Supporting Design for Remanufacture through Waste-Stream Analysis of Automotive Remanufacturers

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Abstract

Waste streams of three automotive remanufacturers were analyzed to determine factors that impede the reuse of parts. The eventual goal of this work is to enable the design of products that facilitate reuse. Remanufacturers disassemble and clean used products, replace or repair failed parts, and reassemble products in a production-batch process. Although design that facilitates any of these steps benefits remanufacture, the essential goal of remanufacture is to reuse parts. Parts not reused enter the waste stream. Worn parts that could not be further refurbished were found to constitute the highest contribution to the waste streams of the remanufacturers studied.

Keywords: Design, Remanufacture, Waste stream

1 INTRODUCTION

This work is in the area of environmentally conscious product design and manufacture. An overall approach for environmental assessment of products is Life-Cycle Analysis (LCA) which tracks resource inputs and outputs used for a product from material extraction to end-of-life disposition [1]. While much of the research that addresses product end-of-life is in the area of design for recycling, Kimura et al. [2] simulate product quality under deteriorated conditions to support design for reuse and upgrade. Research in design for disassembly aims to facilitate disassembly, typically for recycling, but occasionally also for maintenance and remanufacture [3].

Specifically related to remanufacturing, Hammond et al. [4] conducted a survey of automotive remanufacturers to uncover process difficulties and generated design-for-remanufacture guidelines and metrics [5]. Shu and Flowers have also investigated design for remanufacture through case studies [6]. There remains, however, a need for a comprehensive, systematic study of remanufacturing difficulties to ensure that no significant issues are overlooked in the development of design-for-remanufacture theory.

The essential purpose of remanufacture is to reuse parts, and parts that are not reused enter the waste stream. The approach here is novel in that design for remanufacture will be based on remanufacture difficulties quantified by part-count and mass contributions to remanufacturers' waste streams [7]. The most significant factors that impede reuse will be identified and can be targeted for elimination or reduction through product redesign.

2 DATA COLLECTION

Data was collected at three automotive remanufacturers. One, an Original Equipment Remanufacturer (OER), has a contract with a specific automotive manufacturer. The two others, Independent Remanufacturers (IRs), select whose parts they will buy and refurbish. Several engine models, produced by three manufacturers, were studied. Data collection lasted four months.

2.1 Differences between OER and IRs

The OER operation differs greatly from that of the two IRs. First, the OER is a much larger operation than the IRs. At the OER, parts are discarded during disassembly, sorting, and machining. The recycling bins here were visited several times a day, three days a week. It proved sufficient to visit the independent remanufacturers once every two weeks to count all parts that were scrapped. At the IRs, the throughput is only a few engines a day. Therefore, the number of parts scrapped per day is much lower, and the workers set aside all parts that could not be refurbished until a visit to the shops could be made. The difference in scale between OER and IR operations results in data sets of very different sizes. Over 1800 parts were counted at the OER, while only 200 pieces of scrap were counted at the two IRs.

The IRs also have a different scope of work from the OER. The goal of the OER is to assemble a certain number of remanufactured engines per day, week, or month. A part that is difficult to remanufacture, e.g., requiring longer than normal to repair, is uneconomical to work with. This part is scrapped rather than reused. At the IR, priority is given to saving a part. IRs, who must purchase all of their cores, need to make a return on their investment, and therefore will use repair methods that the OER does not. Consequently, a part that would be scrap at the OER may be sent from the IR to specialty repair shops. For example, IRs send shafts out for welding, while the OER does not use welding for such parts, and also scraps any part with welding on it. Therefore, even less scrap is generated at the IRs.

2.2 Assumptions

The waste-stream analysis is simplified as follows. Often there is more than one reason why a part cannot be remanufactured. For example, there might be deep grooves on a journal of a crankshaft, and it might be bent. An engine block can have gouges out of the cylinder bore, and a hole. In this analysis, a part is described by the single most prominent difficulty determined through consultation with the remanufacture worker discarding it.

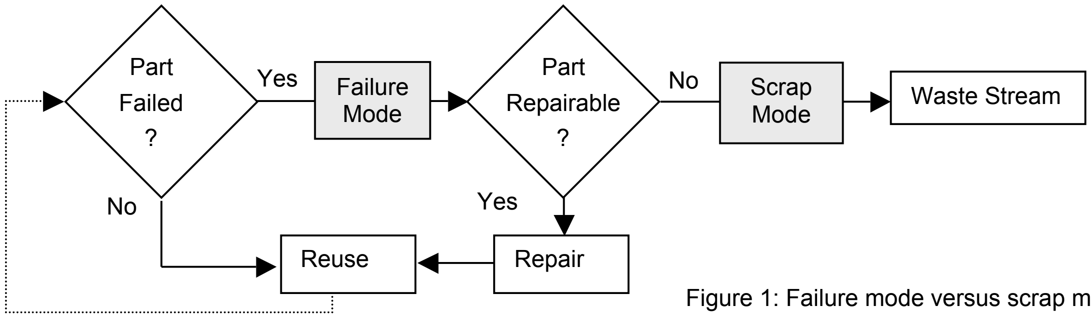

Figure 1: Failure mode versus scrap mode.

