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A STRUCTURED APPROACH TO DESIGN FOR REMANUFACTURE

Li Shu and Woodie Flowers
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts

ABSTRACT

Product design for ease of remanufacture could be a means for realizing resource conservation and waste disposal minimization. Unfortunately, few design for remanufacture guidelines are available. To gain insight into how to design for the overall remanufacturing operation, the design structure matrix, applied to a sequence of remanufacturing processes, is used to identify the information flow patterns between processes at different stages of the remanufacturing operation. It is concluded that iteration loops between processes as applied to a single product unit should be eliminated and that other interprocess dependencies should be minimized. Next, axiomatic design is applied to specific remanufacturing processes to gain insight into how products should be designed to facilitate each process. Finally, use of axiomatic design to perform remanufacturing process planning for an existing product is discussed. A simple case study involving the design of a panel for an appliance, or other apparatus, to facilitate refurbishment is presented. These methodical techniques seem well suited to support a computer-based design for remanufacture advisor.

MOTIVATION

Design of durable products for ease of remanufacture is often a sensible approach to environmentally responsible product design. Remanufacturing transforms durable products that are worn, defective, or obsolete to a “like-new or better” condition through a production-batch process of disassembly, cleaning, refurbishment and replacement of parts, reassembly, and testing. Value is added during the original manufacturing process in the form of energy and labor required to shape the raw material into a usable component. By recycling at the higher level of components rather than the raw material level, remanufacturing preserves this value-added as well as the material content of the product [Lund 83]. Not only is resource consumption for unnecessary reprocessing of material avoided, but the eventual degradation of the raw material through contamination and molecular breakdown, frequently characteristic of scrap material recycling, is postponed. Also, the production-batch nature of the remanufacturing industry enables it to salvage functionally failed, but repairable products that are discarded due to high labor costs associated with individual repair [Warnecke & Steinhilper 85].

One limiting factor in remanufacturing has been the availability of cores in good condition at a sufficiently low price. Another obstacle develops when original equipment manufacturers (OEMs) view independent remanufacturers as competitors. Consequently, OEMs may act to discourage remanufacture of their products by not sharing product specifications and manufacturing processes, or more aggressively, by incorporating subtle design changes that specifically hinder remanufacturing [Lund 83]. Product takeback laws such as those proposed in Germany [Ziwica 93] that require manufacturers to take back their durable products at the end of life would help to remove these hindrances. If Germany’s proposed takeback law is a harbinger of future practices globally, it may behoove the OEM to design products that are easy to remanufacture.

Unfortunately, there is a paucity of available knowledge on how to design for ease of remanufacture. The few rules found in literature that are generated from experience tend to be product specific. The basis and application range of these rules are not always available, resulting in a set of seemingly conflictive guidelines. The apparent arbitrary nature of these rules induces low confidence that the sets of rules are complete. A structured, systematic approach to viewing the remanufacturing process is needed to generate a sense of how to best design for it.

	disassemble	sort	clean	assess	refurbish	assemble	test
disassemble	•						$*_{dt}$
sort	x_{sd}	•	$*_{sc}$				
clean	$*_{cd}$	$*_{cs}$	•				
assess	$*_{ad}$	$*_{as}$	$*_{ac}$	•	$*_{ar}$		
refurbish	$*_{rd}$	$*_{rs}$	$*_{rc}$	x_{ra}	•		
assemble	x_{abd}		$*_{abc}$		$*_{abr}$	•	
test	$*_{td}$		$*_{tc}$		x_{tr}	$*_{tab}$	•

FIGURE 1. REMANUFACTURE STRUCTURE MATRIX.

PRODUCT CHARACTERISTICS CONDUCIVE TO SUCCESSFUL REMANUFACTURING

[Lund 83] identifies some fundamental constraints that a product should satisfy to be a suitable candidate for remanufacture. For remanufacture to be technically feasible, a durable core must exist at the time of product disposal. Consequently, an infrastructure to collect and transport cores is also necessary. For economic feasibility, the cost of the remanufacture process should be less than the cost of the original manufacture, unless the cost of disposal is high enough to justify a more expensive remanufacture. Finally, a mass-produced item is more likely to provide enough units and components for a remanufacturing operation that could benefit from economies of scale.

