Biomimetic Design for Remanufacture in the Context of DFA

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Abstract

Remanufacture involves the disassembly, cleaning, repair, reuse, and reassembly of parts in an end-of-life product. Three case studies describe examples of fastening and joining that facilitate assembly and recycling but impede remanufacturing. To illustrate the effect of fastening choices on remanufacture relative to other life-cycle concerns, the cost consequences of fastening and joining on assembly, recycling and remanufacture are estimated 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. However, this conclusion directly contradicts the part-consolidation tenet of design for assembly. Biomimetic design, which identifies and uses biological phenomena to inspire design ideas, was used to develop concepts that facilitate remanufacture, while considering assembly preferences. Three examples of biomimicry at the molecular, organism, and ecosystem levels, applied to design for remanufacture, are described.

Introduction

Product end-of-life

Product design for end-of-life is prompted by existing and anticipated legislation that relegates to manufacturers responsibility for their products at the end-of-life. Three alternatives to landfill or incineration include recycling for scrap material, remanufacture and maintenance. 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. Scrap-material recycling involves separating a product into its constituent materials and reprocessing the materials.

Benefits of Remanufacture

Remanufacturing is 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. Remanufacturing also postpones the eventual degradation of the raw material through contamination and molecular breakdown, which is frequently characteristic of scrap-material recycling. 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 that are discarded due to high labor costs associated with individual repair.

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. These refurbishment processes can be labor and equipment intensive. Also, refurbishment processes that further consume a part, such as reboring a worn cylinder to fit an oversized piston, can be performed only a limited number of times. The reliability of a reworked part may also be compromised.

Literature on automotive remanufacturing and collaboration with remanufacturers of photocopiers, toner cartridges, and automotive after-market products revealed a strong preference for failure and wear to be isolated in as small a part as possible. For example, sleeved cylinders 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 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 is problematic. Thus, the simultaneous consideration of multiple design-for-x perspectives is appropriate.

Chosen for consideration are the perspectives of manufacture and assembly, remanufacture and recycling. Since efforts required for assembly, disassembly and reassembly are particularly relevant to the selected perspectives, focus is made on the effect of fastening or joining methods.

Related Work

Since disassembly is a necessary and critical process for all three end-of-life options, there has been much research on how to design products for easier disassembly. Much of this research emphasizes disassembly to facilitate recycling. The goal of disassembly for recycling is to separate different materials to the greatest extent with the 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 as well as remanufacture. The primary emphasis in disassembly to facilitate maintenance is to minimize machine downtime and maintenance labor cost.

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 which fastening methods are preferred. 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.

Estimation of Cost Components

To show the effect of fastening choices on remanufacture relative to other life-cycle concerns, the cost consequences on assembly, recycling and remanufacture of fastening methods that are used in three case studies are compared with those of alternative fastening methods.

The estimated life cost consists of first (manufacture and assembly), 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 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 compiled by Whyland (1993). For remanufacture, the assumption is that the joint must be disassembled to enable further remanufacture tasks.

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 to modify 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.

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 part nor fastening method is included. It is assumed that the fastening method will not affect the reprocessing cost of the parts if incompatible materials introduced by the fastening method are removed.

Remanufacture Cost

Remanufacture involves disassembly and reassembly, and part and fastener reuse where possible. The remanufacture cost imposed by the fastening method consists of labor required for disassembly and reassembly, and the expected cost of part and fastener replacement due to damage incurred during disassembly and assembly. Three types of failure that affect reuse follow. The first is failure of the fastening or joining method during disassembly or reassembly. For example, rivets and welds are destroyed during disassembly, and the head of a threaded fastener may be 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 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.

Case Studies

The following case studies aim to highlight difficulties unique to remanufacture caused by the choice in fastening or joining method. Using the above model, the life cost of the fastening method used in each case study is compared with an alternative method. In the following tables, the first total refers to the estimated life cost if the product is remanufactured once, and the second total refers to the estimated life cost if the product is remanufactured twice.

Thread-forming Screws in Paper Guide

The first case study is provided by a photocopier remanufacturer. Figure 1 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.

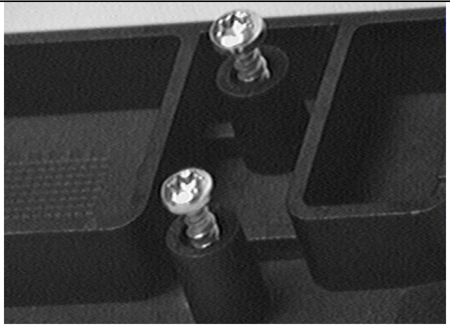


Figure 1. Thread-forming screws used to fasten paper guide to base.