2.3 Failure mode versus scrap mode

Typically, there are two conditions a part must satisfy before being discarded. The first is that it has failed, i.e., it can no longer fulfill its intended function. The next is that the part is deemed unrepairable. Failure mode signals why the part needs to be repaired (a crack or bend) while scrap mode describes why the part is not repaired, including no process available for refurbishment. Figure 1 depicts the relationship between failure and scrap modes. Only the parts entering the waste stream, described according to both failure mode and scrap mode, were counted.

3 DATA ANALYSIS

3.1 Statistical analysis

A statistical analysis to determine the 95 percent confidence interval for the actual proportions of failure modes and scrap modes in the population was performed. Although the distribution of discarded parts is actually multinomial (e.g., there are multiple failure modes), it was treated as a binomial, since this analysis is not concerned with identifying when a part will fail according to two or more modes **at the same time**, as previously described.

The binomial distribution can be used to model a discrete event, that is, a pass–fail or go–no go situation. Part failures are modeled in this way: e.g., either a part cracked, or it did not; only one failure category applies. The probability that a part will fail in a certain way is p.

Table 1 shows the results of statistical testing on failure and scrap modes for the OER and IRs combined. The 95% confidence interval of $\hat{p}$ is always less than ± 1.1% for failure modes and ±1.65% for scrap modes.

3.2 Description of failure modes

Twelve failure categories are identified, in addition to ‘no failure,’ which accounts for the sound parts discarded.

The failure categories are described in order of the most to least common, as determined by statistical analysis on the overall (OER and IR) part count shown in Table 1. Percentages beside each category heading below give the representation of the failure mode by part count and by mass, respectively.

Wear [26.6%, 23.0%]: Wear occurs at shaft bearings and in cylinder bores. Most camshafts are worn during ordinary use, while crankshafts are gouged and grooved from improper engine operation and care. Cylinder bores are worn from the normal sliding action of the piston.

Burn [21.5%, 6.9%]: A burn results from vehicle owner maintenance failure, usually a lack of oil in the engine.

No failure [19.3%, 28.1%]: There is a large category of parts discarded that are not flawed.

Bent [9.9%, 1.2%]: Connecting rods are bent as they are twisted between piston and crankshaft. Crankshafts are occasionally bent. A very few large pieces, like cylinder heads and engine blocks are warped.

Crack [5.9%, 9.1%]: Most cracks spotted by disassemblers are deep cracks and tears. Timing covers, blocks, cylinder heads, cylinder sleeves may all crack.

Corrosion [4.5%, 1.9%]: Two types of corrosion are grouped together here: atmospheric and direct chemical attack. Blocks, crankshafts, camshafts and oil pans are exposed to water vapor and may rust. Cylinder heads are corroded by cooling agent that leaks under the head seal, penetrating to the combustion chamber or flat of the head.

Hole [4.2%, 19.8%]: Holes are large material segments removed from the body of the part. Engine blocks comprise the majority of parts with holes. Occasionally, an oil pan has a hole from being punctured and more rarely, cylinder heads develop holes around valve seats.

Fracture [3.4%, 1.3%]: Fracture refers to a part broken into pieces, rather than merely cracked. Cracked parts are viewed as potentially retrievable, if a repair process exists. Fractured parts are irretrievably damaged. The same types of parts that are cracked are fractured.

Handling damage [1.5%, 0.8%]: This category accounts for damage that occurs when parts are occasionally dropped or struck against other parts during transit.

Failure mode	Prob. of failure mode	Confi-dence interval width	Scrap mode	Prob. of scrap mode	Confi-dence interval width
Wear	0.266	0.000	Makes oversize	0.177	0.033
Burnt	0.215	0.012	Makes undersize	0.172	0.032
No failure	0.193	0.011	Overstock	0.150	0.031
Bent	0.099	0.022	Weakens part	0.128	0.029
Crack	0.059	0.017	No process	0.119	0.028
Corrosion	0.045	0.015	Material loss	0.093	0.025
Hole	0.042	0.017	Last undersize	0.060	0.020
Fracture	0.034	0.013	Last oversize	0.056	0.020
Handling	0.015	0.009	Mating part lost	0.032	0.015
Fastener	0.013	0.009	Cosmetic	0.013	0.010
Dent	0.011	0.008			
Loosened	0.008	0.007			
Design flaw	0.002	0.004			

Table 1: Probability and confidence interval of failure modes and scrap modes for combined OER and IRs.

