, corrosion, holes, fractures, fastener failure, dents, looseness, design flaws.

Others: Please specify missing parts, unknown condition

12. Why are some parts scrap? And how to manage it (Scrap/Repair)?

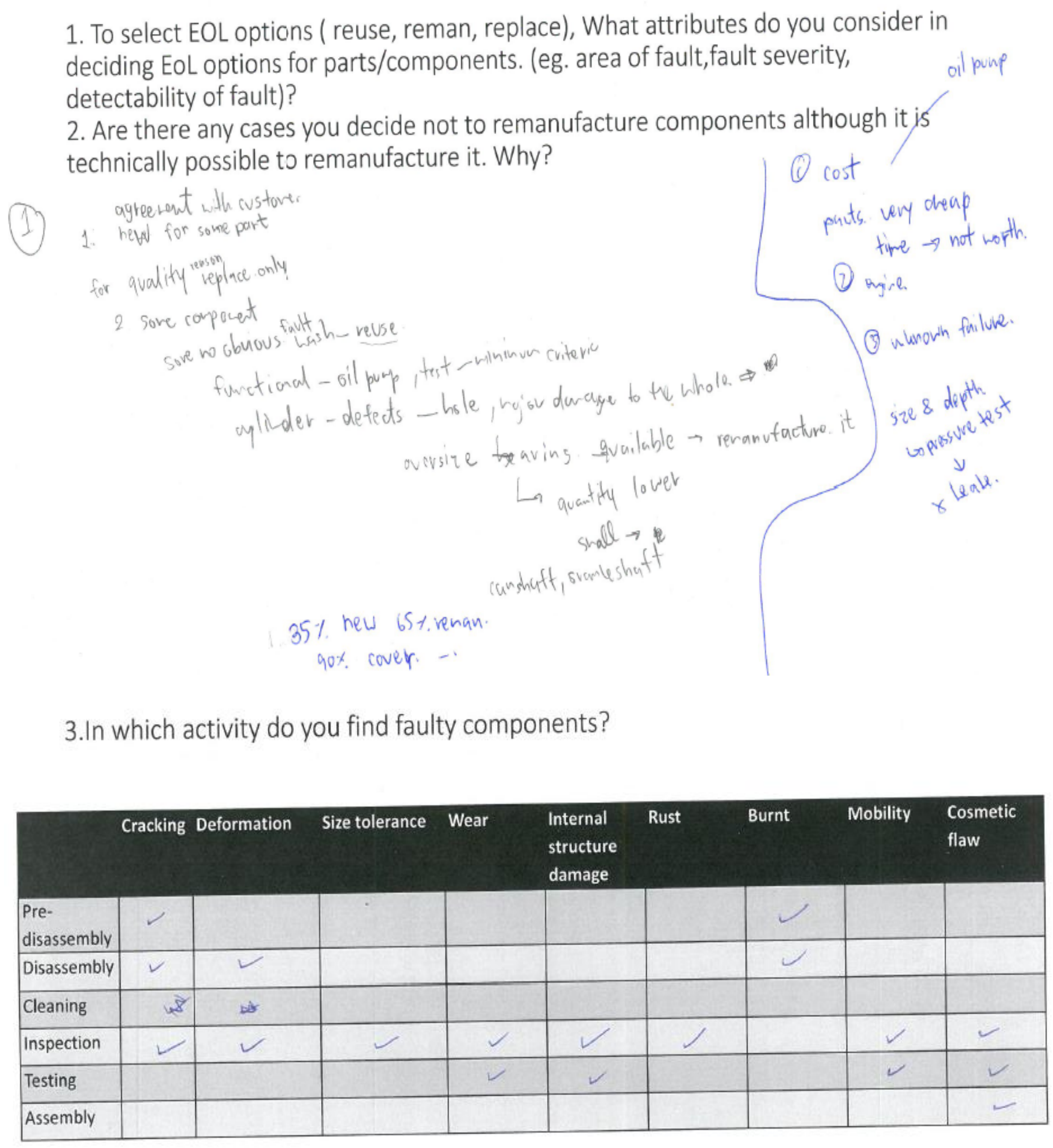
Failure	Company B (Contract remanufacturer who provides remanufactured engines)
Body damage	Unless there is serious damage to expensive parts, we will try to repair it first.
Mating part lost	Repair
Mixing with non-genuine parts or other models	N/A
Obsolete	Scrap
Cosmetic flaw	Repair
Material loss	If it is economically viable to use undersized/oversized parts, we will try to repair them first.
Undersized/oversized parts	
Weakened parts	Scrap
Overstock	Scrap it by agreement with customers that those products are no longer remanufactured

13. What do you do with scrap?

We sell scrap to the recycling centre.

Interview on Sep 2018 (With the manager)

Company General information
What percentage of your operation is?
___90__Made to order ___10__Made for stock ___Assembled to order



1. To select EOL options (reuse, reman, replace), What attributes do you consider in deciding EoL options for parts/components. (eg. area of fault,fault severity, detectability of fault)?

2. Are there any cases you decide not to remanufacture components although it is technically possible to remanufacture it. Why?

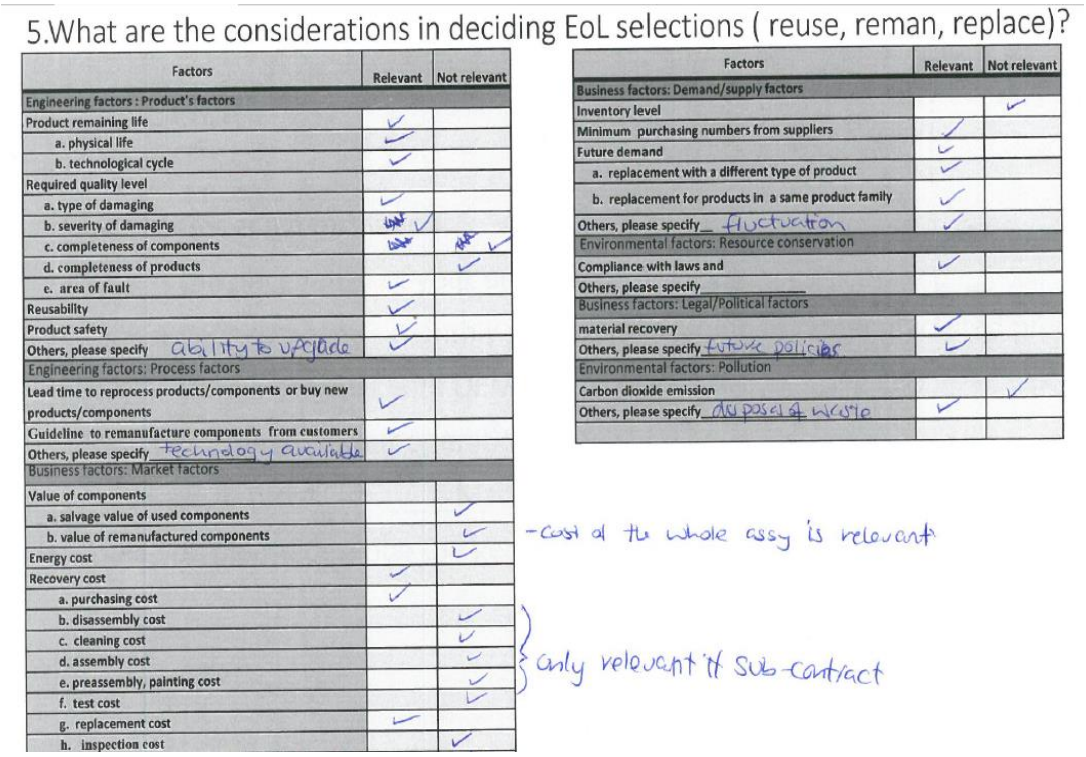
①
1. agreement with customer
new for some part
for quality reason replace only
2 some component
some no obvious fault wash – reuse
functional – oil pump, test – minimum criteria
cylinder – defects – hole, major damage to the whole ⇒ [illegible]
oversize ~~be~~earings available → remanufacture it
↳ quantity lower
small → [illegible]
camshaft, crankshaft

1. 35% new 65% reman.
90% cover. –

oil pump
① cost
parts. very cheap
time → not worth.
② engine.
③ unknown failure.
size & depth
↳ pressure test
↓
× leak.

3.In which activity do you find faulty components?

	Cracking	Deformation	Size tolerance	Wear	Internal structure damage	Rust	Burnt	Mobility	Cosmetic flaw
Pre-disassembly	✓						✓		
Disassembly	✓	✓					✓		
Cleaning									
Inspection	✓	✓	✓	✓	✓	✓		✓	✓
Testing				✓	✓			✓	✓
Assembly									✓



5.What are the considerations in deciding EoL selections (reuse, reman, replace)?

Factors	Relevant	Not relevant
Engineering factors : Product's factors		
Product remaining life	✓	
a. physical life	✓	
b. technological cycle	✓	
Required quality level		
a. type of damaging	✓	
b. severity of damaging	✓	
c. completeness of components		✓
d. completeness of products		✓
e. area of fault	✓	
Reusability	✓	
Product safety	✓	
Others, please specify ability to upgrade	✓	
Engineering factors: Process factors		
Lead time to reprocess products/components or buy new products/components	✓	
Guideline to remanufacture components from customers	✓	
Others, please specify technology available	✓	
Business factors: Market factors		
Value of components		
a. salvage value of used components		✓
b. value of remanufactured components		✓
Energy cost		✓
Recovery cost	✓	
a. purchasing cost	✓	
b. disassembly cost		✓
c. cleaning cost		✓
d. assembly cost		✓
e. preassembly, painting cost		✓
f. test cost		✓
g. replacement cost	✓	
h. inspection cost		✓

-cost of the whole assy is relevant

} only relevant if sub-contract

Factors	Relevant	Not relevant
Business factors: Demand/supply factors		
Inventory level		✓
Minimum purchasing numbers from suppliers	✓	
Future demand	✓	
a. replacement with a different type of product	✓	
b. replacement for products in a same product family	✓	
Others, please specify__ fluctuation	✓	
Environmental factors: Resource conservation		
Compliance with laws and	✓	
Others, please specify__________		
Business factors: Legal/Political factors		
material recovery	✓	
Others, please specify future policies	✓	
Environmental factors: Pollution		
Carbon dioxide emission		✓
Others, please specify disposal of waste	✓	

Crankshaft processing - generic for a "typical" 4 cylinder block

Operation - Grind	Time (mins)	Capacity / shift
C Degreasing wash	7.0	52
C Corrosion removal	11.0	33
C Wash	7.5	48
Inspection ✓	3.8	97
Crack detection	2.3	158
Grind mains ✓	10.0	36
Grind oil seal diameter ✓	2.9	128
Grind pins ✓	8.6	42
Deburr oilways ✓	0.4	914
Surface polishing ✓	4.9	74
Demagnetise	0.2	1589
C Solvent clean	2.3	162
C Final wash	2.5	146

Operation - Polish only	Time (mins)	Capacity / shift
Degreasing wash	7.0	52
Corrosion removal	11.0	33
Wash	7.5	48
Inspection	3.8	97
Crack detection	2.3	158
Polish mains	4.2	87
Polish oil seal diameter	2.3	162
Polish pins	3.8	97
Deburr oilways	0.4	914
Demagnetise	0.2	1589
Solvent clean	2.3	162
Final wash	2.5	146

Sakraan,

I have separated the washes as they use different machinery.

We do not separate the grinding time for mains or pins into individual journals but record it for the whole assembly.

If we are unable to grind the crankshaft and reduce the diameter of the mains and pins, we would usually polish the journals to recover the crankshaft. This option is captured in the second table.

In proactice the process capacity is limited by the longest operation but the washes take multiple components and so the bottleneck operation is grinding or polishing. We have several machines and can remove this bottleneck if required.

Hope this is helpful

Interview on Sep 2018 (with the production engineer)

General information about company

What is the price range for your products? 800 pounds

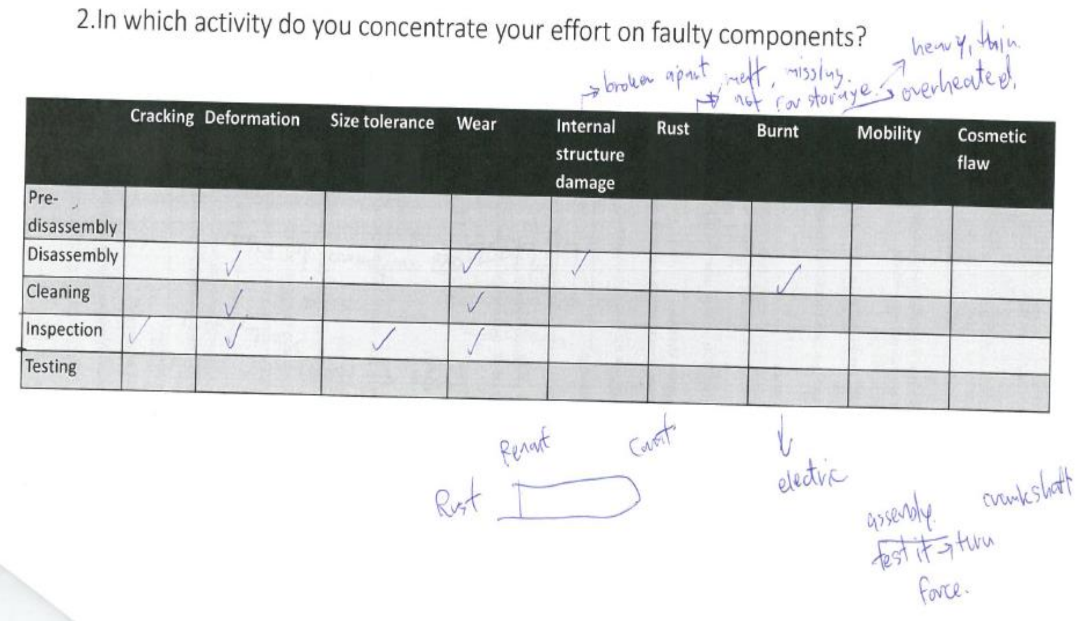
What is your company's monthly production volume of remanufactured products 1500 units / per month

1. To select EOL options (reuse, remain, replace), What attributes do you consider in deciding EOL options for parts/components. (e.g. area of fault, fault severity, detectability of fault)?

Normally, we remanufacture cylinder heads, camshafts, cylinder blocks, conrods, crankshafts, valves. We reuse gears after checking them. We replace seals and reuse covers.

Crankshafts with the following faults are remanufactured.

1. No cracks 2. No deformation 3. Bent - We will use a machine to recover if the components pass their assessment. 4. Wear at the pin of the crankshaft.



2.In which activity do you concentrate your effort on faulty components?

→ broken apart

melt, missing

→ not for storage

heavy, thin

overheated,

	Cracking	Deformation	Size tolerance	Wear	Internal structure damage	Rust	Burnt	Mobility	Cosmetic flaw
Pre-disassembly									
Disassembly		✓		✓	✓		✓		
Cleaning		✓		✓					
Inspection	✓	✓	✓	✓					
Testing									

Repaint

Coat

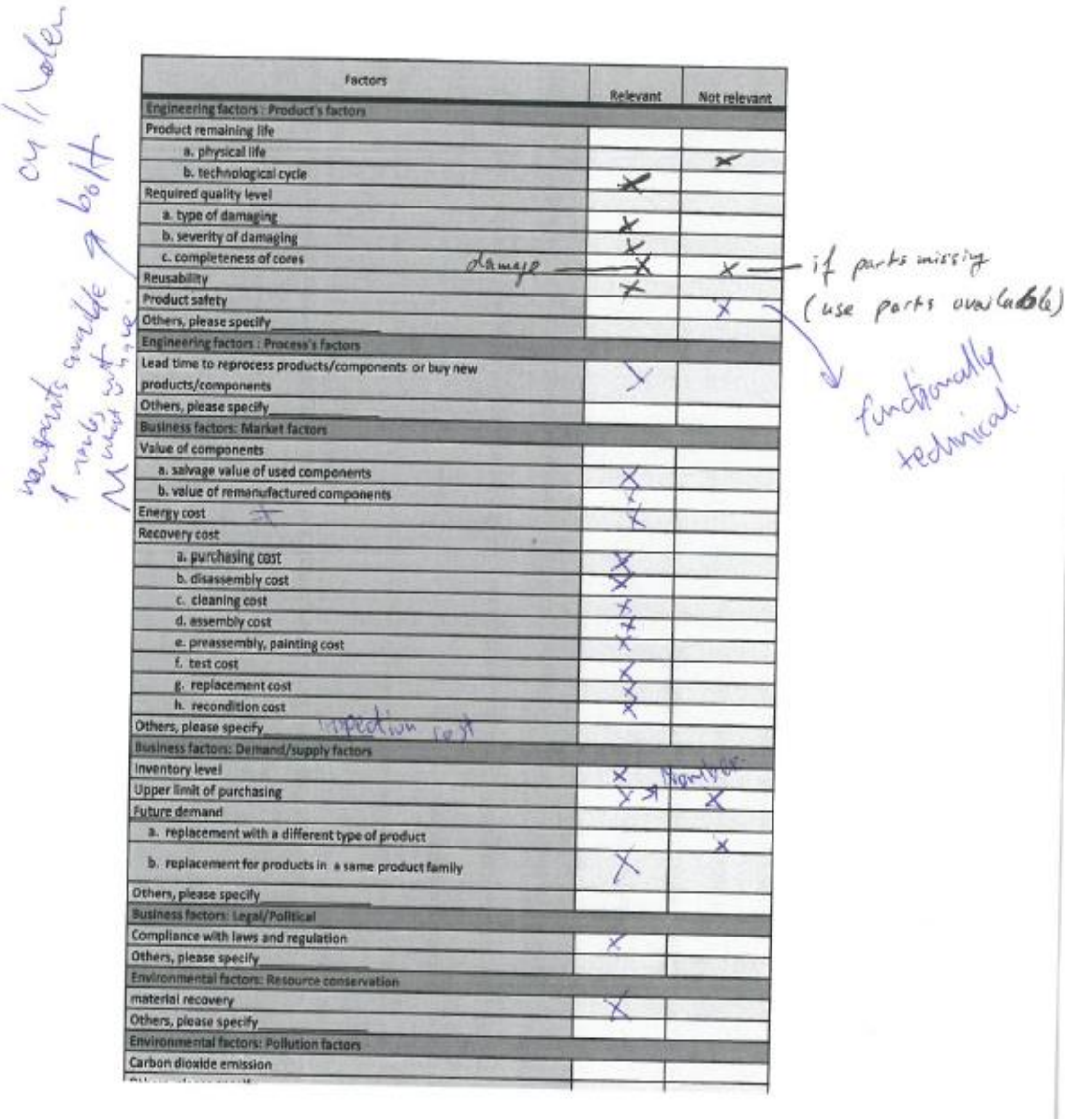
Rust

electric

assembly

crankshaft

test it → turn force.



cylinder

bolt

newparts available

[illegible]

Factors	Relevant	Not relevant
Engineering factors : Product's factors		
Product remaining life		
a. physical life		X
b. technological cycle	X	
Required quality level		
a. type of damaging	X	
b. severity of damaging	X	
c. completeness of cores	X	
Reusability damage	X	X if parts missing (use parts available)
Product safety	X	
Others, please specify		X functionally technical
Engineering factors : Process's factors		
Lead time to reprocess products/components or buy new products/components	X	
Others, please specify		
Business factors: Market factors		
Value of components		
a. salvage value of used components	X	
b. value of remanufactured components	X	
Energy cost	X	
Recovery cost		
a. purchasing cost	X	
b. disassembly cost	X	
c. cleaning cost	X	
d. assembly cost	X	
e. preassembly, painting cost	X	
f. test cost	X	
g. replacement cost	X	
h. recondition cost	X	
Others, please specify inspection cost		
Business factors: Demand/supply factors		
Inventory level	X	Number
Upper limit of purchasing	X →	X
Future demand		
a. replacement with a different type of product		X
b. replacement for products in a same product family	X	
Others, please specify		
Business factors: Legal/Political		
Compliance with laws and regulation	X	
Others, please specify		
Environmental factors: Resource conservation		
material recovery	X	
Others, please specify		
Environmental factors: Pollution factors		
Carbon dioxide emission		

Cylinder block

1. Which techniques are more preferable and why? (e.g. Safety, cost, time, the difficulty of a technique)

These three techniques are the same in terms of safety standards. However, they have some differences as follows.

1. PTWA
   It is a preferred technique since it can give a robust finish for all standard and all required number of products, but it is very expensive. We can charge customers more if we use this technique. The salvage value of the components shows it is worth remanufacturing rather than buying new components
2. Oversized bore with oversized piston
   This is the most straightforward technique with the cheapest technology; however, an oversized piston is not always available. For a large company like Ford, they may not have enough serviceable parts.

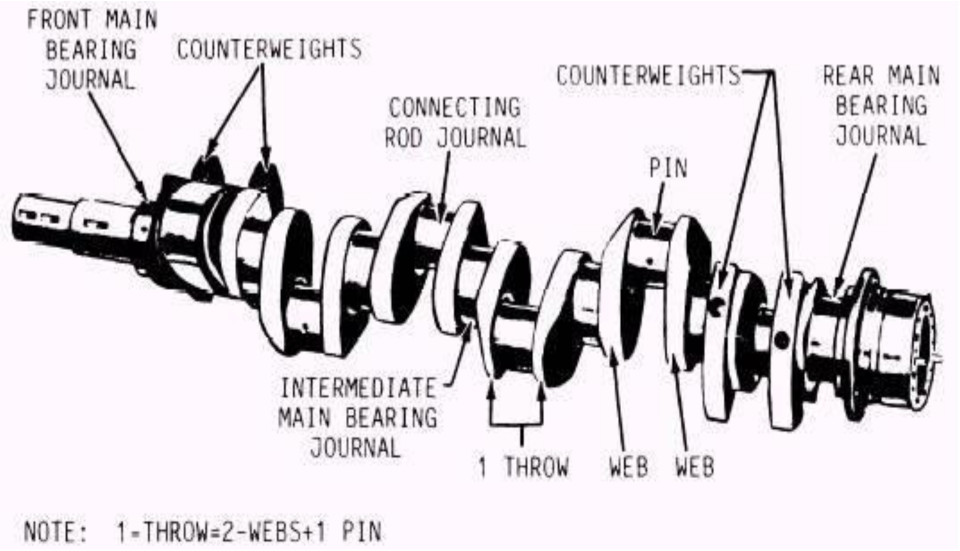
3. Oversized bore with liner
   This is the second most straightforward technique; however, liner with the required thickness is not always available.

Camshaft

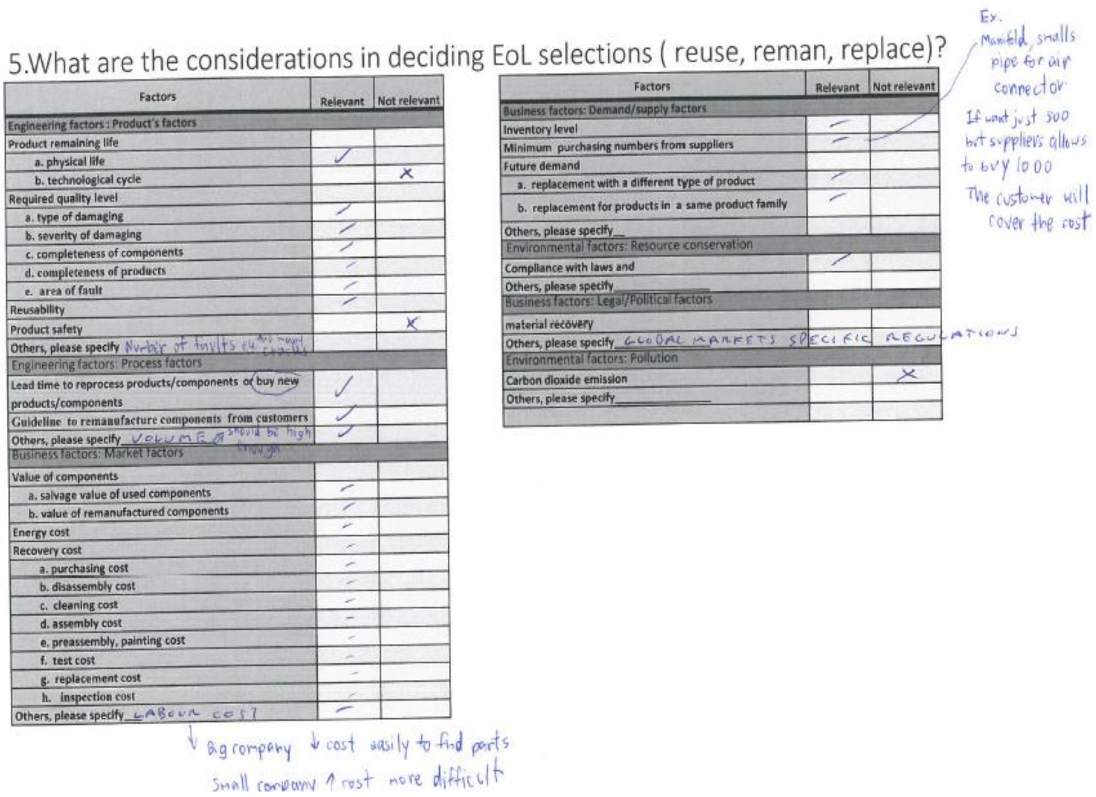
1. Why are camshafts with cracks, damage to sealing surfaces, mounting surfaces, thrust surfaces and threaded holes non-conforming?
Cracks are not acceptable because of safety concerns since the camshaft's journal will fail. Some types of damage can be repaired technically. If the new component is not too costly, and we need to recheck the hardness of a fixed component, we will decide to replace it.

2. Is additive manufacturing possible with cylinder surfaces and crankshafts?

It is possible on the bearing journal and the pin of crankshafts; however, this technique is not being used at the moment because we need to have an emission test although anyone else has tested it yet. The customer wants this test result from our company but it is costly. Also, damage to the webs and the counterweights is rare.



Interview in September 2018 (with the engineering director)



5.What are the considerations in deciding EoL selections (reuse, reman, replace)?

