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FMEA-based Design for Remanufacture using Automotive-Remanufacturer Data

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ABSTRACT

This paper describes the development of a Failure Modes and Effects Analysis (FMEA) modified to support design for remanufacture. The results of the waste-stream analysis of an automotive remanufacturer were used for this FMEA. The remanufacturer waste stream was assessed to determine factors that impede the reuse of parts. The use of the modified FMEA allows consideration of factors such as ease of detection and repair of failure, in conjunction with contribution to the waste stream of each failure mode, to develop priorities in design for remanufacture.

INTRODUCTION

The long-term goal of this research is to develop a methodology for designing products that can be more easily remanufactured. Remanufacturers take back, disassemble and clean used products, replace or repair failed parts, and reassemble products in a production-batch process. The essential goal of remanufacture is to reuse parts. Parts that cannot be reused are discarded and enter the remanufacturer's waste stream. Therefore, analysis of this waste stream will identify barriers to the reuse of parts. The results of such an analysis may be used to develop design strategies, such as guidelines and metrics, which enable more efficient remanufacture of future products. Specifically in this study, we quantified through data, the FMEA indices of occurrence (OCC), detectability (DET), and repairability (REP), which is our measure of severity (SEV), of the failure modes identified in the remanufacturer’s waste stream.

BACKGROUND AND MOTIVATION

Traditionally, products have been designed and manufactured to meet functional needs during the product's useful lifetime, with little regard for the product's end-of-life. Recently, in response to stricter environmental legislation, particularly in Europe and parts of Asia, that assigns responsibility for products at the end-of-life to manufacturers, more products have been designed for ease of scrap-material recycling. Scrap-material recycling involves separating a product into different materials and reprocessing the materials for use in similar or degraded applications.

For appropriate products, remanufacturing offers significant environmental and economic benefits over scrap-material recycling. Remanufacturing involves recycling at the parts level as opposed to the material level. Recycling at the higher level of components avoids resource consumption for possibly unnecessary reprocessing of material. Remanufacturing also postpones the repeated degradation of the raw material through contamination and molecular breakdown, frequently characteristic of scrap-material recycling. Furthermore, remanufacturing can divert parts that are not recyclable for material content from landfill and incineration. The production-batch nature of the remanufacturing process enables it to salvage functionally failed but repairable products that are discarded due to high labor costs associated with individual repair.

The relationship between manufacturing and remanufacturing is depicted in Figure 1, which shows that while the manufacturing process produces new products, the remanufacturing process can repeatedly take products at the end-of-life and transform them to a "like-new" condition for reuse. A few manufacturers remanufacture their own products. In the office equipment market, companies such as the Xerox Corporation have achieved $200 million in annual savings by remanufacturing their photocopiers [U.S. Congress 1992]. Some manufacturers, such as the Ford Motor Company have "Authorized Remanufacturers" to process after-market parts for their cars. With increasing international product take-back legislation, more manufacturers are likely to become interested in the remanufacture of their products.

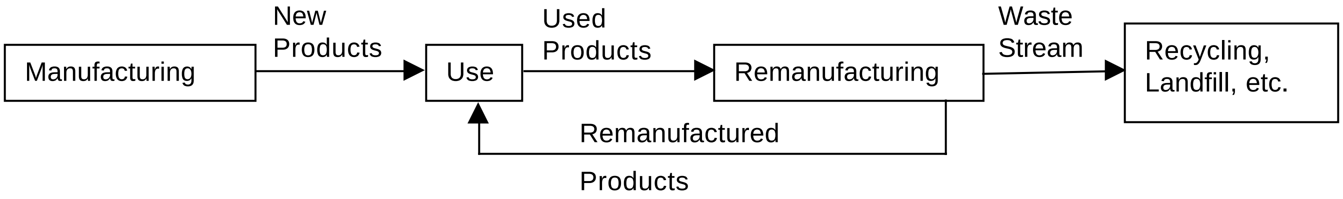

Figure 1. Relationship between manufacturing and remanufacturing.

RELATED WORK

Design for recycling is the focus of much research related to product retirement [Ishii and Lee 1996]. It is an area that is mostly complementary to design for remanufacture. Any of the steps of remanufacture, e.g., disassembly, cleaning, etc., treated as a design-for-x method also supports design for remanufacture. Thus some research in design-for-disassembly include maintenance and remanufacture [Zussman et al. 1994]. Other research has developed strategies to aid product reuse [Umeda et al. 1999, Mangun and Thurston 2000]. Shu and Flowers consider reliability and fastening and joining with respect to remanufacture (1998, 1999). Hammond et al. (1998) conducted a survey of automotive remanufacturers to uncover process difficulties and generated design-for-remanufacture guidelines and metrics [Hammond and Bras 1996]. Sherwood and Shu summarized the results of waste-stream analyses of three automotive remanufacturers and proposed the use of a modified FMEA to support design for remanufacture (2000).

Research that addresses FMEA in the context of redesign is also relevant [Eubanks et al. 1996, Kmenta et al. 1999]. Despite the work on specific aspects and general surveys of remanufacture, a systematic study of remanufacturing difficulties is necessary to ensure that no significant issues are overlooked in the development of design-for-remanufacture strategies.

The approach of this work is novel in that the remanufacturer's waste stream and other process data is quantified to uncover design-for-remanufacture strategies.

REMANUFACTURE INDUSTRIES

Lund (1996) compiled a list of 9,903 remanufacturers and identified the most dominant product sectors as automotive, electrical apparatus, tires, and toner cartridges. The automotive sector, with typical products of alternators, starter motors, water pumps, clutches and engines, comprises the highest percentage, 46% of Lund's database population. Next are electrical apparatus (transformers, electrical motors, switch gear) at 23%, toner cartridges at 14% and retreaded tires at 12%. Other categories comprise 5% of Lund's database of remanufacturers.

