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Considering Remanufacture and other End-of-Life Options in Selection of Fastening and Joining Methods

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Abstract—This paper emphasizes remanufacturing as an end-of-life option and the effects of fastening and joining methods on remanufacture. Three case studies describe examples of fastening and joining that facilitate assembly and recycling but impede remanufacturing. To illustrate the impact of fastening choices on remanufacture relative to other life-cycle concerns, the development of a computer tool that estimates the effects of fastening and joining choices on manufacture, assembly, maintenance, remanufacture and recycling is in progress. The current implementation of the tool is described and used to compare the fastening methods that are used in the case studies with alternative fastening methods. These comparisons suggest that elements of fastening methods that are prone to failure be made separable from the remainder of the part.

I. Background

A. Design for End-of-Life

Product design for end-of-life is prompted by existing and anticipated legislation that requires manufacturers to reclaim responsibility for their products at the end-of-life [1]. Three alternatives to landfill or incineration include recycling for scrap material, remanufacture and maintenance.

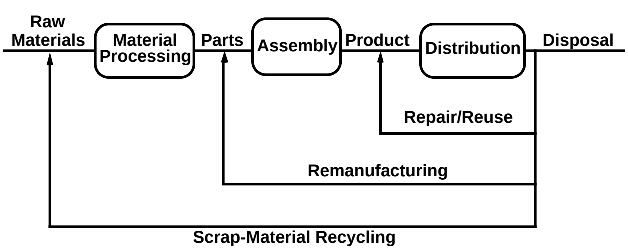

Fig. 1. End-of-Life Options.

Maintenance extends product life through individual upkeep or repair of specific failures. Remanufacture is a production batch process of disassembly, cleaning, refurbishment and replacement of parts in worn, defective or obsolete products [2]. Scrap-material recycling involves separating a product into its constituent materials and reprocessing the materials.

B. Benefits of Remanufacture

Remanufacturing involves recycling at the parts level as opposed to the scrap-material level. Recycling at the higher level of components avoids resource consumption for possibly unnecessary reprocessing of material while preserving value-added of components [2]. Remanufacturing also postpones the eventual degradation of the raw material through contamination and molecular breakdown, which is frequently characteristic of scrap-material recycling [3]. In addition, remanufacture can divert parts made from unrecyclable materials from landfill. The production-batch nature of the remanufacturing process enables it to salvage functionally failed but repairable products which are discarded due to high labor costs associated with individual repair.

While remanufacture is not suitable for all products, it is especially appropriate for products that are technologically mature, and where a large fraction of the product can be reused after refurbishment [2]. Products are also favorable when upgrades can be accomplished through software, enabling the reuse of physical components across product generations.

C. Design to Facilitate Remanufacture

While product design that facilitates any of the steps involved in remanufacture, namely disassembly, sorting, cleaning, refurbishment, reassembly and testing, will facilitate remanufacture, the essential goal in remanufacture is part reuse. If a part cannot be reused as is or after refurbishment, the ease of disassembly, cleaning or reassembly will not matter.

Examples of part refurbishment include application of mechanical force to reverse plastic deformation such as warps and creases, closing and filling cracks through mechanical pressure or welding, and rebuilding worn surfaces using metal spraying and welding [4]. These refurbishment processes can be labor and equipment intensive. Furthermore, refurbishment processes that further consume a part, such as reboring a worn cylinder to fit an oversized piston, can only be performed a limited number of times. The reliability of a reworked part may also be unpredictable.

Literature on automotive remanufacturing [3][5][6][7] and the results of extensive collaboration with Eastman Kodak's photocopier remanufacturing facilities revealed a strong preference for failure and wear to be isolated in as small a part as possible. For example, sleeved cylinders [8][9] and some screw inserts can be replaced several times, enabling the bulk of the part to be reused without rework.

