Application of a Design-for-Remanufacture Framework to the Selection of Product Life-Cycle Fastening and Joining Methods

by

Lily Hwei-Li Shu

B.S., Mechanical Engineering (1989)
University of Nevada, Reno

S.M., Mechanical Engineering (1992)
Massachusetts Institute of Technology

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy in Mechanical Engineering

at the
Massachusetts Institute of Technology

June 1996

Signature of Author ______________________________
Department of Mechanical Engineering
March 12, 1996

Certified by ______________________________
Woodie C. Flowers
Pappalardo Professor of Mechanical Engineering
Thesis Supervisor

Accepted by ______________________________
Ain A. Sonin
Chairman, Graduate Committee

Application of a Design-for-Remanufacture Framework to the Selection of Product Life-Cycle Fastening and Joining Methods

by

Lily Hwei-Li Shu

Submitted to the Department of Mechanical Engineering
at the Massachusetts Institute of Technology
on March 12, 1996 in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy in Mechanical Engineering

ABSTRACT

The goal of this research in environmentally responsible product design is to enable design for remanufacture. Remanufacture is a production-batch process of disassembly, cleaning, refurbishment and replacement of parts in products that are worn, defective or obsolete. By recycling at the parts level, remanufacturing preserves the valued added to the part during manufacture. Furthermore, remanufacture postpones the eventual degradation of the raw material due to contamination and molecular breakdown, frequently characteristic of scrap-material recycling. The production-batch nature of remanufacturing enables it to salvage functionally failed but repairable products that are discarded due to high labor costs associated with individual repair.

Insights on how products can be designed to facilitate remanufacture were gained through collaboration with three companies that remanufacture different products. The most essential aspect of design for remanufacture was revealed to be in conflict with other prevalent design-for-x methodologies, such as design for assembly and design for recycling. Design for remanufacture was therefore viewed in the context of other design-for-x methodologies. The domains selected for simultaneous consideration were manufacture and assembly, maintenance, remanufacture, and scrap-material recycling. Since fastening and joining issues are common to all these domains, a framework that evaluates the effect of joint design on each of these life-cycle stages was developed. This framework was applied to case studies of joints that did not facilitate remanufacture to estimate the cost of remanufacture relative to other life-cycle costs determined by the joint design.

These case studies identified the importance of reliability modeling for remanufacture. A probabilistic reliability model was developed to describe the effect of remanufacture on the reliability of parts and systems. The basic behavior of this model, which simulates the replacement of failed parts with parts of the same type, was experimentally verified. The model was further developed to accommodate the common practice of system modification during remanufacture. The various inputs to this reliability model are factors that can be combinatorially optimized to minimize life-cycle cost. The optimization of life-cycle fastening and joining costs using genetic algorithms was implemented.

Thesis Supervisor: Woodie C. Flowers
Title: Pappalardo Professor of Mechanical Engineering

Thesis Committee:
David E. Hardt
Mark J. Jakiela
David R. Wallace

Acknowledgments

There are a great number of people who contributed to the development of this thesis.

First, I want to thank Woodie Flowers for being a consistently encouraging advisor, whose willingness to challenge convention gave me the freedom to define this thesis. I am also grateful to my committee members: David Hardt, for always having keen and insightful comments about my work; Mark Jakiela, for several excellent suggestions both for the preparation of this thesis and for future directions; and David Wallace, for inspiring me to do research in this field and supporting my subsequent efforts.

I thank the **Eastman Kodak Company**, whose financial support in the form of a fellowship made this work possible. Glen Pearson provided the support enabling the collaboration with Eastman Kodak that was crucial to this thesis. I am grateful to John Border for being a superb mentor, who coordinated several visits and ensured that my visits were successful. Several periods of collaboration with the Office Imaging Remanufacturing division formed the foundation for this thesis. I am indebted to many people in this division for welcoming me into their work environment. In particular, I thank Arthur Gable for his steadfast support of my endeavors, Douglas Chase, for helping me find the information I sought, and Cliff Cook for identifying valuable case studies. Rose Bothner, Robert Colls, Mike Davis, John Gambon, and Fred Judge were also instrumental in helping me learn about the remanufacture of photocopiers. Michael DeCecca revealed to me the many considerations that make design for remanufacture a challenging thesis goal.

I was fortunate to have met Peter Swart of **Nashua Cartridge Products**, who provided me with some wonderful examples in the remanufacture of toner cartridges.

I am also very grateful to Bob Holzwasser of **Arrow Automotive Industries**, who was remarkably helpful in introducing me to the remanufacture of automotive aftermarket parts.

I thank all of my officemates and members of the CADLab for their support, both technical and personal. In particular, I thank Nicola Senin for his help in implementing the reliability model. Matthew Wall provided several critical instances of computer assistance which are much appreciated. I thank Jim Duda and Mark Jakiela for reading my manuscripts and identifying errors in the reliability modeling section. I am indebted to Adenike Adewuya for "sharing" her desk. I appreciate the many technical and nontechnical discussions I had with Jayaram Krishnasamy and Ben Linder.

I thank Edwin Ozawa for proofreading several of my papers and listening to all my practice talks. Akhil Madhani is gratefully acknowledged for helping me prepare the experiments and the defense presentation.

I will always be indebted to my friends, Kendra Borgmann, Peggy Leung, Karon MacLean and Jeannie Sullivan, who helped me through challenging phases and celebrated milestones with me. Jose Arocha and Jane Gould have also motivated me to appreciate the many dimensions of life.

I want to thank my undergraduate department of Mechanical Engineering at the University of Nevada, Reno, in particular Miles Greiner, Brad Snyder, and Richard Wirtz, for their early encouragement and continued support of my professional development.

Finally, I thank my parents for being my first and most solid source of encouragement.

Table of Contents

Application of a Design-for-Remanufacture Framework to the Selection of Product Life-Cycle Fastening and Joining Methods

List of Figures

Chapter 1. Problem Definition

1.1. Introduction and Motivation

1.1.1. Design for End-of-Life

Product design for end-of-life is prompted by existing and anticipated legislation (U.S. Congress 1992) that requires manufacturers to reclaim responsibility for their products at the end-of-life. Three alternatives to landfill or incineration include recycling for scrap material, remanufacture and maintenance. Maintenance, or repair/reuse, 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 (Lund 1983). Scrap-material recycling involves separating a product into its constituent materials and reprocessing the materials for use in similar or degraded applications.

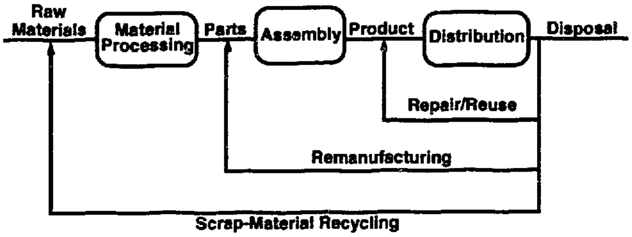


Fig. 1.1. End-of-life options

1.1.2. Benefits of Remanufacture as an End-of-Life Option

Remanufacturing involves recycling at the parts level as opposed to the scrap-material level. 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. Recycling at the higher level of components avoids resource consumption for possibly unnecessary reprocessing of material while preserving this added value (Lund 1983). Remanufacturing also postpones the eventual degradation of the raw material through contamination and molecular breakdown, frequently characteristic of current scrap-material recycling technologies (Lund 1983; Warnecke and Steinhilper 1983). 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.

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 (Lund 1983). Products are also favorable when upgrades can be accomplished through software, enabling the reuse of most of the components across product generations.

The most visible example of remanufacturing in the U.S. is in the automotive aftermarket. Haynsworth and Lyons (1987) estimate this segment of remanufacturing to be worth $1 to $2 billion dollars. Holzwasser (1977) estimates that 50 percent of an automotive starter is recovered in the remanufacturing process, which can result in annual savings of 8.2 million gallons of crude oil from steel manufacturing, 51,500 tons of iron ore, and 6,000 tons of copper and other metals. In the office equipment market, the Eastman Kodak Company has financially benefited significantly by remanufacturing their photocopiers at the end of leases. In 1991, the Xerox Corporation saved approximately $200 million by remanufacturing their photocopiers (U.S. Congress 1992).

1.2. Overview of Thesis

The purpose of this research is to enable product design that facilitates remanufacture. This thesis is organized in sequential efforts towards this goal. First described are insights on how products can be designed to facilitate remanufacture. These insights are distilled from a limited body of literature and extensive collaboration with companies that remanufacture products. The most essential aspect of design for remanufacture is identified as one that conflicts with other more prevalent design-for-x methodologies, such as design for assembly and design for recycling. It is therefore necessary to view design for remanufacture in the context of other design-for-x methodologies. The domains selected for simultaneous consideration are manufacture and assembly, maintenance, remanufacture, and scrap-material recycling. Since fastening and joining issues are common to all these domains, a framework that evaluates the effect of joint design on each of these life-cycle stages is developed. This framework, outlined in Chapter 2, estimates the cost of remanufacture relative to other life-cycle costs determined by the joint design, and is applied to case studies of joints that did not facilitate remanufacture. These case studies identify the importance of reliability modeling for remanufacture. Chapter 3 details a probabilistic reliability model that describes the effect of remanufacture on the reliability of parts and systems. The basic behavior of the model is experimentally verified. The inputs to this reliability model are factors that can be combinatorially optimized to minimize the life-cycle cost. In Chapter 4, the reliability model is applied to joint systems and the implementation of genetic algorithm-based optimization of life-cycle fastening and joining costs is described. A summary and suggestions for future work in Chapter 5 close the thesis.

1.3. Defining Design for Remanufacture

Collaboration with three companies that remanufacture a variety of products was initiated to learn about the remanufacture process and how products can be designed to facilitate remanufacture. These companies are Eastman Kodak in Rochester, New York, a manufacturer and remanufacturer of photocopiers, single-use cameras, and medical analysis equipment; Nashua Cartridge Products, an independent remanufacturer of toner cartridges in Exeter, New Hampshire; and Arrow Automotive Industries, an independent remanufacturer of automotive aftermarket parts. Arrow Automotive Industries has plants in several locations, one of which is Spartanburg, South Carolina. The extended collaboration with the Eastman Kodak Office Imaging Remanufacturing division, including a summer working on a photocopier remanufacturing line, formed the foundation for this thesis. The knowledge acquired through collaboration confirmed and supplemented remanufacturing literature, which emphasizes the remanufacture of automotive parts.