This paper continues to address the results of data collection in the automotive sector. Previous work in this sector is described in Sherwood and Shu (2000). Williams and Shu (2000) present results of data collection for toner cartridges.

REMANUFACTURING PROCESS

At the original-equipment remanufacturer (OER) of automotive engines where this study was conducted, the production-batch process proceeds as follows. The received engines are delivered to the disassembly station. In each batch, seven to fifteen engines, depending on the size of the engine, are disassembled. The engines are dismantled and the parts sorted into baskets for cleaning. The cleaning process uses either chemical spray or high-pressure water. The processes for the different parts are as follows.

Block - After a cleaning process that removes grease and other chemicals from engine blocks, the bore diameters are measured using gauges and compared to specifications. For blocks within specification, threads are tapped before the blocks are sent to machining lines. The bores for the crankshafts are checked for straightness and size, and machining is performed as necessary. Next, the seat is milled and the piston housing is bored. Finally, the blocks are washed to remove metal chips accumulated during the machining processes and await delivery to the assembly line.

Cylinder Head - Cylinder heads disassembled from engine blocks proceed to a subsequent station for further disassembly of the springs, rocker arms, valve pins, etc. The aluminum cylinder heads are then washed in a separate machine since they cannot be treated together with iron and steel parts. The cylinder heads are then sand blasted before threads are tapped. Next, guides for the valve pins and valve seats are replaced before seat cutting or milling is performed. Like the engine blocks, cylinder heads are washed to remove excess metal chips accumulated during machining before proceeding to assembly.

Crankshaft - After being cleaned together with camshafts, connecting rods, oil pans and valve covers, crankshafts are delivered to machining lines. The crankshafts are first gauged to check the dimensions of all shafts. When a part satisfies all the specifications, it proceeds to stations for grinding and polishing. Crankshafts are gauged again before being delivered to the assembly line.

Camshaft - The process for camshafts is similar to that for crankshafts. They are cleaned, gauged, ground and polished. However, after cleaning, instead of proceeding to a machining line, they are brought to a station where usually one employee is responsible for all the remaining processes to be performed on a particular camshaft.

Connecting Rod - There is no machining process in use for connecting rods. After cleaning, all connecting rods are delivered to a station where they are sorted according to engine model. Then, all rods from the same engine type will be loaded onto a shaft that serves as an initial measuring tool. If a rod cannot fit onto the shaft, it is scrapped because the attached cap is likely mismatched. All bolts are replaced before the connecting rods are gauged to check dimensions. Finally, connecting rods are weighed and grouped by weight. Depending on the number required by the engine type, four to eight rods with the same weight, within an accepted tolerance, are grouped together to enhance crankshaft performance.

Oil Pan/Valve Cover - Comparatively, the refurbishment of oil pans/valve covers requires simpler processes. After cleaning, accessible dents are removed from the oil pans/valve covers. If the convex side of the dent is inaccessible, the dent cannot be removed and the pan/cover will be scrapped. The oil pans/valve covers are then painted before proceeding to assembly.

Cylinder Sleeve - After cleaning, cylinder sleeves are sand blasted. The bores are then gauged and the seats polished. Lastly, the cylinder sleeves are bored. Special care must be taken during the boring process and consequently a considerable number of sleeves are machined oversized.

FAILURE AND SCRAP CATEGORIES

Typically, a part must satisfy two conditions before entering the waste stream of a remanufacturer. The first condition is that the part has failed, i.e., it can no longer fulfill its intended function. The second condition is that the part is deemed not repairable. Failure mode refers to why the part cannot be reused without repair, e.g., due to presence of crack, excessive wear or corrosion. Many failed parts can be repaired. For example, some cracks may be welded and dents may be removed. Scrap mode refers to why the part was not repaired, typically due to technical limitations, and includes reasons such as no process is available for repair or the repair is not economically justifiable. Figure 2 depicts the relationship between failure and scrap modes. Each part entering the waste stream was counted and described according to both failure and scrap modes. Sound parts that were scrapped were labeled ‘no failure,’ as described below.

FAILURE MODES

Fifteen failure categories, including the “no failure” category were identified and described as follows.

Bent - This category includes connecting rods, the occasional crankshaft, and very few large pieces such as cylinder heads that are warped.

Burnt - Parts become burnt due to lack of oil in the engine, a result of maintenance failure by the vehicle owner.

Corrosion - This category includes blocks, crankshafts, camshafts, connecting rods, and oil pans that rust when exposed to water vapor, and cylinder heads that are corroded by cooling agent.

Crack - Parts that crack include blocks, camshafts, cylinder heads, and cylinder sleeves. Most cracks spotted by disassemblers are deep cracks and tears.