Unfortunately, making separable parts that are prone to wear directly counters the part consolidation tenet of design for assembly. In addition, while screw inserts are favorable for remanufacturing, metal inserts inadvertently left in plastic

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parts will damage plastic reprocessing machinery and are detrimental from a recycling point of view. It would be difficult to promote design for remanufacture in isolation from other design-for-x considerations. Further, the blind application of any one design-for-x in isolation, including assembly, has been found to be problematic [10]. Thus, the simultaneous consideration of multiple design-for-x perspectives seems appropriate.

Chosen for consideration in this work are the perspectives of manufacture and assembly, maintenance, remanufacture and recycling. Efforts required for assembly, disassembly and reassembly are particularly pertinent to the selected perspectives. Therefore, this work concentrates on the selection of a fastening or joining method.

II. Related Work

Since disassembly is a necessary and critical process for all three end-of-life options, there has been much research in how to design products for easier disassembly. Much of this research emphasizes disassembly to facilitate recycling [11][12][13][14]. The goal of disassembly for recycling is to separate different materials to the greatest extent with least effort. Joints between parts of the same material need not be separated if the joining element is recycling-compatible with the part material. Disassembly that damages the part is frequently acceptable as long as cross-contamination of materials does not result. Other work extends to include disassembly for maintenance [15][16][17][18] as well as remanufacture [19][20][21]. The primary emphasis in disassembly to facilitate maintenance is to minimize machine downtime and maintenance labor cost.

A database of time estimates for disassembly and reassembly for various fastening and joining methods is developed in [22], and is used in this work. Reference [1] identifies other work that compares fastening methods in assembly and disassembly at VDI in Germany.

Although design that facilitates disassembly for maintenance and recycling can frequently benefit remanufacture, it does not encompass disassembly to facilitate remanufacture. Remanufacture often requires disassembly of joints that are not accessed for routine maintenance tasks. The labor rate for remanufacture is typically lower than for field maintenance. Also, the urgency of returning equipment to operation is not as great in remanufacture as it can be for maintenance. While speed of access is important in remanufacture, unplanned and unrepairable damage to the part as a result of disassembly or reassembly prevents part reuse. For example, while a snap fit may provide fast assembly and possibly disassembly and reassembly without introducing a different material, a failed snap fit is difficult to repair and may render the part unusable. Similarly, a part with stripped threads preventable by threaded inserts may also be unsalvageable. As part cost increases, the extra effort required to install an insert in the part will likely pay off, particularly if the product will undergo several remanufacture cycles. On the other hand, disassembly methods destructive to the fastener that do not damage the fastened parts, such as drilling out and replacing a rivet, are acceptable in remanufacture.

Difficulties in disassembly for service and recycling have been distilled into design guidelines that include recommendations on fastening methods to be preferred and fastening methods to be avoided [1][23][24][25]. These guidelines are presented in the context of product design for remanufacture as well as recycling and maintenance. Guidelines and examples that promote the use of snap fits abound. "Do not use inserts" rules are also ubiquitous. While these rules are based on valid difficulties in disassembly, problems due to parts rendered unusable as a result of disassembly were not emphasized.

III. Description of Case Studies

The following case studies aim to describe difficulties unique to remanufacture caused by the choice in fastening or joining method. The cost estimates for these examples appear later.

A. Thread-forming Screws in Paper Guide

The first case study is provided by Eastman Kodak Office Imaging Remanufacturing, who remanufactures photocopiers, duplicators and other office equipment. Fig. 2 shows part of a paper guide that taps the sides of a photocopied document to align the edges before it is stapled. Two guides are used and each is secured to a metal plate at the two bosses with thread-forming screws. These guides are removed during the remanufacture process to allow access to other parts. If the screws are reinserted during assembly, new threads are formed, compromising the reliability of the joint. The bosses are not large enough to install inserts that accommodate the original screws. Since it is important to maintain the same screw size, the bosses could be neither redrilled to accommodate larger thread-forming screws, nor fitted with inserts to accommodate smaller screws. Therefore these parts are replaced with new parts during remanufacture. Specifying inserts for the bosses in the original design is speculated as one possibility that would have enabled reuse of these parts.

