**Improving the efficiency of remanufacture through enhanced pre-processing inspection – a comprehensive study of over 2000 engines at Caterpillar Remanufacturing, UK.**

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**Abstract**
Remanufacture, an industrial process to return used product to an “as-new” condition, is a key strategy in environmentally conscious manufacturing and waste management as well as being a profitable revenue stream for OEMs and independent companies. However, strategies to improve the efficiency of the process are hampered by a lack of remanufacturing-specific knowledge and tools. This paper presents the results of quantitative research, conducted in an industrial remanufacturing facility, to establish the relationship between pre-processing inspection levels and the subsequent remanufacturing process time for returned used products (known as cores). It concludes that for components (i.e. cores) having either complex geometry (such as internal ports), a large number of sub-components or that are constructed from, or comprising of, multiple materials the remanufacturing process is shortened by increased inspection prior to processing. However, these benefits are currently limited by the amount of information that can be gained from the inspection methods used. The paper describes the practical use of these results in both a decision-making methodology for inspection and a cost assessment tool.

**Keywords**: remanufacturing, pre-processing inspection, decision-making, cost-assessment; productivity

## 1. Introduction

Remanufacture is a process which returns used products an "as-new" functionality with a warranty that is at least equal to a newly manufactured equivalent (Ijomah, 2002; BSI (2009); BSI (2006)). It is typically carried out on complex mechanical assemblies as the remaining value in the used product justifies the costs incurred. Remanufacturing activities are categorised as 'reduction' and 'reuse', the top two preferred waste management options identified in the EU's Fifth Environmental Action Programme. Nevertheless, recycling is often the default end-of-life choice for environmentally conscious enterprises. Indeed, UK government figures (DEFRA, 2009) estimate that of the waste going to landfill, only between 2% and 9% is diverted to remanufacturing and other reuse methods, whereas 44% is recycled. The reduction in landfill from reuse benefits society as proliferating landfill sites can drive down property prices and subject residents to nuisance such as odour, noise and an increase in vermin (DEFRA, 2003).

Remanufacturing is also a more efficient reuse strategy as, in addition to similar reductions in landfill and the use of virgin material, it reduces the amount of energy used in production by removing the need for raw material production and the subsequent forming processes (e.g. machining or casting). Thus slowing, or reducing, the production of greenhouse gas emissions such as $CO_2$. For example, Sutherland *et al*. (2008) found that at the component level, the energy savings could reach 90%. Lund (1984) suggested that up to 85% by weight of a remanufactured product may come from reclaimed components.
Remanufacturing also benefits wider society as it creates employment, particularly for unskilled and semi-skilled workers (Tang *et al.*, 2007) whilst providing products of the same quality as equivalent new products from conventional manufacturing but at typically 30% to 40% less cost.

Ilgin and Gupta, (2010), note that despite an increase in research during the first decade of this century, there is still a lack of remanufacturing specific tools and techniques. Parkinson and Thompson (2003) argue that this same lack of focus leads to the significance of remanufacturing in terms of sustainable development being underestimated. However, despite all of these factors, remanufacturers also have to be commercially, as well as environmentally sustainable, and so they seek to reduce costs and increase profit by both decreasing work content and reducing the included quantity of new material.

Guide (2000) identified that remanufacturers perceive the scarcity of effective remanufacturing tools and techniques as a key threat to the industry. Ijomah (2002) quantified these key characteristics and found that remanufacturers rated component inspection as critical. Observation of the industrial remanufacturing process by the authors suggested that the pre-processing inspection activity, although it can have significant bearing on overall productivity, is often undertaken in a hap-hazard manner based almost purely on experience or guesswork and consequently lacks proper methodologies and tools. However, it is known that efficiency and effectiveness are key requirements for enhancing productivity
(Womak *et al*., 2007). Motivated by these observations this paper presents the results of an experimental investigation to quantify the effects of differing levels of pre-processing inspection of cores on remanufacturing efficiency.

The rest of this paper is structured as follows: Section 2 briefly explains the remanufacturing context and reviews literature around the inspection process; section 3 then introduces the methodology, section 4 gives the experimental results, their analysis and significance whilst section 5 discusses the validation of the findings. Section 6 gives the limitations of the research and recommendations for future work and before the paper is concluded in section 7.

## 2. Theoretical Background and Industrial Setting of the Research

Remanufacturing has been carried out since the early decades of the $20^{th}$ century, but expanded significantly around the time of the Second World War because of the need to reuse military equipment coupled with the scarcity of new parts. OEMs (Original Equipment Manufacturer) and/or their agents and dealers remanufactured their own products (such as compressors and gearboxes) generally on a fairly small scale.
Lund (1984) defined three basic types of remanufacturer:

- OEM remanufacturers – often a process alongside their manufacturing operations;
- Third-party remanufacturers – remanufacturing under licence for the OEM and often, but not always with their technical support; and
- Independent remanufacturers – remanufacturing other people's goods without licence or support for direct sales into the aftermarket.

The key difference, in the context of this research, between independent remanufacturers on the one hand and OEM and contract remanufacturers on the other, is in terms of cores. Cores are used products at the end of their working life. In almost all cases the customers are responsible for return of core units with the remanufacturer having little control over the quantity, mix or quality of returns. This can have a significant impact on ability to supply customers as the cores received cannot be guaranteed to match the mix of remanufactured units required by the customer. In addition, contract remanufacturers operate with fixed cost contracts that allow for no additional charge to be made for badly damaged or incorrect core.

The actual remanufacturing process varies by product and methods. So processes such as direct material deposition, may be appropriate for more expensive components like cylinder blocks, but would not be suitable for remanufacturing mobile phones. Despite these differences the generic process (regardless of product) can be described schematically (Figure 1) (Hatcher *et al.*, 2013):

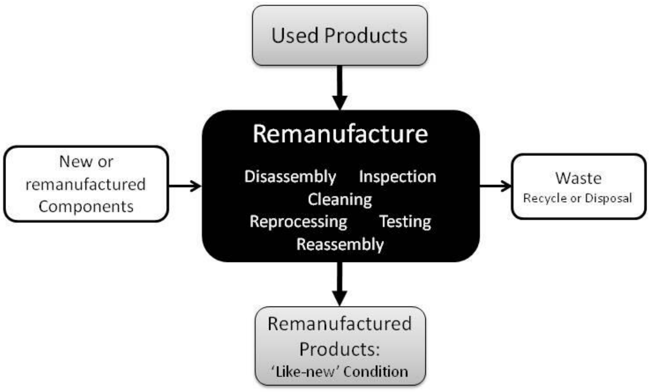


Figure 1 Typical Remanufacturing Process

Many authors (Fleischmann *et al.*, 1997, Guide 2000, Guide and Jayaraman 2000, Toktay *et al.*, 2000, Inderfurth 2005, Ketzenberg *et al.*, 2006, Savaskan *et al.*, 2004, Errington 2009, Teunter and Flapper, 2010 etc.) acknowledge that uncertainty about the quality (and often the quantity) of cores has a detrimental effect on the productivity and profitability of remanufacturers. Errington (2009) describes the use of core inspection to eliminate those that would be either prohibitively expensive or extremely difficult to remanufacture. This practice is particularly useful to independent remanufacturers, especially where they do not have an identified customer for their product, but contract remanufacturers often have very little choice when specific customer demand exists regardless of the supplied quantity or quality of cores.