Product design that facilitates any of the steps involved in remanufacture, namely disassembly, sorting, cleaning, refurbishment, reassembly and testing, will facilitate remanufacture. Examples of product design that facilitate the individual steps follow.

1.3.1. Transportation

Although transportation of products to the remanufacturing facility is not often included as a remanufacturing process, products should be designed to minimize damage incurred during transit.

For example, large products such as photocopiers, whose movement requires 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.

1.3.2. Disassembly

There is an abundance of design-for-disassembly guidelines that aim to facilitate disassembly. Schmaus and Kahmeyer recommend a linear and unified disassembly direction, a sandwich structure with central joining elements, minimizing the number of joining elements, and using standard and simple joining techniques. Simon et al. recommend a reduction in the quantity and variety of fasteners, the use of standard fasteners, and avoidance of long disassembly paths and awkward access. Many design-for-assembly guidelines, such as those that facilitate part handling and access, are not only beneficial for assembly, but also for disassembly. In addition, it is often easier to take a set of components from a higher state of order in the assembled state, to a lower state of order in the disassembled state, than the reverse.

Much of the disassembly of photocopiers is performed by human operators, using a power-assisted device whenever access allows. An initial overall cleaning using compressed air is performed to remove excess toner, paper dust, and other dirt. Cleaning of extraordinarily dirty parts helps in both locating the fasteners and fitting the fastening bit into or over the fastener. This is an example of where steps of the remanufacture process interact and are dependent, requiring either a certain order of processes or iteration between processes. Avoidance of such interaction improves the efficiency of the overall remanufacture process. For example, if dirt is expected to be a problem, fasteners should be selected such that even dirty ones are easy to locate and remove.

Pieces that drop due to orientation and gravity after disassembly save the operator from performing the part removal step, but may cause damage, both to the operator and the piece. Operators who have worked on both newer models, that were designed with assembly in mind, and older machines, that were not, confirmed the convenience and time savings that result from using identical fasteners across a machine.

1.3.3. Sorting

To facilitate parts sorting after disassembly, Warnecke and Steinhilper (1983) suggest the use of either identical or grossly dissimilar parts such that effort is not expended in discerning subtly different, but not interchangeable, parts. In order to facilitate identification, BMW uses a color coding system to differentiate various automobile fluids and as well as parts made from different types of plastics (Ziwica 1993). In the remanufacture of automotive aftermarket parts, many of the components are returned so dirty that they must be cleaned before they can be accurately identified.

1.3.4. Cleaning

Cleaning is frequently the most energy and labor intensive process in remanufacturing (Gonzalez 1983). An improvement in the efficiency of this process could significantly increase the cost effectiveness of the overall remanufacturing operation.

Accessibility is a key factor in determining ease of cleaning. Cleaning methods used for copier components include ultrasonic methods, which are appropriate for intricate parts. For water or solvent based cleaning methods that use either the motion of the cleaning fluid or a mechanical brush to help remove dirt, geometries that trap dirt, such as sharp grooves and recesses, are problematic. The choice of solvent is selected based on the particular dirt and materials commonly encountered for the product type, but is also subject to environmental, particularly disposal, and health concerns. Health factors include worker antagonism toward certain solvent odors as well as the effects of extended exposure to solvent fumes. When hand cleaning the inside of enclosed product frames, operators can be exposed to higher concentrations of solvent fumes than predicted for nominal cleaning conditions.

For external components, surface characteristics, such as texture and color, that do not require frequent or extensive cleaning, are preferred. 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 during both product use and cleaning, 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. However, a texture that is too coarse may trap dirt and also complicate cleaning.

An example of damage that occurred during cleaning as cited by Warnecke and Steinhilper (1983) involves the inadvertent destruction of the labeling on the glass bell of a hot water boiler while removing lime deposits from the boiler. This damage could have been 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. Enabling the separation of the labeling from the glass bell by using removable labels is also a possibility.

1.3.5. Assessment

Component assessment is a critical process in remanufacturing. If the assessment criterion is too high, many potentially usable parts may be discarded; if it is too low, parts will fail prematurely (Warnecke and Steinhilper 1983). 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 1983). A component designed to accurately and explicitly indicate its remaining useful life would reduce the subjectiveness of this process.

1.3.6. Refurbishment

While product design that facilitates any of the above steps in remanufacture 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.

To enable reuse, components could be designed to never wear or fail. For example, literature on automotive remanufacture frequently suggests that products be designed for "greater durability" (Overby 1980; Holzwasser 1983; D'Amore 1984). Durable products with bulky, over-designed components seem to be preferred over less material-intensive products such as plastic or die-cast components (Kutta 1980), partly because bulkier parts provide more of a margin of material to work with, for processes such as the reboring of cylinders. Sturdier parts also incur less damage during both product use and remanufacturing operations, including refurbishing processes. 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 not be salvaged.

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 (Gonzalez 1983). 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.

To repair defects such as holes and cracks in photocopier external panels, a process sometimes used involves melting reinforcements, such as metal rods, washers, or gauze into the plastic panel. The reinforcement is then covered with filler material, which is smoothed so that the repair is not noticeable after the overall panel surface is refurbished. This process is difficult for blow-molded parts, since the reinforcing and filler material can fall into the hollow center. While these types of reinforcements 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. Damaged molded-in ventilation grates on copier panels are often cut out and replaced by a new piece of grating. Most of these spot-patching processes are performed prior to overall surface refurbishment processes, such as sanding and repainting.

Various difficulties involving silk-screening labels on refurbished copier panels 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 is normally used to hide small, surface-material defects not acceptable for silk-screening. Additionally, many painting vendors lack silk-screen capabilities.

While attempts to design entire products for infinite life are likely to result in a waste of resources (Kutta 1980), it may be possible to incorporate some properties of more durable products that facilitate remanufacture without undue expense. Concentrating anticipated wear and failure in detachable, consumable parts such as inserts and sleeves is one way of facilitating refurbishment. Overby (1980) 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. Warnecke and Steinhilper (1983), Kutta (1980), Holzwasser (1983), and D'Amore (1984) also revealed a strong preference for failure and wear to be isolated in as small a part as possible. Sleeved cylinders (Overby 1980; Schrader 1985) and some screw inserts can be replaced several times, enabling the bulk of the part to be reused without costly rework.

The refurbishability of a copier panel can be improved by specifying detachable fastening methods, such as screws and bosses with screw inserts for attachment to the machine, detachable ventilation grates, and detachable labels. By enabling the physical separation of the durable and failure-prone features, their respective refurbishment processes are uncoupled. For example, failure-prone features such as grates and label panels that are detachable can be refurbished after disassembly from the main panel. If replacement grates and label panels are available, the refurbishment of the damaged features need not be completed for other remanufacturing processes to continue for the main panel.

There are reasons other than wear or failure which result in product disposal. Products may become technologically 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 (1980), Gonzalez (1983) and Lund (1983) note that many products are updated to the latest technology, in control modules for example, during the remanufacturing process.

1.4. Design for Remanufacture and Other Design Methodologies

Unfortunately, making features that are prone to wear separable directly counters the part-consolidation tenet of design for assembly. In addition, separable parts that introduce a new material may counter recycling efforts. For example, while screw inserts are favorable for remanufacturing, metal inserts inadvertently left in plastic parts will damage plastic reprocessing machinery. Currently, both design-for-assembly and design-for-recycling methodologies are more prevalent than design for remanufacture. 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 (Barkan and Hinckley 1993). Therefore, to reveal the effect of initial product design on remanufacture relative to other life-cycle stages, a framework was developed that simultaneously considers the life-cycle perspectives of manufacture and assembly, recycling, remanufacture and maintenance.

Chapter 2. Basic Design-for-Remanufacture Framework

The previous chapter described several ways in which products can be designed to facilitate remanufacture. An essential aspect of design for remanufacture was revealed to conflict with other life-cycle design-for-x methodologies such as design for assembly and design for recycling. It was therefore decided to examine design for remanufacture in the context of other life-cycle domains. Chosen for simultaneous consideration 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.

This chapter begins with an overview of related work in the field of life-cycle design. While conflicts between different design objectives often occur, much of the related work that mentions remanufacture does not acknowledge a conflict between design for remanufacture and other design-for-x considerations. Three examples of joints in products that are currently remanufactured are used to illustrate these conflicts. The implementation of a design tool that estimates the costs for each of the selected life-cycle perspectives as determined by the joint design is outlined. This tool is then used to calculate life-cycle costs for the case studies. The results of these case studies and their implications for product design and life-cycle modeling conclude this chapter.

2.1. Related Work in Design for Disassembly

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 (Henstock 1988; Chen et al. 1993; Kirby and Wadehra 1993; Noller 1992). 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 (Subramani and Dewhurst 1991; Bryan et al. 1992; Gershenson and Ishii 1991; Laperriere and ElMaraghy 1992) as well as remanufacture (Schmaus and Kaymeyer; Simon et al.; Zussman et al. 1994, Amezquita et al. 1995). The primary emphasis in disassembly to facilitate maintenance is to minimize machine downtime and maintenance labor cost. Amezquita et al. (1995) emphasize fast disassembly and reassembly for ease of remanufacture. Chen et al. (1993) and Cobas et al. (1995) examine cost tradeoffs implicit in life-cycle design.

A database of disassembly and reassembly time estimates for several fastening and joining methods tabulated by Whyland (1993) is used in this work. VDI in Germany qualitatively compared the suitability of fastening and joining methods for different end-of-life options (VDI 1993; VerGow and Bras 1994).