Factors	Relevant	Not relevant
Engineering factors : Product's factors		
Product remaining life		
a. physical life	✓	
b. technological cycle		✗
Required quality level		
a. type of damaging	✓	
b. severity of damaging	✓	
c. completeness of components	✓	
d. completeness of products	✓	
e. area of fault	✓	
Reusability	✓	
Product safety		✗
Others, please specify Number of faults [illegible] the money charged		
Engineering factors: Process factors		
Lead time to reprocess products/components or buy new products/components	✓	
Guideline to remanufacture components from customers	✓	
Others, please specify VOLUME ↗ should be high though	✓	
Business factors: Market factors		
Value of components		
a. salvage value of used components	✓	
b. value of remanufactured components	✓	
Energy cost	✓	
Recovery cost	✓	
a. purchasing cost	✓	
b. disassembly cost	✓	
c. cleaning cost	✓	
d. assembly cost	✓	
e. preassembly, painting cost	✓	
f. test cost	✓	
g. replacement cost	✓	
h. inspection cost	✓	
Others, please specify LABOUR COST	✓	

↓ Big company ↓ cost easily to find parts
Small company ↑ cost more difficult

Factors	Relevant	Not relevant
Business factors: Demand/supply factors		
Inventory level	✓	
Minimum purchasing numbers from suppliers	✓	
Future demand		
a. replacement with a different type of product	✓	
b. replacement for products in a same product family	✓	
Others, please specify		
Environmental factors: Resource conservation		
Compliance with laws and	✓	
Others, please specify		
Business factors: Legal/Political factors		
material recovery		
Others, please specify GLOBAL MARKETS SPECIFIC REGULATIONS		
Environmental factors: Pollution		
Carbon dioxide emission		✗
Others, please specify		

Ex.
Manifold, smalls pipe for air connector
If want just 500 but suppliers allows to buy 1000
The customer will cover the cost

Interview on September 2018 (with shop-floor staff)

Time spent on remanufacturing engine blocks

Task	Time spent per unit (minutes)
1. Disassemble	26
2. Inspect and recover damaged thread	23.5
3. Inspect cylinder wall	
4. Inspect and measure main bearing bores and cap alignment	
5. Clean cylinder wall	
6. Cylinder boring	11
7. Cylinder honing	28
8. Machine the block deck surface	
9. Machine after PTWA	
10. Install liner	5 to 15
11. PTWA	13
12. Final Cleaning	30 to 45

Appendix I C: Interview with Company C

Interview in May 2018 (with the manager)

Question set 2: Find the factors used in decision making for each process ; Find sequence of decision making

General information about the company

1. What is the price range for your products? 500-10000

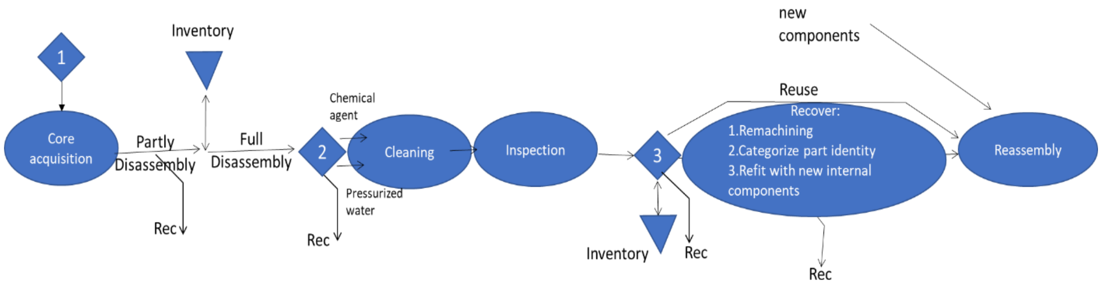
2. What is your company's monthly production volume of remanufactured products 16 units

3. What percentage of your operation is?

_____Made to order _5%___Made for stock _95%__Assembled to order

Material flow

1. Could you draw the material flow in the remanufacturing process



Remanufacturing process

1. Sources of components are repurchased components or cannibalised units to obtain parts. After receiving the order from customers, we disassemble products to find out what work is necessary and we estimate the costs. If customers decide not to proceed with the work anymore, then they have to pay for the costs of stripping down.

2. Visual inspection - We decide on the level of disassembly depending on the quality of the cores. If the cores are good enough, we will disassemble the cores fully.

3.Cleaning or salvage - If we find any of the disassembled components are too worn, we scrap them. Deep cleaning and degreasing can remove oil carbonization by sand blasting

4. Inspection - We decide on its suitability based on the specifications.

We measure the size and surface finishing. The size affects the product design and the surfaces affect the surface treatment technique.

5. Select suitable EOL options (Repair/reuse/replace components)

- Replace without disassembly: bearings, gaskets, sealed oil pumps, water pumps, rubbers, sealed points, some types of nuts and bolts

- Cleaning and reuse: engine case

- Repair: moving parts

Recovery method

1. Machine components to OEM specifications (flat, straight, round): Regrind crankshaft, Rebore cylinder block to change its size

2. Categorise components according to their exact application (find out the identification numbers of the components) e.g. conrod from Volvo 1995

3. Refit new internal components where necessary. For example, we refit crankshafts, cylinder blocks with valve guides

Exception: If the cylinder head, block or crankshaft are cracked or have disappeared, the company charges customers extra costs.

2. What are the advantages and disadvantages of the current layout?

Advantage - Suitable components are selected depending on the condition of the engine.

Disadvantage - We need to know the condition of components before making further decisions.

This can be improved by making a quicker decision through integrated decision making and training staffs about testing equipment.

3. Is there any point in the process which limits the flow of the materials (e.g. lead time, bottlenecks)?

1. It is always time-consuming to categorise cores as good or bad depending on the OEM specifications.

The solution is that we need to buy new parts before we find the information after inspecting the engines.

2. There are various techniques for cleaning.

4. Is it a sequential process (every part of the core in the same carrier is waiting for the next process) or parallel process (each part is remanufactured separately) in handling the materials?

We wash all the components together. Each part is remanufactured separately in a dedicated area for specific jobs.

5. Is there a single inventory point for returned cores, reusable/recyclable, reprocessed, new components?

We have two inventory points - 1. inventory of the core and 2. inventory of disassembled components

A computer system shows what components we have to produce. However, the system does not show the separate types of components (reusable/recyclable, reprocessed, new components) because it is not worth creating such a database.

However, we store reprocessed, reused and recycled components separately.

Planning

1. Do you estimate the quantities of returned cores from the historical data?

No, because we only sell a small number of the products, but it would be good if we could buy specific models of cores.

2. How do you plan the scheduling of timing and quantity in these processes

Most assembly guides show each engine takes three days to finish. The remanufacturer builds up data of the average time taken for the operations.

3. In which process do you consider component commonality in your decision making?

The same engine uses the same internal components. The common components are conrods, guide valves, and bearing journals. For example, 6 cylinder engines have the same components but may have different numbers of bearing journals. Different engines have the same number of bearing journals with different lengths of the crankshafts.

Pistons - If they are not the right size, we wait to fit a piston from another engine

Conrods - OEM may not inform remanufacturers which components can be used in different engines but remanufacturers can share this database among the group members of remanufacturers (FER).

4. How do you manage component commonality to maximize reusability?

MRP (material requirement planning)

Decision making

1. How can you decide on the number of cores to be disassembled?

Previous sales

2 How can you decide on the level of disassembly (no disassembly, partial disassembly, full disassembly) of products?

1. Visual inspection - We strip the core and salvage cores/components. If we find severe damage, we do not need to disassemble further.

3. How do you decide what to do with disassembled products?

Our decisions are based on our experience in selecting end-of-life options.

4. How do you decide which components should be reused, reprocessed or whether new components should be reassembled to make a new product?

1. Usual practice

Some components are always recovered by these methods.

1.1 Cleaning and reusing: outer components of cylinder head covers, intake manifolds, oil pan gaskets, and exhaust manifolds

1.2 Recovering: cylinder heads, cylinder blocks and crankshafts

1.3 New components: pistons, bushing, bearings, timing chain tension, water pumps, oil pumps, gaskets, seal fasteners

2. To decide to recover components or buy new components, we consider quality, price, availability, equipment/techniques necessary for the recovering

5. How can you order new/used components when considering lead time?

We consider the cost-effectiveness of using used cores before new ones.

If a customer cannot wait for two weeks, we will do other things such as purchasing new orders rather than recovering used components

6 How do you decide to buy new components instead of reprocessing used components?

Due to the metal fatigue of used products, we use new components before recoveringused components by considering the residual life of the components. If the working environment of products is extreme such as marine, critical areas, fire engines, we use new components. We use used components for milder working environments such as dusty areas.

Other topics

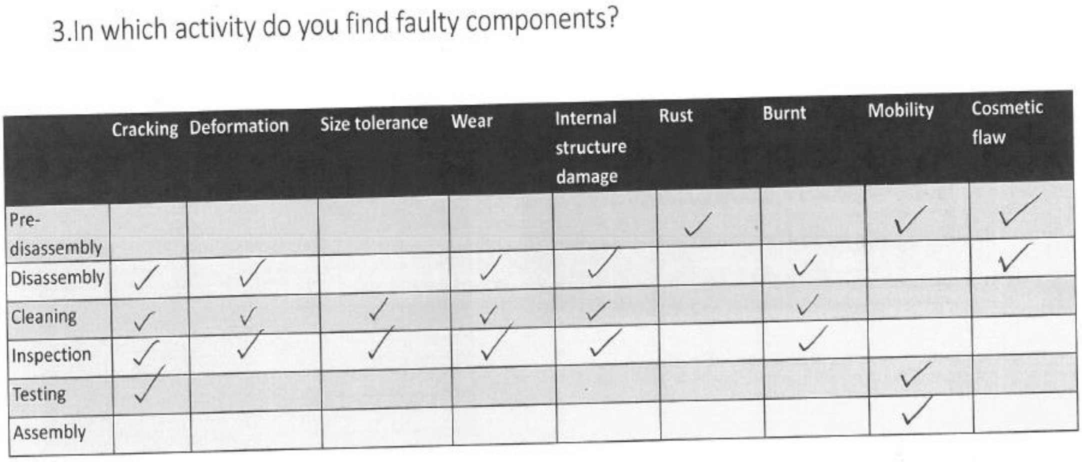
1. There are two cleaning methods: using a chemical agent and using pressurized water

1.1 glass bead blasting with pressurized water is a non-destructive method which does not change the dimensions. For example, cylinder blocks and heads are two components which are cleaned by this method. Aggressive methods (such as using silicon carbide) can change dimensions.

1.2 Alkaline detergents do not change the dimensions but there are cleaning costs when using a chemical agent.

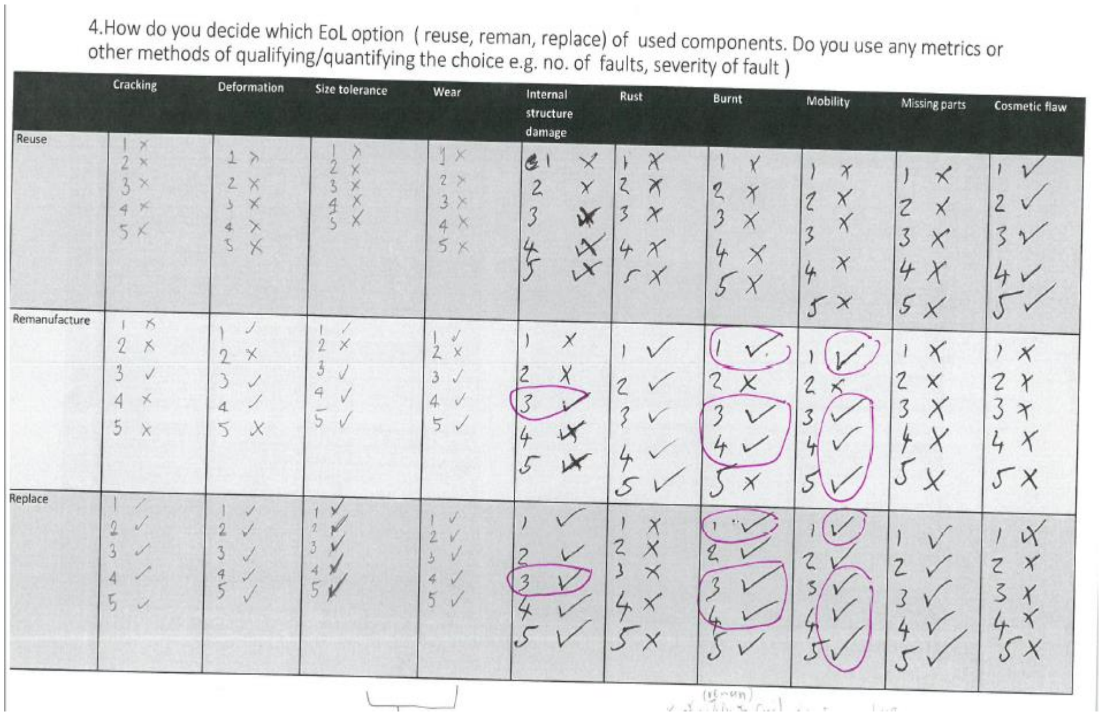
2. Unavailability of products and components is not a serious issue since we can obtain them within 2 days.

3. If a customer wants products with a lower warranty, we will sell them at a cheaper price.



3.In which activity do you find faulty components?

	Cracking	Deformation	Size tolerance	Wear	Internal structure damage	Rust	Burnt	Mobility	Cosmetic flaw
Pre-disassembly						✓		✓	✓
Disassembly	✓	✓		✓	✓		✓		✓
Cleaning	✓	✓	✓	✓	✓		✓		
Inspection	✓	✓	✓	✓	✓		✓		
Testing	✓							✓	
Assembly								✓	



4.How do you decide which EoL option (reuse, reman, replace) of used components. Do you use any metrics or other methods of qualifying/quantifying the choice e.g. no. of faults, severity of fault)

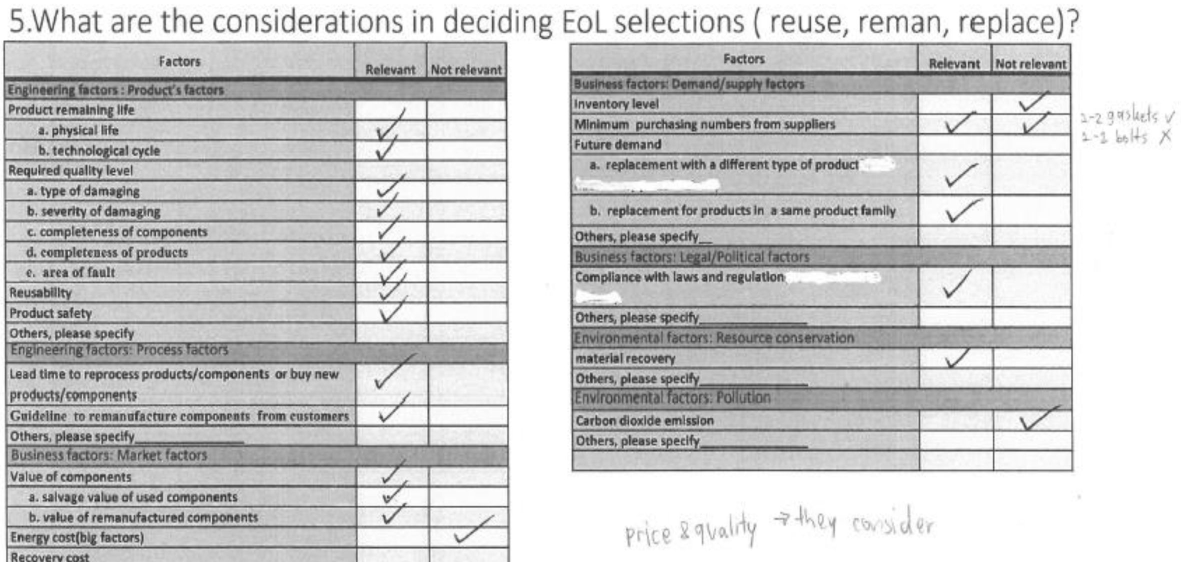
	Cracking	Deformation	Size tolerance	Wear	Internal structure damage	Rust	Burnt	Mobility	Missing parts	Cosmetic flaw
Reuse	1 ✗ 2 ✗ 3 ✗ 4 ✗ 5 ✗	1 ✗ 2 ✗ 3 ✗ 4 ✗ 5 ✗	1 ✗ 2 ✗ 3 ✗ 4 ✗ 5 ✗	1 ✗ 2 ✗ 3 ✗ 4 ✗ 5 ✗	1 ✗ 2 ✗ 3 ✗ 4 ✗ 5 ✗	1 ✗ 2 ✗ 3 ✗ 4 ✗ 5 ✗	1 ✗ 2 ✗ 3 ✗ 4 ✗ 5 ✗	1 ✗ 2 ✗ 3 ✗ 4 ✗ 5 ✗	1 ✗ 2 ✗ 3 ✗ 4 ✗ 5 ✗	1 ✓ 2 ✓ 3 ✓ 4 ✓ 5 ✓
Remanufacture	1 ✗ 2 ✗ 3 ✓ 4 ✗ 5 ✗	1 ✓ 2 ✗ 3 ✓ 4 ✓ 5 ✗	1 ✓ 2 ✗ 3 ✓ 4 ✓ 5 ✓	1 ✓ 2 ✗ 3 ✓ 4 ✓ 5 ✓	1 ✗ 2 ✗ 3 ✓ 4 ✗ 5 ✗	1 ✓ 2 ✓ 3 ✓ 4 ✓ 5 ✓	1 ✓ 2 ✗ 3 ✓ 4 ✓ 5 ✗	1 ✓ 2 ✗ 3 ✓ 4 ✓ 5 ✓	1 ✗ 2 ✗ 3 ✗ 4 ✗ 5 ✗	1 ✗ 2 ✗ 3 ✗ 4 ✗ 5 ✗
Replace	1 ✓ 2 ✓ 3 ✓ 4 ✓ 5 ✓	1 ✓ 2 ✓ 3 ✓ 4 ✓ 5 ✓	1 ✓ 2 ✓ 3 ✓ 4 ✓ 5 ✓	1 ✓ 2 ✓ 3 ✓ 4 ✓ 5 ✓	1 ✓ 2 ✓ 3 ✓ 4 ✓ 5 ✓	1 ✗ 2 ✗ 3 ✗ 4 ✗ 5 ✗	1 ✓ 2 ✓ 3 ✓ 4 ✓ 5 ✓	1 ✓ 2 ✓ 3 ✓ 4 ✓ 5 ✓	1 ✓ 2 ✓ 3 ✓ 4 ✓ 5 ✓	1 ✗ 2 ✗ 3 ✗ 4 ✗ 5 ✗

Engine Repair

	component	crack	Size dimension			Deformation			Wear			
			What is inspected?	Degree of fault that are remanufacturable	Recovery method	What is inspected?	Degree of fault that are remanufacturable	Recovery Method	What is inspected?	Degree of fault that are remanufacturable	Recovery Method	
1	**Cylinder head**	replace	~~Bore of cylinder~~ - Gasket face - Valve & guides - water jacket - ports.	Compression ratio?	Remachine, piston0.015-0.020 inch shorter than usual to avoid raising the compressing ratio beyond stock rating Valve heights have to be taken into consideration.	check in multiple planes by feeler gauge under a straightedge held against the head surface	Guided by OEM	1. replace if it ismanufacturing specification incl. all [illegible] bolt ~~2. machine for resurfacing& use shorter piston prevent increasing the compression ratio~~ Resurface Gasket face [illegible] replace first [illegible] certain that you [illegible] not being [illegible] back	Wear on valve guide and valve seat? Rocker Assy. sealing	Guided by OEM gasket sealing rings & damage within [illegible] should be [illegible] thickness of cylinder head [illegible]	Valve guide- replace and use oversized valve if possible, otherwise knurl valve guide(not exceed ~~0.005 inch~~ 0.002") Valve seat- try to recover it first by grounding to match the valve (need to recover valve guide before) , if it is not possible to recover then replace,	
2	**Camshaft** remanufacture for commercial but possible for racing cars	replace	check size of journal and lobes for three dimension for taper and outround	thick liner	 expensive may be buy a new one No matter what, don't remanufacture camshaft	*Straightness on journals, lobes and skew gear* Alignment i.e. bend.		*Cam lobes should be reprofiled or* *Replace new camshaft*	Wear on camshaft(Where of camshaft?)		If the outer hardness wears off, weld the lobes The lobes and journals are grounded to proper size, 1.cast iron- then recoat with phosphate coating) 2.steel camshafts-hardening involve heating the camshaft)	time, cost replace because [illegible] economically viable trucks may be possible economic to [illegible] but for general engine → NO
3	Engine block	replace Repair if possible	Bore of engine block water jacket Gasket face Mains Camshaft bearings	not found in bottom of bore, gov. of circumference - if this pic, Yes	~~Remachine, piston0.015-0.020 inch shorter than~~ usual to avoid raising the compressing ratio beyond stock rating, threaded hole repair by tapping and cleaning Resurface gasket face Machine cylinders to 0.010" or 0.020"	surface warpage The level of the deck of a block is measured by straight-edge and a feeler gauge in six places(p.401)	Guided by OEM [illegible]	recover by surface finishing (402) Reboreing. Honing.	Most wear will be found below the ridge. The least amount of wear will occur below the lowest ring travel(402):	Max 0.003 inch out-of round, no more than 0.005 inch taper, no deep scratches in the cylinder wall size, quality	rebore and hone the cylinder with new oversize piston(depends on cylinder wal *overbore=> leads to structural weakness * minimum amount for honing is 0.002 inch	
4	Crankshaft	replaced	Measure out-of-round and taper of every 120degrees of journal, Then,compare with factory satisfaction	Max. regrind 0.020"	machining if necessary go beyond this → reharden or change the structure hardness of journal → if more than this the crankshaft → twist	~~bend and warpage~~ Alignment. twist Size.	1.slightly bent(How can you know) measure 2.Excessive deform → on V-blocks	1.grinding+ further check for surface finishing Polish 2.otherwise replaced if it can break *3.be straightened depend on material+ further crack detection*	scored bearing journals by fingernail catch on a groove Journal=> out-of-round or taper [illegible]	size, quality Guided by OEM	reground to undersize crankshaft reground to undersize Polish.	
5	Connecting rod	replace	The parting surface of the rod and cap should be smooth. or Crack Cap? *Check size and quality of big end bearing housing* alignment *Small end bushes: bush clearance*	except cradle cap which may replace	Grind the surface of rod and rod cap(reduce bore size 0.003 to 0.006 inch)(not compatible with powdered metal connecting rod), Install cap on the rod. Then,The hole is bored or honed to perfectly round. The inside of bore at the big end should have a 60-90 microinch finish for proper bearing contact and heat transfer *Resized* *Renewed and remachoned*	Check rod twist by using fixture to check for twist. The hole at the small end and the hole at the big end should be parallel *Stretch/damage*	~~no more than 0.002 inch twist is acceptable~~ No twist	~~1.recover by parting surfaces and bending the rod cold(cast and forged)~~ ~~2.or replace(powdered metal). (surface treatment affect compression ratio very little)~~ *replace*	Journals Mains & Big ends for Size.	Guided by OEM - size, tolerance quality, running surface quality	~~Regrind & Polish~~ ~~Regrind & Polish~~	

≯ 100 - replace
≮ 1000 - recover if again possible they can bend again

one sight - crankshaft from center



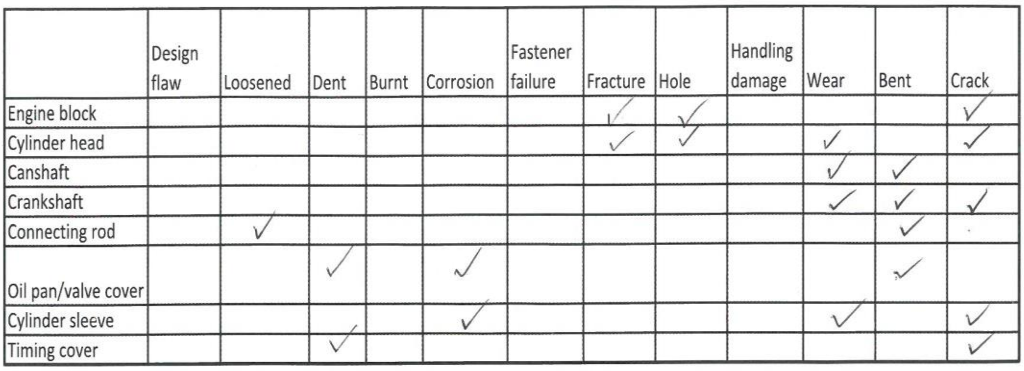
5.What are the considerations in deciding EoL selections (reuse, reman, replace)?

Factors	Relevant	Not relevant
Engineering factors : Product's factors		
Product remaining life		
a. physical life	✓	
b. technological cycle	✓	
Required quality level		
a. type of damaging	✓	
b. severity of damaging	✓	
c. completeness of components	✓	
d. completeness of products	✓	
e. area of fault	✓	
Reusability	✓	
Product safety	✓	
Others, please specify		
Engineering factors: Process factors		
Lead time to reprocess products/components or buy new products/components	✓	
Guideline to remanufacture components from customers	✓	
Others, please specify_______________		
Business factors: Market factors		
Value of components	✓	
a. salvage value of used components	✓	
b. value of remanufactured components	✓	
Energy cost(big factors)		✓
Recovery cost		
a. purchasing cost	✓	
b. disassembly cost	✓	
c. cleaning cost	✓	
d. assembly cost	✓	
e. preassembly, painting cost	✓	
f. test cost	✓	
g. replacement cost	✓	
h. recovery cost		
i. inspection cost	✓	
Others, please specify___		

Factors	Relevant	Not relevant
Business factors: Demand/supply factors		
Inventory level		✓
Minimum purchasing numbers from suppliers	✓	✓
Future demand		
a. replacement with a different type of product [redacted]	✓	
b. replacement for products in a same product family	✓	
Others, please specify__		
Business factors: Legal/Political factors		
Compliance with laws and regulation [redacted]	✓	
Others, please specify_______________		
Environmental factors: Resource conservation		
material recovery	✓	
Others, please specify_______________		
Environmental factors: Pollution		
Carbon dioxide emission		✓
Others, please specify_______________		

1-2 gaskets ✓
1-1 bolts X

price & quality → they consider



	Design flaw	Loosened	Dent	Burnt	Corrosion	Fastener failure	Fracture	Hole	Handling damage	Wear	Bent	Crack
Engine block							✓	✓				✓
Cylinder head							✓	✓		✓		✓
Canshaft										✓	✓	
Crankshaft										✓	✓	✓
Connecting rod		✓									✓	
Oil pan/valve cover			✓		✓						✓	
Cylinder sleeve					✓					✓		✓
Timing cover			✓									✓

Interview in June 2018 (with the director)

Question set 2: Find the factors used in decision making for each process and find out the sequence of decisions

Company General information

1 What is the price range for your products? £.1,300 small engine – £ 20,000 engine for trucks, excavators, plants)

2 What is your company's monthly production volume of remanufactured products 16 units

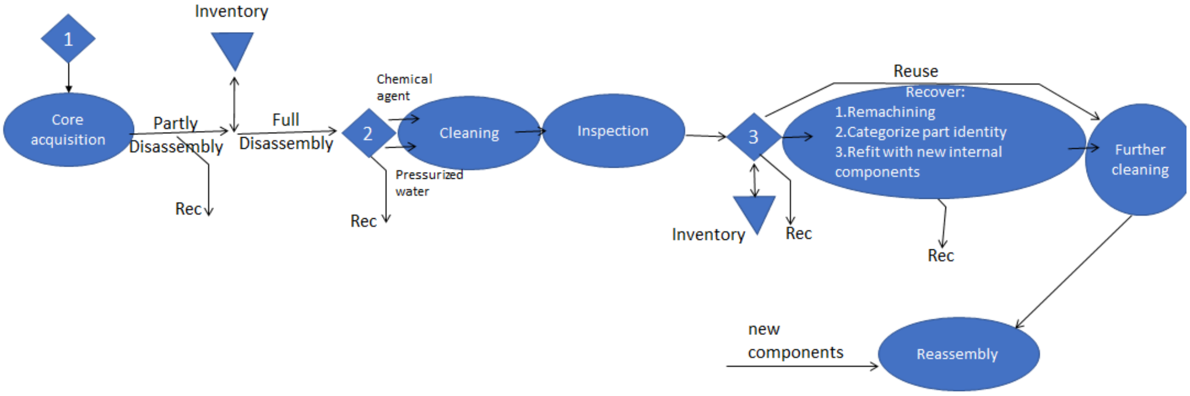
3 What percentage of your operation is?