Subramoniam *et al.* (2009) proposed that a lack of remanufacturing-specific cost-benefit analysis tools has led to poor decision making for remanufacturers and this can be observed in remanufacturing companies particularly in the case of inspection. Inspection is a fundamental part of any remanufacturing process (Ijomah, 2002, Georgiadis and Vlachos, 2004, Östlin *et al.*, 2008, Mukhopadhyay and Ma, 2008 etc.). It is usual practice in remanufacturing to inspect at many stages through the process, often functionally and in all cases visually, indeed Brent and Steinhilper (2004) state that remanufacturing always requires 100% inspection at one or more of the remanufacturing phases. The result of this is a high quality product for customers but lowered profitability for the remanufacturer through either too little initial inspection leading to unnecessary processing and further inspection later through the process, or through cores being unnecessarily rejected early in the process resulting in a poor recovery rate. These circumstances are all due to the uncertainty concerning the quality and condition of the returned products. Despite this perceived importance, inspection at component level has not been addressed at the "Receive Core" (Ijomah *et al*., 2007, Ijomah *et al*, 1999) stage of the remanufacturing process.

Remanufacturers have varying strategies for disassembly including two major options for volume disassembly (Lambert and Gupta, 2016): all assemblies are completely disassembled and, after washing, form a supermarket of parts that will be inspected and recovered when required; or alternatively entire assemblies are disassembled and processed together and then reassembled with whatever new material is needed into what remains essentially the same assembly. The Caterpillar site in question, prior to the completion of this research, typically used the former method as this was assumed to be the most cost-effective through historic practice. Little emphasis was placed upon inspection at the disassembly phase because the uncertainty of the condition of the returned cores was seen as the greatest unknown and therefore the drive was to dismantle as much as possible to avoid parts shortages later in the process. In addition, wage rates for disassembly were lower than those for processing or assembly as the latter activities were valued more.

The initial phase of remanufacturing is the most cost-effective time to detect potential defects with the cores as little or no processing work has been carried out and consequently little cost has been added to the cores. Indeed, literature suggests that there is a strategic benefit in core sorting. Mähl and Östlin (2007) and Errington (2009) recommend grading cores for quality to improve the disassembly process. These studies rely on a visual condition inspection or disassembly sampling of a large batch of cores to estimate the overall condition and likelihood of recovery, these are all based on the inherent value of the cores, lower value cores receiving a visual inspection and higher values cores, sample disassembly. Teunter and Flapper (2010) go further and propose four initial grades of cores, established visually and from any known data concerning the initial use of the cores, as part of their acquisition policy. They all note a benefit (unquantified) to remanufacturers when they are able to process high quality cores.

To address this gap in the literature this research, investigates whether (and by how much) the overall remanufacturing process of engines could be made more efficient with a robust inspection of cores, was carried out at the Caterpillar Remanufacturing Services (a division of Caterpillar Inc.) facility in Rushden, U.K. This facility primarily remanufactured petrol and diesel engines both as an OEM for Caterpillar Inc. and as a contract remanufacturer for a variety of other OEMs. Remanufacturing is a mature business in the automotive sector and consequently offers an ideal environment for experimental research. The researcher's employment at the facility as a production manager also facilitated unprecedented access over an extended period to all aspects of the remanufacturing process.

## 3. Methodology

One of the researcher's employment within the remanufacturer made it possible to adopt a methodology,(Campbell and Stanley, 1966, Polit and Hungler, 1999 etc.) that included a control group to protect internal validity. Other threats to validity were negated by the randomisation of subjects into treatment groups (Antony, 2003).

### 3.1 Independent Variables

The aim of the research was to understand whether the overall remanufacturing process was made more efficient by a regime of pre-processing inspection. It was consequently important to understand which elements of the inspection resulted in the greatest benefits. Therefore the content of the pre-processing inspection, the independent variable in the experiment, was manipulated by the researcher.

Four inspection protocols were developed, limited by the technology available in the remanufacturing facility. These were:

Protocol 1 **No inspection**: decant, establish part number and reuse. This protocol was used to test whether inspection of core made any material difference. Small assemblies such as connecting rods and oil pumps were frequently removed and processed without inspection until the point of reuse and this protocol would test whether this strategy could be applied successfully to whole assemblies.

Protocol 2 **Light Inspection:** Decant, establish part number, brief visual, external inspection and determining one of three gradings. Either, 1) Use as regular cores, 2) close to new – bypass the usual process or 3) severely damaged – use as a parts donor. This was the usual process and acted as the baseline.

Protocol 3 **Moderate Inspection:** Protocol 2 plus manual rotation of moving parts, visual and scent inspection of rotating electrics and close inspection of open ports and oilways. This latter inspection is commonly known by practitioners as the "scratch and sniff" test because burnt electric components can often be detected from their smell.

Protocol 4 **Full Inspection:** Protocol 3 plus inspection using a fibre optic endoscope to investigate the internal condition of cylinder bores, turbochargers, alternators etc.

Standard work sheets were produced, detailing the exact work content for each individual protocol; any safety considerations; relevant quality standards; what tools are required and in what order the work should be undertaken and , were produced. These were used to define training programs for each operator.

The output from each inspection protocol was a feedback sheet for every engine in the experiment. This sheet noted the unique core number, the specific OEM part number and the outcome of the inspection dependent upon the protocol used. Typically for a core inspected to protocol 1, this would only include the unique core number and the specific OEM part number, whereas for protocol 2 the core grading would also be included as would any obviously missing parts. Protocol 3 reported information on damaged electrical and/or rotating parts and protocol 4, would additionally note specifics concerning additional missing or damaged components, reports of the internal condition of sub-assemblies and the basic structure of the engine.

### 3.2 Dependent Variables

The purpose of this research was to determine what factors affect pre-processing inspection of the subjects and as a consequence the overriding factor in the choice of dependent variables was the ability to measure the direct effects of the experimental treatments. Processing time for each remanufacturing activity, from unpacking and inspection to final post-production testing, was measured both at individual component/sub-assembly level and at overall engine level.

An engine is an assembly of individual components and smaller assemblies and, as a consequence, provided opportunities to establish whether the experimental treatments were equally effective on a variety of differing materials, complexities and scales. Measurement of the overall processing time would establish whether the benefits of the inspection protocols outweighed the scale of the intervention.

Four engines were selected, representing a variety of customers and a relatively large volume of product. The automotive and off-highway remanufacturing market includes both petrol and diesel engines of many capacities and specification, including components sold in competition with new offerings, consequently the research selections were designed to promote the ability to generalize the findings and increase their industry relevance. The automotive industry supplies remanufactured engines at various different levels of completion depending on their customer preference. Two levels were investigated in this study, fully dressed and long engine level. The former is generally referred to as “vehicle-ready” although the specific components included are entirely customer-dependent and the latter comprises broadly, cylinder block, cylinder head, crankshaft, pistons, connecting rods, camshafts, timing gear, oil pump, oil sump and covers. Details of components on each engine studied are included in the descriptions below.

Engine A - 4 cylinder engine with a capacity of less than 2 litres. This engine was supplied to the customer at a long engine level. This comprised: cylinder block assembled with pistons, connecting-rods, crankshaft, fully assembled and timed cylinder head, oil sump, oil pump, timing gear and outer covers.

Engine B - 6 cylinder engine of a capacity greater than 2 litres. This engine was also supplied to the customer at a long engine level comprising: cylinder block assembled with pistons, connecting-rods, crankshaft, fully assembled and timed cylinder head, oil sump, oil pump, timing gear, outer covers and vacuum pump.