REMANUFACTURE STRUCTURE MATRIX

First, the design structure matrix will be used as a tool to examine information flow between processes in a remanufacturing operation. The design structure matrix is a representation used by [Steward 81] [Gebala & Eppinger 91] to map the information flow relationships between design activity tasks. This tool can be similarly used to show the relationships between various remanufacturing tasks. Remanufacturing operations documented in [Gonzalez 83], that are executed sequentially on each product unit, are presented in Figure 1.

In this matrix, lower triangular entries represent feed-forward information flow from the operation identified by the column heading to the operation identified by the row heading. For example, x_{sd} indicates that the disassembly operation provides information to a later task, the sorting operation, and x_{tr} indicates that the refurbishment process transfers information forward to the test process. Conversely, upper triangular entries represent feedback information flow. For example, it is possible that the refurbishment operation would provide information back to an earlier task, the assessment operation, thereby establishing an iteration loop. In practice, assessment at some level is performed during each process, as there is no need to further process an obviously unrecoverable part.

In accordance with [Gebala & Eppinger 91], iteration loops, when applied to a single product unit, are expensive, in terms of both information and time. Feedback from the final testing process to the disassembly process for one single unit occurs when a processed unit fails the final test, and is returned to repeat the sequence of remanufacturing processes. This iteration loop is the most expensive since it is the largest and involves repeating the most steps. In practice, this particular iteration is avoided by intermediate test points that detect problems before the final testing process. Appropriate design for remanufacture would aim to eliminate the information feedback entries, with priority given to those that cause the largest iteration loops. For example, the product, or remanufacturing processes, could be designed such that refurbishment of a part does not incur further assessment of that part.

It would also be beneficial to eliminate as many off-diagonal, lower triangular entries as possible. In the limit that there were no off-diagonal entries, none of the processes would require information from or supply information to other processes. Since the processes would then be independent, the order in which they are executed would be inconsequential, and thus they could be executed in parallel. In the remanufacture structure matrix (Figure 1), 'x' entries represent necessary information transfer between processes, whereas '*' entries represent information transfer that frequently occurs, but may be eliminated.

The above conclusions to minimize information feedback and feedforward apply only to information flow as applied to a single unit that flows through the system. Conversely, information flow as applied to the system, with a continuous flow of units, is essential. That is, if it is discovered that all the outflow units have a particular defect, this information should be supplied to the appropriate place in the sequence of processes to correct for the defect.

Similar to the matrix equations expressed for disassembly, uncoupled cleaning processes can be represented by a diagonal matrix, and decoupled cleaning processes can be represented by a triangular matrix. One example of a decoupled cleaning process as cited in [Warnecke & Steinhilper 83] involves the inadvertent destruction of the labeling on the glass bell of a hot water boiler during the removal of lime deposits from the boiler.

The cleaning processes are coupled when the cleaning methods of Part A and Part B affect each other. This coupling can be prevented during the product design phase for example, by appropriate choice of materials, or during the remanufacturing process planning stage by appropriate choice of cleaning methods. It is also possible to remove this coupling by separating the parts prior to the cleaning process. This can be inferred from the remanufacture structure matrix (Figure 1), which indicates that disassembly and sorting may affect the cleaning process.

The information axiom implies that surface characteristics, such as texture and color, that do not require frequent or extensive cleaning are preferred. Specifically, a very smooth surface that is easily marred may involve substantial effort to restore to a like-new condition. For example, clear or smoked plastic parts with smooth finishes may scratch easily and require extensive buffing to remove minor blemishes. Other imperfections that may not affect the function of the part, such as small cracks, chips, or stressed areas visible as clouded regions, prohibit the restoration of the part to a cosmetically perfect condition. On the other extreme, a texture that is too coarse may trap dirt and also complicate cleaning.

Assessment

Component assessment is a critical process in remanufacturing. If the assessment criterion is too high, many potentially usable parts are discarded; if it is too low, parts will fail prematurely [Warnecke & Steinhilper 85]. Assessment procedures can range from objective and easily performable to subjective or nonexistent. A highly experienced person is required to make subjective decisions when the assessment process is information intensive [Gonzalez 83]. A component designed such that it accurately and explicitly indicates its remaining useful life would take the subjectiveness out of this process.

Refurbishment

Design for remanufacture guidelines frequently suggest that products be designed for “greater durability.” [Overby 80][Holzwasser 83][D’Amore 84]. While attempts to design entire products for infinite life are likely to result in a waste of resources [Kutta 80], it may be possible to incorporate some properties of more durable products that facilitate remanufacture without undue expense.