Fastener failure [1.3%, 3.2%]: Transmission mounts, the brackets on the corners of the engine block, are vulnerable because they project from the side of the block. Often, bolts snap off in holes, and cannot be pressed out without damaging thread and hole. The crankshaft incidents of fastener failure refer to keyways that are stretched.

Dent [1.1%, 0.1%]: This category is largely made up of oil pans and valve covers. Oil pans are often dented by drivers running over curbs or parking barriers. Valve covers are dented upon removal for repair or in transport.

Loosened [0.8%, 4.0%]: Loosened parts describe a specific form of wear usually caused when mismatched parts are installed, or parts are installed improperly.

Design flaw [0.2%, 0.8%]: Some parts are discarded at the remanufacture stage when it is recognized that the original design was flawed and is not correctable.

3.3 Description of scrap modes

Scrap modes result from the descriptions given by remanufacture workers as to why a part is discarded.

Oversize/Undersize [46.5%, 30.9%]: This category combines the categories of *makes oversize, makes undersize, last oversize, last undersize* listed in Table 1. Cylinders that are worn out of round can be rebored to fit a larger piston. Material can also be removed from worn external surfaces to yield a smaller diameter part. Strength requirements and manufacturer-specified tolerances may limit the number of times such procedures can be performed. Parts that have been remanufactured before and are at their last allowed under- or oversize dimension are scrapped. Other pieces have wear marks that cannot be removed without being made under- or oversize by the refurbishing process, and are scrap.

Overstock [15.0%, 24.4%]: When parts can be bought more cheaply than they can be refurbished, old parts are scrapped. Parts are also discarded when there is sufficient inventory and no more storage capacity.

Weakens part [12.8%, 1.2%]: Connecting rods (and a few other parts) can be straightened when bent but may be weakened, and cannot be warranted for the original (or remanufacture) lifetime. Because reliability testing of such small parts is costly, most bent parts are scrapped.

No process [11.9%, 19.3%]: Most ‘no process’ parts are those with cracks that cannot be welded, corroded parts with metal loss, fractured pieces with no joining process, etc. Some parts in this category are from late model engines for which tooling is nonexistent.

Material loss [9.3%, 22.0%]: Some parts are discarded because material has been removed in the body of the part, i.e., on non-wear surfaces that cannot be replaced.

Mating part lost [3.2%, 2.1%]: Some parts that wear together must be kept together. Examples include bearing caps and connecting rods. If one piece of the part is missing or mismatched, the part must be discarded.

Cosmetic [1.3%, 0.2%]: Some scratches and dents in plastic parts cannot be fully removed. The part is functional, but will not be resold due to imperfections.

3.4 Discussion

Tables 2 and 3 contain waste-stream data separated by OER and IRs. The presentation format shows the relationship between failure modes and scrap modes. Most failure modes have a corresponding scrap mode. For example, both the *wear* and *burnt* failure modes correspond most significantly with the *under/oversize* scrap mode. Most of the cracked parts were discarded due to a lack of process to repair the cracks, and bent parts were scrapped because the repair process would weaken the parts.

The data is also presented both by number of parts and by mass. Design-for-remanufacture strategies can be developed from the analysis using either contribution by part count or contribution by mass as ranking criteria. If a manufacturer wants to redesign parts similar to parts currently remanufactured and have the greatest impact on reducing the waste stream quantity, then guidelines may be ranked using the contributions by mass. That is, priority is given to preventing larger-mass parts from entering the waste stream. On the other hand, contribution by part count may identify what factors constitute the most part rejections. Thus, these factors may be avoided on parts that are different and possibly more or less massive than the parts actually counted during data collection.

Top failure modes (OER vs. IRs)

The noticeable difference between OER and IR data is the predominance of the *no failure* category for the OER. Since IRs are more selective about the pieces they buy and they avoid discarding parts, undamaged pieces comprise very little scrap. Neglecting the *no failure* category, the most significant failure modes for IRs and OER on a part basis are similar: *wear* and *burnt*.

On a mass basis for the OER, *wear*, *hole*, and *crack* are the leading failure modes, whereas for the IRs, the order is *hole*, *crack*, and *wear*, again neglecting *no failure*.

In general, then, the IRs and OER show basic similarities in the failure modes that contribute most heavily to the waste stream. Overall, *wear* takes precedence, and corresponds to the *under/oversize* scrap category.

Top scrap modes (OER vs. IRs)

On a part basis, *under/oversize* is by far the leading scrap mode for the OER. The top scrap modes at the IRs are *under/oversize* and *weakens part*, which represent a large number of camshafts and connecting rods.