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 that were preventable by the use of threaded inserts may also be unsalvageable. As part cost increases, the extra effort required to install an insert in a screw-fastened 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 (Jovane et al. 1993; Boothroyd and Alting 1992; Berko-Boateng et al. 1993; Seaver 1994). 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.

2.2. 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.

2.2.1. Thread-Forming Screws in Paper Guide

The first example is provided by Eastman Kodak Office Imaging Remanufacturing, who remanufactures photocopiers, duplicators and other office equipment. Fig. 2.1 shows part of a paper guide that taps the sides of a photocopied document to align the edges before the document 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 remanufacture to allow access to other parts. If the screws are reinserted for 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 one possibility that would have enabled the reuse of these parts.

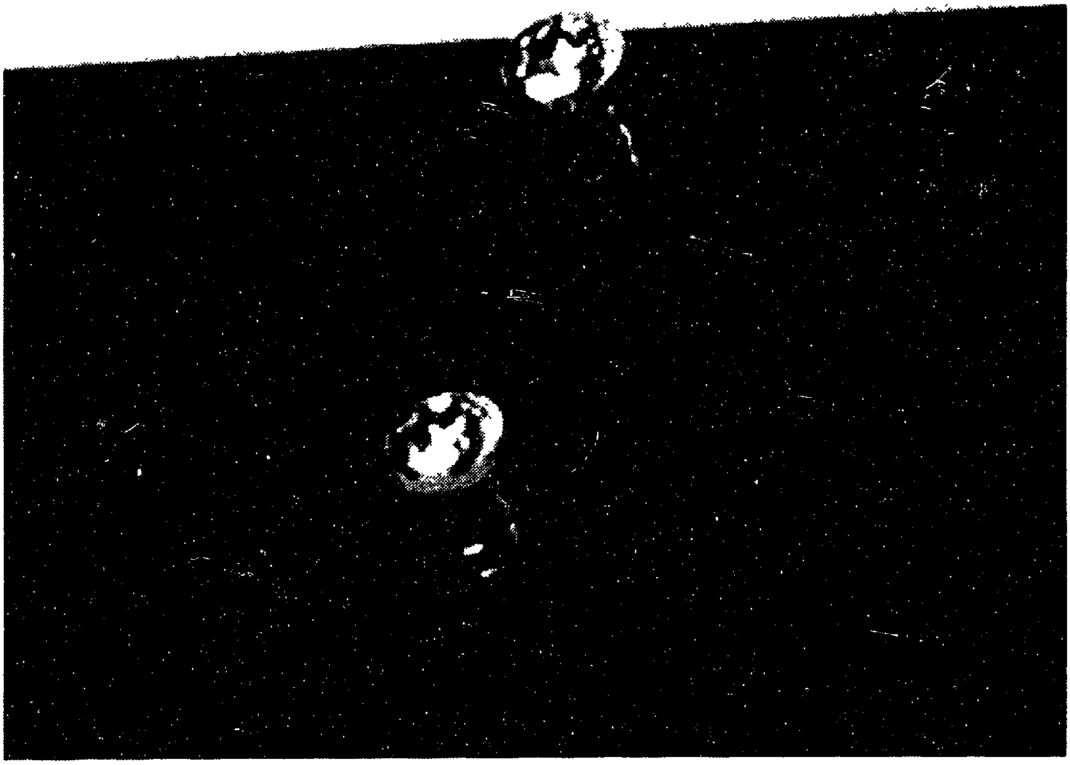


Fig. 2.1. Thread-forming screws used to fasten paper guide to base

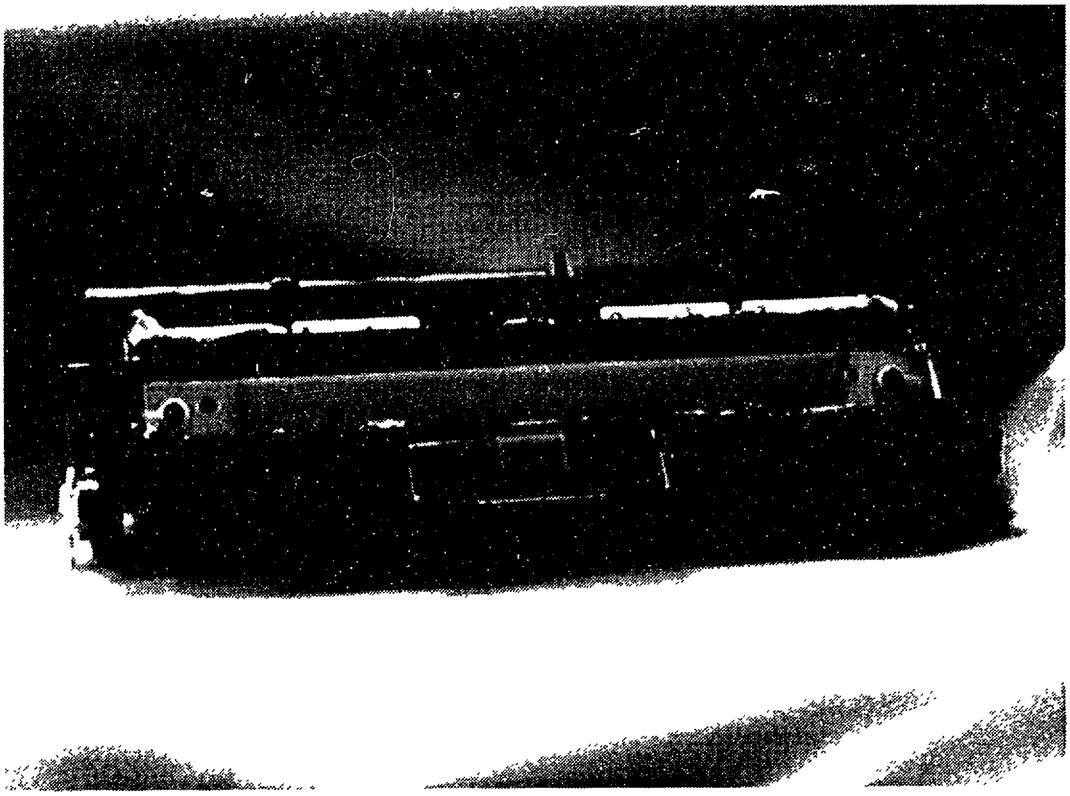


Fig. 2.2a. Cut-out in toner-cartridge cover to access mounting screws

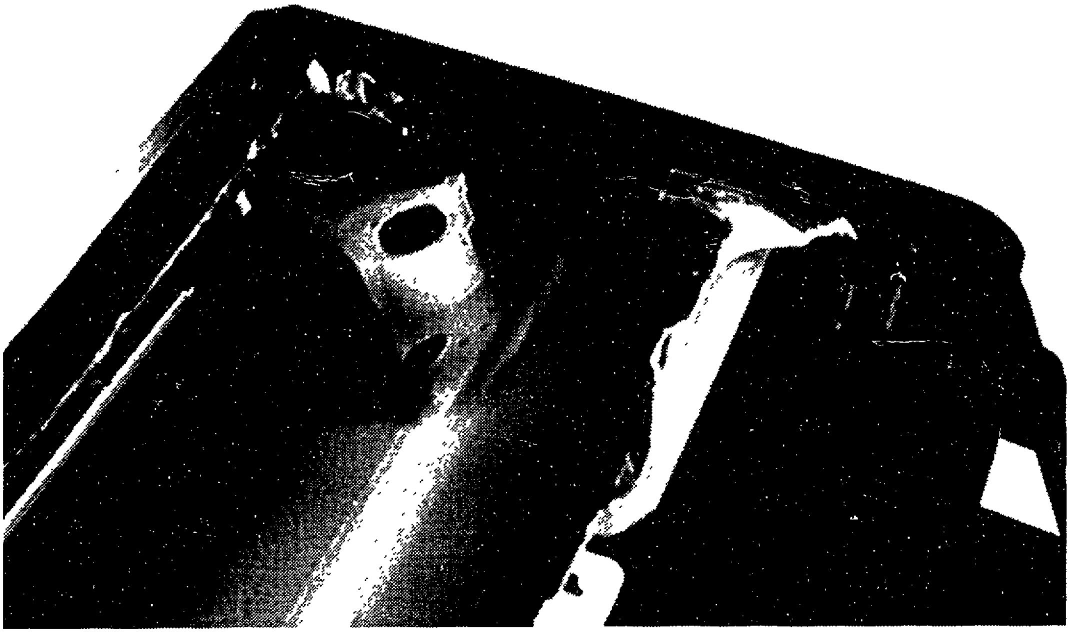


Fig. 2.2b. Close-up of cut-out in toner-cartridge cover

The following two case studies are provided by Nashua Cartridge Products, an independent remanufacturer of toner cartridges produced by different original equipment manufacturers.

2.2.2. Welded Cover on Toner Cartridge

Figs. 2.2a and 2.2b show a toner cartridge where a hole was machined in a cover that is ultrasonically welded onto the 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 in similar applications where screws were used instead, the screws can be successfully removed and reinstalled up to three times before switching to coarser-threaded screws.

Fig. 2.3. Toner-cartridge housing cracked around snap-through hole.

2.2.3. Snap Fit in Toner-Cartridge Housing

Fig. 2.3 shows a snap-through joint, where the housing around the through-hole was cracked during disassembly. A through-hole is located on both sides of the toner-cartridge housing. The snap-foot is located on the endcap of the drum. The part of the housing with the through-hole is deflected during original assembly, and is pried apart to release the snap-foot during disassembly.