Table 1. Normalized estimated costs for paper guide attachment.

Fastening method	First cost	Recycle cost	Remanufacture cost	Total w/ 1 reman.	Total w/ 2 reman.
screws	1.81	0.41	**13.65**	15.87	29.52
screws & insert	4.05	0.82	**2.00**	6.87	8.87

Table 1 compares the estimated, normalized costs of using screws without inserts and screws with inserts. The part and fastener replacement rate is known to be 100% without the insert and estimated at 5% with the insert. Table 1 shows that the use of inserts increases both first and recycling cost but decreases total cost if the part will be remanufactured.

The following two case studies are provided by a remanufacturer of toner cartridges.

Welded Cover in Toner Cartridge

Figure 2 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. The toner-cartridge remanufacturer has observed that appropriate screws can be successfully removed and reinstalled up to three times in similar applications before switching to coarser-threaded screws.

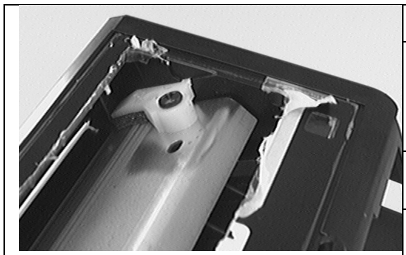


Figure 2. Cut-out in toner-cartridge cover to access mounting screws

Table 2. Estimated costs for cover attachment

Fastening method	First cost	Recycle cost	Remanufacture cost	Total w/ 1 reman.	Total w/ 2 reman.
weld	—[a]	0.00[b]	**5.25**	>5.25	>10.5
8 screws & gasket	2.81	0.74	**2.15**	5.70	7.85

[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 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 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.

Slot in Toner-cartridge Shell

Figure 3 shows 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.

Table 3 compares the estimated costs of using two slot-and-tabs with using four screws to fasten the toner-cartridge housing. Also compared are damage or replacement rates of 3% per screw/snap fit versus 50% per screw or snap fit to show the sensitivity of the total cost to failure rates for both methods. 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. A loaded labor rate of $60 is used for all tasks. Table 3 shows that the snap fits are more cost effective if they are not likely to fail, but with high failure rates, less cost effective than screws.

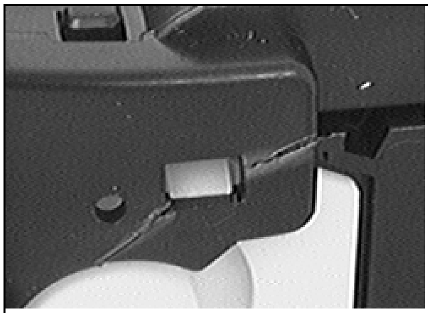


Figure 3. Cracked Slot in Toner-cartridge Housing.

Table 3. Estimated costs for housing fastening.

Method	First	Recycle	Remanufacture 3% replace	Remanufacture 50% replace	Total w/1 reman. 3% replace	Total w/1 reman. 50% replace
2 snaps	>0.07[a]	0.06	**0.61**	**6.23**	>0.74	>6.36
4 screws	1.27	0.29	**0.88**	**1.33**	2.44	2.89

[a] Assembly cost only.

Conclusions from Case Studies

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. However, making failure-prone parts separate directly contradicts the part-consolidation tenet of design for assembly. The next section aims to use biomimicry to develop concepts to address this contradiction.

Biomimetic Design for Remanufacture

Biomimetic design, which identifies and uses biological phenomena to solve engineering problems, was used to develop concepts that facilitate remanufacture, while considering assembly preferences. Three examples of biomimicry at the molecular, organism, and ecosystem levels follow. First presented in each example is the biological phenomenon of interest.

Molecular-level analogy

DNA replication refers to the process of forming new DNA from old DNA, thereby passing on genetic material. “Yet, the replication of DNA is not perfectly accurate, and the DNA of nondividing cells is subject to damage by environmental agents.” DNA repair mechanisms “include a ‘proofreading’ function that corrects errors as DNA polymerase makes them; a mismatch repair function that scans DNA after it has been made and corrects any base-pairing mismatches; and excision repair, in which abnormal bases that have formed because of chemical damage are removed and replaced with functional bases.” (Purves *et al.,* 1998)