Durable products that evoke images of bulky, cast-iron-like components seem to be preferred over less material-intensive products such as plastic or die cast parts [Kutta 80]. This is partly because bulkier parts provide more of a margin of material to work with, for processes such as the reboring of cylinders. This preference may also be due to impressions that severe damage during use or even some stage of remanufacturing, including the refurbishing process, is less likely to occur with a material-intensive component. With respect to information content, it is often easier to refurbish a component that has minor defects than one that has catastrophically failed. The higher resources invested in the original manufacture of a material-intensive component that is only slightly worn help to justify incremental resources needed for refurbishment. Conversely, there is little incentive to salvage a cheaper part that is mostly worn. Hence, unless the part can be refurbished with additional resources that are acceptably proportional to its residual value, it will be discarded.

Concentrating anticipated wear and failure in detachable, consumable parts such as inserts and sleeves is one way of facilitating refurbishment, as well as minimizing both the amount discarded and necessary reconditioning of the parts to be salvaged. Resources expended on these consumable parts are proportional to their life expectancy. Clearly, unless the consumable parts are readily replaceable, the value of this concept is diminished. By enabling the physical separation of the consumable and nonconsumable parts, their respective refurbishment processes are uncoupled. [Overby 80] notes that valve inserts and sleeved cylinders in diesel engines, design features not often found in automobile engines, result in diesel engines that are easier to remanufacture than automobile engines.

There are reasons other than wear or failure which result in product disposal. Products may become technically or aesthetically obsolete, or they may have never successfully satisfied their intended function, for example due to poor user interface design. If these factors could be concentrated and modularized, the product would be more easily functionally or aesthetically upgraded. [Kutta 80] [Gonzalez 83] and [Lund 83] note that many products are updated to the latest technology, in control modules for example, during the remanufacturing process.

Transportation

Although transportation of products to the remanufacturing facility is not often included as a remanufacturing process, products could be designed to minimize damage incurred during transit. For example, large machines that require the use of fork lifts should provide sufficient clearance and support at the bottom. Also, modules that extend outside a regular geometrical volume, a rectangular block for instance, tend to become damaged during transportation and may hinder efficient stacking during storage.

REMANUFACTURE PROCESS PLANNING USING AXIOMATIC DESIGN

Finally, axiomatic design may be used to plan remanufacture processes for an existing product. By mapping the remanufacturing objectives to the processes by which these objectives could be achieved, the relationships between the operations can be determined and used either to select between various processes, or to perform processes in a particular order, to yield optimal results.

Although the utility of this tool may be better appreciated for a complex process that involves more dimensions, simple examples will be used for purposes of illustration.

Consider a part that contains a crack or hole in addition to being warped. Various closing tasks such as mechanical pressure, impingement, welding, or adhesive joining can be used to remove cracks and voids. However, manual or press straightening performed to remove warps may reopen the crack or hole. This relationship can be represented in matrix form as follows.

$$\begin{Bmatrix}\text{Repair Crack}\\ \text{Remove Warp}\end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12}\\ 0 & a_{22}\end{bmatrix}\begin{Bmatrix}\text{Closing Process}\\ \text{Shaping Process}\end{Bmatrix}$$

In this case, the straightening operation should be performed first to avoid repetition of the closing process.

Similarly, a part that has both soil and grease contamination could be cleaned using a solvent and a mechanical brush.

$$\begin{Bmatrix}\text{Remove Soil}\\ \text{Remove Grease}\end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12}\\ 0 & a_{22}\end{bmatrix}\begin{Bmatrix}\text{Mechanical Brush}\\ \text{Solvent}\end{Bmatrix}$$

Consider the case where the mechanical brush will only remove the soil, and the solvent will both dissolve the grease and rinse away soil. It is then favorable to first use the solvent, and then choose a brush appropriate for removal of remaining soil.

When the selected processes are coupled, attempts should be made to choose alternative remanufacturing processes to decouple the system. Finally, it would be clearly advantageous if product design changes that would alleviate remanufacturing difficulties could be identified and fed back to the design phase to be incorporated into future products.