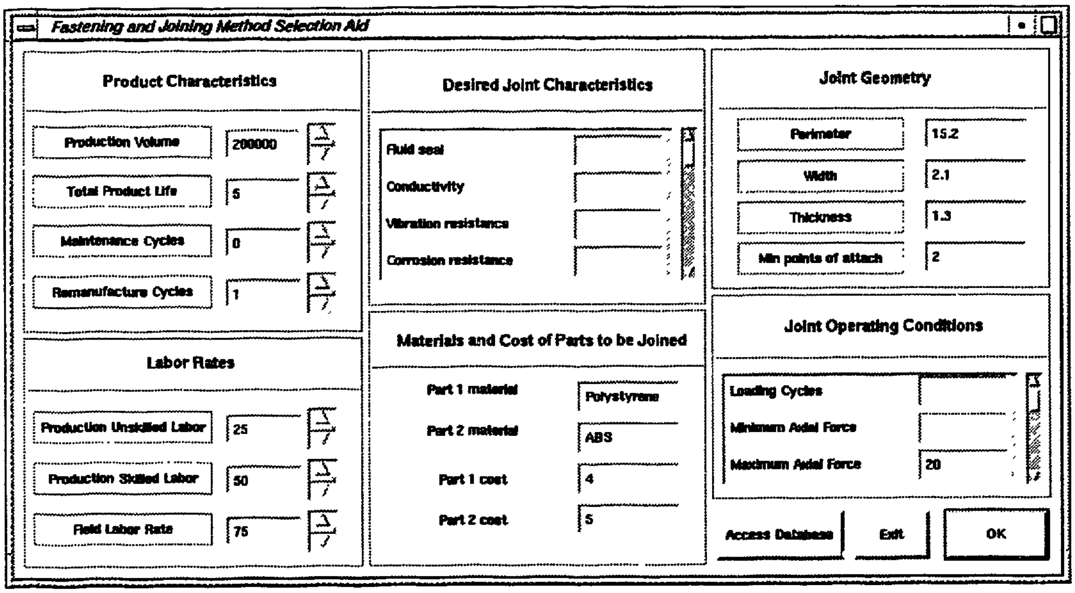
2.3. Computer Tool Implementation

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, a computer tool was implemented that simultaneously estimates the cost of manufacture and assembly, maintenance, remanufacture and recycling, as imposed by fastening and joining methods. This tool aims to help the product designer make a rational choice between fastening and joining methods for specific applications, rather then blindly apply generic and possibly inappropriate design guidelines.

2.3.1. Interface

This tool estimates 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 input interface is shown in Fig. 2.4a. 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. 2.4b.

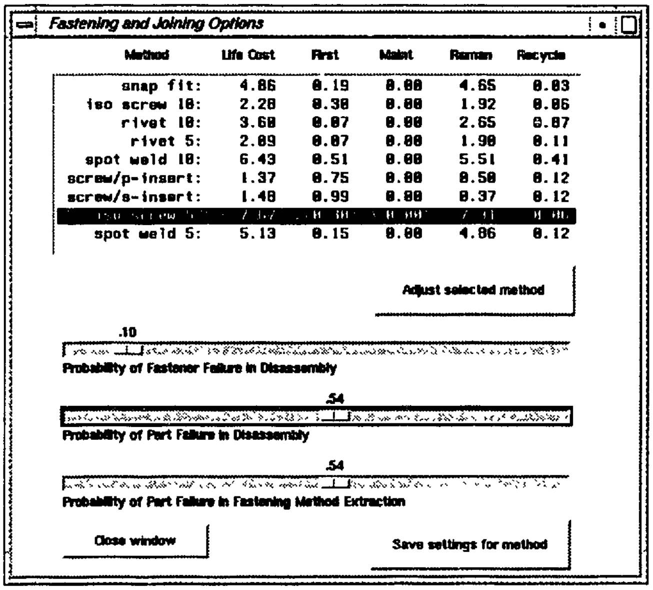
Factors such as the expected number of remanufacture cycles, number of maintenance cycles and labor rates can be varied in the input interface to observe the effects on cost. Similarly, probabilities of failure due to disassembly and reassembly associated with each method can be varied using sliders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



Production Volume 200000
Total Product Life 5
Maintenance Cycles 0
Remanufacture Cycles 1
Production Unskilled Labor 25
Production Skilled Labor 50
Field Labor Rate 75
Part 1 material Polystyrene
Part 2 material ABS
Part 1 cost 4
Part 2 cost 5
Perimeter 15.2
Width 2.1
Thickness 1.3
Min points of attach 2
Maximum Axial Force 20

Fig. 2.4a. Computer tool input interface

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



Method	Life Cost	First	Maint	Reman	Recycle
snap fit:	4.06	0.19	0.00	4.65	0.03
iso screw 10:	2.28	0.30	0.00	1.92	0.06
rivet 10:	3.60	0.07	0.00	2.65	0.07
rivet 5:	2.09	0.07	0.00	1.90	0.11
spot weld 10:	6.43	0.51	0.00	5.51	0.41
screw/p-insert:	1.37	0.75	0.00	0.50	0.12
screw/s-insert:	1.48	0.99	0.00	0.37	0.12
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
spot weld 5:	5.13	0.15	0.00	4.86	0.12

.10
Probability of Fastener Failure in Disassembly

.54
Probability of Part Failure in Disassembly

.54
Probability of Part Failure in Fastening Method Extraction

Fig. 2.4b. Computer tool output interface

2.3.2. 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 expenses associated with joint disassembly and reassembly necessary for a maintenance task, and not the cost of other activities associated with the maintenance task.

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 several fastening and joining methods tabulated by Whyland (1993). For maintenance and remanufacture, the assumption is that the joint must be disassembled to enable further maintenance and remanufacture tasks.

2.3.2.1. *First Cost*

The first cost consists of the manufacture and first assembly cost as determined by the fastening or joining method. The part manufacture cost is modeled as consisting of a basic part manufacturing cost that remains constant for different connecting methods, and an additional manufacturing cost to modify the 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.

2.3.2.2. 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 material reprocessing costs for neither the fastened parts nor the parts introduced by the fastening method are included. The fastening method is assumed to not affect the reprocessing expense of the parts if incompatible materials, including those introduced by the fastening method, can be separated.

2.3.2.3. 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 categorized 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 with 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 disassembly tool bit damages the head of a screw, 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.

2.3.2.4. *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.

2.3.2.5. *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 elements 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:

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

The remanufacture cost imposed by a riveted joint, for instance, 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, assembly and the consequential cost of part and fastener failure.

That is, for $P_f = 1$ and $P_{pe} = 1$, the general remanufacture cost reduces to:

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

2.3.2.6. Preliminary 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. 2.4b. Using the sliders on the interface, the designer can select each method and adjust the values closer to known or expected values for the particular application. The cost for that method will be recalculated based on the new values. The sliders greatly simplify the continuous variation of unknown values of failure probabilities, so that critical factors can be identified and appropriate data may be collected.

2.4. 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.

2.4.1. Thread-Forming Screws in Paper Guide

Table 2.1 compares the estimated costs of using screws without inserts and screws with inserts, normalized by 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 2.1. Normalized estimated costs for paper guide attachment

Fastening Method	Life cost with 1 remanufacture	Life cost with 2 remanufactures	First cost	Remanufacture cost	Separation for recycling cost
screws	15.87	29.52	1.81	**13.65**	0.41
screws & insert	6.87	8.87	4.05	**2.00**	0.82

Table 2.1 shows that the use of inserts increases both first and recycling cost but significantly decreases life cost if the part will be remanufactured.

2.4.2. Welded Toner-Cartridge Cover

Table 2.2 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 2.2. Estimated costs for toner-cartridge cover attachment

Fastening Method	Life cost with 1 remanufacture	Life cost with 2 remanufactures	First cost	Remanufacture cost	Separation for recycling cost
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 2.2 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.

2.4.3. Snap-Fit Toner-Cartridge Housing

Tables 2.3 and 2.4 compare the estimated costs of using two snap fits with using four screws to fasten the toner-cartridge housing. In Table 2.3, the rate of damage that results in part replacement using snap fits is estimated at 3% per snap. 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 2.3. Estimated costs for toner-cartridge housing fastening

Fastening Method	Life cost with 1 remanufacture	First cost	Remanufacture cost	Separation for recycling cost
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 2.4 shows the results of increasing the estimated failure rate of the method to 50% for both the snap fits and the screws. The failure of the snaps results in part replacement, and the stripping of the internal screw threads results in replacement by a coarser-thread screw. Comparison between Tables 2.3 and 2.4 reveals the relative sensitivities of the life cost to fastening method failure for both methods.

Table 2.4. Estimated costs for toner-cartridge housing fastening

Fastening Method	Life cost with 1 remanufacture	First cost	Remanufacture cost	Separation for recycling cost
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.

2.5. 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. In the next chapter, a reliability model is developed to better describe failure probabilities.

Chapter 3. Reliability Modeling for Remanufacture

Since the essential goal of remanufacture is part reuse, the reliability of components is of primary importance. This chapter considers the effect of reliability on life-cycle costs. Existing reliability models are unsuitable for describing systems that undergo repairs performed during remanufacture. The goal of the work in this chapter is to develop and verify reliability models to be used in life-cycle cost estimations of systems where reuse of working components is possible. This model is used in a genetic-algorithm based optimization of life-cycle cost estimations. The implementation of this optimization, described in the next chapter, helps explore initial part design and remanufacture alternatives in the context of other life-cycle concerns.

3.1. Chapter Overview

This chapter begins by highlighting related work in the fields of both life-cycle design and reliability. Selected reliability models with features closest to those desired are detailed before introducing the motivation for distinct characteristics incorporated into the model developed here. This chapter illustrates properties of this model and how it can be applied to compare design alternatives for mechanical series systems. This model currently describes series systems whose components have Weibull-distributed densities of time to failure. Therefore Weibull-related terminology and notation are first defined. The model simulates the replacement of failed parts with components of either the same or a different type. Replacement parts can be either new or remanufactured. Parts of the same type are those that have identical failure characteristics to the original part. The simulation results of replacement with the same type of parts were experimentally verified. Replacement of failed parts by components of a different type often more accurately portrays remanufacture, where the replacement part has different failure properties from those of the original part. The modification can be subtle, due to different sources for replacement parts, or drastic, due to reconfiguration of the system for upgrades or correction of known reliability problems. The interaction of multiple parts in a system is described using series-system reliability theory. An example applies the model to compare the life-cycle costs of various combinations of mechanical elements, and illustrates additional considerations for application to mechanical systems.