Engine C - 4 cylinder engine with a capacity greater than 2 litres. This engine was supplied to the customer at a fully dressed level. This comprised: cylinder block assembled with pistons, connecting-rods, crankshaft, fully assembled and timed cylinder head, oil sump, oil pump, timing gear, outer covers, vacuum pump, fuel lift pump, exhaust gas recirculation (EGR) valve, starter motor, alternator, flywheel, turbocharger and fuel injection equipment.

Engine D - 6 cylinder engine with a capacity greater than 2 litres. This engine was supplied to the customer at a fully dressed level. This comprised: cylinder block assembled with pistons, connecting-rods, crankshaft, fully assembled and timed cylinder head, oil sump, oil pump, timing gear, outer covers, vacuum pump, fuel lift pump, compressor, turbocharger and fuel injection equipment.

Each activity in the overall remanufacturing process (i.e. disassembly, cleaning, any appropriate salvage activities, reassembly and testing) was timed for each component, and sub-assembly, of each engine so any changes could be identified. In total 2196 engines were investigated over a six month period.

**3.3 Design of Experiments**

The experiments were constructed from a post-test only control group, designed using the “Solomon Four group design” method (Solomon, 1949) as a template to ensure all variables were covered.

Engines of each type were randomly assigned upon receipt, sight-unseen, to one of four groups comprising of that engine type only. Consideration was given to mixing the different engine types into these groups but as the component mix, engine size (both capacity and physical size) and complexity varied considerably, different machines and operators were required to process the components: this proved infeasible. Four common pre-processing inspection protocols were then applied, one to each group, and the processing times for each activity measured. Both the protocols and their application were randomised and so at any one time engines of all four types (being processed by any one of the four protocols) were passing through the facility.

The research design assumes that inspection protocol 2, which is the existing level of pre-inspection prior to the experiments being conducted, is the equivalent of “no treatment” and that all groups subjected to this protocol form the control group. In all cases, R represents a randomisation of the group, X represents a treatment, a pre-processing protocol, ($X_1$, $X_2$ etc.) and O represents a group (i.e. engines) in this research ($O_1$, $O_2$ etc.). The overall experimental design is represented in Figure 2 below.

| | | | |
|---|---|---|---|
| R | $O1_A$ | $X_1$ | $O1_A$......$O1_{An}$ |
| R | $O2_A$ | $(X_2)$ | $O2_A$...... $O2_{An}$ |
| R | $O3_A$ | $X_3$ | $O3_A$...... $O3_{An}$ |
| R | $O4_A$ | $X_4$ | $O4_A$...... $O4_{An}$ |
| | | | |
| R | $O1_B$ | $X_1$ | $O1_B$......$O1_{Bn}$ |
| R | $O2_B$ | $(X_2)$ | $O2_B$...... $O2_{Bn}$ |
| R | $O3_B$ | $X_3$ | $O3_B$...... $O3_{Bn}$ |
| R | $O4_B$ | $X_4$ | $O4_B$...... $O4_{Bn}$ |
| | | | |
| R | $O1_C$ | $X_1$ | $O1_C$......$O1_{Cn}$ |
| R | $O2_C$ | $(X_2)$ | $O2_C$...... $O2_{Cn}$ |
| R | $O3_C$ | $X_3$ | $O3_C$...... $O3_{Cn}$ |
| R | $O4_C$ | $X_4$ | $O4_C$...... $O4_{Cn}$ |
| | | | |
| R | $O1_D$ | $X_1$ | $O1_D$......$O1_{Dn}$ |
| R | $O2_D$ | $(X_2)$ | $O2_D$...... $O2_{Dn}$ |
| R | $O3_D$ | $X_3$ | $O3_D$...... $O3_{Dn}$ |
| R | $O4_D$ | $X_4$ | $O4_D$...... $O4_{Dn}$ |

Figure 2 Experimental Research Design

This design satisfies all the concerns of validity: having a control group, involving the manipulation of one independent variable and measuring all of the dependent variables. It also satisfies the recommendations of Charness *et al* (2011) by combining between-subject and within-subject design.

### 3.4 Randomisation of Subjects

Randomisation of the experimental subjects was an essential part of the experiment to ensure that both the internal and external validity was maintained. Cores typically arrived at the Rushden remanufacturing facility from collection sites after consolidation. No information was available concerning the condition, quality or use history for any cores. Cores were often shipped under generic part numbers that encompassed a range of similar engines rather than by individual part number, a consequence of the earlier consolidation process. This meant that the cores were a random mix both of specific part number and of condition.

It could be argued that the existing level of randomisation, present upon receipt, was sufficient to guarantee validity, however to comply with Antony's (2003) recommendation to randomise treatment in time to avoid the potential effects of any systematic bias or unconsidered factors, further randomization was implemented.

Operatives were issued with four sets of tags in opaque bags marked with an appropriate letter, one for each engine A to D inclusive. Each set included an equal number of each of the four colours of tags, red, blue, green and yellow. The colour designated the inspection protocol; red for protocol 1, blue for protocol 2, green for protocol 3 and yellow for protocol 4. Every tag had a unique tracking number written on it: Engine A tags were labelled $A_1$, $A_2$, $A_3$…An; Engine B tags, $B_1$, $B_2$, $B_3$…$B_n$; Engine C tags, $C_1$, $C_2$, $C_3$…$C_n$ and Engine D tags, $D_1$, $D_2$, $D_3$…$D_n$. However the numbers on each colour tags were not sequential. The operator removed one tag at random from the appropriate bag for each piece of core that arrived and attached it to the core. No inspection took place at this time. The cores were then located and stored as normal until required by production. Inspection to the assigned protocol took place at this time, prior to preparing the core for disassembly. The engine then progressed with the engine letter and number only e.g. A32, B225 etc. Each of the components or sub-assemblies, once removed was labelled with the unique number of the engine it had been removed from.

The decision to assign a protocol at receipt but not to inspect until a core was required for production was driven by two factors: the need to disrupt normal working practices as little as possible, and the need to minimise the cost impact of the experiment. Disruption of normal working practices more than was necessary to administer the treatments was undesirable because it might introduce unforeseen variables that could contaminate the results.

The allocation of a unique tracking number ensured that once the engine was passed to disassembly none of the up-stream operatives were able to determine which inspection protocol had been applied to which engines or components. This further anonymity aided internal validity as operatives could not alter their behaviour based on any assumptions about the components being processed. All activities were kept within normal production boundaries in order that individual operators could exert no influence on the outcome of the experiments.

### 3.5 Data Collection and Integrity

The nature of the experiment and the quantity of cores involved meant that a considerable amount of data would be collected. It would be impossible for one person to collect all of the results, particularly as many of the operations were undertaken simultaneously. The primary concern therefore became the ability to ensure data integrity if the collection of processing times was dispersed amongst operators. Processing times were captured in decimal minutes and collated in spreadsheet form for analysis.

The data collection required for this experiment was part of the data normally collected by operators and consequently the only additional requirement was that the unique tracking number was recorded alongside the processing time. A slight change to the recording sheet made this a simple adjustment for operators.

Data was not routinely collected in the initial decant and inspect process or in the disassembly process. Nevertheless the operators were routinely using process monitoring tools and consequently a method similar to that used to record times later in the process was implemented with very little disruption. The operators decanting and inspecting cores preferred to write their times down and these were collected daily by the researcher and added to the master spreadsheet; whereas the disassembly operators, who were already using a computer to record other information, recorded their processing times themselves. All the operators involved noted the times against the unique tracking numbers.