CASE STUDY

The design and subsequent remanufacturing of a panel, for an appliance or other apparatus, will be used to illustrate both axiomatic design for remanufacture and process planning using axiomatic design matrices. First, axiomatic design will be used to map functional requirements of the panel into design parameters, which will then be mapped into process variables. The panel will be assessed for refurbishability by mapping the features that need refurbishment to the appropriate refurbishment processes. The difficulties in refurbishing this panel and the optimum order to perform refurbishment processes will be identified. An improved design for refurbishment will be proposed, and the subsequent process planning for the improved design will be performed.

It is desired that this panel be sufficiently rigid, have an aesthetically pleasing surface, attach to the machine, allow for ventilation to portions of the machine, and provide instructions to users. Using axiomatic design, these traits are identified as functional requirements (FRs) in the functional domain. These functional requirements are then mapped into design parameters (DPs) in the physical domain. The design parameters can be thought of as one set of possibilities for satisfying the functional requirements.

$$\{FR\} \quad = \quad [A] \quad \{DP\}$$

$$\begin{Bmatrix}\text{Rigidity}\\ \text{Aesthetic surface}\\ \text{Attach to machine}\\ \text{Ventilation}\\ \text{Provide instructions}\end{Bmatrix} = \begin{bmatrix} x & & & & \\ & x & & & \\ & & x & & \\ & & & x & \\ & & & & x\end{bmatrix}\begin{Bmatrix}\text{Structure}\\ \text{Texture / color}\\ \text{Joining method}\\ \text{Ventilation openings}\\ \text{Labeling}\end{Bmatrix}$$

The design parameters now become the objectives to be satisfied for the following mapping into the process domain. The process variables (PVs) represent one combination of manufacturing processes that can realize the physical parameters.

One possible design of the panel has molded-in ventilation grates, silk-screened labeling, and is welded to the machine. The design parameters are mapped to process variables as follows.

$$\{DP\} \quad = \quad [B] \quad \{PV\}$$

$$\begin{Bmatrix}\text{Structure}\\ \text{Texture}\\ \text{Joining method}\\ \text{Ventilation openings}\\ \text{Labeling}\end{Bmatrix} = \begin{bmatrix} x & & & & \\ & x & & & \\ & & x & & \\ & & & x & \\ & & & & x\end{bmatrix}\begin{Bmatrix}\text{Mold shape}\\ \text{Mold texture}\\ \text{Weld}\\ \text{Mold - in grates}\\ \text{Silk - screen}\end{Bmatrix}$$

According to axiomatic design, this is a manufacturable design in that the matrix product of [A][B], which maps the functional requirements to the process variables, is not coupled.

Some degree of disassembly or cleaning may be desired prior to the refurbishment process. Damage may occur during disassembly of the panel from the machine, as a consequence of the welded joint. It is also possible that the cleaning process may damage the silk-screened labeling.

The refurbishability of the panel is examined by mapping the features that need refurbishment to the processes that can realize the refurbishment.

$$\begin{Bmatrix} \text{Repair panel face defects} \\ \text{Refurbish surface/texture} \\ \text{Refurbish joint} \\ \text{Refurbish molded-in grate} \\ \text{Refurbish silk-screen label} \end{Bmatrix} = \begin{bmatrix} x & (x) & & & \\ x & x & & x & \\ & & x & & \\ & (x) & & x & \\ & x & & & x \end{bmatrix} \begin{Bmatrix} \text{Reinforce, fill \& shape} \\ \text{Sand \& paint} \\ \text{Reweld} \\ \text{Cut, patch \& shape} \\ \text{Redo silk-screen} \end{Bmatrix}$$

To repair defects such as holes and cracks in thermoplastic panels, a process that may be used involves melting reinforcements, such as metal rods, washers, or gauze into the plastic, covering the reinforcement with filler material, and shaping the filler so that the repair is not noticeable after the overall panel surface is refurbished. This process is somewhat more difficult for blow-molded parts, since the reinforcing and filler material tend to fall into the hollow center. While this process may present a problem for scrap-material recycling when the panel can no longer be refurbished, it is conceivable that a reinforcement material that is more recycling compatible with the panel material may be used.

Various difficulties involving silk-screening labels on nonvirgin surfaces have been noted. Silk-screening frequently requires a very smooth surface to have a proper appearance. This requirement results in a more expensive surface refurbishment since paint texture can be used to hide small surface material defects. Additionally, many painting vendors lack silk-screen capabilities.