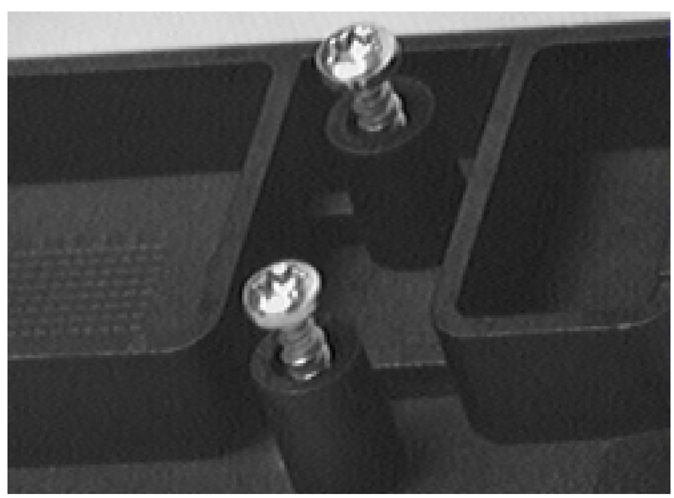

Fig. 2. Thread-forming screws used to fasten paper guide to base.

B. Welded Cover in Toner Cartridge

Fig. 3. Cut-out in toner-cartridge cover to access mounting screws.

The following two case studies are provided by Nashua Cartridge Products, an independent remanufacturer of toner cartridges produced by various original equipment manufacturers. Fig. 3 shows part of a hole machined in a cover that is ultrasonically welded onto a toner-cartridge housing. The machining is performed to gain access to the mounting screws of a wiper-blade assembly. The wiper blade is used to scrape excess toner from a rotating photo-conductive drum. When the blade is determined to be in need of replacement, a hole is milled in the plastic cover in front of the mounting screws. After the replacement of the blade assembly, another similarly shaped cover is adhered over the opening. Nashua Cartridge Products has observed that appropriate screws can be successfully removed and reinstalled up to three times in similar applications before switching to coarser-threaded screws.

C. Slot in Toner-cartridge Shell

Fig. 4. Cracked Slot in Toner-cartridge Housing. Photos: Rajesh Bilimoria

Fig. 4 illustrates a tab-in-slot fastening mechanism, where the slot was cracked during disassembly. A slot is located on both sides of a toner-cartridge housing. The tab is located on the endcap of the drum. In original assembly, the tab is snapped into place in the slot. During disassembly, the part of the housing with the slot is pried apart to release the tab.

IV. Computer Tool Implementation

The preceding case studies exemplify the difficulties unique to remanufacture created by various fastening and joining methods that conform to design-for-assembly and design-for-recycling guidelines. To illustrate the burden placed on remanufacture relative to other life-cycle perspectives, implementation is in progress of a computer tool that simultaneously estimates the cost of manufacture and assembly, maintenance, remanufacture and recycling, as imposed by various fastening and joining methods. This tool aims to provide the product designer with a framework to enable a rational choice between fastening and joining methods for specific applications, rather then blind application of generic, possibly inappropriate design guidelines.

A. Interface

Currently, this tool will estimate the cost of connecting two parts by various fastening and joining means. First identified are the connecting methods that are appropriate for designer-specified part materials, joint operating conditions, loads and functional requirements. The current input interface is shown in Fig. 5a. For each qualifying method, the required amount of fasteners or joining compound based on joint geometry and applied forces is used to estimate the cost of the connecting material, disassembly and assembly. The probability and consequences of connecting method and part damage are included in the maintenance and remanufacture costs. The costs are tabulated in the output interface shown in Fig. 5b.

Factors such as the expected number of remanufacture cycles, number of maintenance cycles and labor rates can be varied in the input interface to observe the effects on cost. Similarly, probabilities of failure due to disassembly and reassembly associated with each method can be varied using sliders on the output interface.

This computer tool is implemented in the C++ programming language on an SGI platform. The interface is developed using UIMX, a graphical user interface builder. A commercial object-oriented database manager, ObjectStore, manages the database of fastening and joining methods.