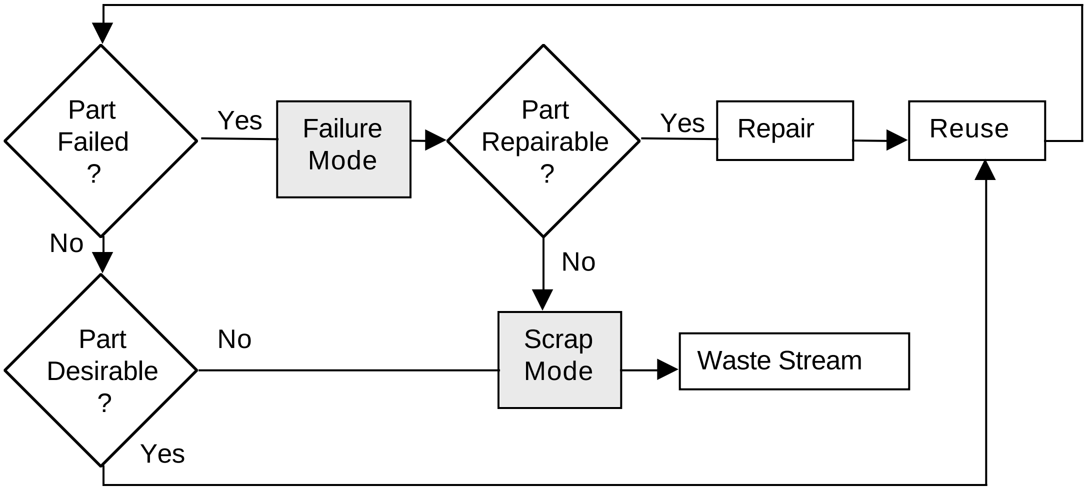

Figure 2. Failure mode versus scrap mode

Dent - This category is mostly comprised of oil pans /valve covers.

Design Flaw - Some parts such as blocks have design flaws that are not correctable during remanufacture.

Disassembly Damage - Some parts are damaged during the disassembly process.

Disassembly Impossible - Other parts cannot be reused because they cannot be disassembled.

Fastener Failure - Included here are damaged transmission mounts that project from the sides of the engine block, bolts that snap off in holes and stretched keyways in crankshafts and camshafts.

Fracture - Fractured parts are broken into pieces. While the same types of parts that crack are fractured, cracked parts may be retrievable while fractured parts are typically not repaired.

Handling Damage - These parts are damaged in different ways while being moved.

Hole - Holes are large material segments removed from the part body. Parts with holes are primarily engine blocks and occasionally punctured oil pans.

Machining Damage - Some parts are damaged due to errors in machining.

Wear – Engine-block piston housings, camshaft bearings and cylinder bores are worn during ordinary use, while crankshafts are gouged and grooved from improper engine operation and care.

No Failure - There is a large category of parts discarded that were not functionally flawed, but were scrapped due to the overstock scrap mode detailed below.

SCRAP MODES

Scrap modes correspond to reasons why parts are discarded and correspond to the FMEA category of effect of failure.

Cosmetic - Functional parts may be discarded due to cosmetic imperfections. Examples include plastic parts with scratches and dents that cannot be fully removed.

Last Oversize/Undersize - The repair process for worn, burnt, or corroded parts is further removal of material, sometimes resulting in under- or oversized parts. Parts are at last oversize/undersize for two observed reasons. First, too much material is lost from the part during use. Second, parts returned to the remanufacturer have had material removed during previous remanufacture processing.

Blocks, cylinder heads, connecting rods and cylinder sleeves have bores that become oversize through wear and/or previous reboring. Crankshafts and camshafts become undersize through material removal. Blocks and crankshafts are the only parts that bear remanufacturers' labels and can thus be more easily identified as having been previously remanufactured.

Makes Oversize/Undersize - This category is similar to "last oversize/undersize" except that the cause of oversize/undersize is within the remanufacturing facility. This occurs when refurbishment requires the removal of an excessive amount of material, such as the case with deep scratches, or the remanufacture worker has erroneously removed too much material in machining. In the first case, the parts would usually be scrapped before refurbishment whereas in the second case, the part is scrapped during or after machining. Again, this scrap mode is mainly associated with wear, burn and corrosion.

The parts scrapped in this category are blocks, cylinder heads, crankshafts, camshafts and cylinder sleeves. Parts requiring boring, such as blocks and cylinder sleeves, are more likely to fall in this category because boring removes more material in one pass than grinding and polishing. In cylinder heads, "makes undersize" usually occurs during seat cutting, which involves the removal of a large amount of material. Even though the depth of cutting is fixed, machining error is still possible. On the other hand, crankshafts are carefully gauged before machining; thus only a few of them are machined undersize.

Material Loss - This category accounts for parts discarded due to material loss that cannot be economically or reliably replaced. Material loss may have occurred through corrosion, scratches, fractures and holes. Patching holes and removing corroded material on blocks are time-consuming and therefore not performed. Cylinder heads lose material around valve seats. This material loss is caused by the impact of valve pins that break off during engine operation. Scratched or fractured camshafts cannot be reliably welded and are scrapped. Other parts scrapped due to material loss, mainly as a result of fracture, include connecting rods, oil pans/valve covers, and cylinder sleeves. Connecting rods may also be discarded because of scratches in the bores. Material loss also has high correlation with the "burnt" failure mode since many of the parts that were scrapped were also burnt.

Mating Part Lost - Some parts, such as bearing caps and connecting rods, wear together and must be kept together. If one piece is missing or mismatched, the part is discarded.

No Process - Parts in this category are scrapped because the remanufacturer does not have equipment or know-how to perform the required repair process. Also included are parts for which the damaged portion is not accessible to the repair process used.

Overstock - Parts are scrapped when new parts can be bought more cheaply than old parts can be refurbished and when there is sufficient inventory and no more storage capacity. Overstock is seasonal and results in a large number of a particular kind of part to be scrapped at once.

Sacrificial Part - This category corresponds to parts that are damaged in disassembly in order to save a more valuable part. A considerable number of connecting rods were scrapped at the disassembly station after being struck out from the block. To salvage the more valuable engine block, the connecting rods are bent, twisted or fractured during removal.

Unknown Damage - This category is designated for those parts that are scrapped without being examined to identify specific damage. For instance, when the remanufacturer receives an engine with a large hole in the block, the entire engine may be scrapped without disassembly, since it is suspected that other severe damage is likely to be present in this engine. Parts that are retained in the engine block and not disassembled are classified in this category, since specific damage was not identified.

Warped Part - This category includes parts that are or are likely to be warped as a result of welding. Parts are frequently preheated before welding. Preheating is done at a higher temperature when welding is required at many locations, or over a large surface, or when the part itself is large. Warping may occur as the part cools. The warped part is scrapped because it cannot be straightened.