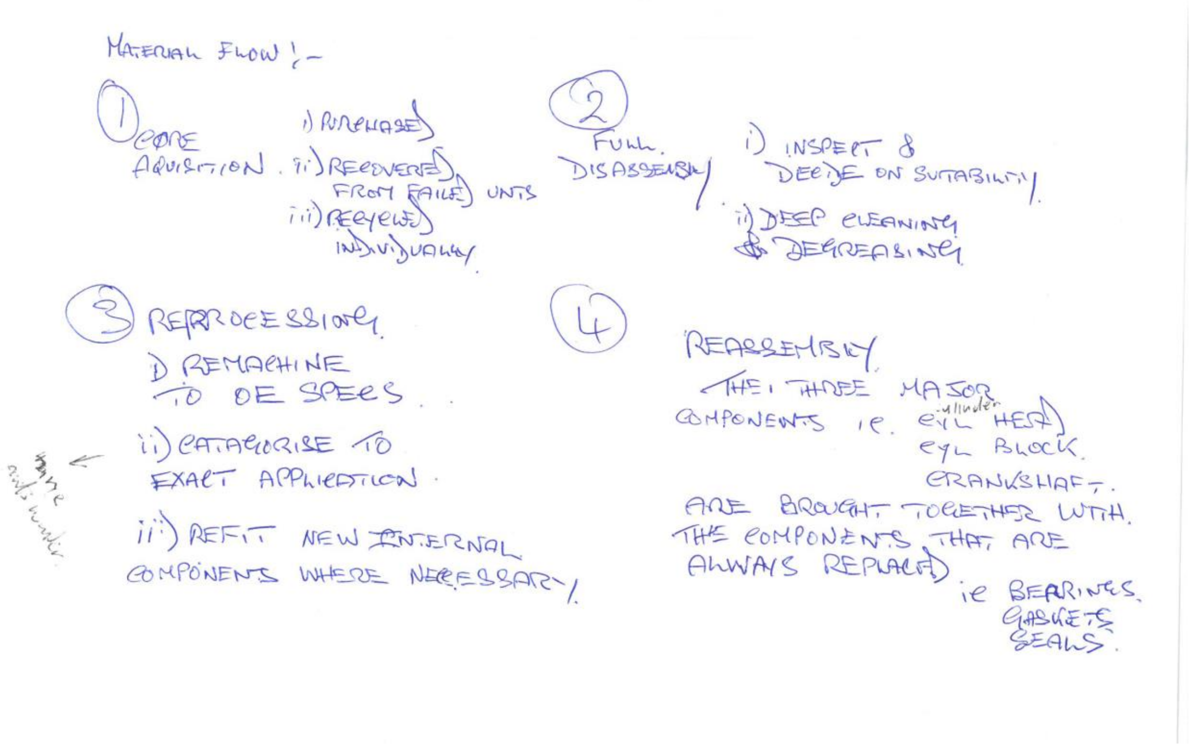
_____Made to order _10%___Made for stock _90%__Assembled to order

We need 50% for stock and 50% for the order. Since we have 5-6 staff, we need to complete orders faster. We spend two to three weeks on each engine. We spend 2-3 days to remove an engine from a vehicle, one day to dismantle the engine, one week for cleaning and recovery, 4 days for the assembly process and 2-3 days for testing equipment and returning the engine to its original vehicle.

Flow of Materials

1. Could you draw the flow of materials in the remanufacturing process?





MATERIAL FLOW :-

① CORE AQUISITION.
i) PURCHASED
ii) RECOVERED FROM FAILED UNITS
iii) RECYCLED INDIVIDUALLY.

② FULL DISASSEMBLY.
i) INSPECT & DECIDE ON SUITABILITY.
ii) DEEP CLEANING & DEGREASING.

③ REPROCESSING.
i) REMACHINE TO OE SPECS.
ii) CATAGORISE TO EXACT APPLICATION.
iii) REFIT NEW INTERNAL COMPONENTS WHERE NECESSARY.

[illegible]

④ REASSEMBLY.
THE THREE MAJOR COMPONENTS i.e. CYL HEAD (cylinder)
CYL BLOCK.
CRANKSHAFT.
ARE BROUGHT TOGETHER WITH THE COMPONENTS THAT ARE ALWAYS REPLACED ie BEARINGS.
GASKETS
SEALS.

To improve the process, there should be a cleaning process before disassembly. When we start to dismantle the engine, there is an increase in dirt. When it is not worth recovering some components, such as cylinder heads, we buy a new used component of a high quality and machine it. We do not carry out additive manufacturing for those components that are extremely worn.

2. Is there any point in the process which limits the flow of the materials (e.g. lead time, bottlenecks)?

After inspection, we have to wait for a customer to decide on what to do after the inspection, which depends on the costs and the budget.

3. Is it a sequential process (every part of the core in the same carrier waiting for the next step in the process) or a parallel process (each part is remanufactured separately) in the handling of the materials?

We wash all the components together. Each part is remanufactured separately and simultaneously in an area assigned for a specific job, and every part is then reassembled at the same point.

4. Is there a single inventory point for returned cores, reusable/recyclable, reprocessed, and new components?

We have two inventory points: 1. inventory of cores and 2. inventory of disassembled parts.

Planning

1. Do you estimate the number of returned cores from the historical data?

We do not have a system to monitor the returned cores since we only remanufacture a small number of products. We know which models are most popular from our experience. We can predict the costs, required parts and lead time for the remanufacturing process.

We believe it would be better to have someone to manage stock properly; however, we are a small company, so we need to think about labour costs, and another problem is that the existing computer programmes do not match our manual.

2. In which process do you consider component commonality in the decision making?

We consider component commonality in pricing and planning for materials. In the planning for materials, we know what components we can reuse, repair or replace. For example, we always replace timing chains, oil pumps, water pumps and pistons.

3. How do you manage component commonality to maximize reusability?

We do not have a computer system to deal with this. We rely on our experience to know what components we need.

4. How do you manage complex components?

We use a simple list of what main parts are required. After inspection, we know what type of components we need in detail. Then, we write a job sheet.

In our job sheet, we show a customer’s problem, a list of parts and suppliers, and what jobs need to be done.

For example, we do not use a computer system to manage all the components. We record only the financial information such as the costs for which we need to know more details.

We group components used for the same brand of engine in the same cage. If we can find the required components from cannibalised cores in our store, we clean and inspect components before use.

So, we know roughly what we have and what we need from suppliers. Then, our suppliers bring what we need the next day.

Decision making

1. How do you know how many cores you need to acquire?

We order one piece of the core when remanufacturing a product. We consider factors such as time and costs.

2. How do you decide on the number of cores to be disassembled?

We disassemble the number of cores when they are needed.

3. How do you decide on the level of disassembly (no disassembly, partial disassembly, full disassembly of products)?

Partial disassembly means to disassemble a group of attached components e.g. (the group including the timing cover and crankshaft).

To disassemble the product fully, we usually take approximately 1-6 hours depending on the size of the engine.

However, we can disassemble partially in 2 particular cases.

1. If customers want to repair only some parts depending on their budget, we can do this for them.

2. If we find usable parts from a cannibalized core and these components are easy to remove, such as ancillary parts, alternators, turbos, EGR, oil coolers, and cylinder heads, we can inspect, test and return these parts easily.

4. How do you decide what to do with disassembled products?

This depends on serviceability and size tolerance

5. How do you decide on cleaning in the remanufacturing process?

Some customers have their own specific solutions (e.g. cleaning with ultrasonic sound). If there are no specific methods, we choose the best way to obtain spotless cleaning before assembly. It is more time-consuming and requires more chemical agents to remove carbon from the cylinder head, oil from the manifold and EGR. To remove dirt from the inner cavities, we use gas to burn carbon, blasting or jet washing. We clean components twice. The first time we remove grease and oil. There are several cleaning methods used for this, including ultrasonic sound, stream jet wash and chemical agents. We find cleaning engines by using stream jet wash is the best. Therefore, currently, we use a chemical agent with a stream jet wash. The second time, the cleaning is carried out by a human worker after the machining process since disassembly can result in large amounts of metal which need to be cleaned before further processing.

To select the cleaning method:

It is efficient to use a chemical agent on steel, iron and cast iron. An abrasive water jet can affect surfaces severely which means we have to improve the surface of the component. Some chemical agents can also melt aluminium.

We will use a small amount of milder chemicals to see what happens. We will then try using other chemicals with a brush and spray water after that. If the chemical agents are not effective, we will use a stronger chemical agent, hot water, and spend more time and use more chemical agents. If we find any of these methods are not effective, we will not use them again.

First of all, we clean the components to ensure that they will be serviceable in the end. We try to avoid the effects of using too strong chemicals (e.g. strong chemicals can burn away seals) since it will cost us more money in the long run. We will make a decision based on 50% costs, 30% cleanliness and 20% adverse effects.

6. How can you decide which components to reassemble into your final product (reused, reprocessed or new components)?

This decision depends on the manual specifications and our experience in whether we should repair or not.

7. How can you order new/used components by considering the lead time?

We base our decision on the budget and the amount of time needed.

8. How do you decide to buy new components instead of reprocessing components?

We will buy new components if it is more economical than reworking components.

Other topics

We are a diesel engine remanufacturer. Our services are dismantling, reassembly, machining, testing, and returning engines to customers. Some tasks costs 40 pounds. We usually produce 3-4 engine units for trucks, buses, generators and plants per month. One person is responsible for everything in remanufacturing a particular engine.

Appendix I D: Interview with Company D

Interview in April 2017 with the director

Question set 2: Find the factors used in making decisions for each process and find out the sequence of the decisions

General information about Company

1. What is the price range for your products? torque converter (£150 - £450); transmission (£800 - £3000)

2. What is your company’s monthly production volume of remanufactured products

Torque converter (300), transmission (100)

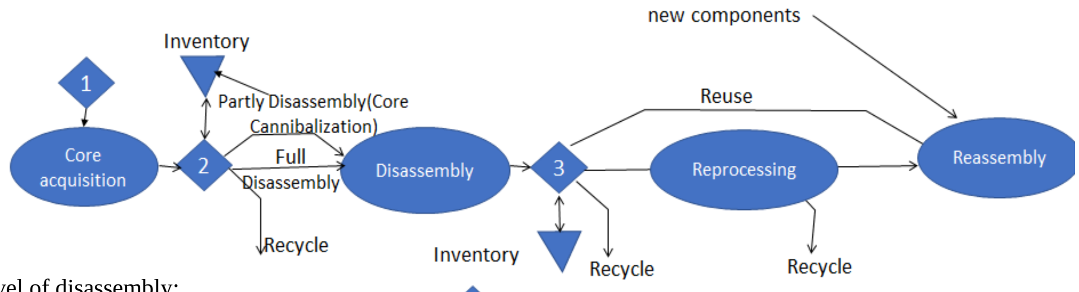
3 What percentage of your operation is?

__60___Made to order __30__Made for stock _10__Assembled to order

Flow of Materials

1. Could you draw the flow of materials in the remanufacturing process

1 Core acquisition: type of cores, quantity of cores



2 Level of disassembly:

No disassembly,

Full disassembly,

Partial disassembly

3 What are the steps in the disassembly of components?

-inventory, recycle, reprocess or reuse

Which components are used for reassembly?

-New, reprocessed or reused components

1. Firstly, we partially disassemble products to see how much excessive damage there is. We check valve bodies for heat damage. If the valve bodies are too burnt, they can cause metal contamination.

2. We stock used cores but we do not stock disassembled components. We only have inventories for new and remanufactured components.

2. Is there any point in the process which limits the flow of materials (e.g. lead time, bottlenecks)?

The disassembly process limits the flow of materials because we have to decide whether to scrap products/components.

3. Is it a sequential process (every part of the core is in the same carrier waiting for the next step in the process) or a parallel process (each part is remanufactured separately) in handling the materials

All parts are remanufactured together except for valve bodies and torque converters for which we have a zone allocated for them because torque converters require specific skills and different test procedures. At the end, we put all the components together for assembly and conduct a final testing.

Planning

1. Do you estimate the number of returned cores from the historical data?

No, but we have information about the returned cores. 99 % of them are returned. We focus on being able to sell these products. If there is a high demand for specific cores and we do not have enough of them in the inventory, we can call customers to return them immediately.

2. How do you plan the schedule for timing and the quantity in these processes?

We usually sell one core to a customer and it is returned to us later. 99% of the cores sold are returned. If we sell products to America, it is not feasible to have the cores returned. Therefore, we will charge customers instead. Sometimes there is not sufficient time to wait for the core to be returned so then we sell the products locally.

Decision making

1. How do you decide on the number of cores to be disassembled?

Our system shows the minimum and maximum numbers of cores to be disassembled based on previous sales. The number of cores change every day.

2. How do you decide on the level of disassembly (no disassembly, partial disassembly, full disassembly of products)?

We can measure the level of disassembly by quality.

1. We use visual inspection.
2. We partially disassemble products.
   If the valve body is too burnt or there is contamination of the valve body, then we reject the cores. This only accounts for 10% of all cases. Usually, 90% of cores are fully disassembled. If there are enough cores, we scrap the bad ones. If there are not enough cores, we accept the bad ones and recover them.

3. How do you decide on what to do with disassembled products?

Selecting EOL options depends on common practice by considering the residual life of products.

- A soft core which always wears out through time is 100% replaced.

- For hard parts, components are examined and measured. If they are within the standards, then they are reused.

- 90% of outer cases and 80-90% of clutches are cleaned and reused, 10% of outer cases and clutches are replaced because they are too worn (e.g. cracked cases). 95 % of hard parts (valve bodies, torque converters) are recovered by remachining so that they have a suitable diameter and the remanufacturers replace the sleeve with the original dimensions.

Selecting recovery techniques depends on the condition of components. There are three techniques: enlarging, changing materials, changing the design, or strengthening.

4. How do you decide which components and the number of components to buy?

Cost - We use the cheaper method.

5. How can you order new/used components by considering lead time?

This usually depends on cost and time. It also depends on the customer's requirements. If a customer wants products immediately, the priority is time and we will increase the price..

6. Is there any complexity in decision making?

Material availability; how to improve components; how to change the materials.

7. How do you decide to buy new components instead of reprocessing the components?

Time and cost

Cost - We use the cheaper method. We have to operate on a specific profit margin.

8. Disassembly Sequence?

Each transmission has the same principle. Different transmission models have different disassembly sequences.

Interview in October 2017 with the director

Description

A product family is a group of related products that share common components

According to my study, planning components by considering the common components of different products within the same product family can improve profitability and environmental sustainability. It can increase the reusability of components from used products. However, there are different levels of demand, various types of returns, and timing uncertainty in the remanufacturing industry. Moreover, to know the total volume of components needed requires full disassembly. Therefore, it might sometimes be difficult to reuse parts from the same product family. To clarify my assumption, I have asked the following questions.

Question

1. Which options do you apply to manage components in your remanufacturing system?

☐ Option 1. Total all the required components from all the products in the same product family before ordering the required components.

Product Component	▲	■	●	Total no. of components required
	No. of components	No. of components	No. of components	
A	2	3		5
B	1	2	3	6
C		4	1	5
D	1		5	6

☑ Option 2. Use BOM (Bill of Material) to plan each product individually before ordering the required components

Product Component	▲
	No. of components
A	2
B	1
C	
D	1

2. Do you need to disassemble products fully before ordering the required components?

Yes.

3. Do the different brands of products share the same common parts?

No.

4. How much percentage of commonality is there for products in the same product family?

10-50% depending on the product family

5. If you are not applying Option 1, what method are you using now? What are the advantages and disadvantages of the existing method?

The current method is planning individually

The current method is quick and easy, however, it cannot handle unavailability of cores.

6. What do you think about Option 1?

☐✓It might be applicable because

☐ ✓It can increase reuse rate

☐ ✓It can increase available components from cannibalized cores

☐ ✓It can reduce costs

☐ Others

Please specify____

☐✓It might not be applicable in the production because

☐ Buying new components is cheaper than waiting for full disassembly and finding recoverable components

☐ Buying other cores is cheaper than waiting for full disassembly and finding recoverable components

☐ There are very few products sharing parts in common

☐ ✓This method is time-consuming - a different volume of demand, various types of returns, and timing uncertainty in the remanufacturing industry

☐ Others

Please specify____

7. Not all products can be remanufactured. Which recovery options are applicable to your business?

☐✓ Reuse ☐ Recycle ☐✓ Remanufacture ☐ Repair ☐ ✓ Cannibalize

8. Do you think the policy on how to decide when you should repair or remanufacture products is beneficial?

☐ Yes, because

☐ You can offer repairs when there is a lack of component supply

☐ You know whether it is economical or not to treat products under the warranty period

☐ Others

Please specify____

☐ ✓No, because

Please specify: The customers will make a decision by themselves. The remanufacturer can only suggest the cost and guarantee repairs and remanufacturing.

9. Which environmental impacts do you need to control in your operation

☐✓Material consumption ☐✓ Energy consumption

☐ Carbon Dioxide ☐ Other air emissions (i.e. Sulfur dioxide)

Please specify__________

10. How are you planning to disassemble/reassemble complex products?

There are two sources of cores: suppliers (50%) and customers (50%)

1. We know the individual parts required and can order them.

2. We sell remanufactured parts with a surcharge and give a discount when they are returned with an intact core and all components.

3. We find the new parts to replace soft parts and find the reusable parts from the core for hard parts.

4. We send the quotation before disassembling products based on the previous data for the last three months. If the cost is higher than expected, we will increase the price next time.

5. We disassemble one core using one person within 3 hours and we dispatch products within two days after customers place an order.

6. Kanban and 5S are used to improve production.

11. To what extent do you think these methods help you to plan complex products?

Very low for each method

● Bill of materials

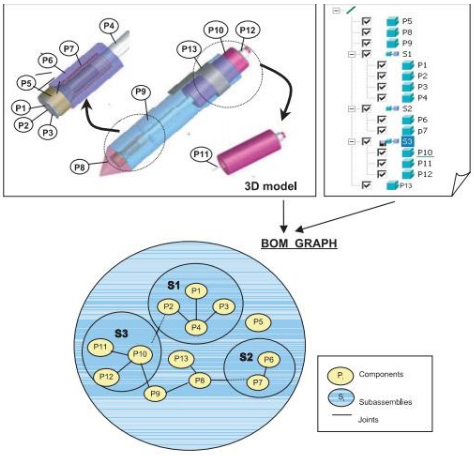


Figure 3. Translating the BOM into the BOM graph, for the example of a mechanical pencil.

☐ Very high ☐ High ☐ Medium ☐ Low ☐ Very low

● And/or graph (to show alternatives how to disassemble/reassemble products)

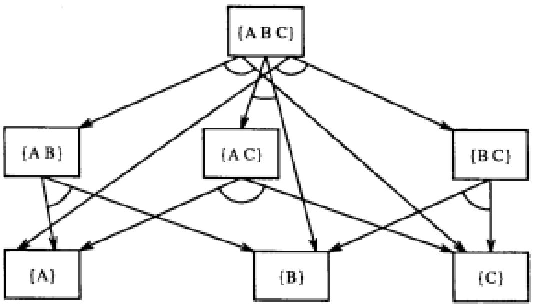


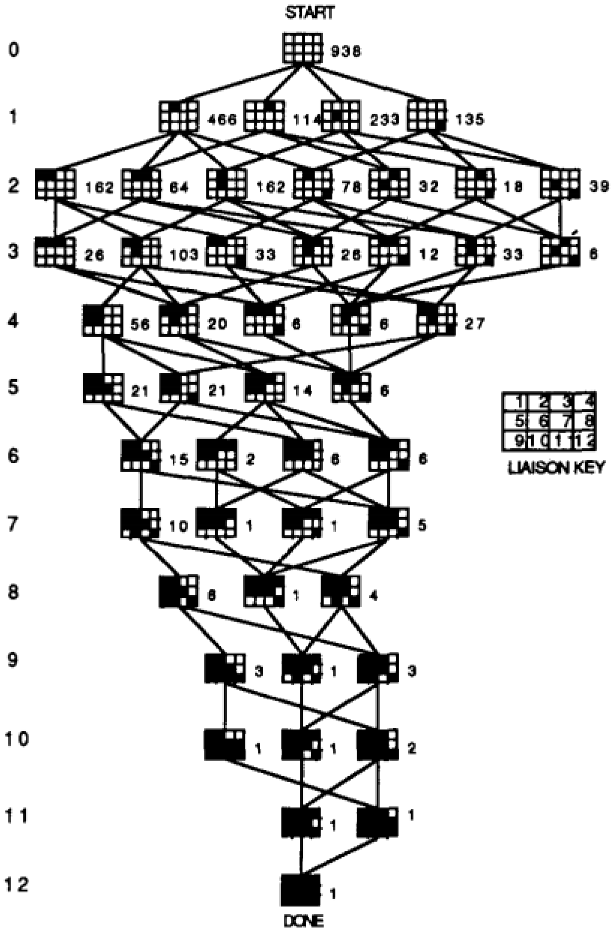
Fig. 2. The AND/OR graph for a three-part assembly.

☐ Very high ☐ High ☐ Medium ☐ Low ☐ Very low

- ● Disassembly possibilities (showing the angular ranges of removal of components or subassembly)

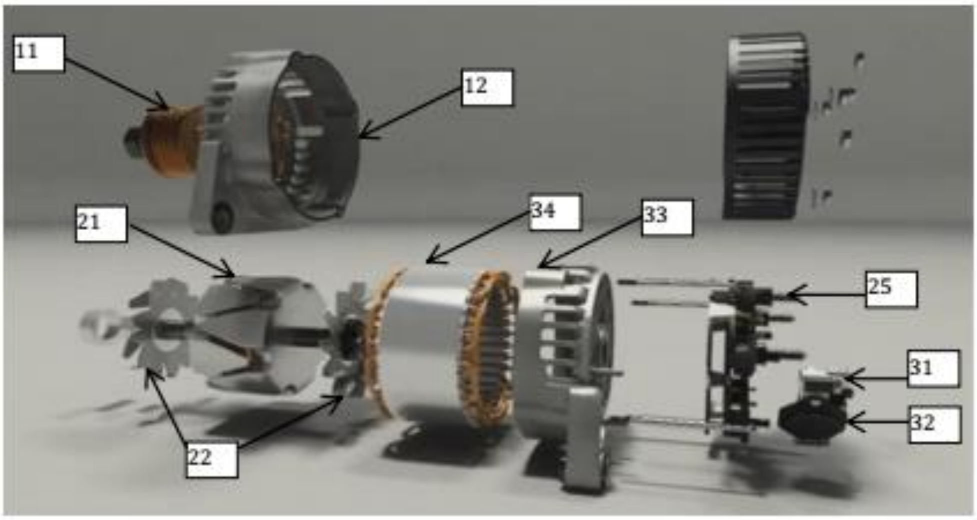
☐ Very high ☐ High ☐ Medium ☐ Low ☐ Very low

- ● Present diagram (to show which is the current state in the production process)



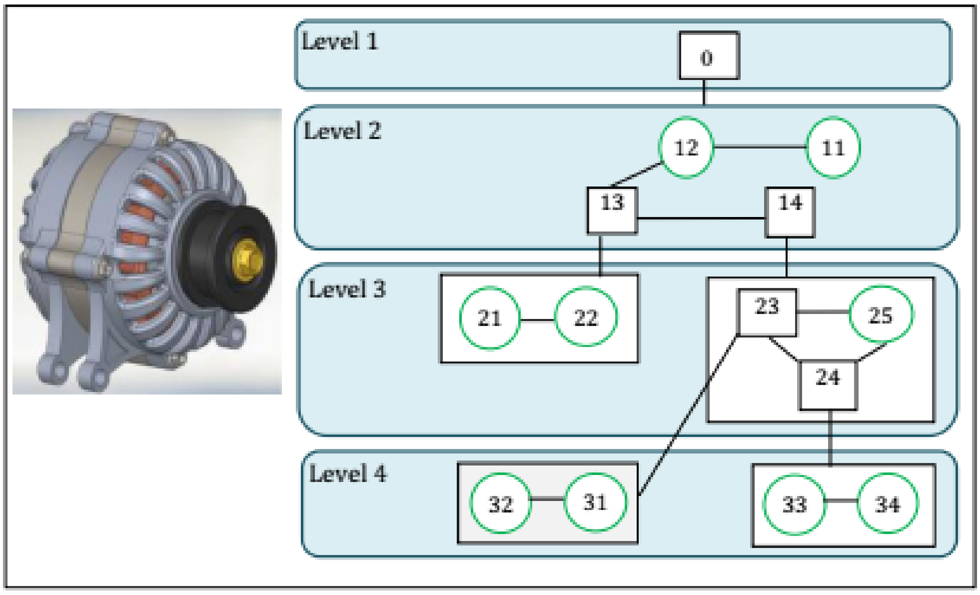
☐ Very high ☐ High ☐ Medium ☐ Low ☐ Very low

- ● 3D product representation



☐ Very high ☐ High ☐ Medium ☐ Low ☐ Very low

- ● Liaison graph (showing subassemblies or components for each level of disassembly)



☐ Very high ☐ High ☐ Medium ☐ Low ☐ Very low

9.What percentage of your operation is

MTS (Made to stock)_30%, MTO (Made to order)__60_%, ATO (Assemble to order)__10__%

10. How stable or predictable is the recovery rate?

☐ Unpredictable and unstable

☐ Predictable and unstable

☐ ✓Predictable and stable - 95% recoverable

11. How stable or predictable is the demand rate?

☐ Unpredictable and unstable

☐ ✓Predictable and unstable

☐ Predictable and stable

12. How stable or predictable is the return rate?

☐✓ Unpredictable and unstable

☐ Predictable and unstable

☐ Predictable and stable

13. In the disassembly of a product, how stable or predictable are the processing times?

☐ Unpredictable and unstable

☐ Predictable and unstable

☐ ✓Predictable and stable

14. In the reassembly of a product, how stable or predictable are the processing times?

☐ Unpredictable and unstable

☐ Predictable and unstable

☐ ✓Predictable and stable

N.B. We cannibalise cores to find reusable parts. We do not throw away usable parts but we use them for other products within the same family.

Appendix I E: Interview with Company E

Interview in November 2017 with a core manager

Optimising core in the automotive remanufacturing industry

1. Do your company remanufacture, recondition or repair products? / Do you provide remanufacturing services but also other services? / What percentages of the following services do provide: remanufacturing /reconditioning / repairs?

   Company E is an independent remanufacturer. 95 % of our activities are remanufacturing while the rest is repairing. Most of our repairing services are for B2B customers (95%).

2. What are the main challenges for managing cores?

   The main challenge is the availability of cores. The company provides various core models. Sometimes customers order rare items, especially newly launched models. The company needs to find cores from reliable sources which can show authentic documents for proof.

   Operational strategy

3. Please allocate a total of 100 points between objectives according to how important they are for core management strategy.

___ 80___ Assembly of a certain number of remanufactured parts

We buy the right cores (with specific part numbers) for the first time. We do not buy a mixture of cores. We set a target of several remanufactured parts we have to produce per day. This level of production is monitored in real-time and depends on historical sales information.

____10___ Neglect unnecessary jobs/tasks because it consumes time, labour and money

We buy authentic cores for the first time (with specific part numbesr), so we can minimise time and labour to strip, clean, repair or scrap purchased cores.

____10___ Make a return on your investment on cores. (e.g. You want to fully utilise every core you acquire)

When we sell cores, we add a surcharge to the bill. We increase the incentives for customers to return the same old units in the system by giving customers credits from which they can discount this surcharge.