B. Cost Model

The estimated life cost consists of the manufacture, assembly, maintenance, remanufacture and recycling costs as determined by the choice of fastening or joining method. Each cost includes only expenses resulting directly from the choice of fastening or joining method. For example, the maintenance cost includes the expenses associated with joint disassembly and reassembly necessary for a maintenance task, and not the cost of other activities associated with the maintenance task.

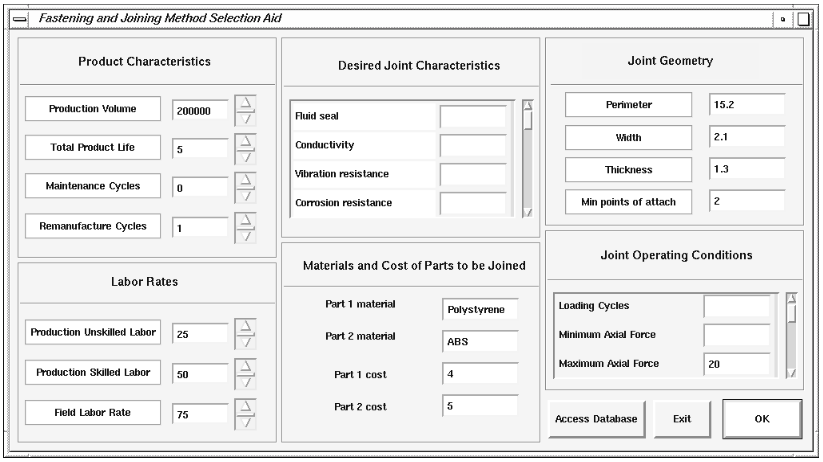

Fig. 5a. Input Interface

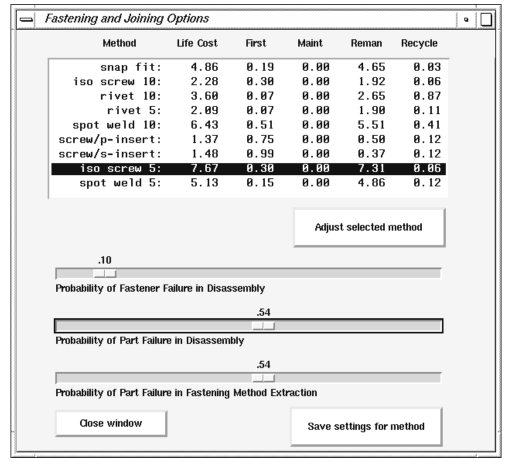

Fig. 5b. Output Interface

Similarly, the recycling cost represents the expense of material separation, and not material reprocessing. The assembly and disassembly costs are estimated using time required for disassembly and assembly of various fastening and joining methods from [22]. For maintenance and remanufacture, the assumption is that the joint must be disassembled to enable further maintenance and remanufacture tasks.

1. First Cost

The first cost consists of the manufacture and first assembly cost as determined by the fastening or joining method. It is assumed that the part manufacture cost can be separated into a basic part manufacturing cost that remains constant for different connecting methods, and the additional manufacturing cost of modifying a part to implement a particular fastening method. For example, if the fastening method involves threaded fasteners, the additional manufacturing effort could include drilling holes in the part. The additional cost may also be due to a more complicated mold to achieve molded holes or snap fits. The first cost includes only the portion of the manufacturing cost determined by the connecting method, and not the basic part manufacturing cost. The first cost also includes the cost of assembly as determined by the type and amount of fasteners or joining compound necessary to achieve the designer-specified joint requirements.

2. Recycling Cost

The recycling expense includes the cost of extracting material introduced by the fastening method that is not recycling-compatible with the part material, or the cost of separating parts made of different materials. The cost of reprocessing the material of neither the part nor the fastening method is included. It is assumed that the fastening method will not affect the reprocessing expense of the parts if incompatible materials introduced by the fastening method can be removed.