Two particular models of cylinder heads had more problems of warping after welding because the cylinder head sizes are larger than other models. Consequently, cracks, scratches and other damages are not repaired on these two types of cylinder heads, resulting in a large number of scrapped parts.

Weakens Part - Some damaged parts can be repaired, but the repair process may adversely affect the function and/or lifetime of the parts. Such parts were scrapped because testing would be too costly. For instance, bent or twisted connecting rods could be straightened, but since the process may weaken the parts, they are scrapped.

DATA COLLECTION

Data collection lasted from May to September 2000 and a total of 1245 parts were counted. The daily production volume of the remanufacturer studied is enormous. Thus, it is not reasonable and feasible to examine every single part that flows through the plant. It was essential to select a certain number of parts for the study. This project was conducted to investigate the occurrence, detectability and the repairability of certain failure modes identified in the waste stream. Therefore, the selected parts must be relevant to these three indices.

The parts studied include blocks, cylinder heads, camshafts, crankshafts, connecting rods, oil pans/valve covers and cylinder sleeves. A route through all the stations on the shop floor was established to effectively collect data. The route started from the disassembly station, through the oil pan/valve cover painting stations located adjacent to the disassembly station, followed by the stations for cylinder heads, connecting rods, crankshafts, blocks, cylinder sleeves and camshafts. The sequence was made according to the shop floor layout.

During each pass, two types of data were recorded. First recorded is the number of parts for which all the required processes at each station had been completed. Next, the scrap bin was inspected and the number of scrapped parts and the discard reasons were recorded.

The remanufacturer studied has contracts with and only processes engines of two OEMs. This characteristic provides stability and consistence of the collected data.

FAILURE AND SCRAP MODE BY PART TYPE

In this section, findings will be discussed on the basis of part type. The dominant failure modes and scrap modes of each part type are described.

Block - The dominant failure mode of blocks is wear of the piston housing bores. This failure mode is associated with the scrap mode of “last oversize”. Another possibility is that the bore is machined oversize, corresponding to the categories of "machining damage" and "makes oversize". This possibility is unlikely because all blocks are gauged first and a standard tool is used for boring.

Bores in the blocks for crankshafts are also worn. The crankshaft is fitted into the block with a cap. Wear loosens the cap resulting in the failure mode "wear" and the scrap mode "last oversize."

Another dominant failure mode for blocks is "disassembly impossible". This failure mode occurs when the block cannot be disassembled because connecting rods retained in the block cannot be drawn out by disassemblers. The block is scrapped because the remanufacturer has no process for disassembly.

Cylinder Head - Cracks on cylinder heads may result from the impact of valve pins. Cracks were found between the intake and exhaust channels, particularly for the middle pistons of one specific model. The remanufacturer can repair smaller cracks. If the crack is too severe, the welding process may cause warping, weakening the part.

Wear is also likely to occur at the interface between cylinder heads and engine blocks. The cylinder heads may be made of a different material from the blocks and therefore have a different degree of thermal expansion, resulting in shear stress and wear along the interface. After a considerable amount of wear, the cylinder head becomes undersize and is thus scrapped.

It should be noted that the failure mode "disassembly impossible" does not occur during the disassembly of cylinder heads from engine blocks, but instead during the disassembly of valve-pin guides. Since the guides are pressed fitted, disassembly without damage is difficult. If the guides are pressed out using excessive force, damage occurs to the cylinder head, resulting in a scrap mode of "weakens part."

Crankshaft - The rotation of crankshafts relative to connecting rods causes wear at the shafts, which become undersize. Furthermore, if an engine is not regularly maintained, it may lack lubricant and become burnt. The majority of scrapped crankshafts have a failure mode of "burnt." Since a large amount of material is worn from burnt parts, these crankshafts become undersize.

On the other hand, many crankshafts were scrapped with the failure mode of “no failure” because the remanufacturer studied overstocked a particular model of crankshafts.

Camshaft - Approximately half of the total camshafts scrapped had failure mode “wear”. Since pieces of material are flaked off from the cams, the scrap mode is “material loss” instead of “undersize.”

Another major failure mode of scrapped camshafts is corrosion, which is more severe during the summer due to higher temperatures and humidity. The camshafts may be stored at the remanufacturer for an extended period of time before being processed.

Connecting Rod - As previously stated, in an engine lacking maintenance, parts including crankshafts and connecting rods would be burnt. Wear at the bore of the connecting rod thus becomes more severe, resulting in oversize of the bore. For connecting rods, “no failure” usually meant a mismatched cap, resulting in a scrap mode of "mating part lost". Caps usually become mismatched during disassembly. Damage to connecting rods may be made during disassembly when connecting rods are wedged inside engine blocks. Disassemblers would strike or pull connecting rods out of blocks using excessive force. To save the more valuable blocks, the less valuable connecting rods would be sacrificed.

The failure mode "disassembly impossible" may result from two possibilities. First, the connecting rods are retained in the engine blocks and cannot be removed using any available method. Second and more commonly, the connecting rods cannot be disassembled from the pistons. In both cases, the impossibility of disassembly could be due to lack of lubricant and/or extended storage time where corrosion within the blocks may cause flaked-off material to impede removal of the connecting rods. In the first case, the connecting rods have scrap mode "unknown damage" since the specific damage could not be identified. In the second case, the connecting rods have scrap mode "no process".

Oil Pan/Valve Cover - Most oil pans/valve covers have failure modes of dent and corrosion since these parts are located at the outer layer of the engine, protecting the cylinder heads and crankshafts. The pans/covers are made of sheet metal that can be easily deformed. Dents may also result during the transportation of engines to the remanufacturer since engines may be dropped on floors or conveyors. Also, oil pans/valve covers have direct contact with the surrounding environment and are vulnerable to corrosion.