Processing times for all stages of the remanufacturing process were recorded in decimal minutes. Digital stopwatches, recording to two decimal places were provided to operators. These stopwatches had a start/stop function that enabled the operator to pause the timing if they needed to step away from the job – for instance to answer the phone or take a scheduled break. Operators were instructed to record the time displayed on the stopwatch at the end of the process exactly as displayed and not to round up or down.

Processing times included all operations that a component was subjected to during that activity where the operator was involved. Therefore cycle times in machines such as wash machines (where there was no operator involvement) were not recorded as part of the processing time. But if the operator was required to be present the entire time, for instance during the post-production test, this period was included in the processing time.

Disassembly time included removing component parts and disassembling them completely where this operation was routinely carried out in the disassembly area. Where parts such as turbochargers, fuel pumps or starter motors etc. were removed as complete assemblies and passed to a specialist area for processing, the only time recorded at disassembly was the time to decouple the minor assembly from the core. Any disassembly time in the specialist area was included in the processing time captured in that area for the individual component.

### 3.6 The Experimental Audit Process

An audit process to check data recorded by operators was already in place at the Rushden facility and a more frequent version of this system was used to verify the data collection. Using this system ensured that operatives experienced working conditions that were as near as possible to usual. This was important to ensure that operators did not alter their behaviour because of the experiments and in some way influence the data collected.

The purpose of the routine audits was to verify activities and look for opportunities for continuous improvement. In contrast, the purpose of the within-experiment audits was ensuring data reliability. Consequently the frequency of the audits and sample size was altered to reflect this. The sample size was calculated on the basis of the predicted data population of around 30,000 entries. The large amount of data being collected, the entire population rather than a sample, meant that there was high confidence that any statistical significance would be directly attributable to treatments and consequently setting the α value at 0.05 and thus the confidence at 95% could be justified (Lipsey and Hurley, 2009). The calculation of sample size based on those parameters required a 7.14% sample size or 2427.6 parts. This equated to one component in every fifteen.

The existing audit scheme was modified to satisfy the requirements of the research design whilst remaining intrinsically the same in order to reassure the operators. The modified approach adopted was:

- Every activity was audited every fifteen components;
- One complete activity only was audited on each occasion because of the high sample size;
- Auditor data was compared with both operator data and that recorded on either the electronic system or the paper version, as appropriate;
- Variances of more than 5% between auditor and operator in either case were recorded as failures and any erroneous entry, corrected;
- Failed audits would result in re-training in the data collection and recording for the operator and a further audit of the next component.

## 4. Results, Analysis and Discussion

Results were collected and analysed for all four of the subject engines but only those for engine C are presented here owing to the quantity of data. Full data and analysis can be found in Ridley (2013). The results from the across-engine analysis of all four engines showed consistent patterns across engines and engine components; consequently engine C was selected as it has the greatest number of constituent components and sub-assemblies can be said to be the most representative of the research as a whole.

### 4.1 Engine C Results

A total of 420 type C engines were examined during the experimental phase. These were randomly allocated on arrival to the four inspection protocols in the following quantities:

- Protocol 1 – 104 engines;
- Protocol 2 – 105 engines;
- Protocol 3 – 105 engines;
- Protocol 4 – 106 engines

Engine C was a 4 cylinder engine with a capacity of more than 2 litres. The activities studied were: decant and inspect to the allocated protocol, disassembly, remanufacture of the cylinder block, cylinder head, crankshaft, camshaft, valves, connecting-rods, rocker shaft, oil pump, fuel lift pump, vacuum pump, exhaust gas recirculation (EGR) valve, starter motor, alternator, flywheel, turbocharger, the small parts kit (covers, brackets etc. as previously described), the engine kitting activity (bringing remanufactured and new parts together into one group, including any selective fit parts such as bearings), the assembly process, the post-production test and paint, pack and despatch activities.

Table 1 shows the percentage change in mean time from the control (protocol 2) for each remanufacturing activity and each protocol.

| | % change in Mean from control | | | |
|---|---|---|---|---|
| **Activity** | **Protocol 1** | **Protocol 2** | **Protocol 3** | **Protocol 4** |
| Decant and Inspect | -21.61 | Control | 23.66 | 85.85 |
| Disassembly | 10.35 | Control | -20.06 | -20.06 |
| Block Remanufacture | 3.12 | Control | 0.63 | -0.83 |
| Head Remanufacture | -0.39 | Control | -3.88 | -3.10 |
| Crankshaft Remanufacture | 0.03 | Control | -1.23 | -1.20 |
| Camshaft Remanufacture | -0.17 | Control | 0.04 | -0.06 |
| Valve Remanufacture | 0.38 | Control | 0.13 | 0.17 |
| Connecting Rods | -0.01 | Control | -0.02 | 0.20 |
| Rocker Shaft Remanufacture | -0.08 | Control | -0.05 | -0.10 |
| Oil Pump Remanufacture | -0.01 | Control | 0.06 | -0.04 |
| Fuel Lift Pump Remanufacture | 3.96 | Control | -1.33 | -0.53 |
| EGR Valve Remanufacture | 1.14 | Control | -3.78 | -3.83 |
| Vacuum Pump Remanufacture | 0.20 | Control | -0.08 | -0.88 |
| Starter Motor Remanufacture | 7.26 | Control | -17.58 | -19.54 |
| Alternator Remanufacture | 7.83 | Control | -6.68 | -9.42 |
| Flywheel Remanufacture | 1.06 | Control | -1.46 | -3.10 |
| Turbocharger Remanufacture | 4.15 | Control | -16.70 | -18.61 |
| Small Parts Remanufacture | 5.85 | Control | -13.52 | -13.31 |
| Engine Kitting | 9.31 | Control | -4.07 | -3.64 |
| Engine Assembly | -0.21 | Control | -0.30 | -0.32 |
| Post-Production Test | 0.19 | Control | 0.04 | 0.02 |
| Paint, Pack and Despatch | -0.02 | Control | -0.04 | -0.03 |
| **Total Remanufacture** | **2.74** | **Control** | **-5.36** | **-5.27** |

Table 1 Percentage change in Mean Activity Times from the Control – Engine C

It can be seen that whilst engines inspected to protocols 1 and 2 have a much lower time for the decant and inspect activity (the application of the protocol), the overall remanufacturing process time is higher than for those engines inspected to protocols 3 and 4, despite their longer decant and inspect activity times. In these latter two cases, the benefits greatly outweigh the additional work. The table also shows that not all activities within the remanufacturing process benefit in the same way from the increasing levels of inspection, for example the starter motor remanufacturing time decreases as more information is gathered prior to processing but very little difference is seen in the valve remanufacturing activity time.

### 4.2 Analysis of Engine C Results

The primary analysis across all the results was within-engine as this clearly demonstrated whether the treatment applied had any effect as each component set was similar. A secondary cross-engine analysis was conducted to establish similarities between engine sub-assemblies and components to better identify any commonalities that would enable a generic inspection methodology to be established. Analysis of the overall data set for each engine was accomplished using IBMs Statistical Processing for Social Scientists (SPSS) package and specifically using one-way ANOVA (Iversen and Norpoth, 1987). One-way ANOVA was selected because there are four randomly selected groups (the four engine types) who together constitute the entire population.