On a mass basis, the order changes for the IRs. The *material loss* category leads, followed by *no process* and *under/oversize*. The IRs put great effort into preserving each of the larger engine parts, resulting in the low percentage by part count of the *material loss* category. The much larger percentage by mass reflects the greater weight of the few engine blocks that could not be salvaged, compared with the weight of the other smaller parts counted at the IRs. For the OER, *under/oversize* is still the most significant, but *overstock*, *material loss*, and *no process* have a more equal share in the scrap profile than in the analysis by part count.

In general, the main discard reason is that an attempt at repair would result in unacceptably under/oversize parts.

4 CONCLUSION

The dominant failure and scrap modes identified above provide insights into areas of focus for design strategies. For example, at both the OER and IRs, *wear* is the leading failure mode on a part basis, and is also significant on a mass basis. The scrap mode that *wear* most closely corresponds to is *under/oversize*, which also emerged as a very significant scrap mode. That is, a large proportion of parts is not directly reusable due to wear, and is not repairable because the repair process would render the parts unacceptably under- or oversize.

To reduce this contribution to the waste stream, either the failure or scrap mode may be targeted. First, if wear is preventable, the parts may be reused without repair. Or, a repair process that does not further remove material from worn parts may enable their reuse. For example, a material build-up process (like welding or plasma spraying) may be developed for parts that are known to wear. Inserts can be used to prevent or reduce wear on the main part itself by isolating the wear in the insert. Therefore, a worn part may be reused with a new insert without the need for a material-addition repair process.

In summary, failure and scrap modes for parts entering the waste stream of independent and original equipment automotive remanufacturers were identified and quantified. An example illustrated how the results of this waste-stream analysis may be used to develop design strategies so that future products may be more efficiently remanufactured.

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	Scrap mode								
Failure mode	Under/oversize	Overstock	No process	Weakens part	Material loss	Mating part lost	Cosmetic	Total	**Percent**
	Number of Parts								
Wear	366	2	64		8			440	**.23**
No failure	32	304		1		66		403	**.21**
Burnt	399							399	**.21**
Bent	2		4	190				196	**.10**
Crack			113					113	**.06**
Corrosion	42		6	12	29		4	93	**.05**
Hole				1	80			81	**.04**
Fracture			11		56		3	70	**.04**
Handling	21		7		3			31	**.02**
Fastener			17		10			27	**.01**
Dent					1		21	22	**.01**
Loosened			16					16	**.01**
Design flaw			3					3	**.00**
Total	862	306	241	204	187	66	28	1894	
Percent	**.46**	**.16**	**.13**	**.11**	**.10**	**.03**	**.01**		
	Mass of Parts (kg)								
Wear	8723	218	695		60			9696	**.23**
No failure	1052	10378		19		912		12361	**.29**
Burnt	2981							2981	**.07**
Bent	39		132	244				415	**.01**
Crack			3507					3507	**.08**
Corrosion	353		142	91	219		10	814	**.02**
Hole				8	8073			8080	**.19**
Fracture			70		458		6	535	**.01**
Handling	159		149		23			331	**.01**
Fastener			1116		176			1293	**.03**
Dent					8		52	59	**.00**
Loosened			1742					1742	**.04**
Design flaw			327					327	**.01**
Total	13307	10595	7880	362	9017	912	68	42141	
Percent	**.32**	**.25**	**.19**	**.01**	**.21**	**.02**	**.00**		

Table 2: OER waste-stream data.

	Scrap mode								
Failure mode	Under/oversize	Overstock	No process	Weakens part	Material loss	Mating part lost	Cosmetic	Total	**Percent**
	Number of Parts								
Wear	111	6						117	**.59**
Burnt				50				50	**.25**
Bent		1	1	9				11	**.06**
Crack			6	4				10	**.05**
Hole					6			6	**.03**
Corrosion					1			1	**.01**
Fastener			1					1	**.01**
No failure						1		1	**.01**
Fracture			1					1	**.01**
Design flaw					1			1	**.01**
Dent								0	**.00**
Handling								0	**.00**
Loosened								0	**.00**
Total	111	7	9	63	8	1		199	
Percent	**.56**	**.04**	**.05**	**.32**	**.04**	**.01**	**.00**		
	Mass of Parts (kg)								
Wear	305	116						420	**.23**
Burnt				35				35	**.02**
Bent		19	19	81				119	**.06**
Crack			451	30				482	**.26**
Hole					654			654	**.35**
Corrosion					8			8	**.00**
Fastener			109					109	**.06**
No failure						1		1	**.00**
Fracture			19					19	**.01**
Design flaw					19			19	**.01**
Dent								0	**.00**
Handling								0	**.00**
Loosened								0	**.00**
Total	305	135	599	146	681	1		1866	
Percent	**.16**	**.07**	**.32**	**.08**	**.36**	**.00**	**.00**		

Table 3: IRs waste-stream data.