Manual reshaping can be used to repair most of the dented oil pans/valve covers. However, some dents cannot be accessed for repair and result in scrap mode “no process". Corroded oil pans/valve covers have scrap mode "material loss".

Cylinder Sleeve - Cylinder sleeves guide the movement of pistons and are used in only certain types of engines. As expected, wear is the dominant failure mode.

STATISTICAL ANALYSIS

The sample of parts was statistically analyzed using a normal approximation to assess the 95 percent confidence level of the probability of assigned failure modes and scrap modes. Parts were analyzed as to their probability of incurring a single failure mode (failed/not failed) and single scrap mode (scrap/not scrap) on a part count basis.

DERIVATION OF FMEA INDICES

OCCURRENCE

Table 1 shows the percentage of each part type entering the waste stream categorized into the different failure modes. The bottom row of Table 1 represents the probability that a part entering the waste stream has a particular failure mode and is relevant to the FMEA index of occurrence (OCC). These probabilities are used to derive the OCC index as follows. The largest probability, in our case, 21.8% for “wear”, is assigned an OCC value of 10, while the smallest probability, 0.1% for “handling damage” is assigned an OCC value of 1. All other probabilities are normalized to these two extremes to obtain corresponding values for OCC. Derivation of OCC values for each failure mode is shown in Table 5a.

Table 2 shows the proportion of scrap modes for each part type. These percentages are not used to derive an FMEA index, but the scrap modes do correspond to the FMEA category of effect of failure. In our case, the scrap mode corresponds to the actual, rather than the expected, effect of failure modes.

DETECTABILITY

The next FMEA index of interest is DET or detectability. In our study, we relate detectability to the point in the remanufacture process that a failure is detected. For example, it is far better that a crack is detected at disassembly, so that an immediate decision can be made whether the crack is repairable and if so, by which processes, than if that same crack were not detected until final assembly. Therefore, the later the detection, the higher the value of the DET index. Table 3 shows the proportion of all parts combined that were detected at a particular processing station with a particular failure mode.

Parts are first analyzed with respect to the processing sequence. Generally, all parts go through the stages of disassembly, cleaning, painting and inspection. After inspection, the sequence of processes depends on the part type. Processes are grouped according to the location of the process in the sequence. For example, grinding for crankshafts is grouped together with polishing for camshafts under “Process 1” since these are the first processes immediately following inspection for these part types.

Combining failure modes, 35% and 56% of all failures were detected at the disassembly and inspection stations, respectively. Except for the failure modes "design flaw", “disassembly damage”, “disassembly impossible”, "fracture," and "handling damage", the majority, greater than 50%, of parts for all other failure modes were detected at the inspection station.

The contrast in detectability between the stations for disassembly and inspection is substantial for wear. Specifically, over 80% of wear was detected at the inspection station, which is the highest percentage of detection at a single station for a failure mode, excluding extreme and special cases. This high contrast is because wear in small amounts is difficult to detect by the disassemblers who do not have the appropriate measurement equipment. Only severe cases of “wear”, as well as “burnt”, “crack”, “fracture” and “hole,” are detectable at the disassembly stage. Hence, the detectability of a failure mode at the inspection station depends on gauging accuracy, and the detectability of a failure mode at the disassembly station depends on the severity of the failure.

Next addressed is the derivation of the FMEA DET detectability index from the data collected. The index reflects the concept that the more parts for a particular failure mode that can be detected at an early stage, the better the detectability of that failure mode.

Each processing stage is assigned with a weight, based on the location in the sequence. Since there are a total of 9 stages defined, the earliest stage, disassembly, is assigned with a weight of 1/9 while the next stage, cleaning, is assigned with a weight of 2/9. Inspection is assigned a weight of 4/9 and the steps grouped together as “Process 1”, or the step immediately following inspection for different parts, are all assigned the identical weight of 5/9. Subsequent steps grouped together as Processes 2, 3 and 4 are also identically weighted by group. The weighting factors and percentages of parts detected at each stage are first multiplied together. Then, the weighted percentages of different stages are combined to obtain the overall weighted percentage. Finally, the overall weighted percentage is multiplied by 10 to obtain a DET index with a range up to 10. Derivation of DET values for each failure mode is shown in Table 5b.

Following this method of calculating detectability, “machining damage” has the highest, least desirable index value. This failure mode is incurred during machining, a fairly late stage, and can therefore only be detected at later stages. The lateness of both the occurrence and detection increases the index, accounting for the fact that resources required to perform earlier activities on a discarded part are wasted.

Furthermore, the DET index of the failure modes "design flaw" and "handling damage" have the most favorable values. The design flaws studied were highly detectable because they can be identified from model labels on the parts. However, the detectability of handling damage calculated is not reliable because only one part, an engine block missing caps, belongs to this category.

All other failure modes have index values in the range which corresponds to moderate to highly desirable detectability. This result is reasonable because most of the failure modes are detected at the inspection station where a reasonable degree of detectability is expected due to the quality of the equipment and the skill of the inspectors.