3.2. Related Work in Reliability

Researchers have considered the roles of failure and serviceability in life-cycle design. Gershenson and Ishii (1991) implemented Service Mode Analysis, which focuses on repair possibilities of system malfunctions, in a computer tool that calculates serviceability indices of user-defined failure phenomena. DiMarco et al. (1995) integrated Failure Modes and Effects Analysis into a computer tool to bring consideration of service costs early in the design process.

Ascher and Feingold (1984) surveyed the considerable body of reliability literature on repairable systems and observed that much of this work models one of two extremes. The first extreme represents the repair process as returning a system to a same-as-new condition. The other extreme, known as "minimal repair," "same-as-old," or the nonhomogeneous Poisson process, describes the system age and reliability after repair as identical to that before failure. This model is rationalized by repairs that involve the replacement of a small fraction of a system's total parts. For this model to be exact, the replacement part must have the same distribution of time to failure as the original part, and the same age if the failure rate is age dependent.

Moderation of the above two extremes include the following. Brown and Proschan (1980) model imperfect repair, where at each repair, renewal to the same-as-new state occurs with probability P and no age reduction or same-as-old occurs with probability $1-P$. Nakagawa (1980) models partial renewal of a system at maintenance times, where the effective unit age is reduced to a proportion of the actual age. De la Mare (1979) fit Weibull distributions to data for successive times between failures for many types of systems. He used the estimated means in a cost model to optimize system life-cycle costs. Cozzolino (1968) developed two models, the n-component device model and the time accumulation model. The n-component device model tracks the ages of a system's constituent parts, and each part can have different distributions of time to failure. The time accumulation model, developed to reduce the complexity of the n-component device model, assumes that the n constituent parts are identical.

Cozzolino's n-component device and time accumulation models have some desirable properties which will underlie the unique features of the model developed here. The Cozzolino models assume neither complete system renewal to the same-as-new condition nor minimal repair to the same-as-before-failure state, a trait retained here.

The n-component device model describes a system composed of n parts in series, such that failure of any one part results in system failure. Each part's failure characteristics are independent of other parts' failure processes. Time to first system failure is the minimum of the components' times to first failure. The device ages by accumulating time on its constituent parts, and the vector of component ages determines the density of future time to failure. Failure of one part is repaired by replacement with a part of the same type. Since only the age of the replaced part is reset to zero while the other components retain their age, the system failure rate never returns to its initial value. The time accumulation model produces behavior similar to the n-component device model in a less structured manner by assuming n identical parts, so that the identity of the repaired part need not be tracked. At each failure, $1/n^{th}$ of the system accumulated age is lost.

3.3. Characteristics of Model

The model developed here describes a population of n-component series systems. The n parts have independent and different distributions of time to failure. The population of n-component systems is represented as a collection of n populations of constituent parts (Fig. 3.1), and parts are treated as members of their respective populations. Populations of "single-component systems" are used to introduce this model.

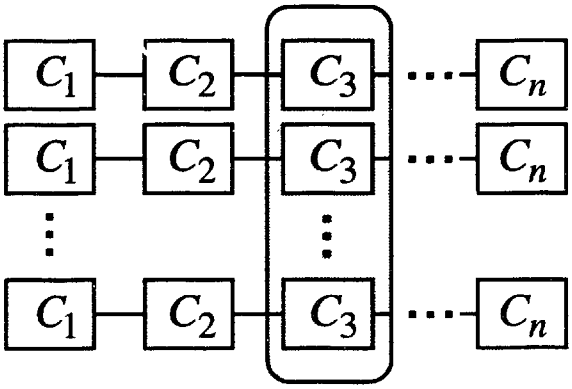


Fig. 3.1. Model of population of n-component systems

The age distributions of each of the part populations are tracked to determine the reliability of the composite system population. Time-to-failure and age distributions associated with each part population are used to calculate the probability of failure of that part at any given time. Failure of a part has different consequences. First, the failed part can be replaced with a part of the same type while retaining the working parts of the system. Second, the failed part can be replaced by a part of a different type, while the rest of the system either remains unchanged or is reconfigured to accommodate the replacement part. Finally, a failed part can cause replacement of the entire system with either an identical or a different system.

The possibility of system modification is not included in many models, including those of Cozzolino, in which replacement is limited to a component of the same type. This additional capability is motivated by common practices in remanufacture. For example, bearings are often replaced with higher-durability bearings during remanufacture. Many refurbishment processes change the reliability characteristics by altering the system configuration. For example, bronze bushings are installed in distributor housings that wore due to the lack of separate bearings in the original design.

In this model, the repair policy determines actions executed upon component failure. In practice, corporate refurbishment policy significantly affects both the system reliability and the consequent remanufacture cost of a given original design. Some companies may choose to always replace a particular component without inspection, either due to product reconfiguration or past reliability problems, while others will replace based on either actual part failure or projected remaining life.

This model describes series systems where the density of time to failure of each component is represented by the two-parameter Weibull distribution. The extension of this model to use other distributions is fairly straightforward. The Weibull distribution was selected because it is appropriate for many engineering applications. Special cases of the Weibull distribution include the exponential and Rayleigh distributions.

3.4. Weibull Distribution Notation

The Weibull probability density function is:

$$f(x)=\frac{\alpha x^{\alpha-1}}{\beta^{\alpha}}\exp[-(\frac{x}{\beta})^{\alpha}] \qquad 0\le x\le\infty \qquad (3.1)$$

where x is a random variable that can represent time. Fig. 3.2 plots Weibull distributions with β=10 and values of α from 1 to 5. α is the shape parameter; a larger α reduces spread about the expected value. β is the scale parameter; as α increases, the peak of the distribution approaches β. A part with a Weibull-distributed density of time to failure has an expected lifetime of approximately β. α indicates the certainty of the expected value. α=1 yields the negative exponential distribution, and α=2, the Rayleigh distribution. The effects of α and β on the model output will appear throughout the chapter.

The value of f(x) is the probability that a part fails between x and x+dx. F(x), the integral of f(x) from 0 to x, is the probability that a part fails at any time up to x, and 1-F(x) is the probability that the part will survive past x.

$$F(x)=\int_{0}^{x} f(x)dx \qquad (3.2)$$

Fig. 3.3 plots F(x) curves corresponding to the distributions of Fig. 3.2. Note that β locates the intersection of the family of integrals.

Another quantity often used in reliability is the failure

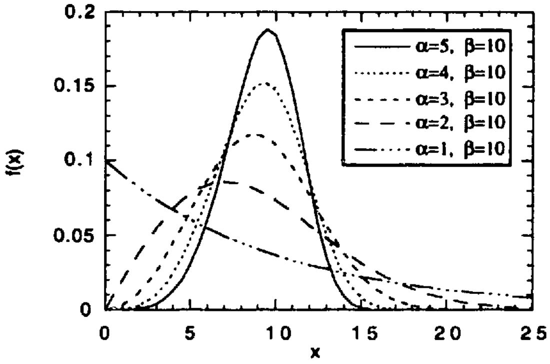


Fig. 3.2. Weibull probability distributions

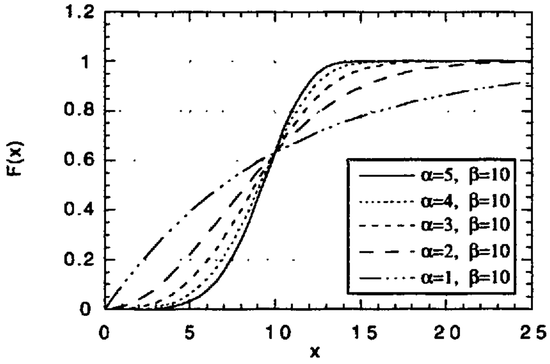


Fig. 3.3. Weibull probability of failure

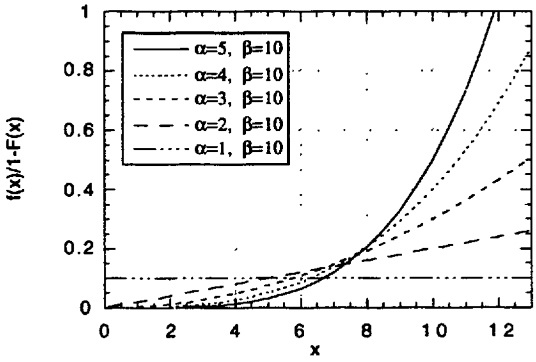


Fig. 3.4. Weibull failure rate

rate function which is represented by:

$$\lambda(x) = \frac{f(x)}{1 - F(x)} \qquad (3.3)$$

The failure rate is the conditional probability of failure at x given survival to x. Note that the failure rate becomes greater than 1, and that the failure rate function is not a density function. The failure rate at x is the height of the failure density function at x divided by the area under that function from x to infinity. Fig. 3.4 plots failure rates corresponding to the distributions of Fig. 3.2. The negative exponential distribution (α=1) yields a constant failure rate, and the Rayleigh distribution (α=2) yields a linearly increasingly failure rate. For Weibull densities, the failure rate increases with x to the power of (α-1).

3.5. Simulation

The time-to-failure density function of each part in a system is used to calculate the life-cycle cost for a population of systems. An age distribution is obtained at each time step for each part population. The age distribution determines failure rates for the following time step. The failure rates of each part determine the replacement-part cost portion of the system life-cycle cost. Failed parts can be replaced with parts of either the same or different type. First presented will be the simulation of replacing failed parts by the same type of parts. The model behavior for this basic simulation is experimentally verified. Next presented is the simulation of replacing failed parts with components of a different type. These sections examine the behavior of the model for a single part population. The following section will describe how the interactions between multiple parts of a system are treated.

3.5.1. Description of Basic Simulation

Age bins are used to track the age distribution of a population of parts. The time-to-failure density determines the portion of the contents of each bin that survive to the next time step, appearing as contents for the next older bin, and the portion that fails, appearing as contents in the zero-age bin. Figs. 3.6a through 3.6f track the age bin distributions for six consecutive time steps for a population of parts whose time-to-failure density and corresponding probability of failure are plotted in Fig. 3.5. Age bins are created at increments equal to the time between events, e.g., number of years between remanufacture activities. Time between events, or bin size, of 1 was used to produce the results shown in Figs. 3.6a through 3.6f.