The within-engine analysis for engine C is presented here. The tabular and graphical outputs from SPSS are shown in full only for the overall remanufacturing process; however the significance figures for the change between Protocols 1 and 3 for each of the activities pertinent to engine C are fully enumerated in Table 3

### 4.2.1 Statistical Correlation

Statistical analysis was carried out for each activity time in the remanufacturing process for every engine studied. This was to understand whether there was a statistical correlation between the increased inspection (the time for the decant and inspect activity) and the subsequent remanufacturing activity time. The results of this analysis for the overall remanufacturing activity time for engine C only are given here.

The collected data for the overall remanufacturing process for engine C comprised a total of 420 individual times across all four inspection protocols. These were subject to one-way ANOVA analysis giving the results shown in Table 2 below. The significance of the results, denoted Sig, is the confidence with which it can be said that the change in processing time was due to the effects of the differing pre-processing inspection protocol.

The confidence level for the population was determined to be 95% based both upon the large size of the population and the use of data from the whole population rather than a sample (Lipsey and Hurley, 2009). Therefore the ANOVA significance figure must be lower than 0.05 for the results to demonstrate a statistically material benefit with the required 95% level of confidence. The strength of the correlation is given by the Significance in table 2 where the maximum correlation is 0 and the minimum correlation is 1, therefore any result lower than 0.05 shows a strong correlation.

The significance figure for the ANOVA analysis on the overall remanufacturing process for engine C was 0.000 as shown in Table 2 below. Therefore it is possible to be confident that the effect of increasing the content of the pre-processing inspection has been a material reduction in the overall processing time of the engine.

| **OVERALL REMANUFACTURING PROCESS** | | | | | |
|---|---|---|---|---|---|
| | Sum of Squares | Df | Mean Square | F | Significance |
| Between Groups | 2244064 | 3 | 748021. | 11352 | 0.000 |
| Within Groups | 27411 | 416 | 65. | | |
| Total | 2271475. | 419 | | | |

Table 2 ANOVA Output for Engine C, Overall Processing Time

It was previously noted that the effects of increasing the pre-processing inspection did not bring a benefit in all activities and the full analysis of each activity for engine C demonstrates this. As an example, Table 3 shows the difference in activity time between protocols 1 and 3 and the statistical correlation (significance) for each of the individual remanufacturing activities. Once again the strength of the correlation is given by the Significance in table 2 (where the maximum correlation is 0 and the minimum correlation is 1) therefore any result lower than 0.05 shows a strong correlation. Negative numbers denotes a decrease in time between activities times at protocols 1 and 3, positive numbers an increase.

| **Remanufacturing Activity** | **Time difference (minutes)** | **Significance** |
|---|---|---|
| Decant and Inspect | 5.90 | 0.000 |
| Disassembly | -40.31 | 0.000 |

| | | |
|---|---|---|
| Block Remanufacture | -2.92 | 0.000 |
| Head Remanufacture | -3.28 | 0.000 |
| Crankshaft Remanufacture | -0.58 | 0.000 |
| Camshaft Remanufacture | 0.04 | 0.972 |
| Valve Remanufacture | -0.08 | 0.472 |
| Connecting Rods | 0.00 | 0.879 |
| Rocker Shaft Remanufacture | 0.00 | 0.996 |
| Oil Pump Remanufacture | 0.01 | 0.995 |
| Fuel Lift Pump Remanufacture | -0.31 | 0.000 |
| EGR Valve Remanufacture | -0.56 | 0.000 |
| Vacuum Pump Remanufacture | -0.03 | 0.509 |
| Starter Motor Remanufacture | -18.78 | 0.000 |
| Alternator Remanufacture | -6.87 | 0.000 |
| Flywheel Remanufacture | -0.39 | 0.000 |
| Turbocharger Remanufacture | -33.35 | 0.000 |
| Small Parts Remanufacture | -24.09 | 0.000 |
| Engine Kitting | -14.66 | 0.000 |
| Engine Assembly | -0.34 | 0.061 |
| Post-Production Test | -0.26 | 0.114 |
| Paint, Pack and Despatch | -0.06 | 0.217 |
| Overall Remanufacture | -140.90 | 0.000 |

Table 3 Statistical Correlation between Protocols 1 and 3 for Engine C

The within-engine analysis also revealed a limit to the benefits accrued from the increasing content of the inspection protocols and this is illustrated in Figure 3 which plots the overall remanufacturing time for every engine C studied. It clearly shows that the processing time drops as the pre-processing inspection content is increased until protocol 4 when the benefit is curtailed. The benefits still outweigh the additional time required for further inspection but no further benefit from inspecting additional elements than with protocol 3 is seen.

Figure 4 confirms these results as the spread of overall remanufacturing times can be seen collated for all engines of type C. Whilst the difference in individual processing times vary by as much as an hour, there remained a distinct, measureable benefit from increasing the pre-processing inspection content.

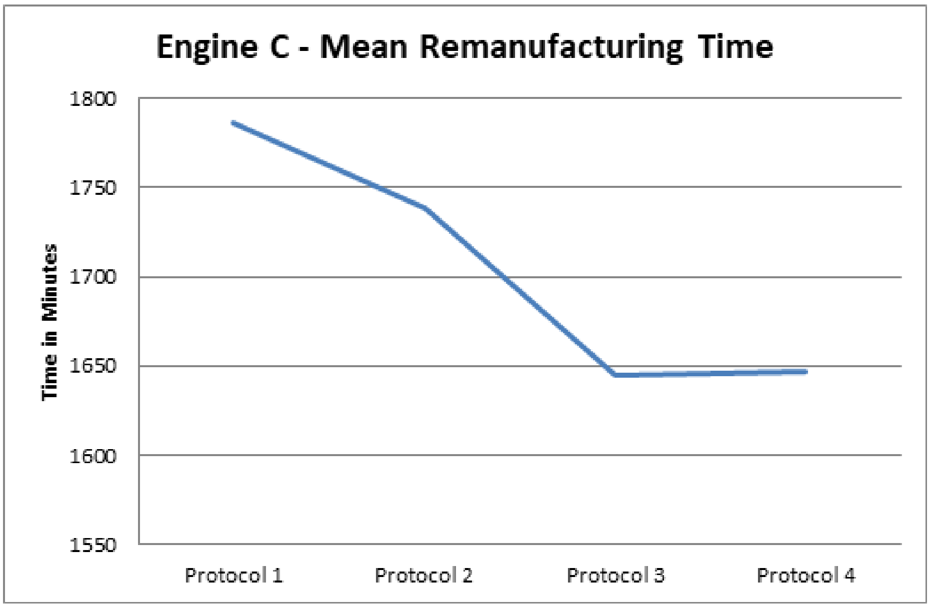


Figure 3 Mean Remanufacturing Time for Engine C across each protocol

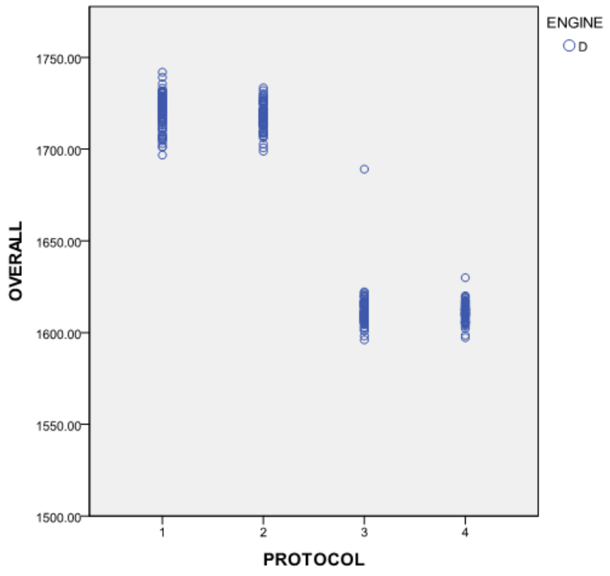


Figure 4 Spread of results for Engine C for the varying Inspection Protocols

**4.3 Discussion**

It can be seen from the results that increasing the content of the pre-processing inspection activity provided a significant benefit for some components and not others. It is possible in most cases to detect underlying themes that group these components together and explain the differences. In all cases however, it is possible to exclude the "decant and inspect" activity as this was the independent variable and deliberately altered.