Others: ____

Please specify: ____

Making a decision

4. How do you decide on remanufacturing or other end of life options?

We used to provide repair services only. However, from 2000, we realised from the price and sales trends that especially common rail engines has high growth in the industry. We saw a business opportunity as a remanufacturer because we can compete with existing players who offer new and existing options. Therefore, we replaced our repair services with remanufacturing which enabled us to earn more profits than before.

5. What are the factors/criteria you consider? Which one is more or less important and why?

Please allocate a total of 100 points among factors according to how important it is to your decision making on remanufacturing.

__10___ Age of parts

Normally the life of new products is 3 years. The remanufacturer will have no opportunities in the market since during that period because the warranty only covers 3 years from the purchasing date. If the models have been launched for more than three years, it is worth remanufacturing them because there are cores available when customers return them to the remanufacturer. Moreover, it is the best time to improve the products' performance after they have been used for 3 years. So we offer remanufactured products for engines of 3 to 15 years of age.

__10____Projected price and costs

The company can decide on the remanufacture of parts and sell them at a competitive price compared with new products from the dealer.

__10____Remanufacturing cycle

The company can track the cycle of its remanufactured products to see how long it takes to remanufacture those parts and to assess the possibility of repeat business.

__10____Complexity of components

This factor is important because if the components are too new and our existing test machine cannot check all the components, we have to invest in a new test bench.

__10____Condition of cores (condition investigated by visual inspection)

We cannot remanufacture products if the units are badly corroded or damaged

___50___Others: Please specify: the ability to access the parts and test data of the OEM (e.g. running with full power, using fuel spray).

6. Do you consider environmental factors to optimise cores? If yes, what are those factors?

   We do not consider environmental factors to optimise cores. However, we follow OEM specifications which cover emission standards. Our operation is under the environmental standard. We believe our business helps the environment by extending the life of products and launches cleaner products on the market.

7. What factors are known and recorded?

   Same answer as for question no.5.

8. How long does it take to decide whether to remanufacture returned products?

   In the component assessment stage, we can decide immediately and send the products to customers within the day of order or the next day.

9. What are the inspection methods? How do inspection results help with a decision on suitability for remanufacturing or other end of life options?

   We use pre-sorting to select grade A cores from a visual inspection. Then, the technician disassembles the product into many sub-parts to inspect the condition of the cores thoroughly.

10. What are the conditions of the cores that you reject for immediate remanufacturing? Which one is more or less important and why?

    Please allocate a total of 100 points between factors according to how important they are to your decision making.

__30___No. of parts damaged. Several damaged parts are not acceptable

__30__Severity of damaging. Severely damaged parts are not acceptable

__40___Types of damage

_____Obsolete

_____Others: Please specify____

11. What types of core failures are commonly found?

cracks, nozzles burnt off, body damage / rust

12. Why are some parts scrap?

_________Undersize _________Oversize
_________Overstocked (They don't buy it, if they don't want it)
___/______Mating part lost
____/_____Obsolete (Cannot find tools, material to repair it)
_________Weakened parts (Further process can weaken parts)
____/_____Cosmetic flaws (cracks, housing damage)
____/_____Material loss (New material costs are too high)
____/_____Others: Please specify: old design components e.g. new seals for driveshaft are replaced, products with mixed model parts, body damage

13. Where is your scrap? What did you do with it?

A recycle dealer collects our scrap and melts it so it can be used as raw material.

14. To what extent do you agree with the following statement?

"If you know the failure/scrap history, you can predict the amount of failure/scrap in the future."

Strongly agree/ [✓ agree]/ moderate / disagree/ strongly disagree

For production planning, we know how many products we will produce.

"If you know the failure/scrap history, you can develop design strategies."

Strongly agree/ agree/ [✓ moderate]/ disagree/ strongly disagree

This might not apply to our strategy because we follow the OEM standard. We do not design products by ourselves

"If you know the failure/scrap history, you can remanufacture products more efficiently."

[✓ Strongly agree]/ agree/ moderate/ disagree/ strongly disagree

We can plan for several parts, so we can plan a process which increases the job's efficiency.

"If you can predict the failure/scrap, you can predict the number and characteristics of the parts you should acquire."

Strongly agree/ agree/ moderate/ disagree/ strongly disagree

We can plan stocks of components.

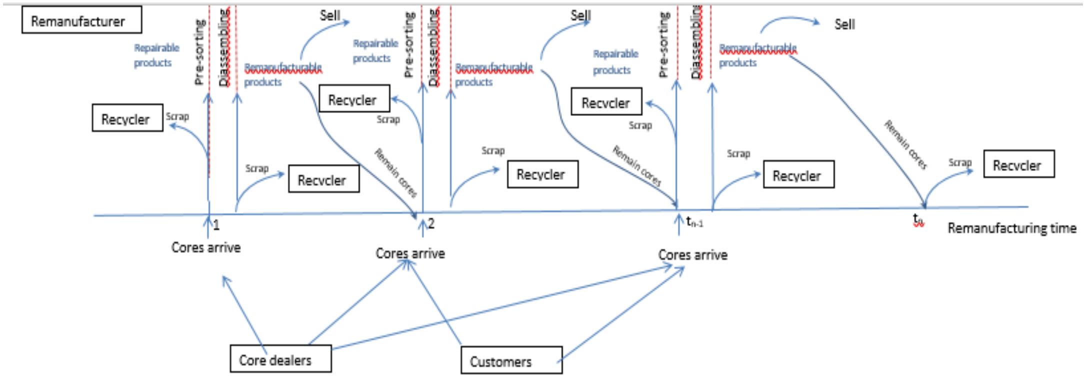
"If you can predict the number and characteristics of the parts you acquire, it can help increase product recovery rate and profit."

Strongly agree/ agree/ moderate/ disagree/ strongly disagree

We can plan for the amount of labour and resources. In the remanufacturing process, labour costs are 60% of the total cost while the rest is for the costs of materials.

Business model

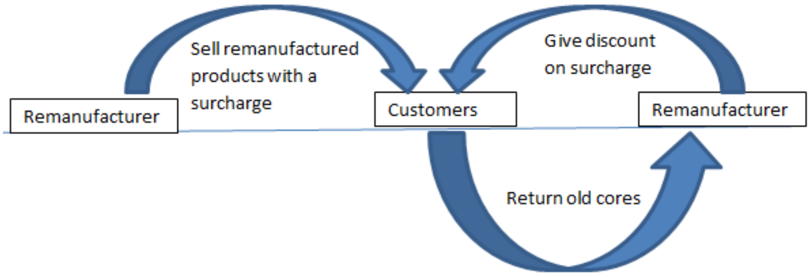
15. Could you tell me about your business model?



We found that three years after launching new products is the best time for remanufactured products because then there will be a good demand and cores will be available. However, we will remanufacture any products customers want whenever these products are introduced.

Our strategy is to acquire class A cores at the beginning, and the core dealers are responsible for sourcing cores. The core dealers find cores at the scrap yard and sell them to the remanufacturer. If we find any defects, we can return the cores immediately and we receive credit from the dealers for our next purchase. The remanufacturer will not pay any money unless the core dealer collects their credits. After we acquire high quality cores, we remanufacture products to OEM standards using OEM Parts and OEM test equipment/data to make sure that our costs are competitive in comparison with new units with cost savings of at least 30%. We sell 95% of products to B2B customers e.g. garages. We add a surcharge when we sell remanufactured products to customers to control the supply chain of cores. We persuade customers to return the same old model cores to us within 12 months of purchase remanufactured products and customers will receive credit which they can discount from the surcharge on their accounts. However, we have to buy 22% of cores from core dealers due to the fact that there are cores missing from the loop of the supply chain. If we find those cores are not worth remanufacturing, we will keep them for 3 months in case the customers want them back, otherwise we will sell them for scrap to the local recyclers.

16. How do you take cores back?



We add a surcharge when we sell remanufactured products to customers to persuade them to return same old model cores to us within 12 months and clients will then receive credit which they can discount from their surcharge in their customer account. The company will give credit to customers if the returned cores are not in a poor condition: e.g. the wrong model, missing parts, or body damage. The company can inspect cores thoroughly within 2-3 days and give customers credits.

17. How do you manage your stock? How do you maintain your inventory and buy new cores?

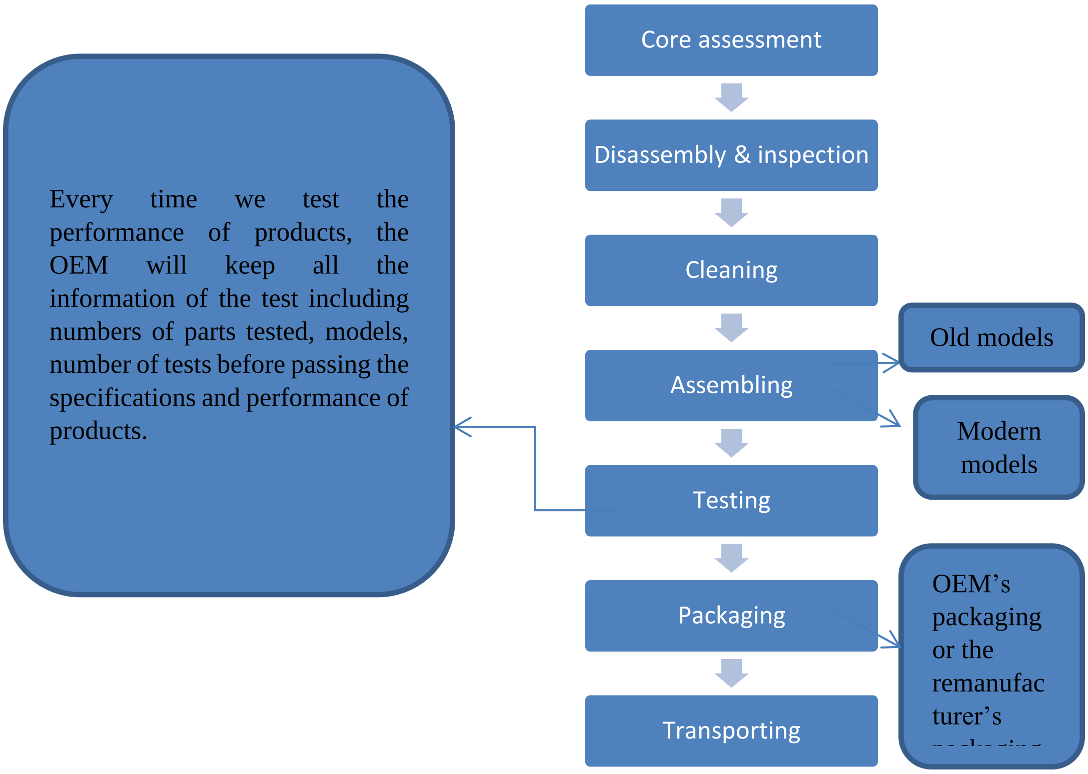
We can monitor our inventory via a real-time monitoring system based on historical sales data. We produce remanufactured products at the production rate recommended by the monitoring system. There are three levels which we take into account as follow.

1. When there are more target units in stock (remanufactured units) than the number of units recommended by the monitoring system.
2. When there are less target units in stock than the sum of units in stock plus old core units (units that are repairable but not remanufacturable).
3. When the sum of units in stock plus old core units are less than the target units.

18. What is the shelf life of your products?

The maximum period for stocking the cores is three years; however, we can usually sell remanufactured products after they have been in stock from 6 months to 2 years.

19. Our process



Every time we test the performance of products, the OEM will keep all the information of the test including numbers of parts tested, models, number of tests before passing the specifications and performance of products.

Interview in November 2017 with a director

Optimising core in automotive remanufacturing industry

1. Do your company remanufacture, ~~recondition~~ or repair products?/ Do you provide 10 remanufacturing services but also other services? /What percentage you do on remanufacturing /~~Reconditioning~~ / Repairing?
   95% 5%
2. What are the main challenges to manage cores?

   Operational strategy

3. Please allocate a total of 100 points among objectives according to how important it is to your strategy to manage cores.

   80 Assemble a certain number of remanufactured parts

   10 Neglect unnecessary jobs/tasks because it consumes time, labour and money

   10 Make a return on your investment on cores. (eg.You want to utilise every cores you acquire)

   ________ Others: Please specify____

4. How did you make a decision on remanufacturing or other end of life options?
5. What are the factors/criteria considered? Which one is more or less important and why?

   Please allocate a total of 100 points among factors according to how important it is to your decision making on remanufacturing.

   ______Market trend

   10 Part's Age

   ______Historical price and cost

   10 Projected price and cost

   10 Remanufacturing cycle

   ______Recycling cycle

   10 Complexity of components = TEST BENCH INVESTMENT.

   ______ Fastener/Parts available

   10 Condition of cores (failure condition investigated by visual inspection)

   ______Condition of cores (internal failure condition eg. crack)

   50 Others: Please specify PARTS & TEST DATA FROM O.E. MANUFACTURER.

8. How long does it take to make a decision on how to remanufacture the returned products?

9. What are the inspection methods? How do inspection results conclude the suitability for remanufacturing or other end of life options?

10. What are conditions of cores that you can reject to remanufacture immediately? Which one is more or less important and why?

    Please allocate a total of 100 points among factors according to how important it is to your decision making.

    30 No. of parts damaged.

    30 Severity of damaging

    40 Types of damaging eg. deformation, burnt, wear, crack, corrosion, hole, fracture, fastener failure, dent, loosened, design flaw

    _____Obsolete

    _____Others: Please specify_____

11. What types of cores' failure are commonly found?

    deformation, burnt, wear, [✓ crack], corrosion, hole, fracture, fastener failure, dent, loosened, design flaw, Others: Please specify NOZZLE BURNT off or [illegible] BODY DAMAGE/RUST

12. Why are some parts scrap?

    _____Undersize
    _____Overstock
    ✓ Obsolete (Cannot find tools, material to repair it)
    _____Weaken parts (Further process can weaken parts)
    ✓ Cosmetic flaw
    ✓ Material loss
    ✓ Others: Please specify_____
    _____Oversize
    _____Mating part lost

13. Where is scrap? What did you do with scrap?

14. How likely you agree with this statement

“If you know the failure/scrap history, you can predict the numbers of failure/scrap in the future ”

Strongly agree/ [✓ agree]/ moderate/disagree/strongly disagree

“If you know the failure/scrap history, you can develop design strategies.”

Strongly agree/ agree/ [✓ moderate]/disagree/strongly disagree

IN SOME CASES.

“If you know the failure/scrap history, you can remanufacture products more efficiently.”

Strongly agree/ [✓ agree]/ moderate/disagree/strongly disagree

→ COMPONENT STOCKS.

“If you can predict the failure/scrap, you can predict number and characteristics of parts you should acquire.”

[✓ Strongly agree]/ agree/ moderate/disagree/strongly disagree

→ COMPONENT STOCKS.

“If you can predict number and characteristics of parts you should acquire, it can help increase product recovery rate and profit.”

[✓ Strongly agree]/ agree/ moderate/disagree/strongly disagree

EFFICIENT USE OF LABOUR RESOURCE.

1.0 VEHICLE REPAIR SERVICE = DIESEL
= ELECTRICAL
= HEATING
= AIR CONDITIONING

BUS.
CV.
PLANT. &
OFF HIGHWAY

ONSITE - OFFSITE

2. AVAILABILITY = VARIABLE QUALITY =
↳ SOURCES (CREDIBLE).
AS OPPOSED TO MAN IN A VAN.

3. 80 * REASONS FOR BEING IN BUSINESS - WE NEED TO UTILISE
EVERY CORE PURCHASED : BUY RIGHT FIRST TIME :
10 * MINIMISE HAVING TO CONVERT OR SCRAP CORE PURCHASED

ATTACHED TO THE NEW UNIT WITH A MARGIN
10 * SELLING THE CORE AS A SURCHARGE WHICH WILL
BE CREDITED ON RETURN OF SAME OLD UNIT

4. WERE AN ELECTRICAL REMANUFACTURER - STARTED 1966
STARTERS - ALTERNATORS
THE PRICE COMPARISON TO NEW & THE TREND WAS
TO COMPETE WITH THE MAIN PLAYERS - LUCAS /BOSCH.
WHO OFFERED NEW & REMAN OPTIONS.
DIESEL AT THAT TIME WAS REPAIR ONLY.
ROTARY & INLINE SYSTEMS.
WITH THE INTRODUCTION OF COMMON RAIL > 2000

8. AT THE COMPONENT ASSESSMENT POINT OF OUR PROCESS.

9. VISUAL = INTERNAL & EXTERNAL CONDITION.

13. SOLD TO LOCAL METAL SCRAPYARD FOR RECYCLING

14. C/4 CORE QUOTE.

15. BUSINESS MODEL

① REMANUFACTURE TO O.E. STANDARDS USING O.E. PARTS & O.E. TEST EQUIPMENT/DATA.

② TO OFFER A FULL RANGE ALL MAKES DIESEL PUMP/INJECTOR PROPOSITION FOR CAR/LCV/TRUCK/MARINE/OFF HIGHWAY PLANT/RAIL/COACH & BUS APPLICATIONS.

③ TO BE COST COMPETITIVE IN COMPARISON WITH NEW UNITS AT LEAST 30% COST SAVINGS.

Appendix II : Results from sensitivity analysis

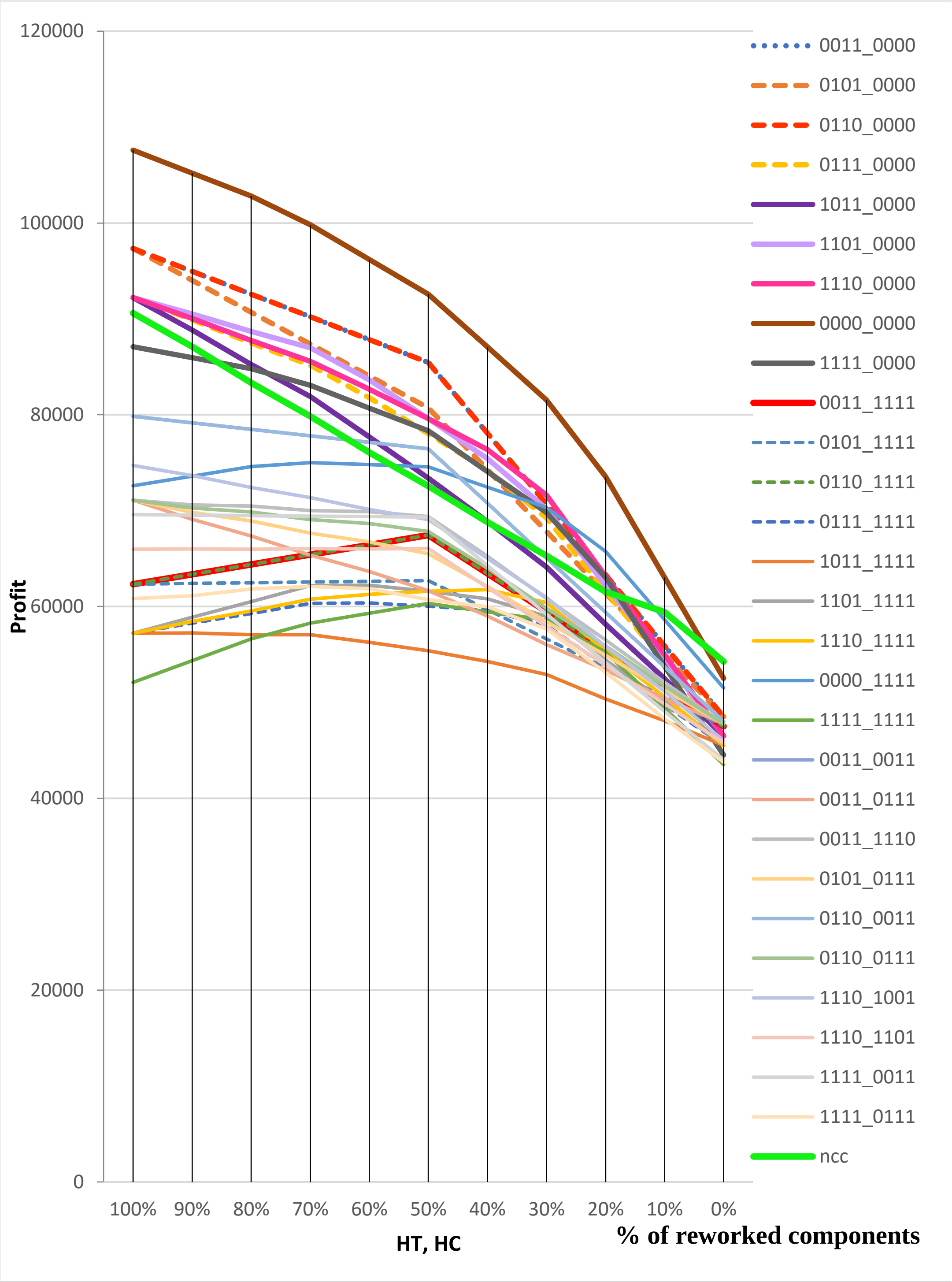


Figure II.1 The relationship between the profit and the percentage of reworked components for cases with high reworking time and high reworking costs (Maximising profit)

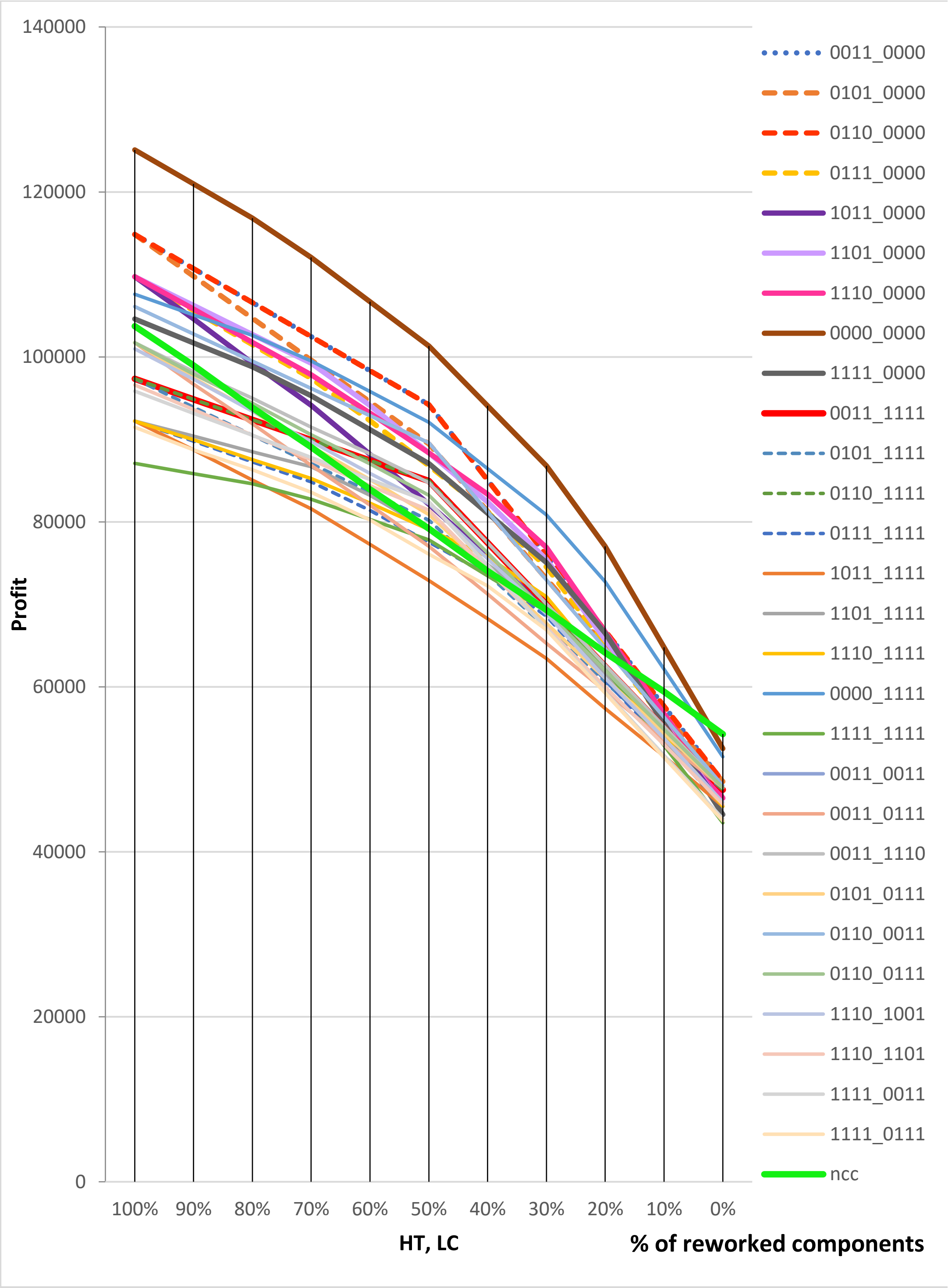


Figure II.2 The relationship between the profit and the percentage of reworked components for cases with high reworking time and low reworking cost (Maximising profit)

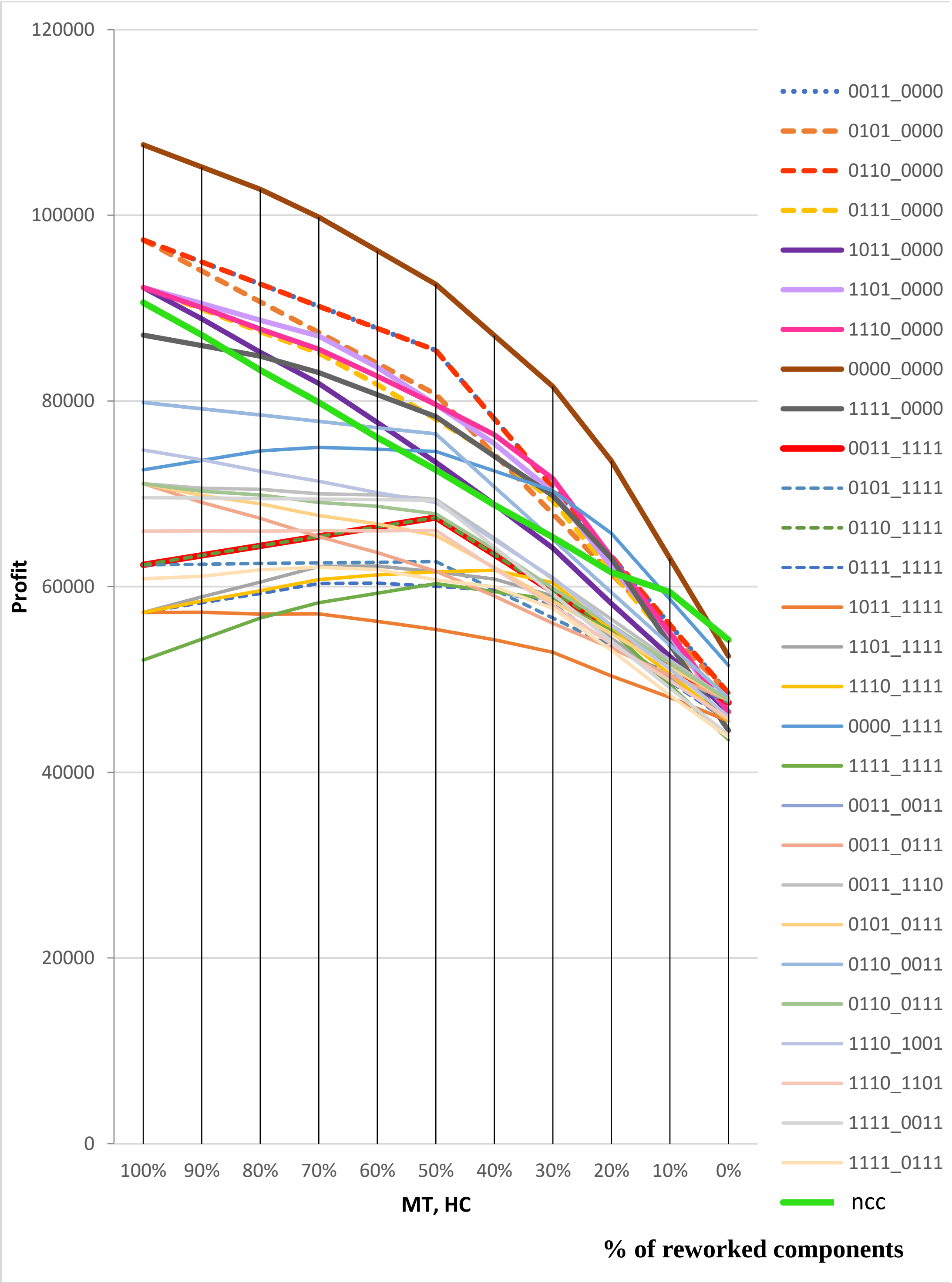


Figure II.3 The relationship between the profit and the percentage of reworked components for cases with medium reworking time and high reworking costs (Maximising profit)