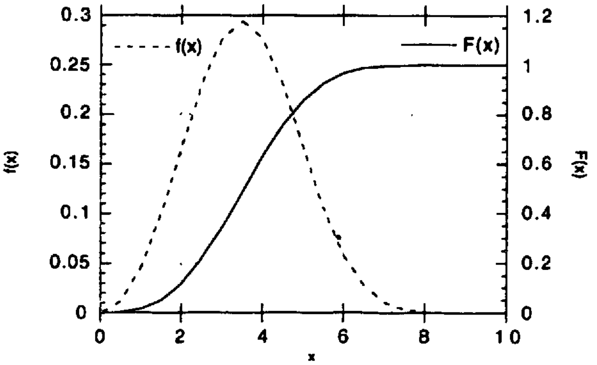


Fig. 3.5. Time to failure and probability of failure for Weibull parameters α=3, β=4.

Initially, all parts are in the first bin as shown in Fig. 3.6a: the population consists only of new parts. That is, at $t_0 = 0$, $q_0(t_0) = 1$, where q_i is the fraction of parts in the i^{th} bin.

At the next time step, the failure density is integrated using numerical methods developed by Senin et al. (1996) from zero to one time increment to find the probability of failure. The portion of the population that survives advances to the next age bin, and the portion that fails is replaced and reappears as items in the first age bin, as shown in Fig. 3.6b. That is, at $t_1 = \Delta t$, the fractions of the first two bins become:

$$q_1(t_1) = q_0(t_0)[1 - \int_0^{\Delta t} f(x)dx]$$
$$q_0(t_1) = q_0(t_0)[\int_0^{\Delta t} f(x)dx] \qquad (3.4)$$

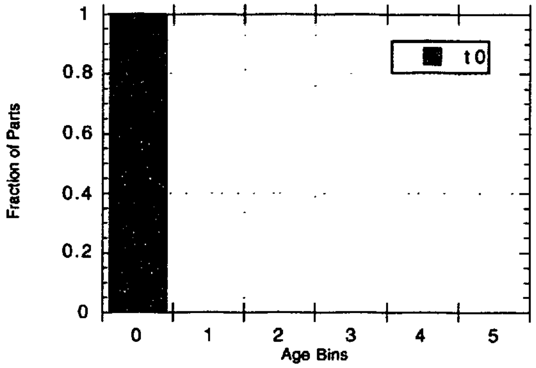


Fig. 3.6a. Bin distribution at t_0=0

Again, portions of both age bins survive and advance to the next age bin, and portions of failed parts from both bins appear as replaced parts in the first bin.

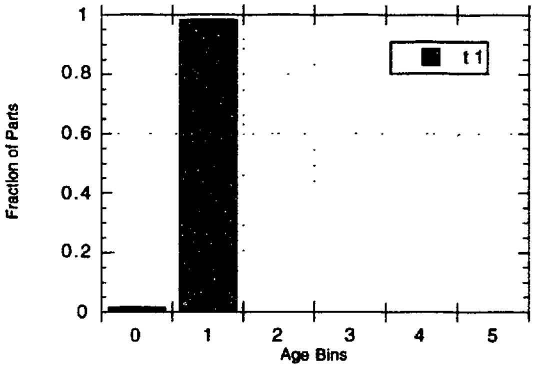


Fig. 3.6b. Bin Distribution at t_1=Δt

The proportions of each bin for $t_2 = 2\Delta t$, the next time step, are calculated as follows.

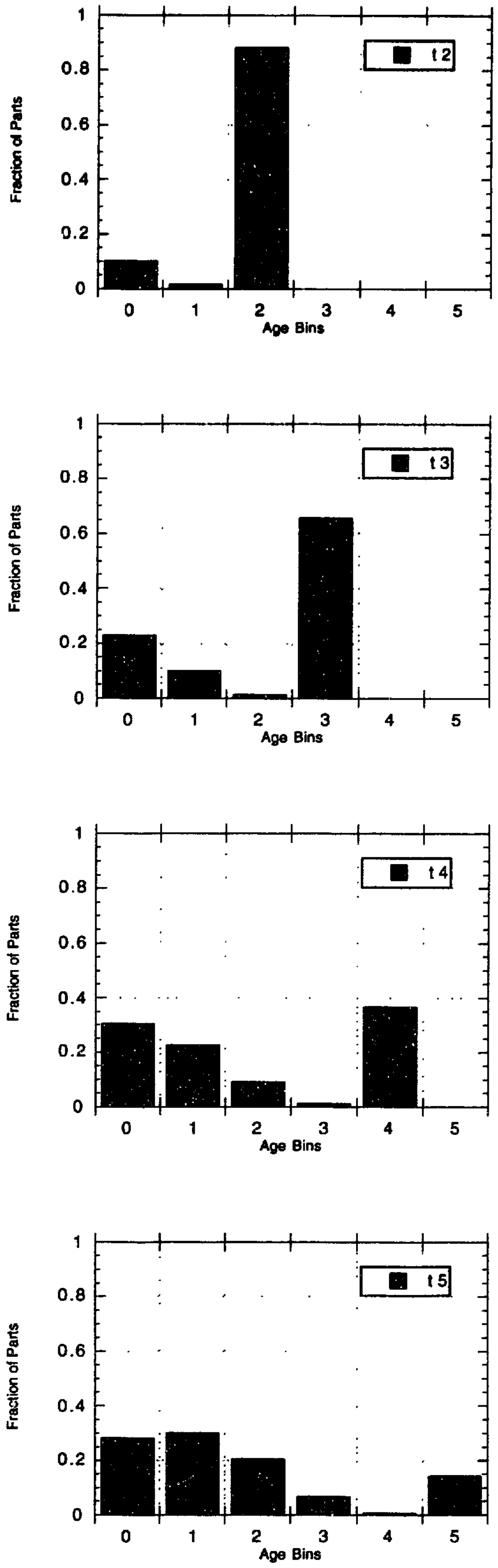
$$
\begin{aligned}
q_2(t_2) &= q_0(t_0)[1-\int_0^{2\Delta t} f(x)dx] \\
q_1(t_2) &= q_0(t_1)[1-\int_0^{\Delta t} f(x)dx] \\
q_0(t_2) &= q_0(t_0)[\int_{\Delta t}^{2\Delta t} f(x)dx] + q_0(t_1)[\int_0^{\Delta t} f(x)dx]
\end{aligned}
\tag{3.5}
$$

Finally, at $t_n = n\Delta t$, the fractions of parts in each bin are:

$$
\begin{aligned}
q_n(t_n) &= q_0(t_0)[1-\int_0^{n\Delta t} f(x)dx] \\
q_{n-1}(t_n) &= q_0(t_1)[1-\int_0^{(n-1)\Delta t} f(x)dx] \\
&\ldots \\
q_2(t_n) &= q_0(t_{n-2})[1-\int_0^{2\Delta t} f(x)dx] \\
q_1(t_n) &= q_0(t_{n-1})[1-\int_0^{\Delta t} f(x)dx] \\
q_0(t_n) &= q_0(t_0)[\int_{(n-1)\Delta t}^{n\Delta t} f(x)dx] + q_0(t_1)[\int_{(n-2)\Delta t}^{(n-1)\Delta t} f(x)dx] + \\
&\ldots + q_0(t_{n-2})[\int_{\Delta t}^{2\Delta t} f(x)dx] + q_0(t_{n-1})[\int_0^{\Delta t} f(x)dx]
\end{aligned}
\tag{3.6}
$$

For the preceding simulation, much of the initial population advances to the next age bin for the first two time steps. At time t3, over 60 percent of the parts put into service at time t0 are still in service. By time t4, under 40 percent of the original parts have survived, and by time t5, fewer than 15 percent of the original parts are still in service. This can be inferred from the probability of failure, F(x) of Fig. 3.5; F(x) is initially very small, but by t5, it is about 85 percent.

The average age of the population is calculated by summing over all the age bins the product of the



Figs. 3.6c-f. Bin distributions at 2Δt, 3Δt, 4Δt, 5Δt

fraction of parts in that bin and the age of the bin:

$$\bar{a}(t)=\sum_{i=0}^{n(t)} q_i(t)a_i \qquad (3.7)$$

3.5.2. Results of Basic Simulation

Fig. 3.7a plots the average age of constant-size populations of identical parts that are replaced by new components of the same type upon failure. Each curve represents a population of parts with a particular Weibull distribution of time to failure. The plots shown correspond to a constant value of β equal to 10 paired with α equal to 1,2,3,5, and 10. Both the horizontal and vertical axes have the same units of time, e.g., minutes, hours, or years.