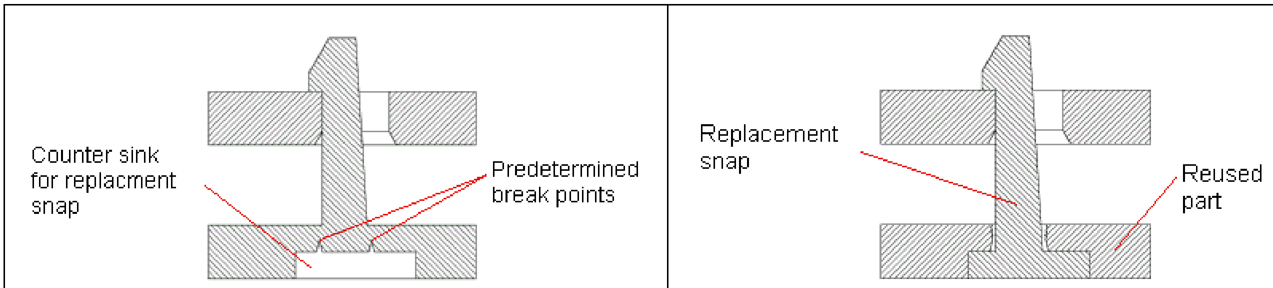
Purves *et al.* (1998) describes three types of DNA repair mechanisms: DNA proofreading during replication, mismatch repair, and excision repair. Both the proofreading and mismatch repairs described refer to corrections of errors in assembly, i.e., an undamaged base in the wrong position. Excision repair targets damaged sections of a DNA molecule, including that which occurs during the life of the cell. This correlates more closely with damage that occurs to a product during its useful life, and is a more useful analogy for remanufacture. The text on excision repair from Purves *et al.* (1998) follows.

> For example, in excision repair, certain enzymes "inspect" the cell's DNA. When they find mispaired bases, chemically modified bases, or points at which one strand has more bases than the other (with the result that one or more bases of one strand form an unpaired loop), these enzymes cut the defective strand. Another enzyme cuts away the bases adjacent to and including the offending base, and DNA polymerase and DNA ligase synthesize and seal up a new (usually correct) piece to replace the excised one.

While this additional information confirms the suitability of the analogy to the problem at hand, there is not enough detail to inspire a novel solution. A more advanced source (Friedberg *et al.,* 1995) contained a figure with the following caption:

> Figure 5-8 Diagrammatic representation of bimodal damage-specific nicking of DNA by the E. coli UvrABC endonuclease. Following the formation of a stable (UvrB)ldamaged-DNA complex (A and B) (see Fig. 5-7), UvrC protein binds at the site (C) and <u>induces a conformational change which enables bound UvrB protein to nick the DNA 4 nucleotides 3' to the site of damage</u> (D) (shown as a pyrimidine dimer). This reaction requires the binding of ATP (or ATP [gS]) by UvrB protein, but no ATP hydrolysis occurs at this step. Following the 3' incision, UvrC protein catalyzes nicking of the DNA 7 nucleotides 5' to the dimer (E).

The underlined portion of the above caption inspired the concept of failure-induced deformation in a product to facilitate removal of the defective zone, enabling easier replacement. Thus the failure-prone zone is not necessarily a separate part during original manufacture, but could be structured such that failure causes self-disassembly. For example, a wear-prone part could be designed such that the gradual thinning of a surface causes that surface to break away from the rest of the part. Applied to fastening and joining, snap fits are often used as a fastening method due to their ease of assembly. However, the snap fits frequently break and are difficult to repair during remanufacture. The redesigned snap fit with break points as shown in Figure 4 so that failure occurs in a predetermined manner may facilitate the reuse of such parts.



a. Snap fit redesigned with counter sink and break points

b. Redesigned snap fit after failure and refurbishment

Figure 4. Break points in snap fit to facilitate repair.

Organism-level analogy

The ability of plants to grow new parts to replace damaged parts was used as an analogy at the organism level. The relevant section from Purves *et al.* (2001) follows.

> The defense systems of plants and animals differ. Animals generally **repair** tissues that have been infected. Plants, on the other hand, do not make r**epair**s. Instead, they seal off and sacrifice the damaged tissue so that the rest of the plant does not become infected. This approach works because most plants, unlike most animals, can replace damaged parts by growing new stems, leaves, and roots.

Applying this analogy to products involves adding a similar part to replace a broken feature, without repairing the broken feature or replacing the entire part that contained the feature.

For example, Figure 5, from the repair manual of a photocopier remanufacturer, shows the inside features of a photocopier door that is opened to remove a paper jam. In the process of clearing the paper path, several levers are moved. These levers must be replaced before another photocopy is made. The function of the cone shown is to prevent the door from being closed without having first replaced the levers. Due to its function, the cone is frequently damaged. During remanufacture, a portion of the damaged cone is cut away and a new cone is glued on.