Table 1. Failure Modes for Each Part Type

Part Type	Failure Mode Bent	Burnt	Corrosion	Crack	Dent	Design Flaw	Disassembly Damage	Disassembly Impossible	Fastener Failure	Fracture	Handling Damage	Hole	Machining Damage	Wear	No Failure	Part Type
Block		0.7%	4.2%	10.5%	0.7%	2.8%	1.4%	22.4%	1.4%	7.0%	0.7%	9.1%	3.5%	24.4%	11.2%	Block
95% CI		1.4%	3.3%	5.0%	1.4%	2.7%	1.9%	6.8%	1.9%	4.2%	1.4%	4.7%	3.0%	7.0%	5.2%	
Cylinder Head	2.8%	6.7%	5.6%	23.0%			7.9%	19.6%	3.4%	0.6%		1.1%	6.2%	22.5%	0.6%	Cylinder Head
95% CI	2.4%	3.7%	3.4%	6.2%			4.0%	5.8%	2.7%			1.5%	3.5%	6.1%	1.1%	
Crankshaft	0.6%	37.2%	5.0%				5.0%	3.7%	2.5%	3.1%			2.5%	20.5%	19.9%	Crankshaft
95% CI	1.2%	7.5%	3.4%				3.4%	2.9%	2.4%	2.7%			2.4%	6.2%	6.2%	
Camshaft		0.6%	13.3%	2.9%			2.3%	2.3%	4.0%	5.2%			6.4%	57.8%	5.2%	Camshaft
95% CI		1.1%	5.1%	2.5%			2.2%	2.2%	2.9%	3.3%			3.6%	7.4%	3.3%	
Connecting Rod	10.3%	26.1%	1.1%				16.9%	20.1%	2.0%	0.9%				6.3%	16.3%	Connecting Rod
95% CI	3.2%	4.6%	1.1%				3.9%	4.2%	1.5%	1.0%				2.5%	3.9%	
Oil Pan / Valve Cover			14.5%		69.8%			1.3%	5.0%			3.8%		4.4%	1.2%	Oil Pan / Valve Cover
95% CI			5.5%		7.1%			1.7%	3.4%			3.0%		3.2%	1.7%	
Cylinder Sleeve		18.3%		11.0%	1.2%			4.9%		7.3%			15.8%	41.5%		Cylinder Sleeve
95% CI		8.4%		6.8%	2.4%			4.7%		5.6%			7.9%	10.7%		
Overall percentage of parts for each failure mode	3.4%	14.5%	5.9%	5.6%	9.1%	0.3%	7.0%	12.3%	2.7%	2.7%	0.1%	1.7%	3.5%	21.8%	9.4%	Overall percentage of parts for each failure mode
95% CI	1.0%	2.0%	1.3%	1.3%	1.6%	0.3%	1.4%	1.8%	0.9%	0.9%	0.2%	0.7%	1.0%	2.3%	1.6%	95% CI

Table 2. Scrap Modes for Each Part Type

Part Type	Scrap Mode Cosmetic	Last Oversize	Last Undersize	Makes Oversize	Makes Undersize	Material Loss	Mating Part Lost	No Process	Overstock	Sacrificial Part	Unknown Damage	Warped Part	Weakens Part	Part Type
Block		25.2%	1.4%	1.4%	0.7%	19.6%	1.4%	32.8%			16.1%		1.4%	Block
95% CI		7.1%	1.9%	1.9%	1.4%	6.5%	1.9%	7.7%			6.0%		1.9%	95% CI
Cylinder Head		7.3%	9.5%		6.2%	18.0%	0.6%	9.5%			11.8%	3.4%	33.7%	Cylinder Head
95% CI		3.8%	4.3%		3.5%	5.6%	1.1%	4.3%			4.7%	2.7%	6.9%	95% CI
Crankshaft			55.9%		2.5%	15.5%		3.1%	19.9%		3.1%			Crankshaft
95% CI			7.7%		2.4%	5.6%		2.7%	6.2%		2.7%			95% CI
Camshaft			20.8%		11.0%	61.3%	0.6%	2.9%			1.7%		1.7%	Camshaft
95% CI			6.0%		4.7%	7.3%	1.1%	2.5%			1.9%		1.9%	95% CI
Connecting Rod		31.8%				3.2%	18.1%	8.3%		16.9%	12.0%		9.7%	Connecting Rod
95% CI		4.9%				1.8%	4.0%	2.9%		3.9%	3.4%		3.1%	95% CI
Oil Pan / Valve Cover	0.6%					18.9%	3.8%	76.7%						Oil Pan / Valve Cover
95% CI	1.2%					6.1%	3.0%	6.6%						95% CI
Cylinder Sleeve	1.2%	28.0%		15.9%		24.4%		23.2%			4.9%		2.4%	Cylinder Sleeve
95% CI		9.7%		7.9%		9.3%		9.1%			4.7%		3.3%	95% CI
Overall percentage of parts for each scrap mode	0.2%	14.7%	11.6%	1.2%	2.8%	20.2%	5.9%	19.6%	2.6%	4.7%	7.9%	0.5%	8.1%	Overall percentage of parts for each scrap mode
95% CI	0.2%	2.0%	1.8%	0.6%	0.9%	2.2%	1.3%	2.2%	0.9%	1.2%	1.5%	0.4%	1.5%	95% CI