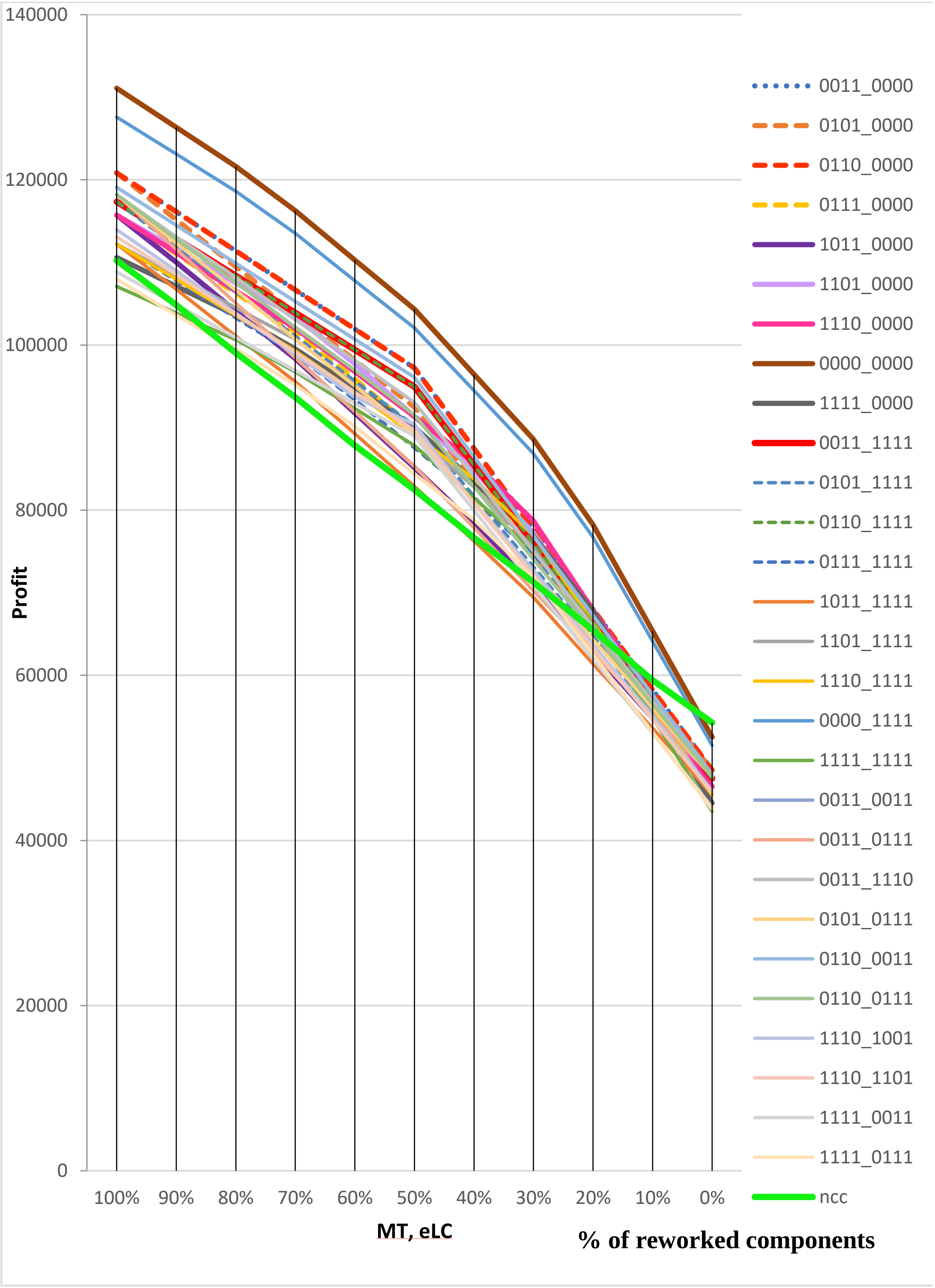


Figure II.4 The relationship between the profit and the percentage of reworked components for cases with medium reworking time and high reworking costs (Maximising profit)

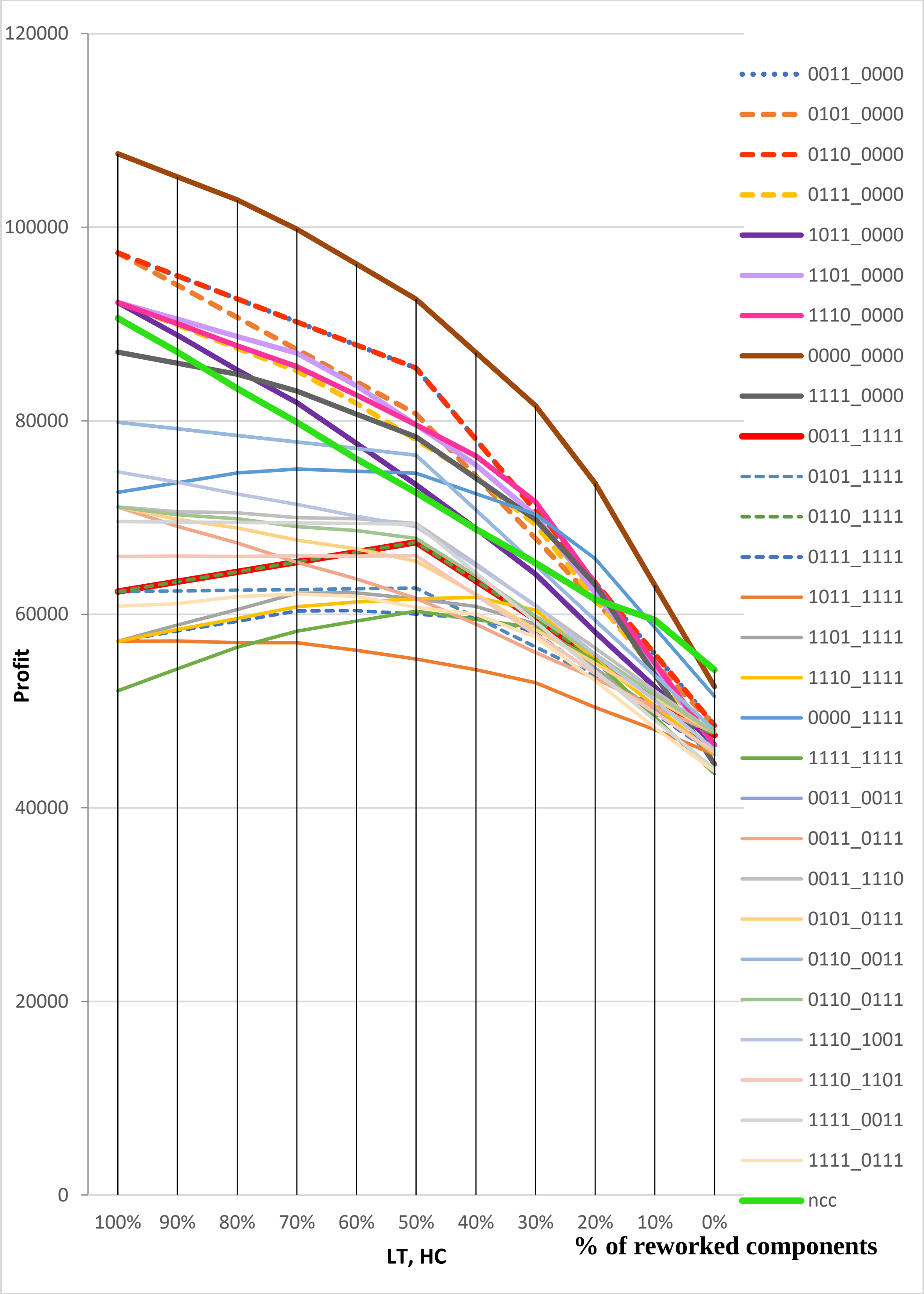


Figure II.5 The relationship between the profit and the percentage of reworked components for cases with low reworking time and high reworking costs (Maximising profit)

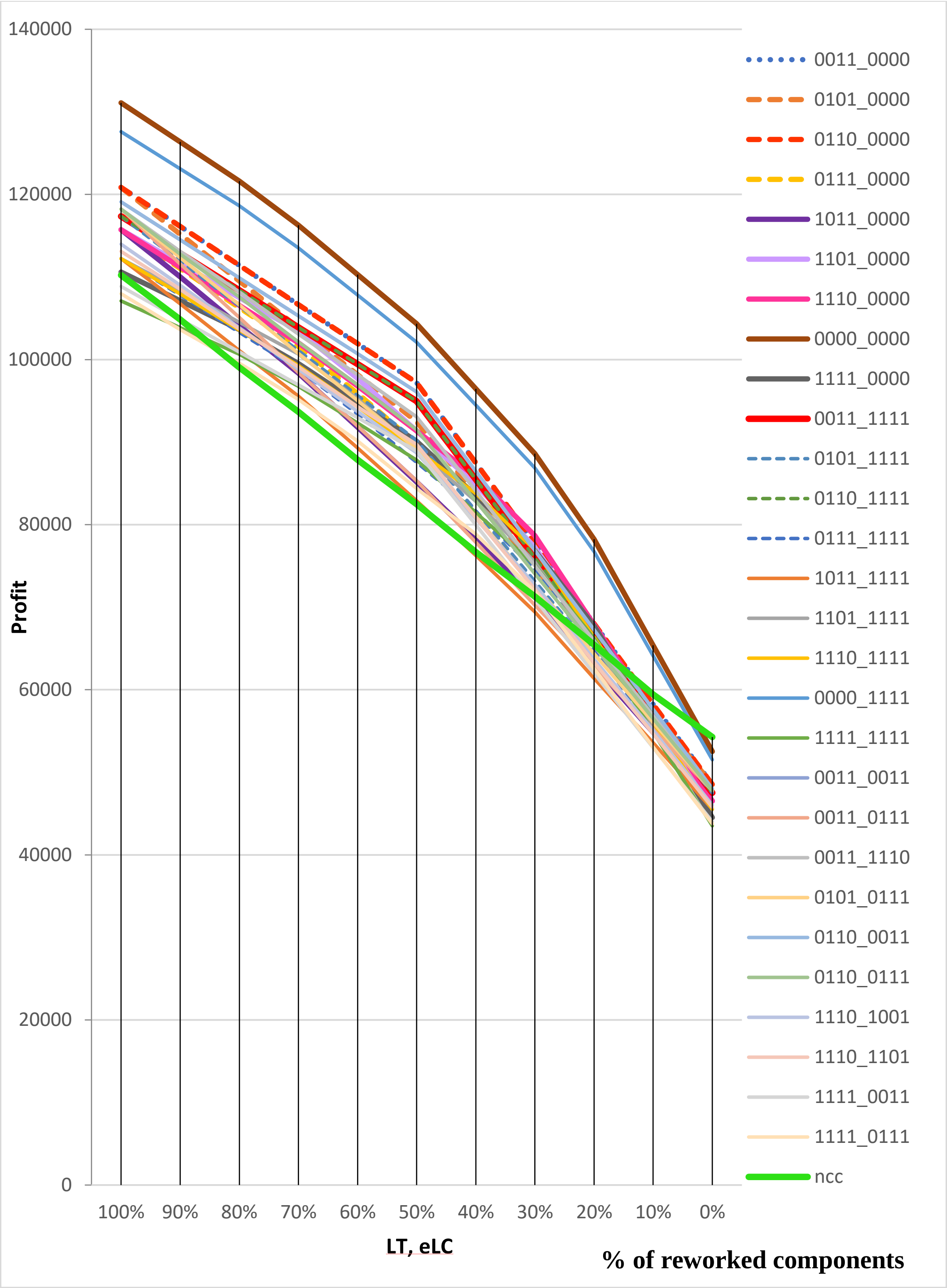


Figure II.6 The relationship between the profit and the percentage of reworked components for cases with low reworking time and extremely low reworking costs (Maximising profit)

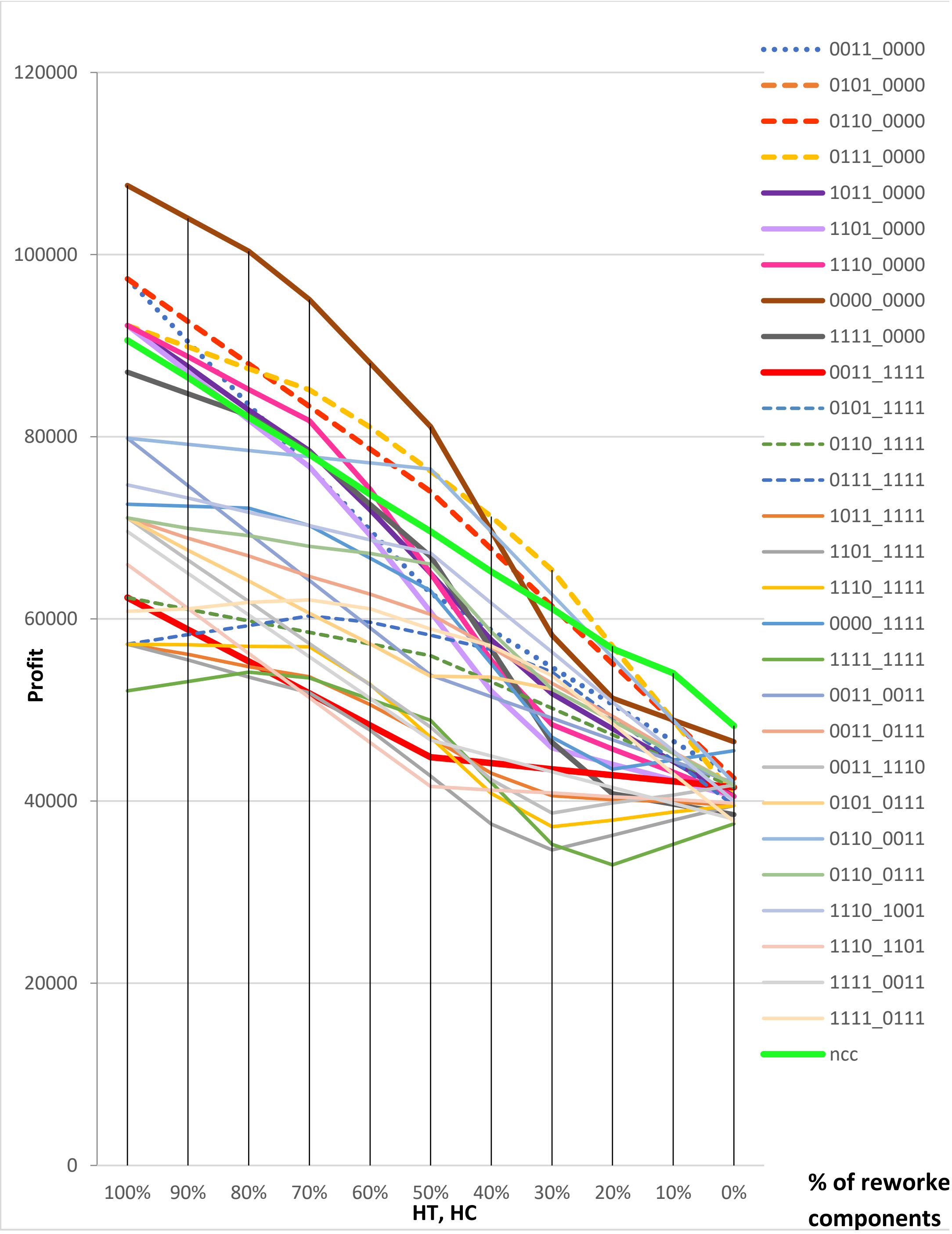


Figure II.7 The relationship between the profit and the percentage of reworked components for cases with high reworking time and high reworking costs (Minimising time)

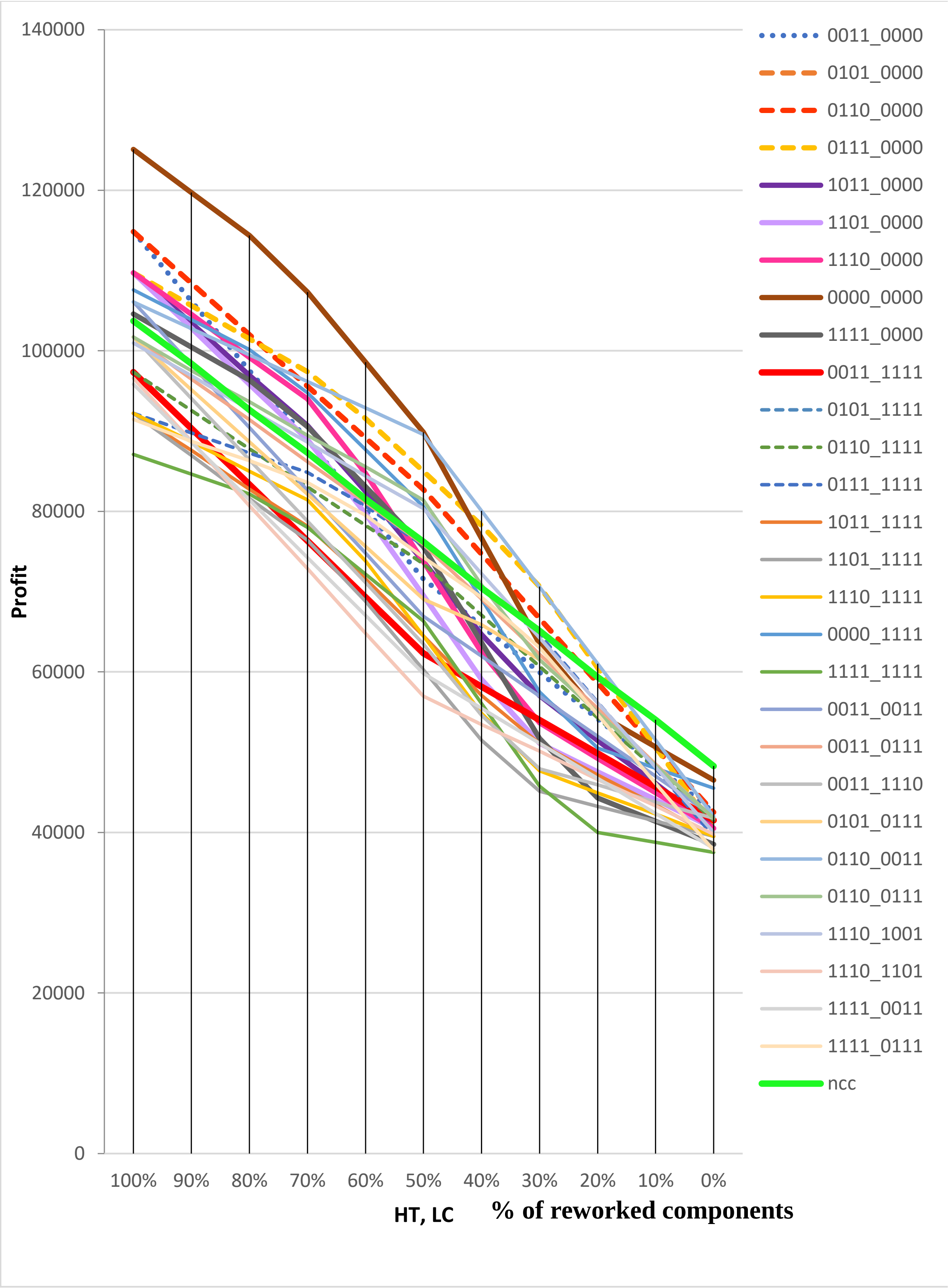


Figure II.8 The relationship between the profit and the percentage of reworked components for cases with high reworking time and low reworking costs (Minimising time)

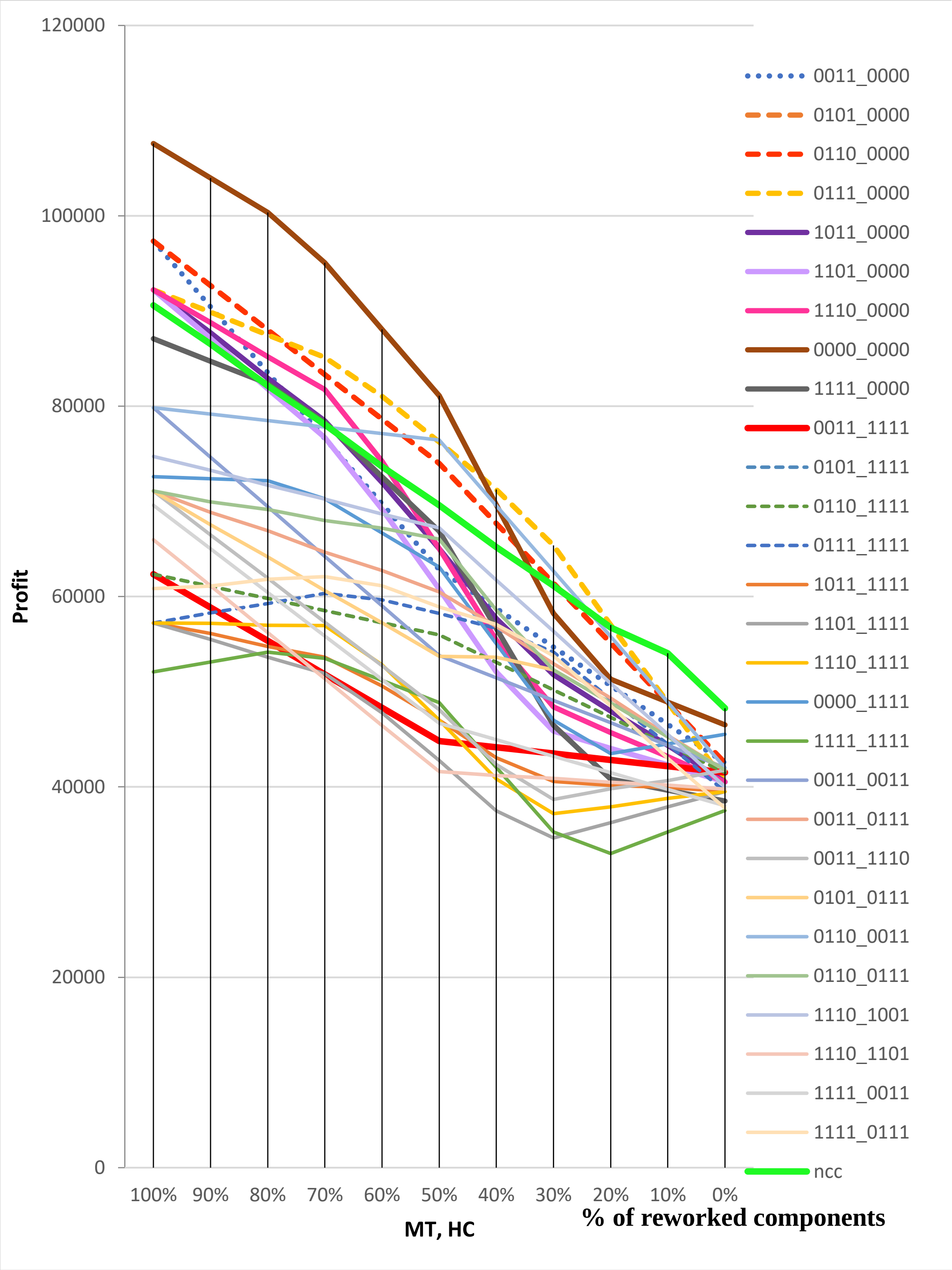


Figure II.9 The relationship between the profit and the percentage of reworked components for cases with medium reworking time and high reworking costs (Minimising time)

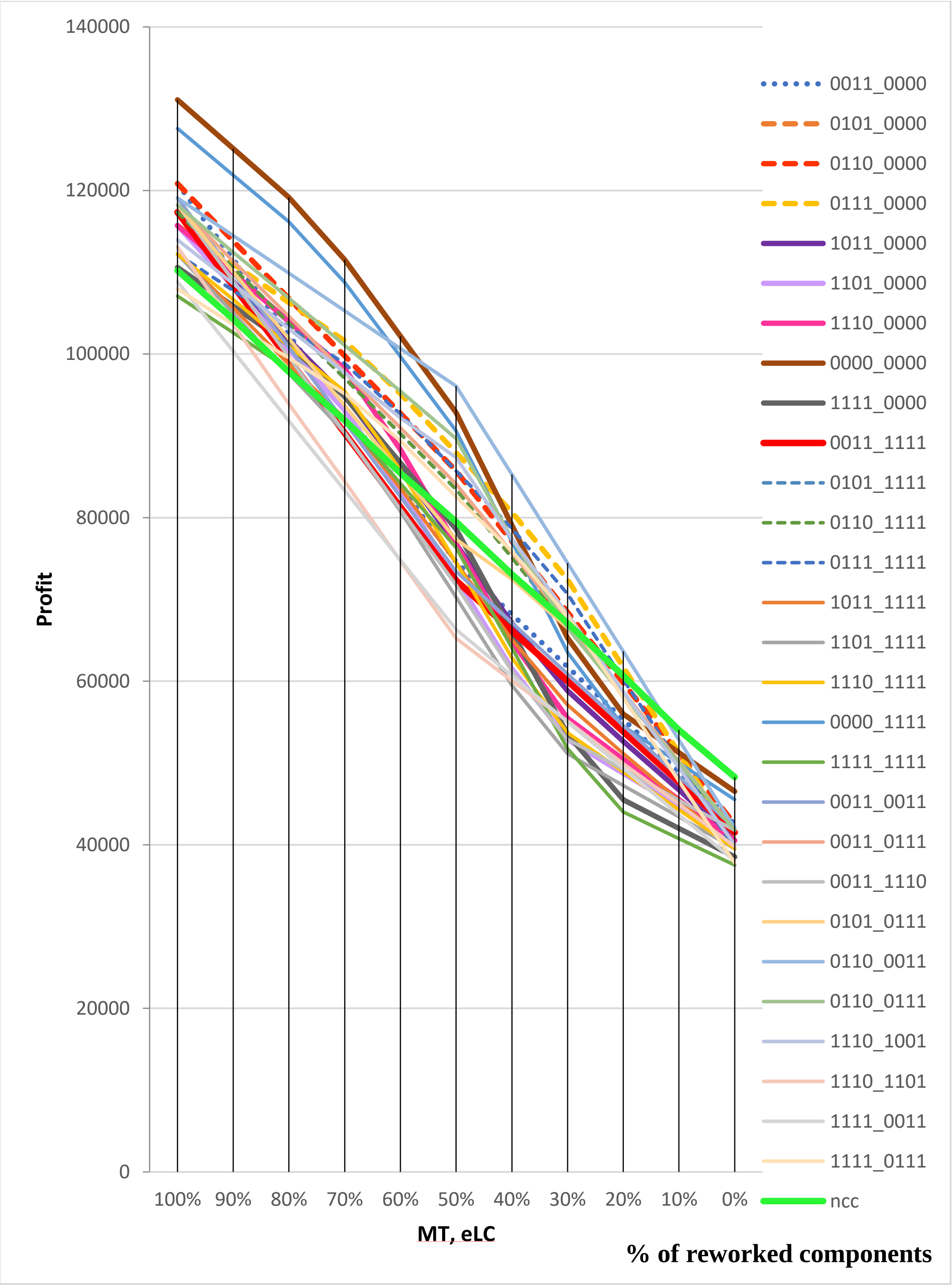


Figure II.10 The relationship between the profit and the percentage of reworked components for cases with medium reworking time and extremely low reworking costs (Minimising time)