To refurbish a damaged molded-in grate, it is often easier to simply cut out the old grate, patch a new piece of grating, and finish the borders. Most of these spot-patching processes should clearly be performed prior to the overall surface refurbishment process.

Although the matrix that relates the features to refurbish and the refurbishment processes is coupled, an ordering of processes to achieve optimal results may be attempted.

$$\begin{Bmatrix} \text{Repair panel face defects} \\ \text{Refurbish molded-in grate} \\ \text{Refurbish surface/texture} \\ \text{Refurbish silk-screen label} \\ \text{Refurbish joint} \end{Bmatrix} = \begin{bmatrix} x & & (x) & & \\ & x & (x) & & \\ x & x & x & & \\ & & x & x & \\ & & & & x \end{bmatrix} \begin{Bmatrix} \text{Reinforce, fill \& shape} \\ \text{Cut, patch, \& shape} \\ \text{Sand and paint} \\ \text{Redo silk-screen} \\ \text{Reweld} \end{Bmatrix}$$

The above matrix indicates that it would be advantageous to perform the first three processes in the order as listed. Although the repainting process affects the panel face defects, it can complement the reinforce and fill process if performed afterward. Likewise, the repaired grates may need to be painted to match the rest of the panel, or they may be masked during the painting process.

The refurbishability of this panel can be improved by specifying screws with bosses and screw inserts for attachment to the machine, detachable ventilation grills, and detachable labeling tags.

$$\begin{Bmatrix} \text{Structure} \\ \text{Texture} \\ \text{Joining method} \\ \text{Ventilation openings} \\ \text{Labeling} \end{Bmatrix} = \begin{bmatrix} x & & & & \\ & x & & & \\ & & x & & \\ & & & x & \\ & & & & x \end{bmatrix} \begin{Bmatrix} \text{Mold shape} \\ \text{Mold texture} \\ \text{Mechanical fasteners} \\ \text{Removable grates} \\ \text{Removable labels} \end{Bmatrix}$$

Again, the refurbishability of the panel is examined by mapping the features that need refurbishment to the processes that can realize the refurbishment.

$$\begin{Bmatrix} \text{Repair panel face defects} \\ \text{Refurbish grates} \\ \text{Refurbish labeling} \\ \text{Refurbish joint} \\ \text{Refurbish surface/texture} \end{Bmatrix} = \begin{bmatrix} x & & & & (x) \\ & x & & & (x) \\ & & x & & (x) \\ & & & x & (x) \\ x & & & & x \end{bmatrix} \begin{Bmatrix} \text{Reinforce, fill \& shape} \\ \text{Replace grate} \\ \text{Replace label} \\ \text{Replace screws, inserts} \\ \text{Sand and paint} \end{Bmatrix}$$

The above matrix indicates only one required sequence, that the reinforce, fill and shape process should precede the sand and paint process. If painting is performed after replacement of screw inserts, grates and label tags, it may be desirable to mask these newly replaced items during the painting process. By specifying detachable grates and label panels, the parts that are susceptible to damage can be isolated from the bulk of the structure. The damaged parts can also be refurbished after disassembly, but if replaceable parts are available, the completion of the refurbishment process is not necessary for other remanufacturing activities to proceed.

SUMMARY AND FURTHER WORK

Product remanufacture was identified as a viable alternative that enables resource conservation and waste disposal minimization. The overall remanufacturing operation as well as specific remanufacturing processes were examined to gain an intuition as to how products and processes could be designed to facilitate remanufacture. The design structure matrix was used as a tool to express information flow interactions between remanufacturing processes. It was concluded that iteration loops applied to single product units should be eliminated and that other interprocess dependencies be minimized. Axiomatic design was applied to specific remanufacturing processes to gain insight into how to design products to facilitate each process. The potential use of axiomatic design for remanufacturing process planning for an already designed, existing product was also illustrated.

It was shown that axiomatic design could be used generate guidelines that are consistent with intuition and those generated from experience. This paper represents initial efforts toward a computer-based tool to facilitate design for remanufacturing. It is anticipated that the use of axiomatic design in conjunction with an appropriately structured database presents advantages in implementation and manageability over an exhaustive rule-based advisor. Also, as guidelines are generated specific to each case, it is less likely that rules generalized from different situations would be applied inappropriately. Immediate future work includes the development of a suitable database.

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