Table 3. Processes where Failure Modes Detected

	Remanufacturing Process																						
					Process 1							Process 2					Process 3			Process 4			
	1	2	3	4	5	5	5	5	5	5	5	6	6	6	6	6	7	7	7	8	8	9	
Failure Mode	Disassembly	Clean	Paint	Inspection	Block: Threading	Cylinder Head: Remove Guide	Crankshaft: Grinding	Camshaft: Polishing	Connecting Rod: Remove Fastener	Oil Pan/Valve Cover: Reshaping	Cylinder Sleeve: Boring	Block: Seat Cutting	Cylinder Head: Threading	Crankshaft: Polishing	Connecting Rod: Polishing	Oil Pan/ Valve Cover: Painting	Block: Boring	Cylinder Head: Boring	Connecting Rod: Weighting	Block: Final Inspection	Cylinder Head: Milling	Assembly	Failure Mode
Bent	40.5%			59.5%																			Bent
95%CI	14.8%			14.8%																			95%CI
Burnt	21.7%			78.3%																			Burnt
95%CI	6.0%			6.0%																			95%CI
Corrosion	24.3%			70.3%				4.1%													1.3%		Corrosion
95%CI	9.8%			10.4%				4.5%													2.6%		95%CI
Crack	34.3%			58.6%													5.7%	1.4%					Crack
95%CI	11.1%			11.5%													5.4%	2.8%					95%CI
Dent	22.1%			77.9%																			Dent
95%CI	7.7%			7.7%																			95%CI
Design Flaw	100.0%																						Design Flaw
95%CI	0.0%																						95%CI
Disassembly Damage	88.5%			9.2%		2.3%																	Disassembly Damage
95%CI	6.7%			6.1%		3.1%																	95%CI
Disassembly Impossible	87.6%			5.9%		6.5%																	Disassembly Impossible
95%CI	5.2%			3.7%		3.9%																	95%CI
Fastener Failure	3.0%			64.7%					26.5%				2.9%					2.9%					Fastener Failure
95%CI	5.7%			16.1%					14.8%				5.7%					5.7%					95%CI
Fracture	70.6%			29.4%																			Fracture
95%CI	15.3%			15.3%																			95%CI
Handling Damage	100.0%																						Handling Damage
95%CI	0.0%																						95%CI
Hole	47.6%			52.4%																			Hole
95%CI	21.4%			21.4%																			95%CI
Machining Damage							9.1%	36.4%			15.9%	4.5%					9.1%	11.4%			13.6%		Machining Damage
95%CI							8.5%	14.2%			10.8%	6.2%					8.5%	9.4%			10.1%		95%CI
Wear	4.4%			81.2%								0.4%					12.9%	0.4%			0.7%		Wear
95%CI	2.4%			4.7%								0.7%					4.0%	0.7%			1.0%		95%CI
No Failure	41.0%			58.1%														0.9%					No Failure
95%CI	8.9%			8.9%														1.7%					95%CI
Overall Percentage of parts Detected at Each Process	34.9%			55.8%		1.0%	0.3%	1.5%	0.7%		0.6%	0.2%	0.1%				3.5%	0.7%			0.7%		Overall Percentage of parts Detected at Each Process
95%CI	2.6%			2.8%		0.5%	0.3%	0.7%	0.5%		0.4%	0.3%	0.2%				1.0%	0.5%			0.5%		95%CI

Table 4. Repairablity of Failure Modes

		Failure Mode															
Part Type		Bent	Burnt	Corrosion	Crack	Dent	Design Flaw	Disassembly Damage	Disassembly Impossible	Fastener Failure	Fracture	Handling Damage	Hole	Machining Damage	Wear	No Failure	Part Type
Block	Repairable																Block
	95%CI																
	Unrepairable																
	95%CI																
Cylinder Head	Repairable			43.1%	78.1%				24.5%	26.3%	50.0%				16.1%		Cylinder Head
	95%CI			12.7%	5.7%				12.0%	19.8%	49.0%				9.6%		
	Unrepairable	100.0%	100.0%	17.2%	21.9%			100.0%	71.4%	31.6%	50.0%		25.0%	100.0%	71.4%	33.3%	
	95%CI	0.0%	0.0%	9.7%	5.7%			0.0%	12.6%	20.9%	49.0%		34.6%	0.0%	11.8%	53.3%	
Crankshaft	Repairable																Crankshaft
	95%CI																
	Unrepairable																
	95%CI																
Camshaft	Repairable																Camshaft
	95%CI																
	Unrepairable																
	95%CI																
Connecting Rod	Repairable																Connecting Rod
	95%CI																
	Unrepairable																
	95%CI																
Oil Pan / Valve Cover	Repairable					93.6%											Oil Pan / Valve Cover
	95%CI					1.2%											
	Unrepairable			39.7%		6.4%			4.1%	42.1%			75.0%		12.5%	66.7%	
	95%CI			12.6%		1.2%			5.5%	22.2%			34.6%		8.7%	53.3%	
Cylinder Sleeve	Repairable																Cylinder Sleeve
	95%CI																
	Unrepairable																
	95%CI																
Overall number of parts for each failure mode	Repairable			43.1%	78.1%	93.6%			24.5%	26.3%	50.0%				16.1%		Overall number of parts for each failure mode
	95%CI			12.7%	5.7%	1.2%			12.0%	19.8%	49.0%				9.6%		
	Unrepairable	100.0%	100.0%	56.9%	21.9%	6.4%		100.0%	75.5%	73.7%	50.0%		100.0%	100.0%	83.9%	100.0%	
	95%CI	0.0%	0.0%	12.7%	5.7%	1.2%		0.0%	12.0%	19.8%	49.0%		0.0%	0.0%	9.6%	0.0%	

Tables 5a,b,c. Derivation of OCC, DET and REP Indices

Failure Mode	% Waste Stream	OCC
Bent	3.4%	2.4
Burnt	14.5%	7.0
Corrosion	5.9%	3.4
Crack	5.6%	3.3
Dent	9.1%	4.7
Design Flaw	0.3%	1.1
Disassembly Damage	7.0%	3.9
Disassembly Impossible	12.3%	6.1
Fastener Failure	2.7%	2.1
Fracture	2.7%	2.1
Handling Damage	0.1%	1.0
Hole	1.7%	1.7
Machining Damage	3.5%	2.4
Wear	21.8%	10.0
No Failure	9.4%	4.9

Failure Mode	Weighted %	DET
Bent	31.0%	3.1
Burnt	37.2%	3.7
Corrosion	37.3%	3.7
Crack	35.4%	3.5
Dent	37.1%	3.7
Design Flaw	11.1%	1.1
Disassembly Damage	15.2%	1.5
Disassembly Impossible	16.0%	1.6
Fastener Failure	48.0%	4.8
Fracture	20.9%	2.1
Handling Damage	11.1%	1.1
Hole	28.6%	2.9
Machining Damage	65.2%	6.5
Wear	47.8%	4.8
No Failure	31.1%	3.1