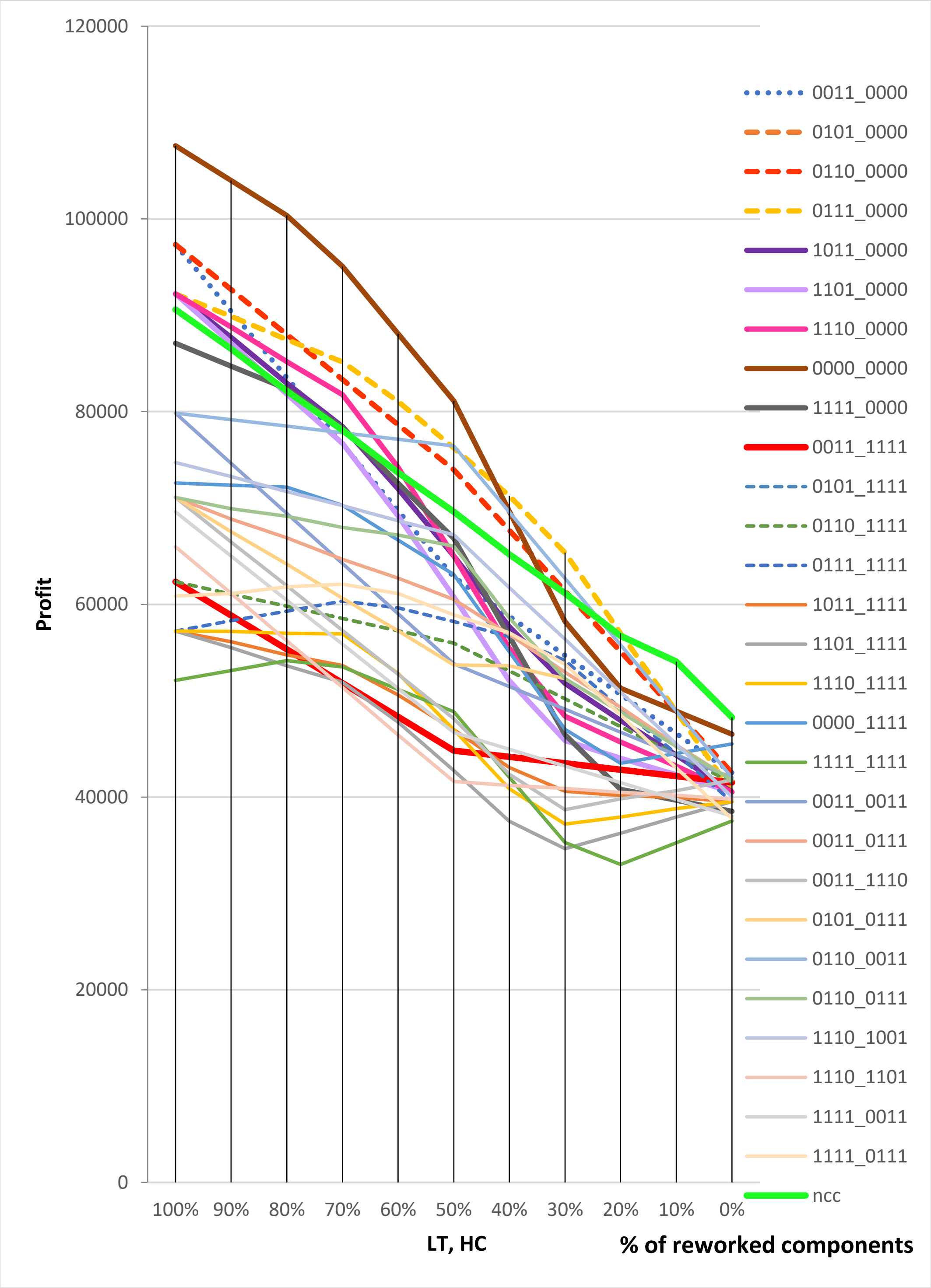


Figure II.11 The relationship between the profit and the percentage of reworked components for cases with low reworking time and high reworking costs (Minimising time)

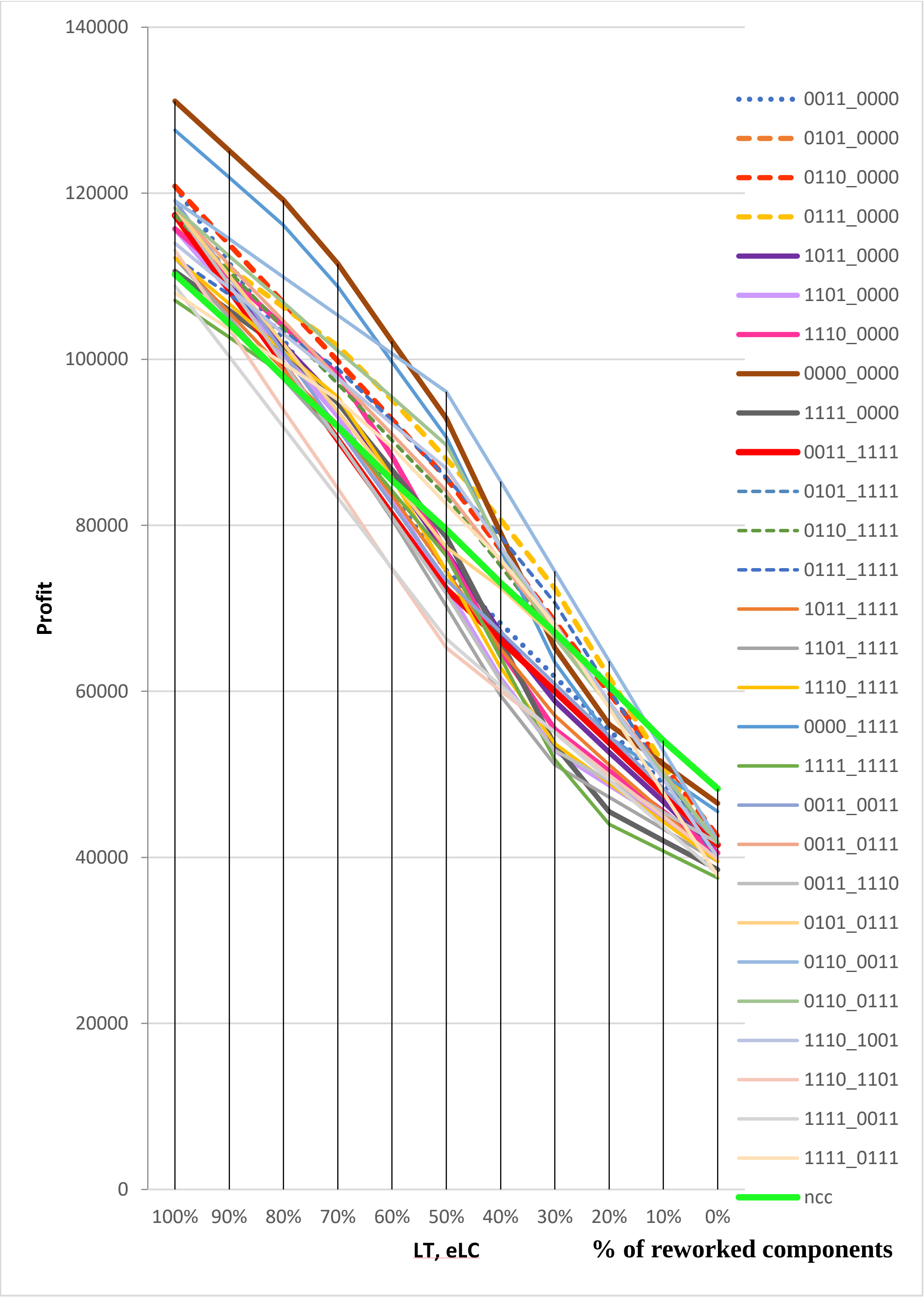


Figure II.12 The relationship between the profit and the percentage of reworked components for cases with low reworking time and extremely low reworking costs (Minimising time)

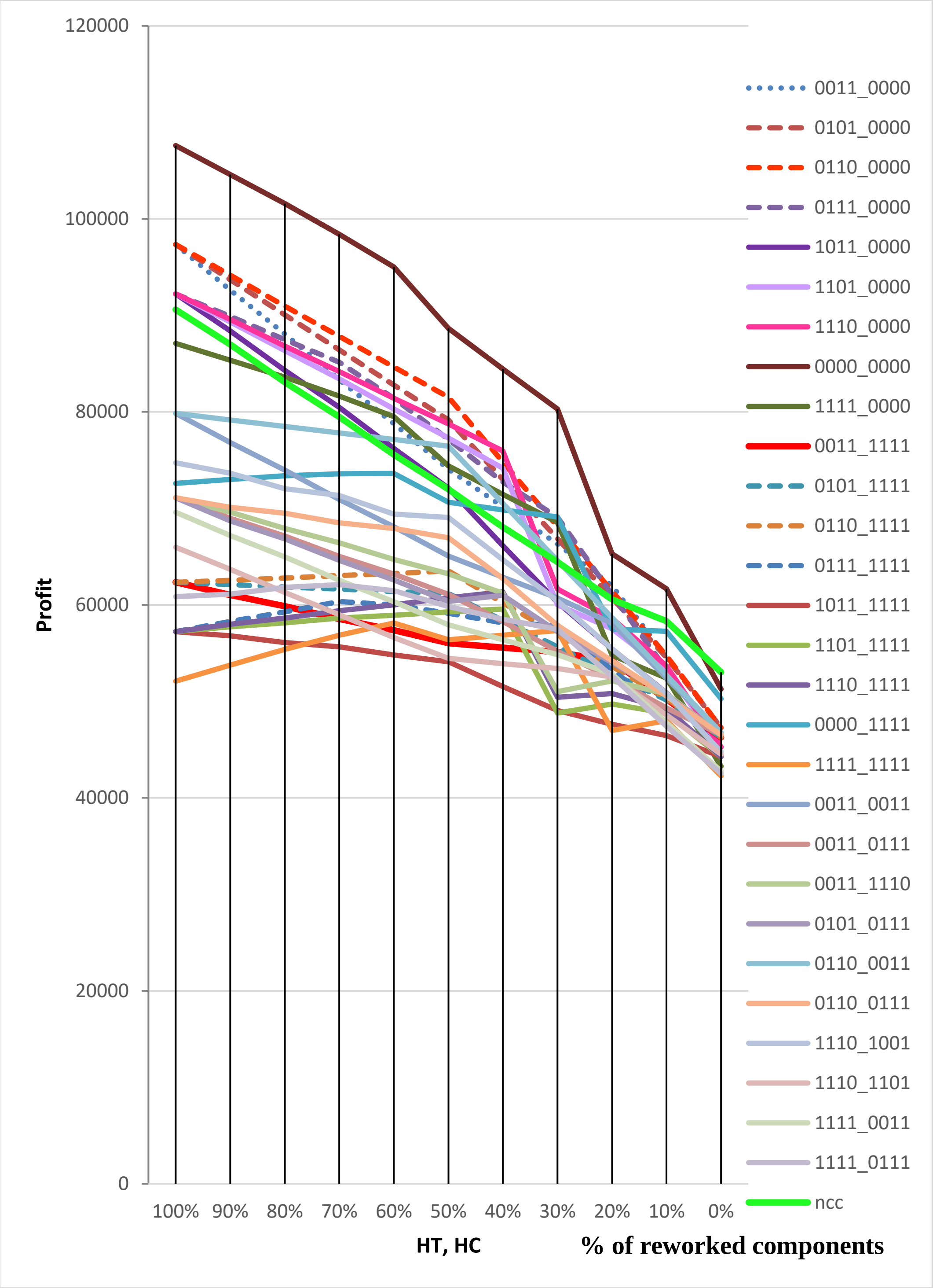


Figure II.13 The relationship between the profit and the percentage of reworked components for cases with high reworking time and high reworking costs (Maximising profit and minimising time)

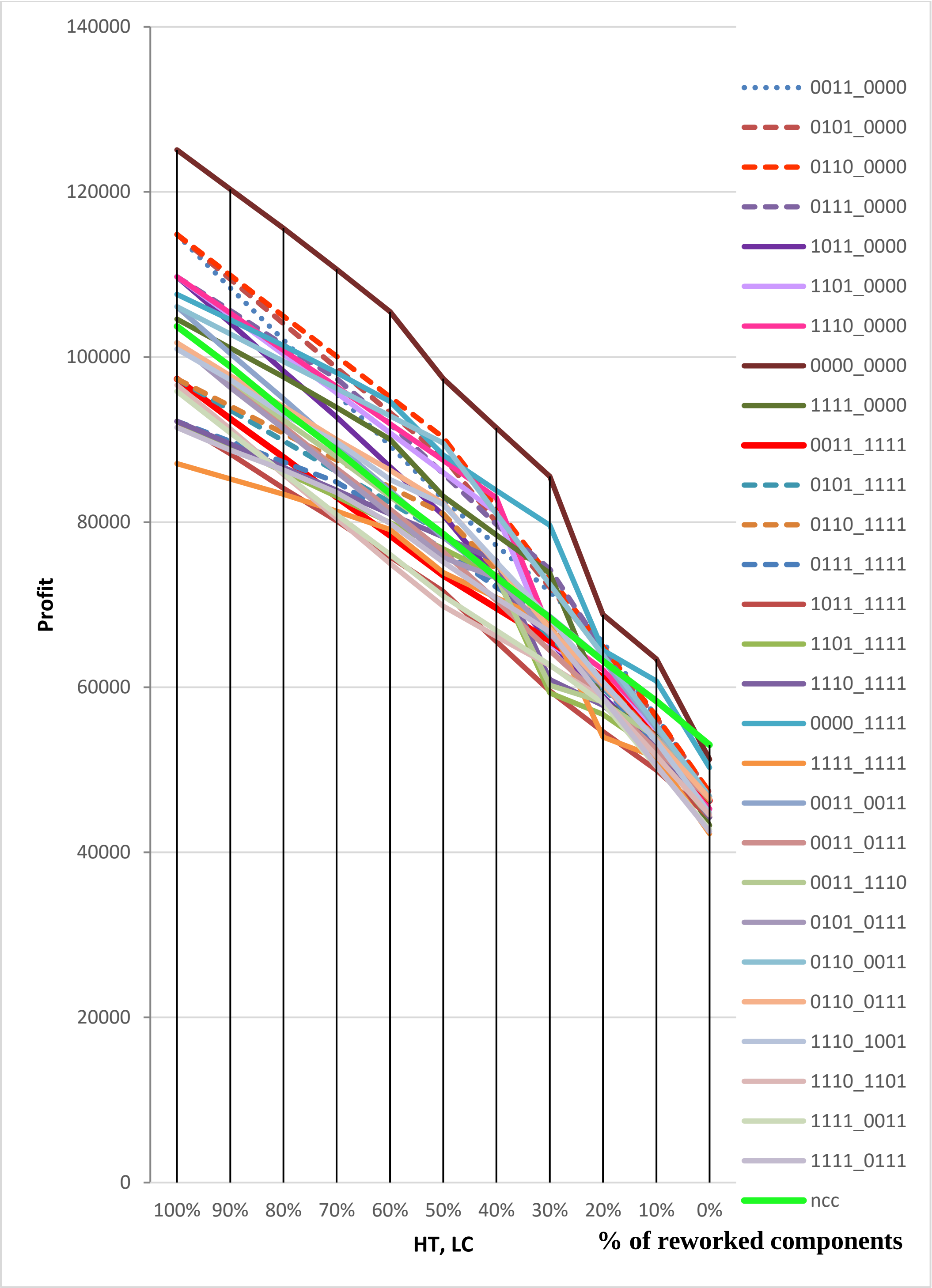


Figure II.14 The relationship between the profit and the percentage of reworked components for cases with high reworking time and low reworking costs (Maximising profit and minimising time)

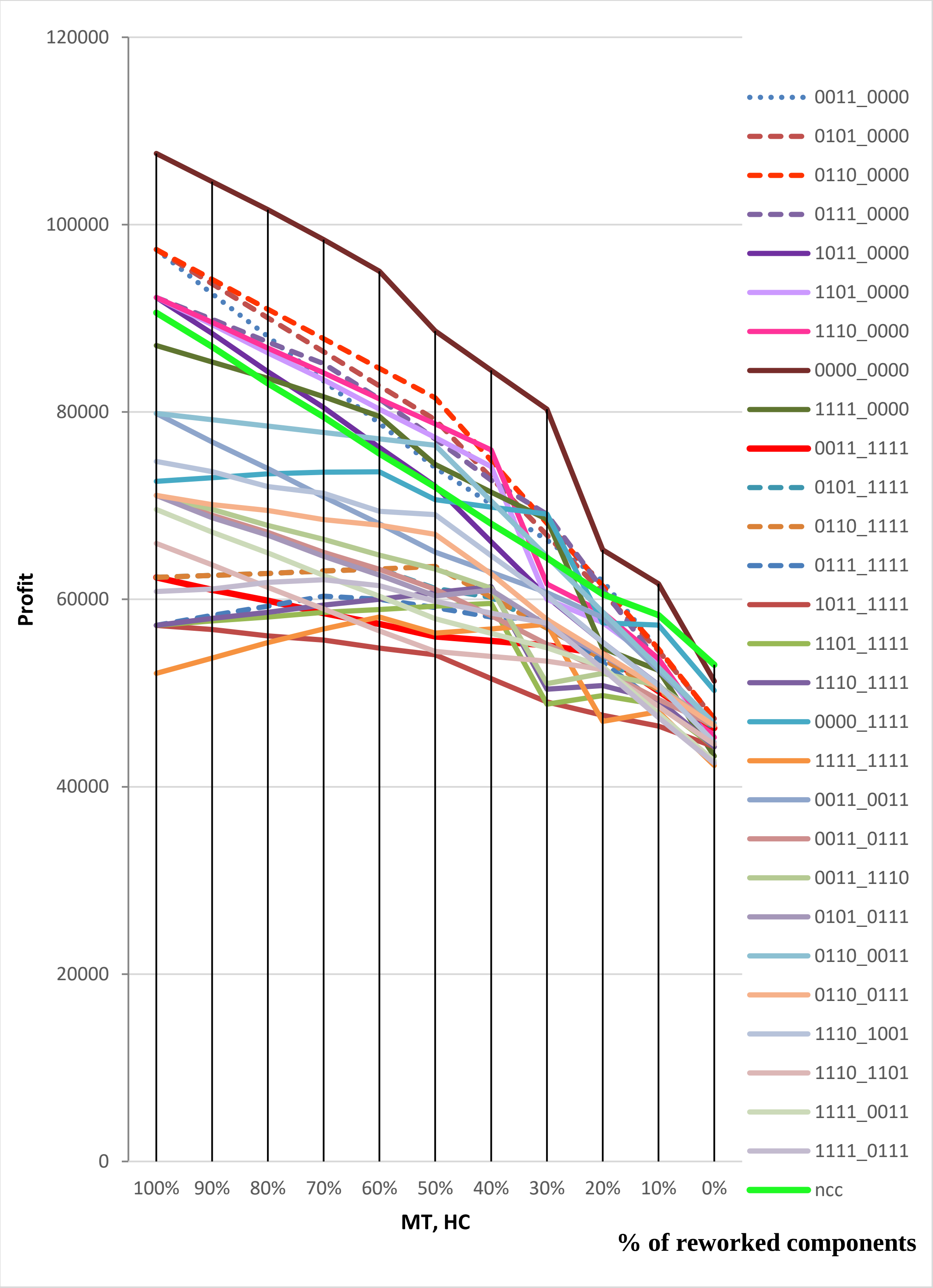


Figure II.15 The relationship between the profit and the percentage of reworked components for cases with medium reworking time and high reworking costs (Maximising profit and minimising time)

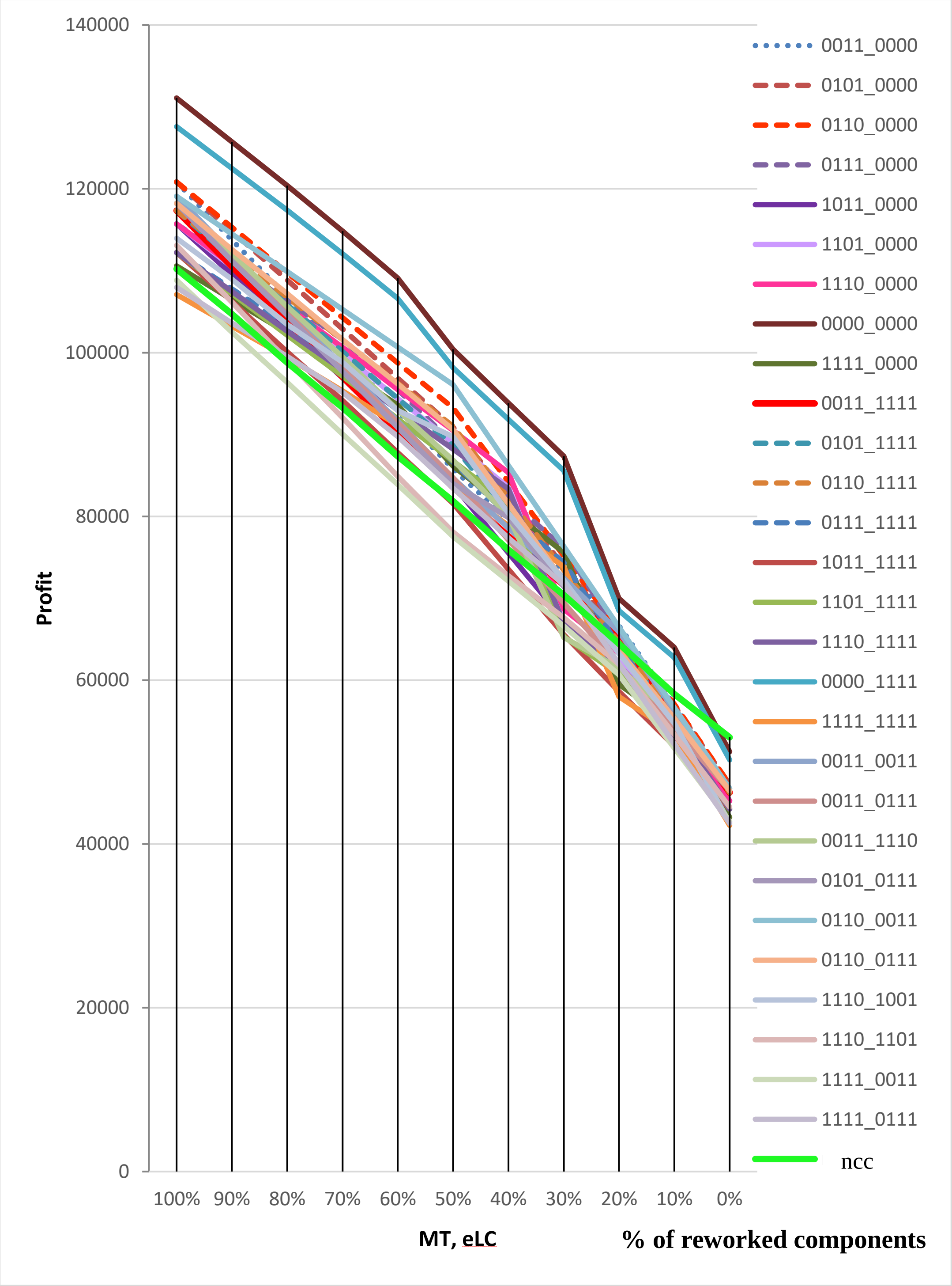


Figure II.16 The relationship between the profit and the percentage of reworked components for cases with medium reworking time and extremely low reworking costs (Maximising profit and minimising time)

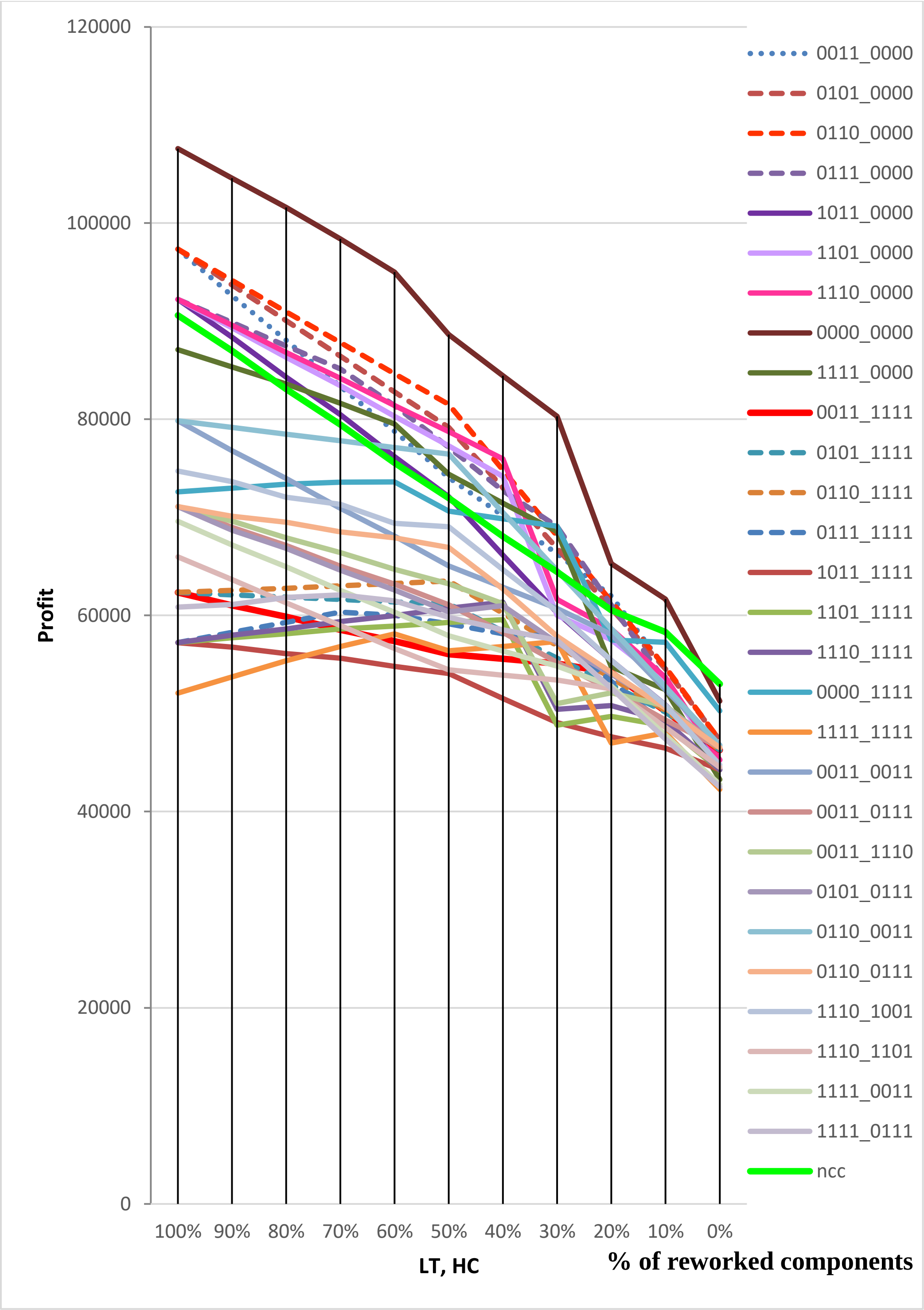


Figure II.17 The relationship between the profit and the percentage of reworked components for cases with low reworking time and high reworking costs (Maximising profit and minimising time)