The benefits do necessarily continue to accrue as the pre-processing inspection content increases as shown in Figure 4 but are limited. This is because there is a finite amount of information concerning the condition of components that can be ascertained prior to disassembly and consequently once that point is reached, further inspection adds to the processing time without providing a commensurate benefit.

Remanufacturing activities and components that demonstrated no effect from the differing inspection protocols were: camshaft, valve, connecting rod, rocker shaft, oil pump, vacuum pump, engine assembly, post-production test and paint, pack and despatch.

Significantly altered remanufacturing activities or components include: disassembly, cylinder block, cylinder head, crankshaft, alternator, fuel lift pump, EGR valve, starter motor, turbocharger, flywheel, small parts salvage and engine kitting.

These latter have at least one of the following characteristics not shared with the first group. These are:

- Complex geometry including internal ports;
- Large number of sub-components; or
- Constructed from or comprising of multiple materials.

These characteristics make pre-processing inspection worthwhile because they all introduce additional variables to the remanufacturing activity. Components with complex geometry are more likely to be affected by a build up of contaminants or to experience wear or corrosion on changing surface forms. This is particularly noticeable on turbochargers where the complex blade profile experiences more corrosion than the smoother, simpler sides of the chamber despite being exposed to the same operating conditions. Likewise components that have either a large number of sub-components or are constructed from multiple metals can be subject to corrosion aggravated by contact between differing materials or the inconsistent wear and fatigue created by the repetitive hot and cold cycling of an engine. Water and coolant pumps often exhibit these types of wear patterns, particularly around the turbine and shaft joints where the differing metals increase the corrosion at the joint.

The benefits of pre-processing inspection accrue from using the knowledge obtained to improve processing activities rather than just from inspection per se. The information gathered during the research period was used to inform the scheduling and procurement operations enabling less material to be purchased because of assumed requirements but rather purchased against a known demand. Longer term this allowed inventory levels to reduce. This latter cannot be quantified as it was ongoing at the point at which the research ended. The knowledge gained also partly mitigated the effects of uncertainty (noted by remanufacturers as a very significant issue) because early knowledge of part number, condition and type of received cores enabled additional cores of a suitable type to be sourced in time to meet demand.

The results recorded for engine C were consistent with those seen in the other three engines and consequently it can be inferred that components with these characteristics or activities involving parts with the same demonstrate a reduction in their overall processing time but that this benefit is curtailed once the limit of information gained by inspection is reached.

### 4.4 Use of the Research Findings

One of the aims of the investigation was to make the findings accessible to those working in industry by embodying them in a tool to aid decision-making about appropriate pre-processing inspection. This tool would then form part of the package of work to be validated.

It became clear, as the research progressed, that the understanding of the remanufacturing activities gained during the experimental phase also influenced the costs to the remanufacturer and consequently the impact of this was also considered.

#### 4.4.1 Decision-Making Model

Understanding what made pre-processing inspection useful enabled decisions to be made about what level of inspection was appropriate for each significant component or assembly within the engine cores. Careful consideration of how these factors could be translated into a means of decision-making led to the conclusion that a decision tree method would be an effective means to make the research useful to others. This is because a decision tree clearly lays out all the options so that a logical path can be followed, they allow the full consequences of each part of the decision to be seen in advance and they provide a simple visual format that can be replicated anywhere. This led to development of the process model illustrated in Figure 5.

This process model was used to route all cores and their sub-components towards the appropriate inspection level. Because the benefits of inspection for sub-assemblies such as starter motors and turbochargers were significant a new handling process was implemented. These sub-assemblies were removed from the cores upon receipt at the remanufacturing facility and sent to the specialist department directly, even when the core they were removed from was stored for future use. Any resulting openings were plugged against the ingress of water or other contaminants. This had the added bonus of better protection for components prior to remanufacture, helping to reduce the activity time as less cleaning and other decontamination work was necessary.