Failure Mode	% Not Repaired	REP
Bent	100.0%	10.0
Burnt	100.0%	10.0
Corrosion	56.9%	5.7
Crack	21.9%	2.2
Dent	6.4%	0.6
Design Flaw	100.0%	10.0
Disassembly Damage	100.0%	10.0
Disassembly Impossible	75.5%	7.6
Fastener Failure	73.7%	7.4
Fracture	50.0%	5.0
Handling Damage	100.0%	10.0
Hole	100.0%	10.0
Machining Damage	100.0%	10.0
Wear	83.9%	8.4
No Failure	100.0%	10.0

Table 6. Derivation of Risk Priority Number (RPN)

Failure Mode	OCC	DET	REP	RPN
Bent	2.4	3.1	10.0	73.4
Burnt	7.0	3.7	10.0	258.0
Corrosion	3.4	3.7	5.7	71.8
Crack	3.3	3.5	2.2	25.3
Dent	4.7	3.7	0.6	10.5
Design Flaw	1.1	1.1	10.0	12.1
Disassembly Damage	3.9	1.5	10.0	57.9
Disassembly Impossible	6.1	1.6	7.6	73.7
Fastener Failure	2.1	4.8	7.4	73.8
Fracture	2.1	2.1	5.0	21.8
Handling Damage	1.0	1.1	10.0	11.0
Hole	1.7	2.9	10.0	48.2
Machining Damage	2.4	6.5	10.0	156.7
Wear	10.0	4.8	8.4	403.2
No Failure	4.9	3.1	10.0	150.6

REPAIRABILITY

In the FMEA adapted for remanufacture, the severity index (SEV) has been renamed repairability (REP) to reflect the severity of a failure mode for a remanufacturer. Repairability reflects the degree to which parts are successfully repaired by the remanufacturer. Consistent with the index values for SEV, the higher the index for REP the lower the repairability. Table 4 shows the proportion of parts that are repaired, as well as the 95% confidence interval of each entry. The percentage of parts that is not repaired is used to derive the REP indices for failure modes as shown in Table 5c.

Since the goal of the OER is to assemble a number of remanufactured engines per day, week or month, if a part requires a longer-than-usual time to repair, it would be scrapped for cost effectiveness. This explains why, in general, OER has a low repair rate of damaged parts. Only two types of engine parts are truly repaired at the OER - cylinder heads with mainly cracks and/or corrosion and oil pans/valve covers with dents.

Cracks on cylinder heads are usually located between the valve seats due to the high stress in this region. To repair cracks, some material surrounding the cracks is first removed. These regions are then welded and machined back to shape. Voids resulting from corrosion are processed using the same procedure. Dents on oil pans/valve covers are removed unless the back of dent is inaccessible.

Even though the OER repairs only these two types of parts, it is possible that a number of other failures may be repaired as follows.

Bent - If a connecting rod is not severely bent, it can be mechanically straightened. After straightening, reliability testing is required.

Corrosion - Corrosion on crankshafts may be repaired by spot welding. Corrosion may also be repaired using liquid-metal filler on engine blocks that are otherwise scrapped due to cosmetic reasons.

Crack - Cracks between water jackets on engine blocks may be repaired by fitting inserts to block leakage through the crack.

Fastener Failure - Worn-out threading may be repaired using inserts. First, the threaded hole is drilled to a larger size. Next, an insert is installed and the desired threading is provided by the insert.

Fracture - Fractured towers on cylinder heads may be repaired using welding.

Wear – Worn, oversized piston housings in engine blocks may be repaired by inserting and machining a sleeve to specifications. Scratches on the journal of crankshafts may be repaired using welding. However, if there are scratches on more than one journal, the repair cost may exceed the value of the crankshaft.

At the OER, failure modes that result in removal of material are scrapped since repair would not be possible without a material-addition repair process. In many cases, welding is not used to repair parts that experience high stresses during engine operation. For instance, burns cannot be repaired since excessive material is usually worn from burnt parts. Corrosion and scratches on camshafts are not repaired using welding because camshafts are subjected to high compressive stresses during engine operation and the durability of the welding is not reliable. Worn journals on crankshafts, camshafts and connecting rods are not repaired since replacement of material is necessary. Due to their low economic value, connecting rods are typically not repaired. Machining damage is not likely to be repaired since no process is used that can replace the amount of material that is mistakenly removed.

RISK PRIORITY NUMBER

Finally, the risk priority numbers (RPN) for each failure mode are determined by finding the product of OCC, DET and REP, as shown in Table 6. Table 6 shows that the RPN for “wear” and “burnt” are highest since these failure modes are very common and cannot be repaired without a material-replacement process. Furthermore, detection of material removal beyond specifications is typically not detected until the inspection stage of the remanufacturing process. Therefore, “wear” and “burnt” are the failure modes that cause the most difficulty for remanufacturers. Product or process design that decreases the occurrence, detection or repairability indices for “wear” and “burnt” would facilitate remanufacture by decreasing the portion of the waste stream that have these failure modes.

SUMMARY

The goal of this work is to enable the more efficient remanufacture of products through design. Since remanufacturers aim to reuse parts, parts that enter their waste stream reveal difficulties in remanufacture. The waste stream of an original-equipment automotive remanufacturer was analyzed to gain insight into reasons why parts are not reused. The data gathered were used to derive values for the indices of occurrence (OCC), detectability (DET) and repairability (REP) for an FMEA modified for remanufacture. Product or process design that aims to reduce the Risk Priority Number (RPN) of the failure modes identified would facilitate remanufacture.

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CONTACT

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