3. Failure During Disassembly and Reassembly

Both maintenance and remanufacture involve disassembly and reassembly, and part and fastener reuse where possible. Three types of failure that affect reuse are identified as follows.

The first is failure of the fastening or joining method during disassembly or reassembly. For example, rivets and welds are typically destroyed during disassembly, and the head of a threaded fastener may become damaged during disassembly and assembly.

The second is failure of the part during disassembly or reassembly. For a joint that uses threaded fasteners, this includes stripping of the internal threads in the part. In cases where the fastening method is integral to the part, such as snap fits, this corresponds to the failure of the snap.

The third is failure of the part during fastening-method extraction. Fastening-method extraction occurs after the fastening method has failed and entails removal of fastening elements from the part. For example, if the head of a screw is stripped, the part may be damaged while extracting the stripped screw. If an insert is damaged, this includes damage to the part that occurs when the insert is removed.

In the maintenance and remanufacture cost estimates, the consequences of the above types of failure are weighted by their respective probabilities. In most cases, the consequence of fastener damage is fastener replacement. The consequence of part failure is the cost of rework if the damaged part can be repaired and part replacement if the damaged part cannot be repaired.

4. Maintenance Cost

The maintenance cost consists of disassembly and reassembly expenses, which represents time required for disassembly and reassembly at field labor rate, and the expected cost of part and fastener replacement due to damage incurred during disassembly and assembly.

5. Remanufacture Cost

The remanufacture cost imposed by the fastening method also consists of expenses related to disassembly, reassembly and the probability of part and fastening method failure.

In general, the remanufacture cost is modeled as follows:

$$C_{rm} = (T_d + T_a)L + P_f C_f + (P_{pd} + P_f P_{pe} - P_{pd} P_f P_{pe})C_p$$

C_{rm}	= Remanufacture cost
T_d	= Disassembly time
T_a	= Assembly time
L	= Labor rate
P_f	= Probability of fastener failure in disassembly and assembly
C_f	= Cost of fastener failure
P_{pd}	= Probability of part failure in disassembly and assembly
P_{pe}	= Probability of part failure in fastening-method extraction
C_p	= Cost of part failure

If the fastening method must be destroyed for disassembly, such as the case with rivets, the resulting damage to the part is categorized as part damage during method extraction. The probability of part damage during disassembly is defined to be zero. The probability of fastener damage in disassembly is 1, and the general remanufacture cost reduces to:

$$C_{rm} = (T_d + T_a)L + C_f + P_{pe}C_p.$$

For example, the remanufacture cost imposed by a riveted joint includes drilling the rivets out, replacing the rivets, and the cost of part failure weighted by the probability that the parts will be damaged during rivet removal. If the part cannot be repaired, the consequential cost is part replacement cost.

For integral fastening methods such as snap fits, the damage that occurs due to disassembly is categorized as damage of the part during disassembly, and the probability of damage to the fastener during disassembly is defined to be zero. The general remanufacture cost then reduces to:

$$C_{rm} = (T_d + T_a)L + P_{pd}C_p.$$

If failure of both the fastening method during disassembly and the part during fastening-method extraction is unavoidable, the remanufacture cost will include disassembly and the consequential cost of part and fastener failure. For $P_f = 1$ and $P_{pe} = 1$, the general remanufacture cost reduces to:

$$C_{rm} = (T_d + T_a)L + C_f + C_p.$$

6. Current Treatment of Failure Probabilities

For some connecting methods, some of the probabilities of failure are defined. For example, $P_f = 1$ for rivets since rivets will be destroyed during disassembly. For other methods, where the probabilities are less than one, a nominal value is entered into the database. The costs are initially calculated using these nominal values and displayed in the output interface of Fig. 5b. Using sliders, the designer can select each method and adjust the values closer to known or expected values for the particular application and the cost for that method will be recalculated. The sliders greatly simplify the continuous variation of unknown values of failure probabilities, so that critical factors may be identified and appropriate data may be collected.

V. Cost Comparisons for Case Studies

Using the above model, the life cost of the fastening method used in each case study is compared with an alternative method. The maintenance costs are not included because these joints are not disassembled for maintenance tasks.