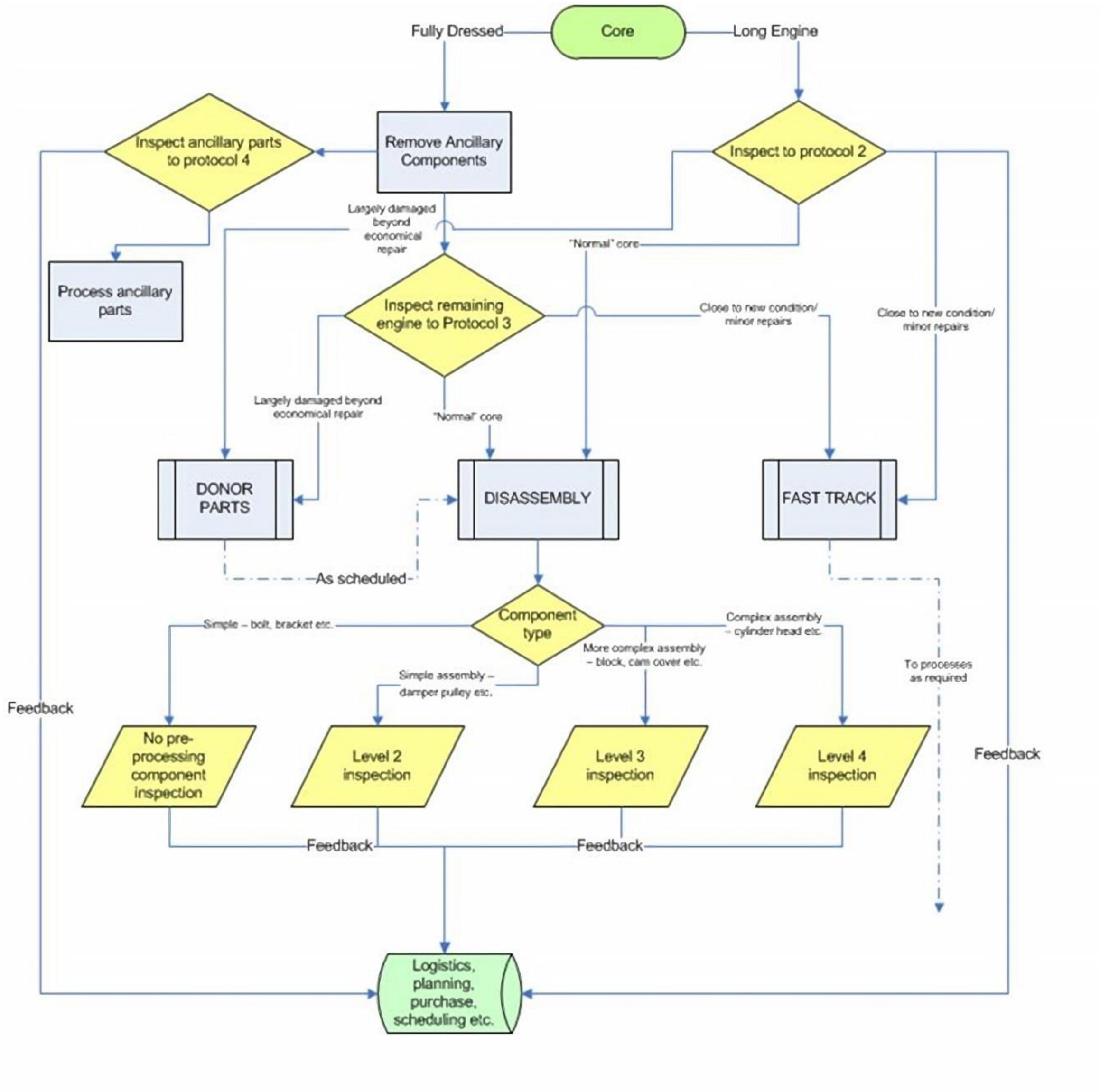


Figure 5 Overall Decision Making Process at the Rushden Remanufacturing Facility

The most important aspect was the feedback loop. The information resulting from any inspection process was sent to the Scheduling Manager, the Logistics Manager and the Production Manager. This enabled informed decisions to be made to minimise delays, shortages and to maintain flow throughout the factory.

### 4.4.2 Remanufacturing Cost Estimation

Various researchers (Ferrer, 2001, Aras *et al*., 2004, Ferguson *et al*., 2009, Liang *et al*., 2009 etc.) have offered models for remanufacturing costs, many of them trying to address the uncertainty surrounding the availability and quality of cores. The researcher's employment and experience in the remanufacturing sector has led to the conclusion that these models are seldom understood or in widespread use in practice.

Remanufacturers, particularly independent and contract ones, usually estimate their costs using a combination of a cost per minute for the amount of work required and the time the remanufacture will take plus the cost of new parts. The cost per minute usually includes an averaged labour cost and an allowance for overheads such as rent, energy etc. whilst the cost of new parts often includes any additional cores that might be required. The amount of new parts and additional cores is usually based upon experience and, although it might be reviewed once the product is in production, is essentially a "best guess". These factors taken together allow an expected cost per product to be calculated and this forms the basis of pricing decisions. Remanufactured products typically sell for around two-thirds of the cost of the equivalent new product, and so the remanufacturer is primarily concerned that this level of pricing can be achieved whilst maintaining an appropriate profit margin.

The experimental study highlighted the variation in the activities and skill levels present in the remanufacturing process. Consequently it enabled a more realistic method of cost estimation to be developed.

The model proposed and validated in this research is an extension of the commonly used method rather than an extension of existing theoretical research and can be easily applied by practitioners using information they already hold and routinely collect.

There are several factors that need to be taken into account. They are:

- Time (in minutes) = $t$;
- Labour rates (in GBP per minute) = $r_1, r_2, r_3 \ldots r_n$;
- Scrap rates = $s_1, s_2, s_3 \ldots s_n$;
- Licenced technology = $l$;
- Overheads (in GBP per minute) = $o$; and
- Cost of new materials = $m$.

The equation that describes the current cost assessment is:

$$\text{Cost} = m + (t \times (r + o))$$

However, in order that all factors are considered, it is necessary to allocate the overall time to each of the differing labour rates. An allowance for the cost of any licenced technology as a percentage of the overall cost applicable to the time involved in the specific activity where it is used is also added and finally the cost of scrap in the process is also allowed for. Where a component is scrapped, the full cost of the remanufacturing activity will not apply to the entirety. Consequently the cost of the scrap will need to be removed from the equation. For the sake of clarity, scrap has been shown at each point where the labour rate changes. This may not be the case in reality and the sum can be adjusted to suit specific conditions.

The equation can then be finally written as:

$$\text{Cost} = m + (((t_1 \times (1-s_1) \times (r_1+o)) + (((t_2 \times (1-s_2) \times (r_2+o)) + ((t_2 \div t) \times l)) + ((t_3 \times (1-s_3)\,(r_3+o)) \ldots + ((t_n \times (1-s_n)\,(r_n+o)))$$

## 5. Validation of the Results

The research findings were presented to the management teams in two Caterpillar remanufacturing facilities along with the decision-making methodology. Validation was undertaken with different engines from those studied so that the results could be tested thoroughly by examining if these other products demonstrated similar patterns to those studied.

Validation in different facilities would verify that the processes developed from the research findings were generally applicable and not unique to the Caterpillar facility studied. Caterpillar Remanufacturing facilities, whilst held to the same corporate quality standards, operate with a good degree of autonomy. The relevant people at each facility were given training in its use and, having made the appropriate decisions for each product the new inspection regimes were put in place. The training for the inspection process was that given to operatives for the experimental phase.

Each facility reported a reduction the overall processing time for each product. These varied between 0.78% and 19.53%. Commercial confidentiality prevents explicit values being reported for this phase however the percentage change at each facility showed an overall saving in time, 4.91% in one case and 5.12% in the other. The facilities also expressed satisfaction with the information gained and their increased ability to schedule both new components and additional salvage operations. This latter was particularly beneficial in the case of using expensive equipment or processes such as direct metal deposition.

The cost assessment methodology was separately presented to the financial teams in the facilities and this was used, alongside the traditional method for assessing costs. The validation of the model for new product requires a longer time than was available however, using the model to assess the cost of remanufacture for existing product and comparing these both with the initial assessment made prior to commencement of remanufacture and the actual known costs of the remanufacture was made for three product lines – all engines. The actual remanufacturing costs used were those for the most recent full month available. Once again, confidentiality prevents the actual figures being reported, however Table 4 gives the percentage differences found in cost for each product examined. Minus figure indicate underestimation of the costs, plus figures overestimation.

| Case | % Variance from Actual – Traditional Method | % Variance from Actual – New Method |
|---|---|---|
| I | -7.61% | -2.18% |
| II | -3.36% | -2.09% |
| III | -4.12% | +1.44% |

Table 4 Variances from Actual for each Cost Assessment Method

It can be seen that in all cases the new method presented in this work gave a more accurate assessment of costs. This is important for financial planning as well as for assessing the viability of remanufacture of a new product. The tools presented are now in use at several Caterpillar Remanufacturing facilities.

## 6. Future Work and Limitations

The experimentation was limited by the available tools and techniques for inspecting cores and could be extended with the use of other non-destructive technology such as ultrasound testing. It was also based exclusively in the automotive sectors and concerned engines and components, work to discover whether the factors identified were applicable to other remanufactured products would be beneficial.

## 7. Conclusions

This research has identified the factors that affect decisions concerning pre-processing inspection. It has determined that these criteria can be used improve the efficiency of the remanufacturing process and also improve the accuracy of cost estimation. It has shown that in the automotive remanufacturing sector time savings of up to 20% can be achieved by properly inspecting cores prior to processing.

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## 9. References

1. Antony, J. (2003) “Design of Experiments for Engineers and Scientists” Butterworth-Heinemann: Oxford.

2. Aras, N., Boyaci, T. and Verter, V. (2004) “The effect of categorizing returned products in remanufacturing” IIE Transactions 36, pp. 319–331.

3. Brent, A.C. and Steinhilper, R. (2004) “Opportunities for remanufactured electronic products from developing countries: Hypotheses to characterise the perspectives of a global remanufacturing industry” Proceedings of 7th AFRICON Conference in Africa Vol. 2, pp. 891-896.