Several characteristics of Fig. 3.7a are of interest. First, the average age eventually reaches a steady state value. This is in agreement with Drenick's Theorem (Drenick 1960), which states that the superposition of an infinite number of independent equilibrium renewal processes is a homogeneous Poisson process. A homogeneous Poisson process is one that can be represented by an exponential distribution. Recall from Fig. 3.4 that the failure rate corresponding to the exponential distribution (α=1) is constant. A population with a constant failure rate and part

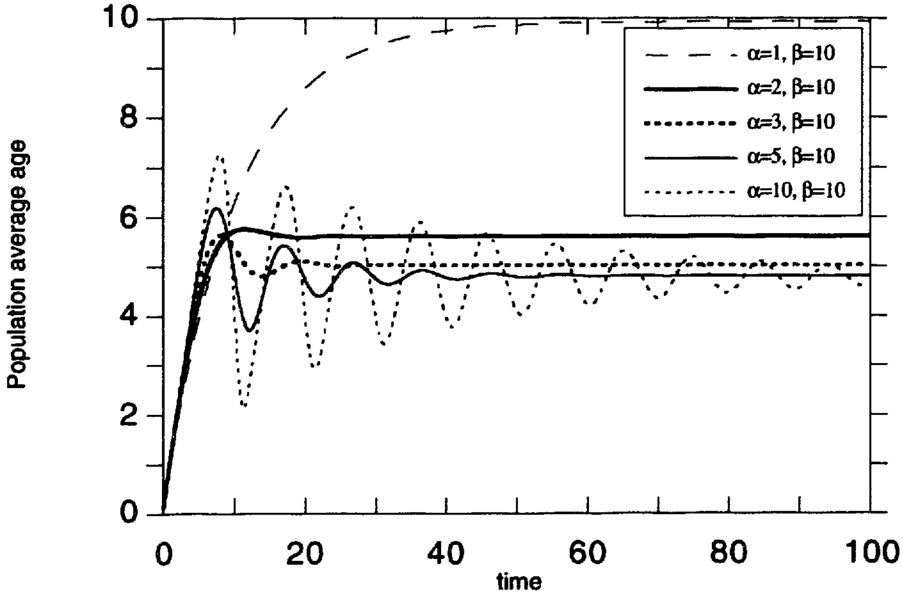


Fig. 3.7a. Population average age of basic simulation

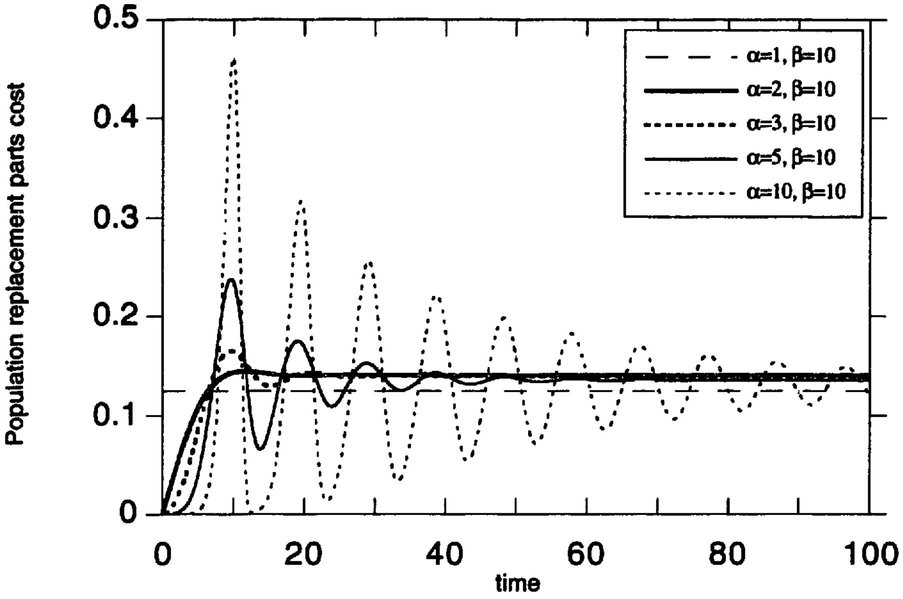


Fig. 3.7b. Population replacement parts cost of basic simulation

renewal upon failure has a constant average age. The value of the steady state age depends upon Weibull parameters α and β. The dependence on β is not surprising; higher values of β for a given set of α's yield higher values for expected time to failure and thus average age.

Alpha affects both the steady state value and the degree of oscillation. Recall from Figures 3.2 through 3.4 that as α increases, the window of time during which a majority of parts fail decreases. For high values of α, very few parts will fail until time equal to β, at which time almost all the parts will fail immediately. During the low-failure period, the average age will increase monotonically. Then as increasingly large numbers of parts fail, the replacement of a significant portion of the population causes the average age to drop until the wave of failure is over. The newly installed base of parts then ages steadily until the next failure wave. During each oscillation, a number of parts fail outside the time window during which most of the population fails. The population thus becomes more age-diversified with each cycle, and the oscillations in average age die down. The higher the value of α, the fewer parts fail outside the tighter expected failure period, and thus the greater the oscillations in average age and the longer it takes for diffusion to occur. As α increases, the mean of the average age approaches β/2. This is intuitive when one considers the upper bound as α approaches infinity. Physically, such a distribution of time to failure implies that no parts fail until time equal to β, at which time all the parts fail. Therefore this population would have a saw-toothed average age plot that does not decay and is bounded between 0 and β.

Fig. 3.7b plots the replacement parts cost corresponding to Fig. 3.7a. For ease of comparison, all parts were assigned an identical normalized cost. In reality, cost is likely to be a function of both α and β. The trends of Fig. 3.7b are consistent with those of Fig. 3.7a. The replacement-part cost increases as average age decreases since parts are being replaced at a higher rate. Steady state replacement costs are higher for lower steady state average ages.

3.6. Experimental Verification of Basic Simulation

3.6.1. Description of Experiment

To verify the basic model behavior described above, the reliability model was applied to a joint system, and a set of experiments was performed that involved obtaining data on the number of disassembly and reassembly cycles before a screw strips a hole in plastic.

For each experiment, a grid of holes was drilled in a sheet of polypropylene. Thread-forming screws were inserted and removed using a power screwdriver at a constant torque until the screw continued to spin when fully inserted. The number of rows of holes represents the number of systems in the population. When a hole fails, "part replacement" involves using the next hole in the same row. A screw removal-and-insertion cycle performed on the population constitutes a time step. The number of screw removal-and-insertion cycles until failure was recorded for each hole. This was used to obtain a distribution of number of cycles-to-failure for the sample. The number of cycles survived by each active hole averaged over the sample at each time step yields the average age plot. The data of the final holes were not used to obtain the histogram because those holes had not failed, but they were used to obtain the average age.

3.6.2. Selection of Experimental Parameters

Pilot trials were used to select a combination of material, material sheet thickness, hole size, and screw. Drywall screws were selected for their ease of alignment and insertion of both screw into hole and of screwdriver bit into screw. The sheet of material must be thick enough to allow at least 2 or 3 threads to be formed. Using drywall screws, the sheet had to be thicker than 2 to 3 threads because the threads do not start immediately under the head of the screw. For #6, fine thread drywall screws, material of 1/2 inch thickness was found suitable. Polypropylene was selected because it was readily available in 1/2 inch sheets and it was a soft enough material that would fail on average in fewer than 5 cycles using the available range of torque settings on the power screwdriver. A hole size of 7/64 inch, approximately the minor diameter of the screw, was found to be most appropriate. A 1/8 inch hole diameter was also attempted, but hole failure usually occurred on either the first or second insertion of the screw regardless of torque level. Each experiment used a population size of 25 systems.

It was also discovered that the threads of drywall screws lost their sharpness with continued use. The screws started pushing the soft polypropylene material aside, instead of cutting threads, and thus would not strip for extraordinarily high number of disassembly and reassembly cycles. It was then decided that new screws were to be used with each new hole.

3.6.3. Data Presentation and Discussion

The data for four experiments are arranged as follows. Two figures are plotted for each experiment. The first figure compares the sample histogram of cycles-to-failure with the Weibull distribution with the least squared error. The error is the difference between the probability density function value and the proportion of the sample that failed at each number of cycles. The second figure compares the average age obtained experimentally with that obtained through simulation using the least-squared-error Weibull distribution of the first figure. Next, the data of two experiments are combined such that the size of the combined population is 50 systems. Both plots are determined similarly for the combined population as they are for the individual populations.

3.6.3.1. Experiment 1

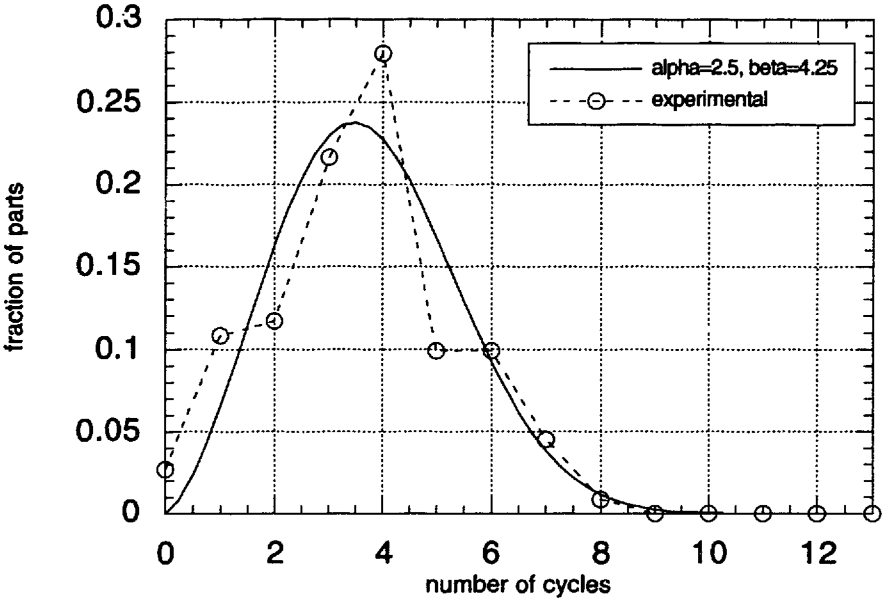


Fig. 3.8a. Comparison of sample cycles-to-failure histogram and closest Weibull distribution (1)

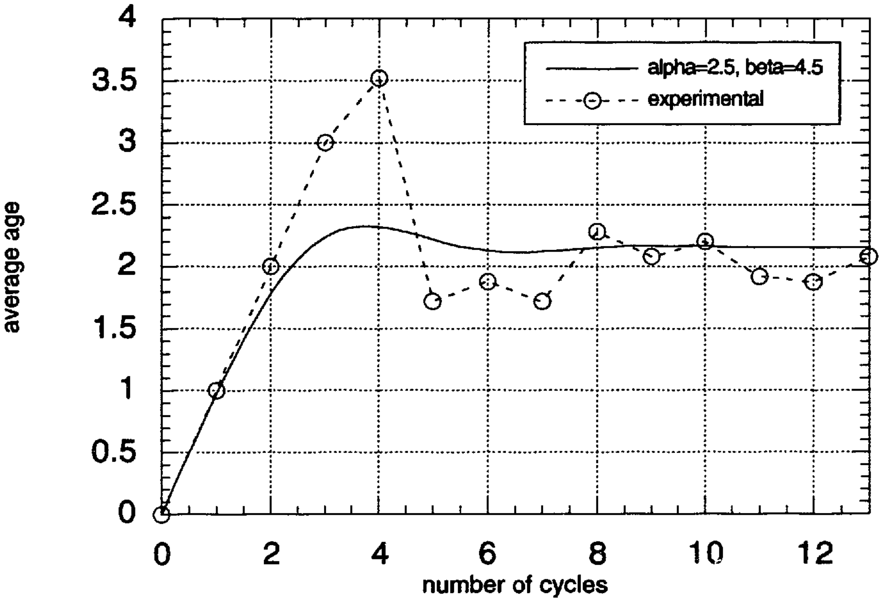


Fig. 3.8b. Average age determined experimentally vs. through simulation (1)