In the following tables, the first cost column contains the estimated life cost if the product is remanufactured once, and the second contains the estimated life cost if the product is remanufactured twice.

A. Thread-forming Screws in Paper Guide

Table 1 compares the estimated costs of using screws without inserts and screws with inserts, normalized to the cost of purchasing and installing one appropriate insert. The part and fastener replacement rate is known to be 100% without the insert and estimated at 5% with the insert.

TABLE 1. NORMALIZED ESTIMATED COSTS FOR PAPER GUIDE ATTACHMENT

Method	Life-1	Life-2	First	**Reman.**	Recycle
screws	15.87	29.52	1.81	**13.65**	0.41
screws & insert	6.87	8.87	4.05	**2.00**	0.82

Table 1 shows that the use of inserts increases both first and recycling cost but decreases life cost if the part will be remanufactured.

B. Welded Toner-cartridge Cover

Table 2 compares the estimated costs of ultrasonically welding the toner-cartridge cover and attaching the cover using screws and a gasket. A loaded labor rate of $60 per hour is used for all tasks. The remanufacture cost estimate for both fastening methods includes cover removal to access the mounting screws of the blade assembly and replacement of the cover. The rate at which the screws for the cover are replaced by coarser-thread screws is averaged at 10% per remanufacture cycle for the first two remanufacture cycles. In reality, the replacement rate increases with each cycle.

TABLE 2. ESTIMATED COSTS FOR COVER ATTACHMENT

Method	Life-1	Life-2	First	**Reman.**	Recycle
weld	>5.25	>10.50	—[a]	**5.25**	0.00[b]
8 screws & gasket	5.70	7.85	2.81	**2.15**	0.74

[a]Insufficient information to estimate first cost.
[b]Assuming recycling-compatible materials welded together that need not be separated for scrap-material recycling.

Table 2 shows that even with as many as eight screws, the life cost of using screws and a gasket will be at most 9%

higher than by welding the cover if the part will be remanufactured once, and significantly lower if the part will be remanufactured twice. It is assumed that the location of the mounting screws cannot be changed and that the cover must be removed to access them.

C. Snap-fit Toner-cartridge Housing

Tables 3 and 4 compare the estimated costs of using two slot-and-tabs with using four screws to fasten the toner-cartridge housing. In table 3, the rate of damage that results in part replacement using the slot-and-tab method is estimated at 3% per side. The rate at which the screws are replaced by larger or coarser-thread screws is estimated at 3% per screw. A loaded labor rate of $60 is used for all tasks.

TABLE 3. ESTIMATED COSTS FOR HOUSING FASTENING

Method	Life-1	First	**Reman.**	Recycle
2 snaps	>0.74	>0.07[a]	**0.61**	0.06
4 screws	2.44	1.27	**0.88**	0.29

[a]Insufficient information to estimate first cost.

Table 4 shows the results of increasing the estimated failure rate of the method to 50% for both the snap fit and the screws. The failure of the slots results in part replacement, and the stripping of the internal screw threads results in replacement by a coarser-thread screw. Comparison between Tables 3 and 4 reveals the relative sensitivities of the life cost to fastening method failure for both methods.

TABLE 4. ESTIMATED COSTS FOR HOUSING FASTENING

Method	Life-1	First	**Reman.**	Recycle
2 snaps	>6.36	>0.07[a]	**6.23**	0.06
4 screws	2.89	1.27	**1.33**	0.29

[a]Insufficient information to estimate first cost.

VI. CONCLUSIONS AND FUTURE WORK

The above case studies illustrate that joints which were designed for ease of assembly and recycling do not necessarily facilitate remanufacture. The probability and consequence of damage during disassembly and reassembly imposed by the fastening or joining method can significantly affect remanufacture and life cost. These examples suggest the disadvantages of integrating a high-failure, unrepairable feature into a high-cost part. Currently, work is underway to better understand and treat the various failure probabilities used in the computer tool.

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