To facilitate this process, the door could be designed with features to assist the fitting or installation of planned replacement parts. For example, the inclusion of perforations at the dotted line shown in Figure 5 that indicate the location where the damaged feature is cut away would facilitate disassembly of the damaged feature. Of possible interest are abscission mechanisms that facilitate the separation of leaves, petals and fruits from a plant. Generalizing this approach, features that are likely to fail should incorporate features to both facilitate disassembly and use of similar replacement parts in remanufacture.

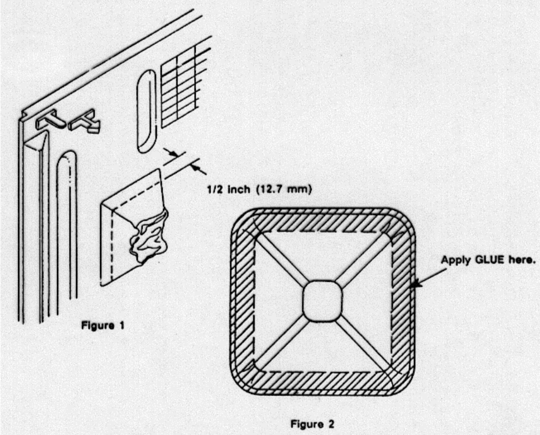


Figure 5.
Refurbishment of photocopier door feature.

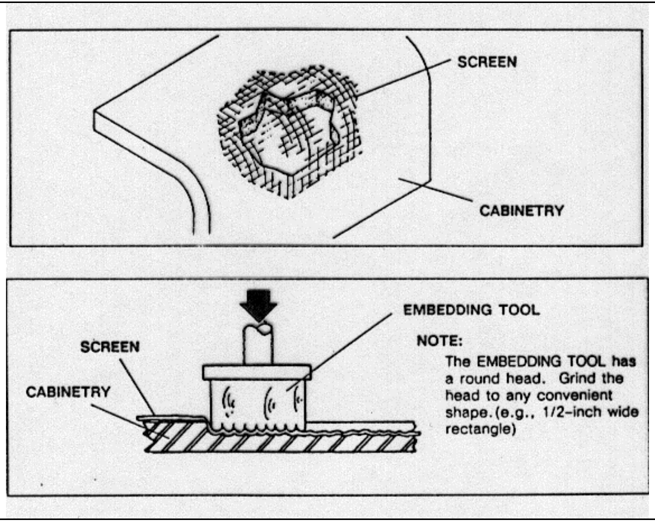
Ecosystem-level analogy

The restoration of ecosystems led to an analogy for the restoration of damaged parts in remanufacture. The relevant section from Purves *et al.* (2001) follows:

> The world's largest restoration project is under way in Guanacaste National Park in northwestern Costa Rica. Its goal is to **restore** a large area of tropical deciduous forest – the most threatened ecosystem in Central America – from small fragments that remain in an area converted mostly to pastures.

The concept to be used from this analogy is that restoration involves a process that builds upon small fragments of preserved forest until they meet to form a large continuous forest. A similar concept can be used for restoring parts in remanufacture.

For example, Figure 6, from the manual of a photocopier remanufacturer, shows a repair method for a photocopier panel that requires the embedding of mesh substrate into a section with a hole. The screen acts as support for filler material to replace the lost material. That is, replacement material bonds onto the screen, and more replacement material is bonded until a continuous panel is restored. The correct positioning of this screen in the panel is important for the structural and aesthetic results of the repair. Design that facilitates this process further could involve having a screen already embedded in portions of the product that are likely to fail, so that effort need not be expended in positioning the screen during remanufacture. To generalize, provide a base or substrate upon which anticipated repairs may build.



NOTE:
The EMBEDDING TOOL has a round head. Grind the head to any convenient shape. (e.g., 1/2-inch wide rectangle)

Figure 6.
Refurbishment of photocopier panels.

SUMMARY

Three case studies illustrate how fastening and joining that facilitate assembly and recycling could impede remanufacturing. These case studies suggest that elements of fastening methods that are prone to failure be made separable from the remainder of the part. However, this conclusion directly contradicts the part-consolidation tenet of design for assembly. Biological analogies were used to develop concepts that facilitate remanufacture, while considering assembly preferences. Three examples of biomimicry at the molecular, organism, and ecosystem levels, applied to design for remanufacture were described. While analogies at some organizational levels were related to existing processes, suggestions of how to further facilitate these processes were made.

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