4. British Standards Institution (2006), “BS 8887-1:2006 - General concepts, process and requirements”.

5. British Standards Institution (2009) “BSI 8887-2. Design for Manufacture, Assembly, Disassembly and End-of-Life Processing (MADE) Part 2: terms and definitions 2009”.

6. British Standards Institution (2009), “BS 8887-2:2009 – Terms and definitions.

7. Campbell, D. J. and Stanley, J. C. (1963) “Experimental and quasi-experimental designs for research” Chicago: Rand-McNally.

8. Charness, G., Gneezy, U. and Kuhn, M.A. (2011) “Experimental methods: Between-subject and within-subject design” Journal of Economic Behavior & Organization 81 (2012) pp. 1– 8.

9. DEFRA (2003) “Landfill Directive Briefing Paper” London: DEFRA Available at: http://www.defra.gov.uk/environment/waste/strategy/legislation/landfill/ {Accessed on 20th January 2010}.

10. DEFRA (2009) “estimated total annual waste arisings, by sector” London: DEFRA Available at: http://www.defra.gov.uk/evidence/statistics/environment/waste/kf/wrkf02.htm {Accessed on 17th January 2010}.

11. Errington, M. (2009) “Business Processes and Strategic Framework for Inspection in Remanufacturing” PhD Dissertation, The University of Exeter, UK.

12. Ferguson, M., Guide, V.D.R., Koca, E. and Souza, G. (2009) “The value of quality grading in remanufacturing” Production and Operations Management 18 (3), pp. 300–314.

13. Ferrer, G. (2001) “On the widget remanufacturing operation” European Journal of Operational Research 135, pp. 373–393.

14. Fleischmann, M., Bloemhof-Ruwaard, J.M., Dekker, R., van der Laan, E., van Nunen, J. and Van Wassenhove, L.N. (1997) “Quantitative models for reverse logistics: a review” European Journal of Operational Research 103, pp. 1–17.

15. Georgiadis, P. and Vlachos, D. (2004) “The effect of environmental parameters on product recovery” European Journal of Operational Research 157, pp. 449-464.

16. Guide, V.D.R. (2000) Production planning and control for remanufacturing: industry practice and research needs. Journal of Operations Management 18, pp. 467–483.

17. Guide, Jr., V.D.R. and Jayaraman, V. (2000) “Product Acquisition Management: current industry practice and a proposed framework” International Journal of Production Research, 38, pp. 3779–3800.

18. Hatcher, G.D., Ijomah, W.L., and Windmill, J.F.C. (2013) “Integrating design for remanufacture into the design process: the operational factors” Journal of Cleaner Production 39 (2013) pp. 200-208.

19. Ijomah, W.L. (2002) “A model-based definition of the generic remanufacturing business process” PhD Dissertation: The University of Plymouth, UK.

20. Ijomah, W.L., McMahon, C., Hammond, G. and Newman, S. (2007) “Development of design for remanufacturing guidelines to support sustainable manufacturing” Robotics and Computer Integrated Manufacturing 23, pp. 712-719.

21. Ilgin M.A. and Gupta, S. (2010) “Environmentally conscious manufacturing and product recovery (ECMPRO): A review of the state of the art” Journal of Environmental Management 91, pp. 563–591.

22. Inderfurth, K. (2005) “Impact of uncertainties on recovery behavior in a remanufacturing Environment” International Journal of Physical Distribution & Logistics Management 35, pp. 318–336.

23. Iversen, G.R. and Norporth, H. (1987) “Analysis of Variance” Sage University Paper Series on Quantitative Applications in the Social Sciences, No. 07-001.

24. Ketzenberg, M.E., van der Laan, E. and Teunter, R.H. (2006) “Value of information in closed loop supply chains” Production & Operations Management 15, pp. 393–406.

25. Lambert, A.J.D. (Fed) and Gupta, S.M. (2016) “Disassembly Modeling for Assembly, Maintenance, Reuse and Recycling” Boca Raton: CRC Press, Chapter 3 pp88-93.

26. Liang, Y., Pokharel, S. and Lim, G. H. (2009) “Pricing used products for remanufacturing” European Journal of Operational Research 193 (2009) pp. 390–395.

27. Lipsey, M. W. and Hurley, S. M. (2009) “Design sensitivity: Statistical power for applied experimental research” In L. Bickman & D. Rog (Eds). “The SAGE Handbook of Applied Social Research Methods” (2nd ed.) Los Angeles: Sage, Chapter 2, pp. 44-76.

28. Lund, R.T. (1984), "Remanufacturing: the experience of the USA and implications for the developing countries" World Bank Technical Paper No. 3.

29. Mähl, M. and Östlin, J. (2007) “Lean Remanufacturing – Material Flows at Volvo Parts Flen” Masters Dissertation: Uppsala University: Sweden.

30. Mukhopadhyay, S. and Ma, H. (2008) “Joint procurement and production decisions in remanufacturing under quality and demand uncertainty” International Journal of Production Economics 120 (2009) pp. 5–17.

31. Östlin, J., Sundin, E. and Björkman, M. (2008) “Importance of closed-loop supply chain relationships for product remanufacturing” International Journal of Production Economics 115, pp. 336–348.

32. Parkinson, H. J. and Thompson, G. (2003) “Analysis and taxonomy of remanufacturing industry practice” Proceedings of the Institution of Mechanical Engineers Vol. 217 Part E: J. Process Mechanical Engineering.

33. Polit, D.F. and Hungler, B.P. (1999) “Nursing Research: Principles and Methods” (6th ed.) Philadelphia: J. B. Lippincott.

34. Ridley, S.J. (2013) “Increasing the Efficiency of Engine Remanufacture by Optimising Pre-Processing Inspection – A comprehensive study of 2196 engines at Caterpillar Remanufacturing in the UK” PhD Dissertation: The University of Strathclyde, UK.

35. Savaskan, R.C., Bhattacharya, S. and Van Wassenhove, L.N. (2004) “Closed-loop supply chain models with product remanufacturing” Management Science 50, pp. 239–252.

36. Solomon, R. L. (1949) “An extension of control group design” Psychological Bulletin, 46, pp. 137-150.

37. Subramoniam, R., Huisingh, D. and Chinnam, R. (2009) “Remanufacturing for the automotive aftermarket-strategic factors: literature review and future research needs” Journal of Cleaner Production 17, pp. 1163–1174.

38. Sutherland, J.W., Adler, D.P., Haapala, K.R. and Kumar, V. (2008) “A comparison of manufacturing and remanufacturing energy intensities with application to diesel engine production” CIRP Annals - Manufacturing Technology 57 pp. 5–8.

39. Tang, O., Grubbström, R.W. and Zanoni, S. (2007) “Planned lead time determination in a make-to-order remanufacturing system” International Journal of Production Economics 108, pp 426–435.

40. Teunter, R.H. and Flapper, S.D.P. (2010) “Optimal core acquisition and remanufacturing policies under uncertain core quality fractions” European Journal of Operational Research, doi: 10.1016/j.ejor. 2010.06.015

41. Toktay, L.B., Wein, L.M. and Zenios, S.A. (2000) “Inventory management of remanufacturable products” Management Science 46, pp. 1412–1426.

42. Womack, J.P., Jones, D.T., and Roos, D. (2007) “The Machine That Changed the World” New ed. New York: Simon and Schuster Inc.