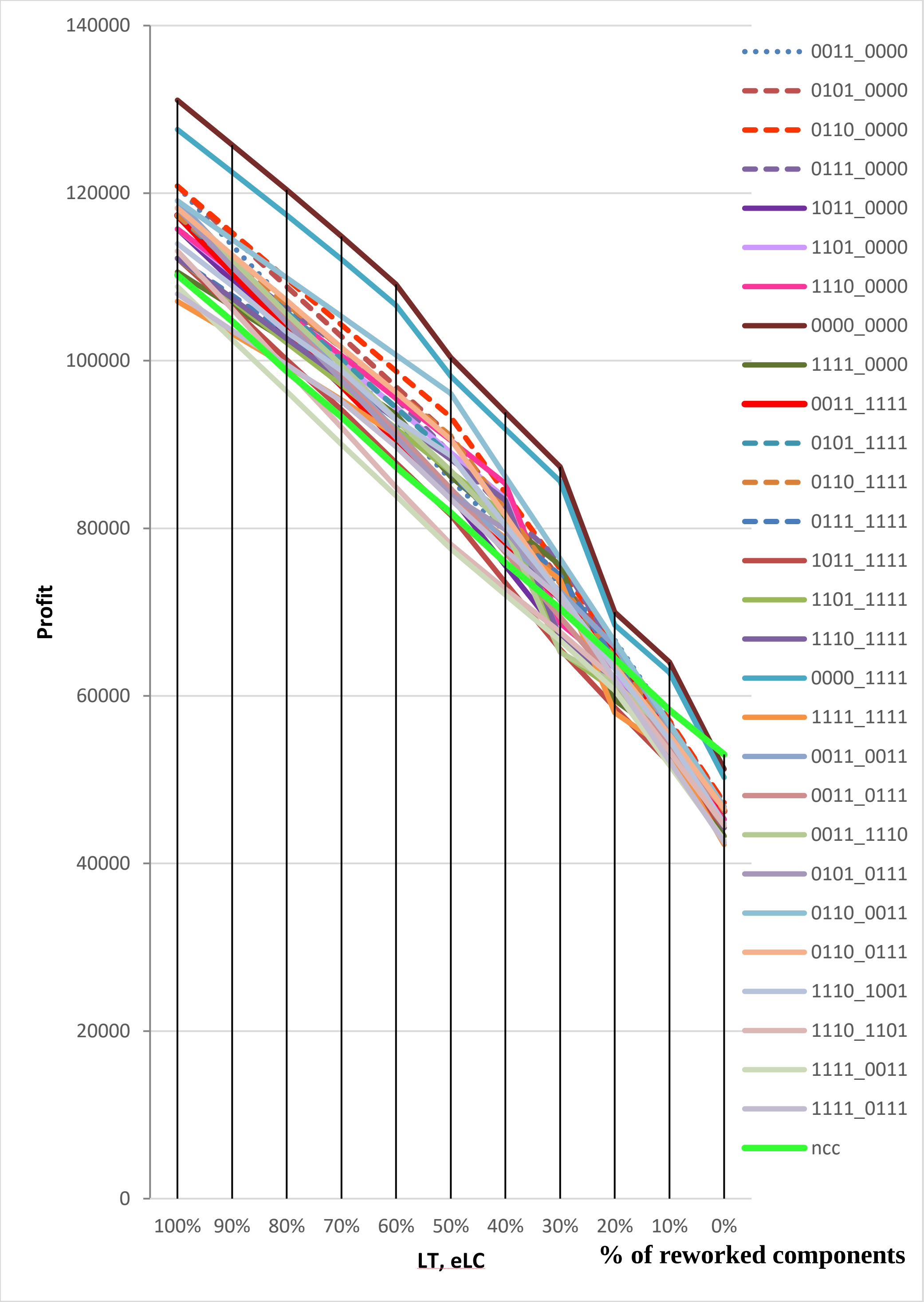


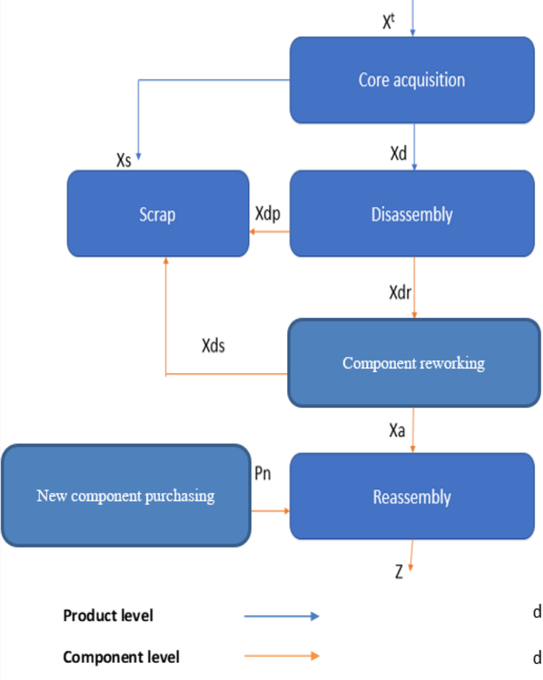
Figure II.18 The relationship between the profit and the percentage of reworked components for cases with low reworking time and extremely low reworking costs (Maximising profit and minimising time)

Appendix III: The model step 2

Benefits of the model

- The goal of this study is to ***find*** the ***optimal number*** of ***components*** and ***products*** for each remanufacturing activity to optimise profit or time.
- This proposed model can provide a company an infinite number of ***remanufacturing plans*** by ***maximising profit, minimising time*** or the combination of these ***two objectives***.

The flow of volume balance of products and components in remanufacturing



Xt=Xs+Xd

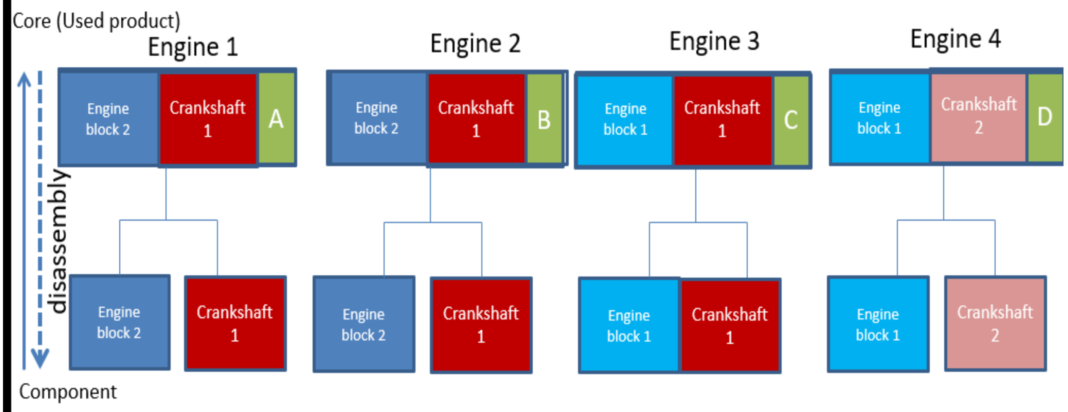
nXd=Xdp+Xdr, n= number of components can be generated from one core

Xdr= Xds+Xa

Z=Xa+Pn

X^t = No. of cores that should be acquired
X^d = No. of cores that should be disassembled
X^s = No. of cores that should be scrapped
X^{dp} = No. of components should be scrapped after disassembly
X^{dr} = No. of components should be reworked after disassembly
X^{ds} = No. of components should be scrapped after reworking
X^a = No. of components should be reworked
P^n = No. of new components should be reassembled
Z = Demand of components

Engine assembly structure



🟩 Other subassembly

This study focus on two types of components: engine block and crankshaft.

Example of Bill of material (0011_1110)

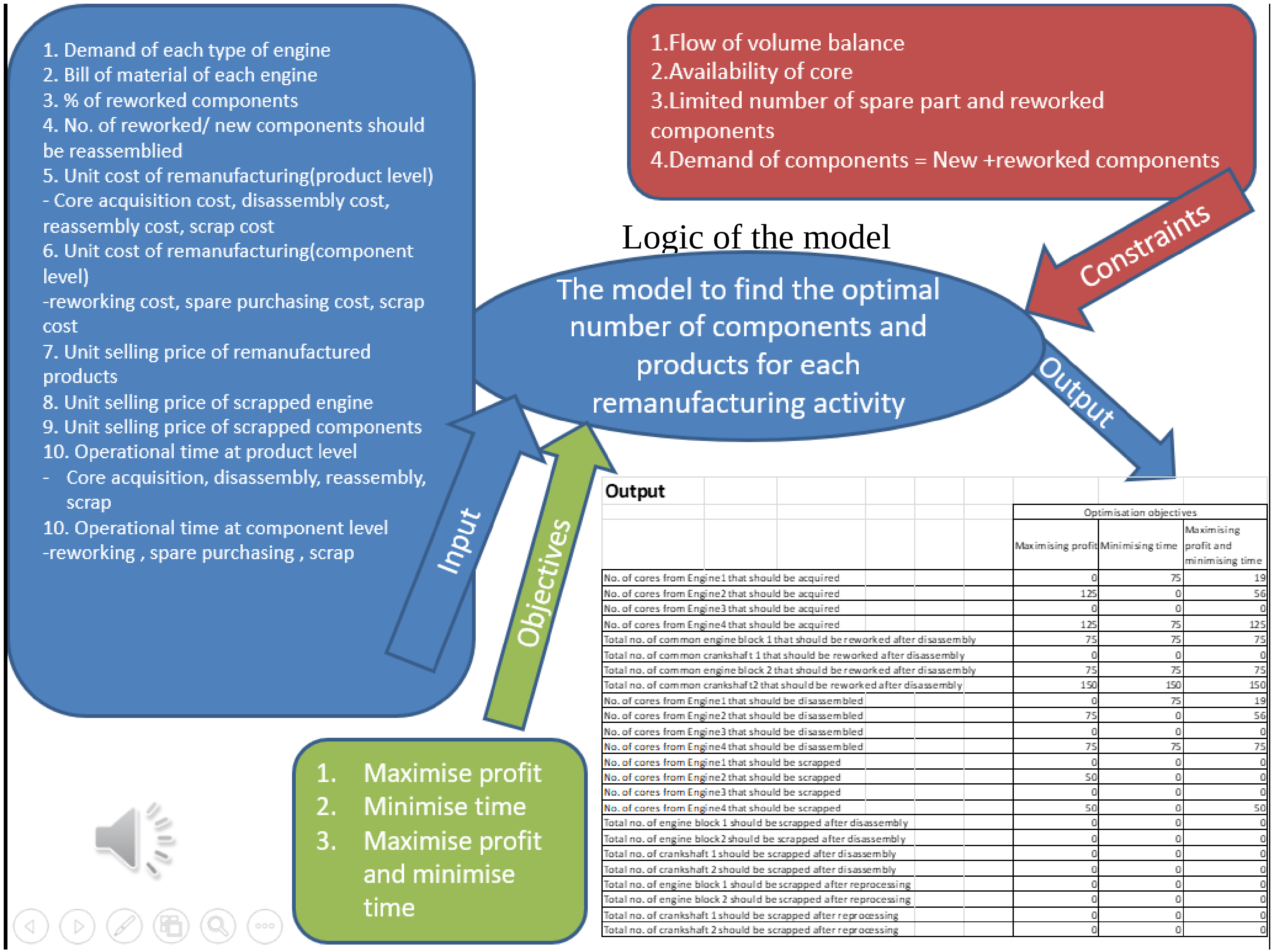
Component	Engine1	Engine 2	Engine3	Engine4	Component	Engine1	Engine 2	Engine3	Engine4
Engine block1	0	0	1	1	Crankshaft1	1	1	1	0
Engine block2	1	1	0	0	Crankshaft2	0	0	0	1

1 = share the components in common

This research studied various cases with different bill of material. The first table uses bill of material 0011_1100 as an example. It shows how bill of material describes the product commonality . This model assumes that there are two types of engine blocks and two types of crankshafts. Since engine 3 and engine 4 share the same engine block 1, engine 1 and engine 2 share the same engine block 2. Since engine 1 and engine 2 share the same crankshaft 1, engine 3 and engine 4 share the same crankshaft 2.

Characteristic of each type of engine and each type of component

Product level				
Engine	1	2	3	4
labour cost	lowest	low	highest	high
total cost	high	lowest	highest	low
time	fastest	fast	slowest	slow
Selling price	low	high	highest	lowest
Profit	low	highest	high	lowest
Component level				
Component	Engine block 1	Engine block2	Crankshaft 1	Crankshaft 2
cost	high	low	high	low
time	high	low	high	low



Logic of the model

1. Demand of each type of engine
2. Bill of material of each engine
3. % of reworked components
4. No. of reworked/ new components should be reassemblied
5. Unit cost of remanufacturing(product level)
- Core acquisition cost, disassembly cost, reassembly cost, scrap cost
6. Unit cost of remanufacturing(component level)
-reworking cost, spare purchasing cost, scrap cost
7. Unit selling price of remanufactured products
8. Unit selling price of scrapped engine
9. Unit selling price of scrapped components
10. Operational time at product level
- Core acquisition, disassembly, reassembly, scrap
10. Operational time at component level
-reworking , spare purchasing , scrap

1.Flow of volume balance
2.Availability of core
3.Limited number of spare part and reworked components
4.Demand of components = New +reworked components

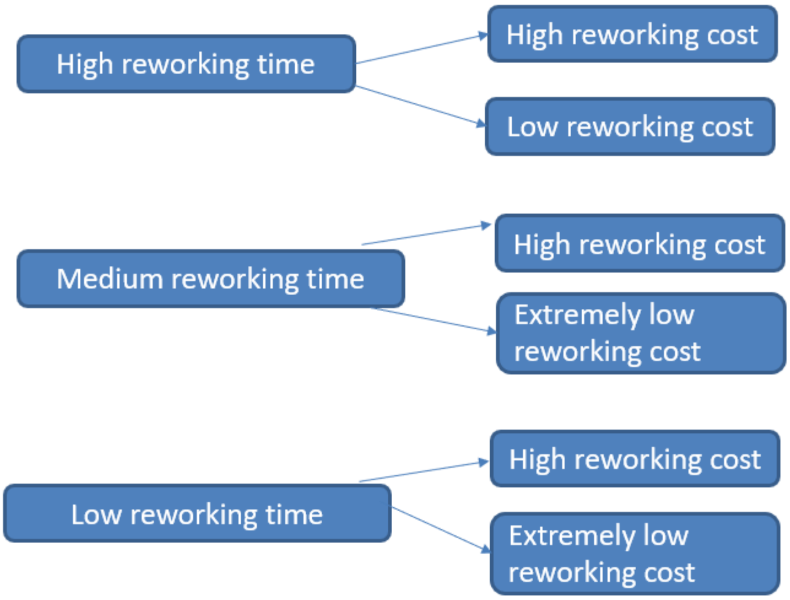
The model to find the optimal number of components and products for each remanufacturing activity

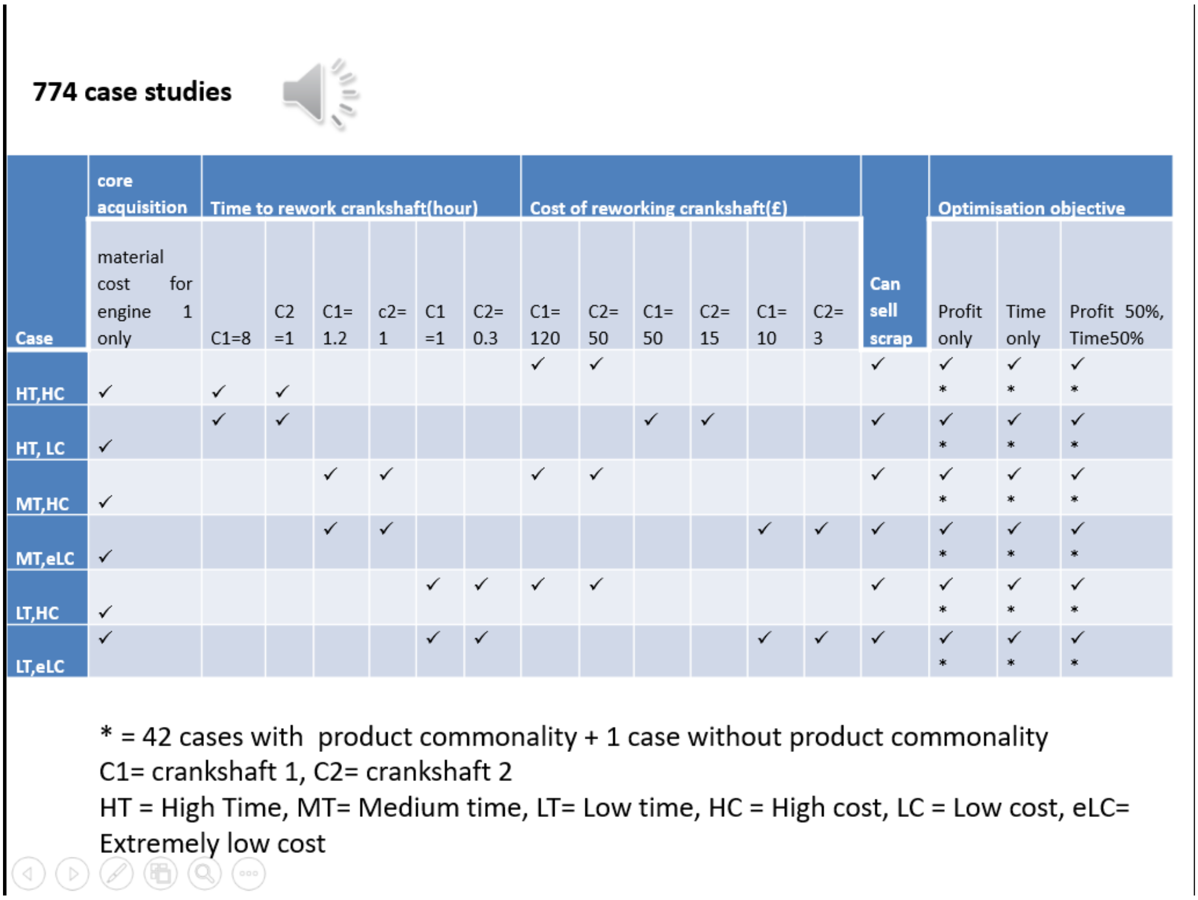
1. Maximise profit
2. Minimise time
3. Maximise profit and minimise time

Output

	Optimisation objectives		
	Maximising profit	Minimising time	Maximising profit and minimising time
No. of cores from Engine1 that should be acquired	0	75	19
No. of cores from Engine2 that should be acquired	125	0	56
No. of cores from Engine3 that should be acquired	0	0	0
No. of cores from Engine4 that should be acquired	125	75	125
Total no. of common engine block 1 that should be reworked after disassembly	75	75	75
Total no. of common crankshaft 1 that should be reworked after disassembly	0	0	0
Total no. of common engine block 2 that should be reworked after disassembly	75	75	75
Total no. of common crankshaft2 that should be reworked after disassembly	150	150	150
No. of cores from Engine1 that should be disassembled	0	75	19
No. of cores from Engine2 that should be disassembled	75	0	56
No. of cores from Engine3 that should be disassembled	0	0	0
No. of cores from Engine4 that should be disassembled	75	75	75
No. of cores from Engine1 that should be scrapped	0	0	0
No. of cores from Engine2 that should be scrapped	50	0	0
No. of cores from Engine3 that should be scrapped	0	0	0
No. of cores from Engine4 that should be scrapped	50	0	50
Total no. of engine block 1 should be scrapped after disassembly	0	0	0
Total no. of engine block2 should be scrapped after disassembly	0	0	0
Total no. of crankshaft 1 should be scrapped after disassembly	0	0	0
Total no. of crankshaft 2 should be scrapped after disassembly	0	0	0
Total no. of engine block 1 should be scrapped after reprocessing	0	0	0
Total no. of engine block 2 should be scrapped after reprocessing	0	0	0
Total no. of crankshaft 1 should be scrapped after reprocessing	0	0	0
Total no. of crankshaft 2 should be scrapped after reprocessing	0	0	0

- This research studies the sensitivity of reworking cost and reworking time

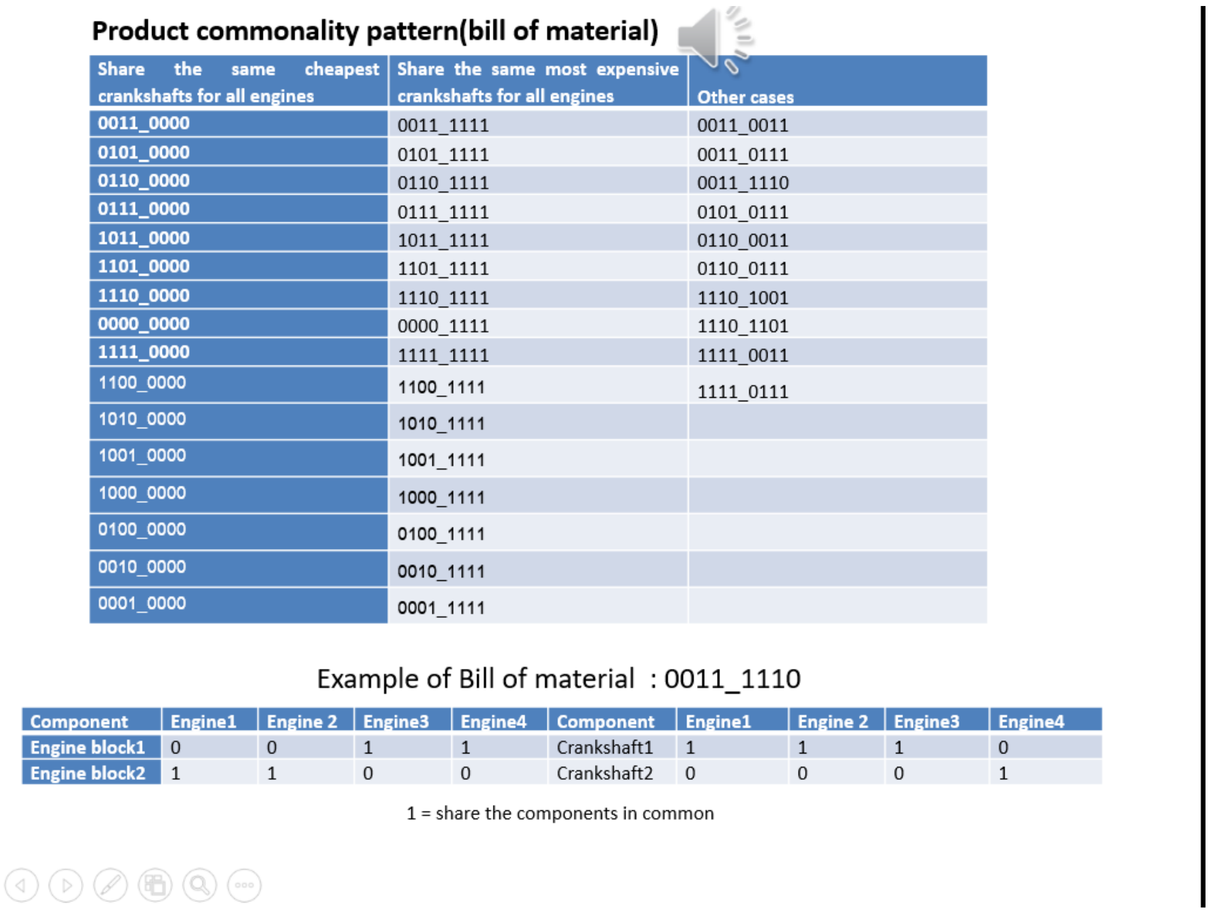




774 case studies

	core acquisition	Time to rework crankshaft(hour)						Cost of reworking crankshaft(£)							Optimisation objective		
Case	material cost for engine 1 only	C1=8	C2 =1	C1= 1.2	c2= 1	C1 =1	C2= 0.3	C1= 120	C2= 50	C1= 50	C2= 15	C1= 10	C2= 3	Can sell scrap	Profit only	Time only	Profit 50%, Time50%
HT,HC	✓	✓	✓					✓	✓					✓	✓ *	✓ *	✓ *
HT, LC	✓	✓	✓							✓	✓			✓	✓ *	✓ *	✓ *
MT,HC	✓			✓	✓			✓	✓					✓	✓ *	✓ *	✓ *
MT,eLC	✓			✓	✓							✓	✓	✓	✓ *	✓ *	✓ *
LT,HC	✓					✓	✓	✓	✓					✓	✓ *	✓ *	✓ *
LT,eLC	✓					✓	✓					✓	✓	✓	✓ *	✓ *	✓ *

* = 42 cases with product commonality + 1 case without product commonality
C1= crankshaft 1, C2= crankshaft 2
HT = High Time, MT= Medium time, LT= Low time, HC = High cost, LC = Low cost, eLC= Extremely low cost



Product commonality pattern(bill of material)

Share the same cheapest crankshafts for all engines	Share the same most expensive crankshafts for all engines	Other cases
0011_0000	0011_1111	0011_0011
0101_0000	0101_1111	0011_0111
0110_0000	0110_1111	0011_1110
0111_0000	0111_1111	0101_0111
1011_0000	1011_1111	0110_0011
1101_0000	1101_1111	0110_0111
1110_0000	1110_1111	1110_1001
0000_0000	0000_1111	1110_1101
1111_0000	1111_1111	1111_0011
1100_0000	1100_1111	1111_0111
1010_0000	1010_1111	
1001_0000	1001_1111	
1000_0000	1000_1111	
0100_0000	0100_1111	
0010_0000	0010_1111	
0001_0000	0001_1111	

Example of Bill of material : 0011_1110

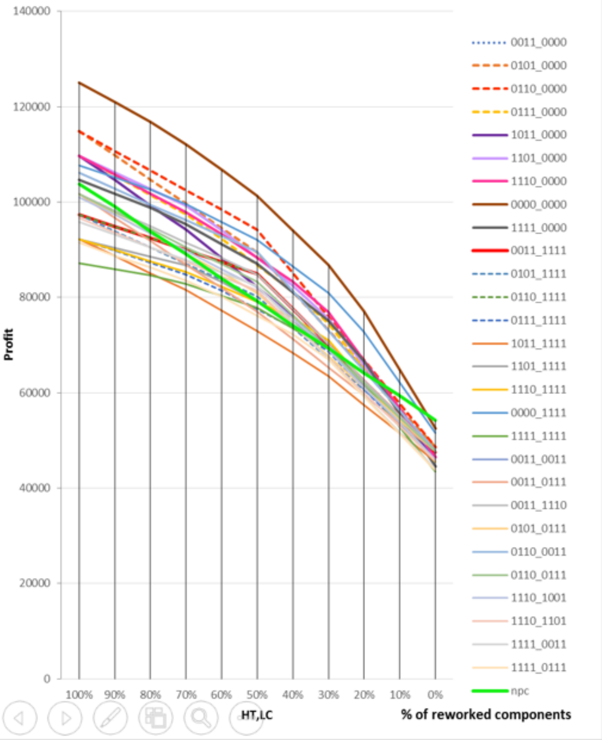
Component	Engine1	Engine 2	Engine3	Engine4	Component	Engine1	Engine 2	Engine3	Engine4
Engine block1	0	0	1	1	Crankshaft1	1	1	1	0
Engine block2	1	1	0	0	Crankshaft2	0	0	0	1

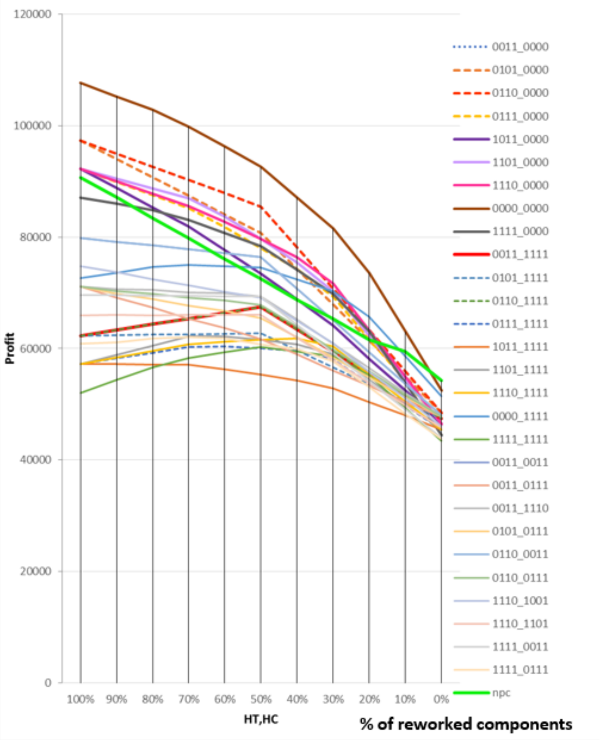
1 = share the components in common

New findings

Results from the model

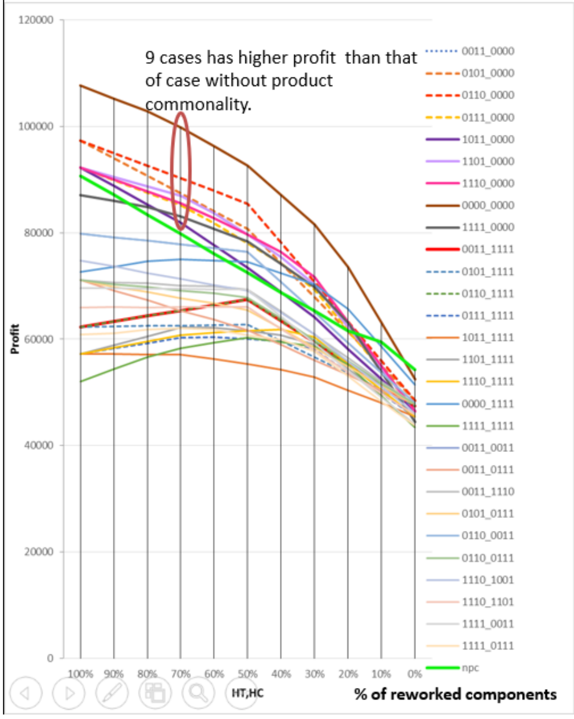
1. When reworking cost is higher and % of reworked components is higher, there is a bigger size of the gap between the highest profit and the lowest profit of different product commonality patterns. The remanufacturer can control this situation by lowering reworking cost or selecting only product commonality patterns that generate high profit to prevent the lower profit and fluctuation of profit.

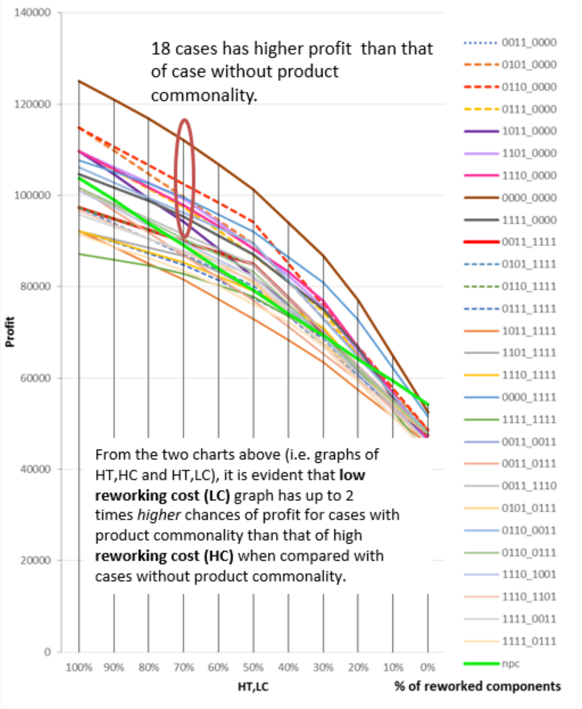




Results from the model

2. When reworking cost is lower, it has higher chance that profit of cases with product commonality is higher than that of case without product commonality


9 cases has higher profit than that of case without product commonality.


18 cases has higher profit than that of case without product commonality.

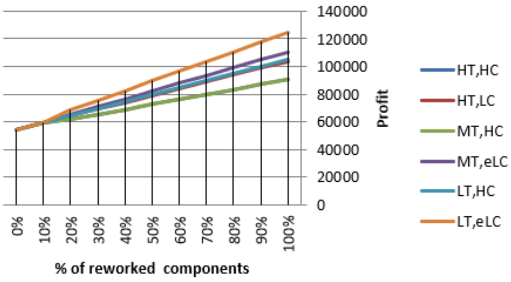
From the two charts above (i.e. graphs of HT,HC and HT,LC), it is evident that **low reworking cost (LC)** graph has up to 2 times *higher* chances of profit for cases with product commonality than that of high **reworking cost (HC)** when compared with cases without product commonality.

Results from the model

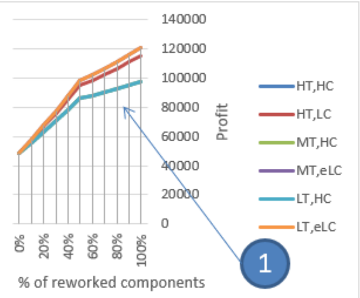
3. Study on correlation of the profit vs % of reworked components

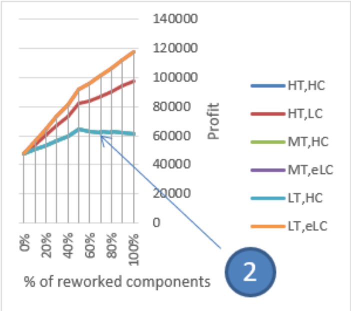
Cases without product commonality

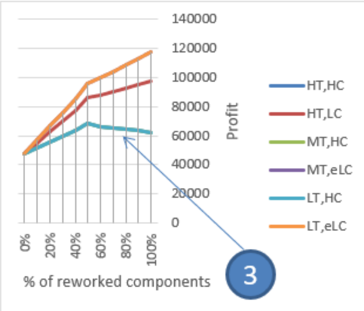
There is a positive correlation between profit and % of reworked components.



Cases with product commonality







At low and extremely low reworking cost, there is a positive correlation between profit and % of reworked components

At high reworking cost, the profit can increase, remain steady or decrease or if there is an increasing % of reworked components ① ② ③

Findings to reinforce existing real practice

Results from the model

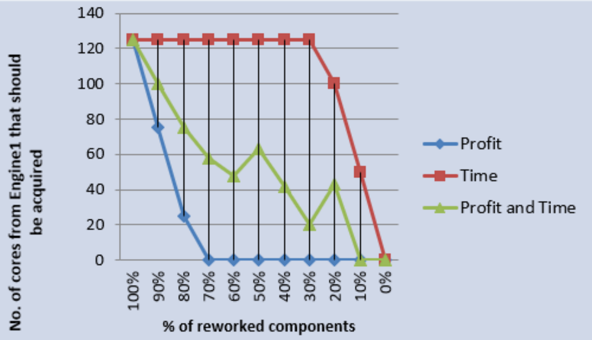
3. If remanufacturers don’t want to lower the profit when increasing % of expensive reworked components , they should avoid sharing the same expensive components for all engines.

4. High sharing can cause high profit. In case of 100% of reworked components are needed, the higher sharing of the cheapest components, the higher profit the remanufacturer can gain.

5.1. Given the same demand of components and the same optimisation objective and the same % of reworked component, the optimal number of components/products required for each remanufacturing activity does not change regardless of reworking time and reworking cost.

Factors	
Reworking cost	**Reworking time**
high	high
high	medium
high	low
low	high
extremely low	medium
extremely low	low

The optimal number of components/products required for each remanufacturing activities of 1111_1111 when changing reworking cost and reworking time



For example, when considering only maximising profit at 70% of reworked components, the optimal number of components/products required for each remanufacturing activity does not change regardless of reworking time and reworking cost.

Example of Bill of material (0011_1110)

Component	Engine1	Engine 2	Engine3	Engine4	Component	Engine1	Engine 2	Engine3	Engine4
Engine block1	0	0	1	1	Crankshaft1	1	1	1	0
Engine block2	1	1	0	0	Crankshaft2	0	0	0	1

1 = share the components in common

Example of Bill of material (0011_0011)

Component	Engine1	Engine 2	Engine3	Engine4	Component	Engine1	Engine 2	Engine3	Engine4
Engine block1	0	0	1	1	Crankshaft1	0	0	1	1
Engine block2	1	1	0	0	Crankshaft2	1	1	0	0

1 = share the components in common

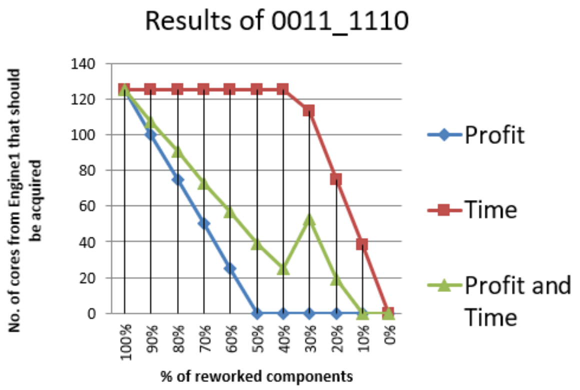
Characteristic of each type of engine and each type of component

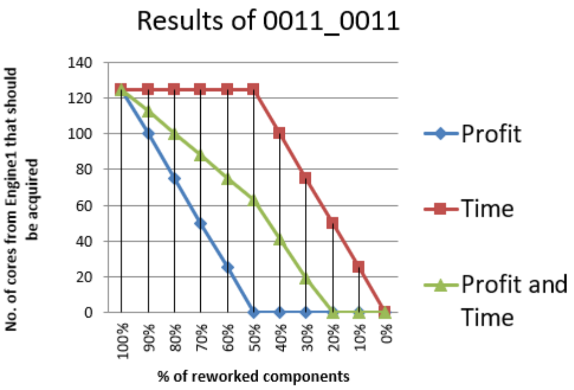
All information is used in result 5.2

Product level				
Engine	1	2	3	4
labour cost	lowest	low	highest	high
total cost	high	lowest	highest	low
time	fastest	fast	slowest	slow
Selling price	low	high	highest	lowest
Profit	low	highest	high	lowest
Component level				
Component	Engine block 1	Engine block2	Crankshaft 1	Crankshaft 2
cost	high	low	high	low
time	high	low	high	low

Results from the model

5.2. Changing components sharing between engines has an impact on the optimal number of components for each remanufacturing activities.





Results from the model

5.3 If remanufacturers want **a fast process**, then they should acquire/disassemble the higher number of fast-processed cores and decrease number of slower- processed cores if the slower processed cores and faster-processed cores share the same components in common

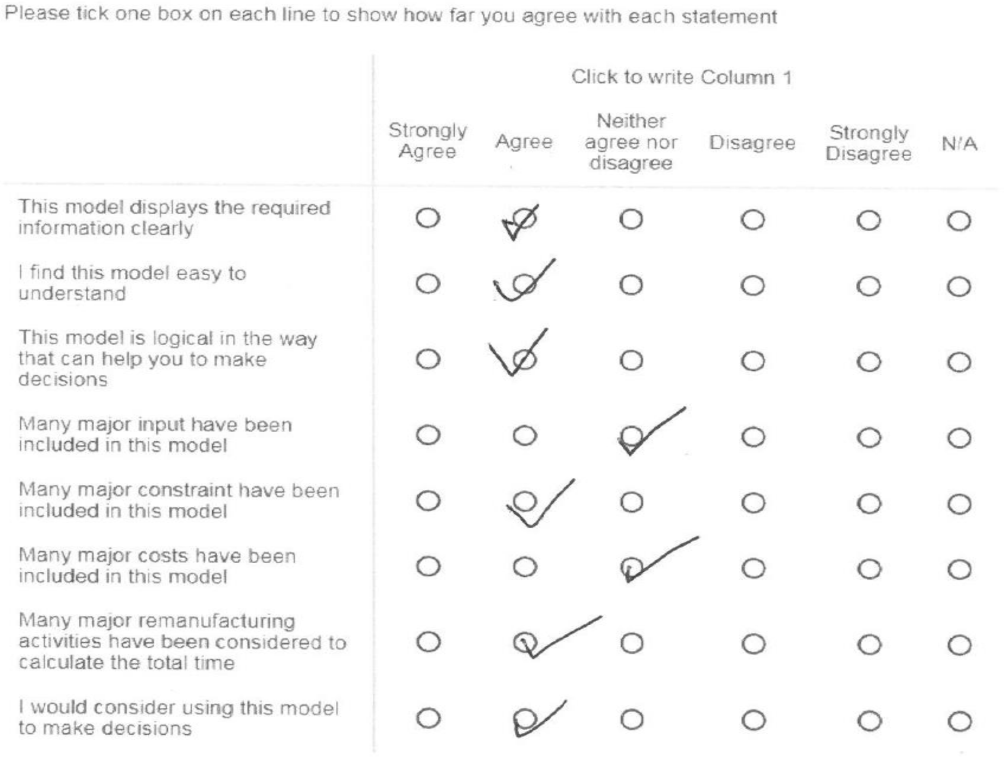
5.4 If remanufacturer wants **higher profit**, then they should avoid core acquisition of expensive products but acquire high-profit cores if the two types of engines: the high profit and the one with the highest acquisition cost share the same components in common

5.5 Remanufacturers should not scrap the most expensive cores. It will waste time and money if they eventually scrap them after remanufacturing them.

5.6 Optimal number of reassembled component after reworking should be as same as the number of components that should be reworked after disassembly. Remanufacturers should not scrap components after reworking in order to operate the system optimally.

5.7 If remanufacturer wants higher profit but not consider product commonality when % of reworked components is lower, they need to maintain acquiring the same amounts of cheap cores. They need to scrap higher number of the cores with the low scrap costs when % of reworked components is lower.

Appendix IV: The example of validation results of the model step 1



Please tick one box on each line to show how far you agree with each statement

	Click to write Column 1					
	Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree	N/A
This model displays the required information clearly	○	☑	○	○	○	○
I find this model easy to understand	○	☑	○	○	○	○
This model is logical in the way that can help you to make decisions	○	☑	○	○	○	○
Many major input have been included in this model	○	○	☑	○	○	○
Many major constraint have been included in this model	○	☑	○	○	○	○
Many major costs have been included in this model	○	○	☑	○	○	○
Many major remanufacturing activities have been considered to calculate the total time	○	☑	○	○	○	○
I would consider using this model to make decisions	○	☑	○	○	○	○

If the model was not complete, what can you suggest?

- more processes should be considered for the 3D printing option as it should be the hybrid process of machining + 3D printing + machining
- Coating may be considered for both machining and 3D printing process

Any additional comments?

Please tick one box on each line to show how far you agree with each statement

	Click to write Column 1					
	Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree	N/A
This model displays the required information clearly	○	●	○	○	○	○
I find this model easy to understand	○	●	○	○	○	○
This model is logical in the way that can help you to make decisions	○	●	○	○	○	○
Many major input have been included in this model	○	●	○	○	○	○
Many major constraint have been included in this model	○	○	●	○	○	○
Many major costs have been included in this model	○	●	○	○	○	○
Many major remanufacturing activities have been considered to calculate the total time	○	●	○	○	○	○
I would consider using this model to make decisions	○	○	●	○	○	○

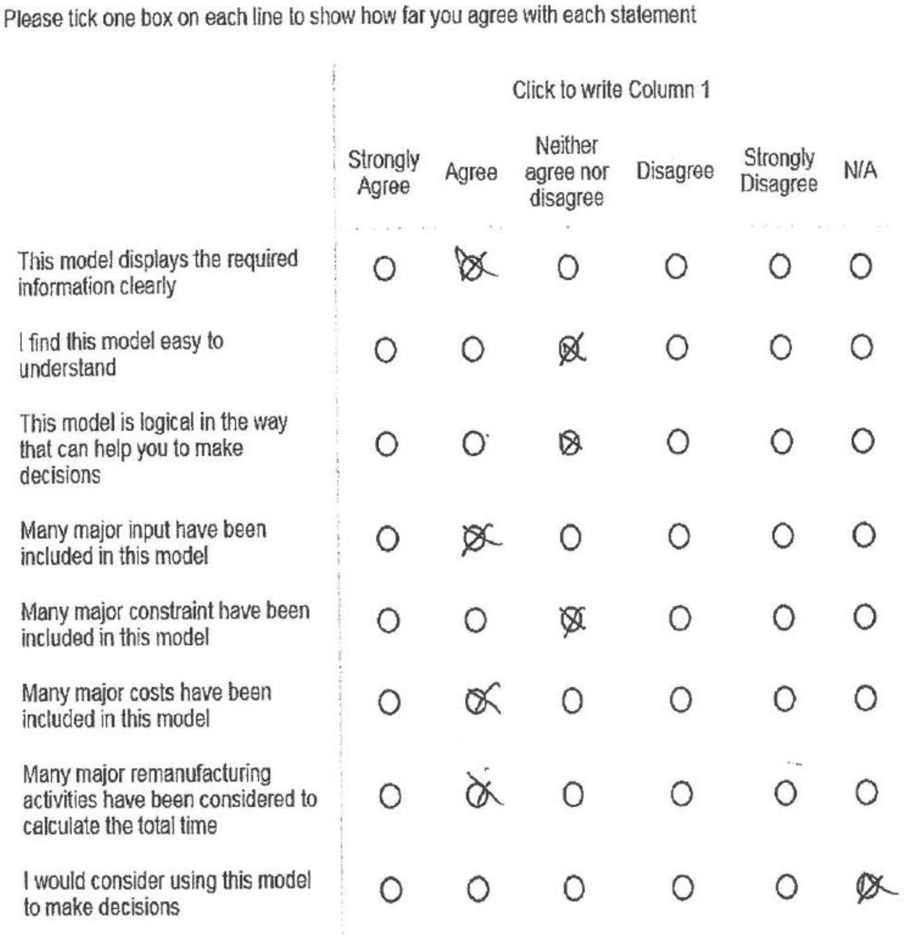
If the model was not complete, what can you suggest?

Your concept of reliability is currently binary. I think you need to consider statistical data and the distributional characteristics.

Any additional comments?

I recommend to talk to industry people. They give you the best feedback in terms of usability of your tool.

Great job :)



Please tick one box on each line to show how far you agree with each statement

	Click to write Column 1					
	Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree	N/A
This model displays the required information clearly	○	☒	○	○	○	○
I find this model easy to understand	○	○	☒	○	○	○
This model is logical in the way that can help you to make decisions	○	○	☒	○	○	○
Many major input have been included in this model	○	☒	○	○	○	○
Many major constraint have been included in this model	○	○	☒	○	○	○
Many major costs have been included in this model	○	☒	○	○	○	○
Many major remanufacturing activities have been considered to calculate the total time	○	☒	○	○	○	○
I would consider using this model to make decisions	○	○	○	○	○	☒

If the model was not complete, what can you suggest?

Any additional comments?

I think you need to explain the model more easy. It was quite hard to understand the model just by looking at the A4-paper and the example.

Some basic questions that needs to be made clear from start are:

a) Who is the intended user?
b) When should the user use the model?
c) What kind of data needs to be inserted at every use?
d) What data input is needed before using the model?
e) What is the overall objective to use the model?

Project Engineer
Automotive

Please tick one box on each line to show how far you agree with each statement

	Click to write Column 1					
	Strongly Agree	Agree	Neither agree nor disagree	Disagree	Strongly Disagree	N/A
This model displays the required information clearly	○	✓	○	○	○	○
I find this model easy to understand	○	✓	○	○	○	○
This model is logical in the way that can help you to make decisions	○	✓	○	○	○	○
Many major input have been included in this model	○	✓	○	○	○	○
Many major constraint have been included in this model	○	✓	○	○	○	○
Many major costs have been included in this model	○	✓	○	○	○	○
Many major remanufacturing activities have been considered to calculate the total time	✓	○	○	○	○	○
I would consider using this model to make decisions	✓	○	○	○	○	○

Project Engineer
Automotive

If the model was not complete, what can you suggest?

o Availability of new replacement components

Any additional comments?

Appendix V: The example of the validation results of the model step 2

Company B

1. On a scale from 1-10, what would you rate the reasonableness of each result for the model (1= the lowest, 10 = the highest)

The result from the model	Score
1	9
2	9
3	9
4	9
5.1	9
5.2	8
5.3	10
5.4	10
5.5	10
5.6	10
5.7	10

2. Could you give any comments regarding clarity of the model, the sufficiency of data and applicability of the model

I can see the point that this model can discover the decision the conventional planning system cannot do because the model allows the users with the following features.

1. The users can select the optimisation objectives and the model can recommend the optimal number of components required for each remanufacturing activity. This model adopted the supports bi-objective optimisation which saves companies from determining the importance of each objective.

2. The model considered component commonality and % of the reworked component to optimise the remanufacturing benefits. New knowledge can tell the company to consider more about component commonality for their business. For example, if there are 10 possible component commonality patterns to use, the decision model may suggest that the remanufacturers use only 2 patterns of component commonality to improve the company profit.

However, I think there are rooms for improvements.

1. The logic of the model was poorly presented, so it should be improved.
2. The sentences describing the results of the model are difficult to understand because they are very long sentences.
3. The component commonality concept should be described clearly.
4. The model did not cover all possible component commonality cases

Company G

1. On a scale from 1-10, what would you rate the reasonableness of each result for the model (1= the lowest, 10 = the highest)

The result from the model	**Score**
1	9
2	9
3	9
4	9
5.1	9
5.2	10
5.3	10
5.4	10
5.5	10
5.6	10
5.7	10

2. Could you give any comments regarding clarity of the model, the sufficiency of data and applicability of the model

Dear Sakraan,

I have taken the time to review your 19-page presentation. I can see that you have put a significant amount of work in since we met on the stand at ReMaTec 2019.

The core is more often free-issued by the OEMs on our higher volume business model, plus we do not build for stock, so there is no risk of resulting scrap of finished units.

I can see some of the merits for smaller businesses should they have the resource that could apply this swiftly.

Kind regards,

Managing Director

Company H

1. On a scale from 1-10, what would you rate the reasonableness of each result for the model (1= the lowest, 10 = the highest)

The result from the model	Score
1	9
2	10
3	9
4	10
5.1	9
5.2	10
5.3	9
5.4	10
5.5	10
5.6	9
5.7	10

2. Could you give any comments regarding clarity of the model, the sufficiency of data and applicability of the model

I can see the point that this model can discover the decision the conventional planning system cannot do because the model allows the users with the following features.

1. The users can select the optimisation objectives and the model can recommend the optimal number of components required for each remanufacturing activity.
2. The model considered component commonality and % of the reworked component to optimise the remanufacturing benefits. New knowledge can tell the company to consider more about component commonality for their business. For example, if there are 10 possible component commonality patterns to use, the decision model may suggest that the remanufacturers use only 2 patterns of component commonality to improve the company profit.
3. With this model, remanufacturers can define the different remanufacturing scenarios and examine the associated effects of component commonality. This will make remanufacturers more proactive in decision-making, such as adjusting remanufacturing time/costs of certain components to optimise the overall remanufacturing outcomes.

However, I think there are rooms for improvements.

1. The logic of the model was poorly presented, so it should be improved.

2. The sentences describing the results of the model are difficult to understand because they are very long sentences.

3. The component commonality concept should be described clearly.

Company I

1. On a scale from 1-10, what would you rate the reasonableness of each result for the model (1= the lowest, 10 = the highest)

The result from the model	**Score**
1	**9**
2	**9**
3	**9**
4	**9**
5.1	**9**
5.2	**9**
5.3	**9**
5.4	**10**
5.5	**10**
5.6	**10**
5.7	**10**

2. Could you give any comments regarding clarity of the model, the sufficiency of data and applicability of the model

Dear Nik

Some comments or advice:

- I understand you limit the study to an engine block and crankshaft. Would your ppt benefit to having some visual (i.e. slide 4). This will illustrate the commonality of parts....it is not obvious for one who is not coming from reman. Also, you have to bring the problematic of latest design index remanufacturing. What I mean is that usually your cores are remanufactured to the latest index....car makers request this to my knowledge...therefore this is creating an array of core values....or new components injected to meet that level
- Slide 5 is not so clear in my view. I guess you want to show that for a given engine you can find a similar block or crankshaft?
- Slide 8. You mention 774 studies...this means you have explored 774 different types of engines BOM? quite impressive. The coefficient like C1 is an example or real value of time to spend? Maybe it should be detailed or explained how you came to this
- Slide 12. Your conclusion is what remanufacturers observe I think. However, the important factor is the scale of the reman component vs labour cost in unit : i.e. situation is not the same when you are remanufacturing a car alternator (where the price is low) or when you remanufacture a large Diesel engine.....maybe a comment to make. I would guess you find the same profit variance when you consider small size vs large engine.

Appendix VI: List of publications

1. SITCHARANGSIE, S., IJOMAH, W. & WONG, T. C. 2017. An investigation of the value recovery process in the automotive remanufacturing industry : an empirical approach. *The 3rd International Conference on Remanufacturing*, Linköping University, Linköping, Sweden, 24-26 October 2017.

2. SITCHARANGSIE, S., IJOMAH, W. & WONG, T. C. 2019. Decision makings in key remanufacturing activities to optimise remanufacturing outcomes: A review. *Journal of Cleaner Production,* 232**,** 1465-1481.