3.6.3.2. Experiment 2

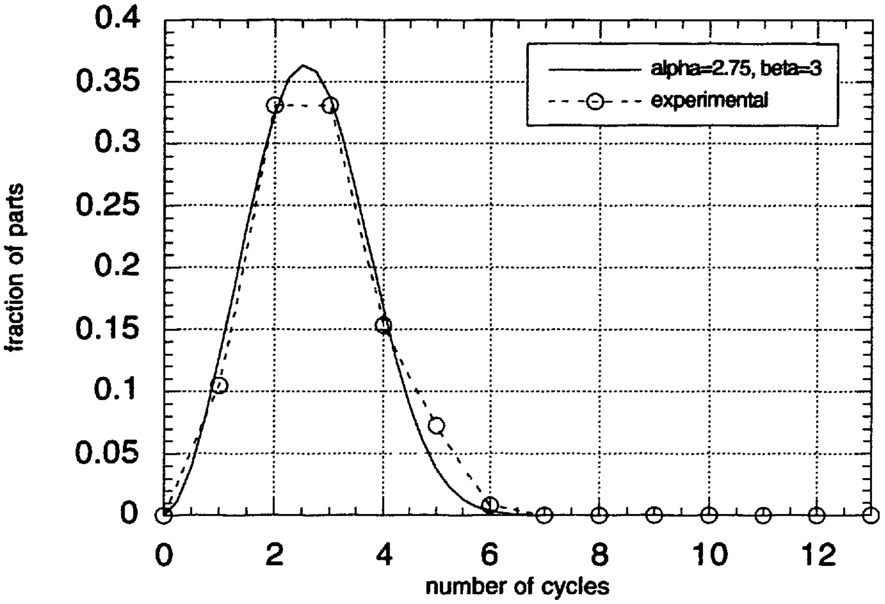


Fig. 3.9a. Comparison of sample cycles-to-failure histogram and closest Weibull distribution (2)

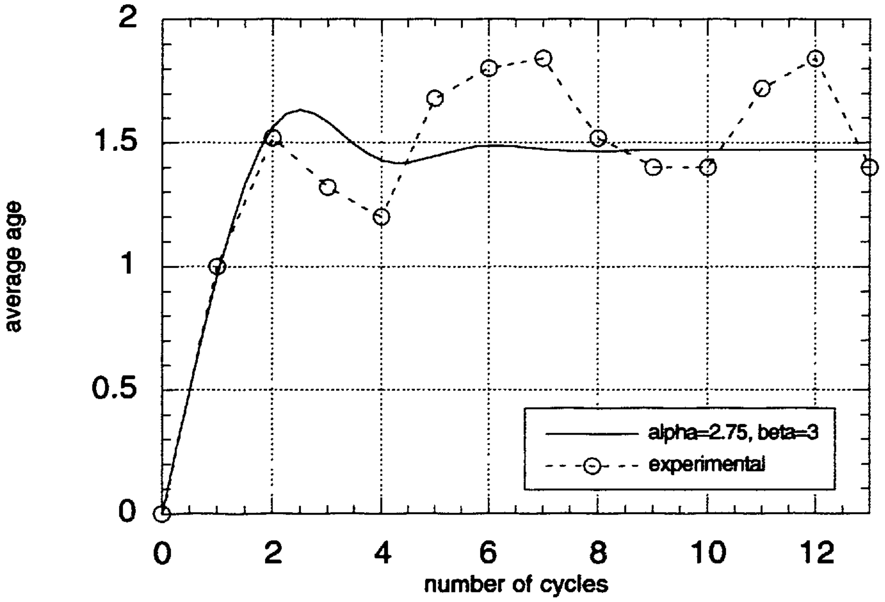


Fig. 3.9b. Average age determined experimentally vs. through simulation (2)

3.6.3.3. Experiments 1 and 2 Combined

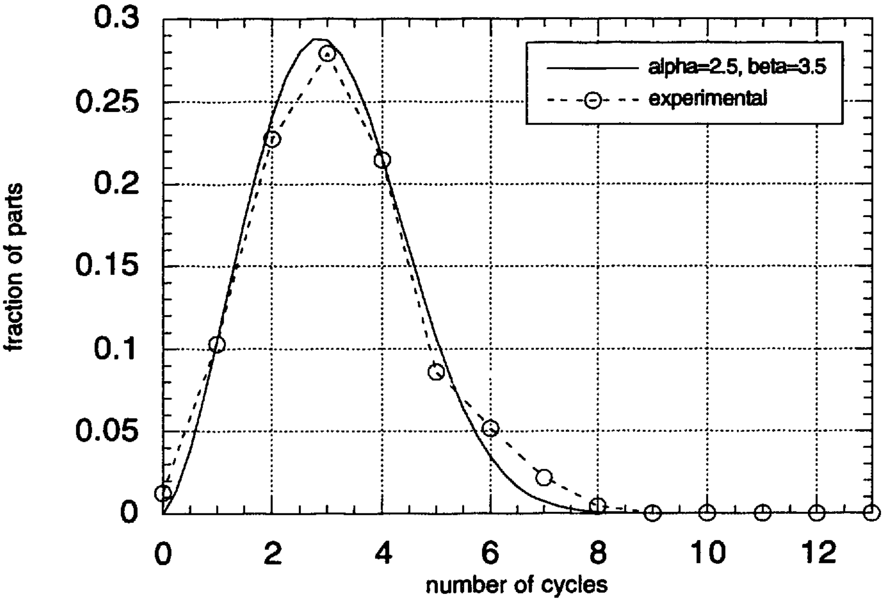


Fig. 3.10a. Comparison of sample cycles-to-failure histogram and closest Weibull distribution (1 & 2)

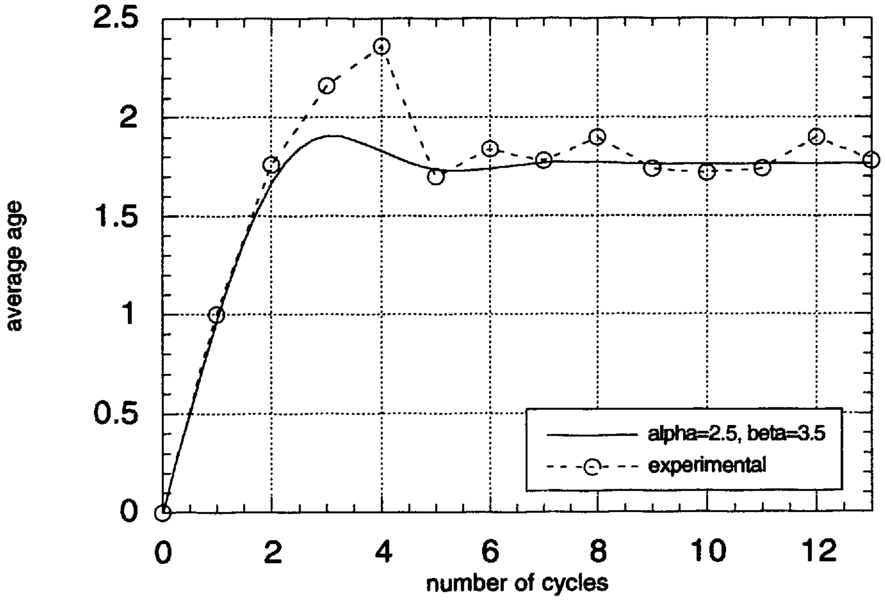


Fig. 3.10b. Average age determined experimentally vs. through simulation (1 & 2)

The previous three sets of figures show that the combined population size of 50 systems yielded a cycles-to-failure distribution that is closer to a continuous Weibull distribution and an average age that is closer to the simulated average age than for the individual experiments. This implies that deviations in the current data from the model behavior are due to the small sample size.

Combining data from multiple experiments is valid when the distribution is recalculated for the new sample, and the simulation with which the experimental average age is compared was generated using the distribution closest to the combined sample. The average age behavior depends solely on the distribution, which must however represent the population at each time step. For example, the combined distribution cannot be used to represent a population that starts out with one distribution and ends with another distribution.

Any set of the experiments could have been combined, but those that yielded similarly shaped cycles-to-failure distributions were, because the combined distribution was more likely to be one that can be described by a Weibull distribution, as opposed to a multimodal distribution.

In experiments 3 and 4, a higher torque setting was used to obtain a different cycles-to-failure distribution. In the data for experiment 3, the original data contained several holes for which the number of cycles-to-failure was exceptionally high. The cycles-to-failure distribution shows that the experimental values for a few of the higher cycles are greater than the values corresponding to the Weibull distribution with the overall least-squared error. Furthermore, there were holes that had exceeded the number of cycles shown, but had not yet failed, so they were not even reflected in the cycles-to-failure distribution. These higher-cycle outliers have a particularly strong influence on increasing the average age of a population of size 25 when they are active, and causes a particularly large drop in the average age when they finally do fail. The removal of 5 rows with the outliers also removes some well-behaved data points. The results of removing these rows on both the average age and the cycles-to-failure distribution are also plotted.

The combination of experiments 3 and 4 used the complete, original data from the two experiments and shows that the increased population size is much less sensitive to the outliers of experiment 3.

3.6.3.4. Experiment 3

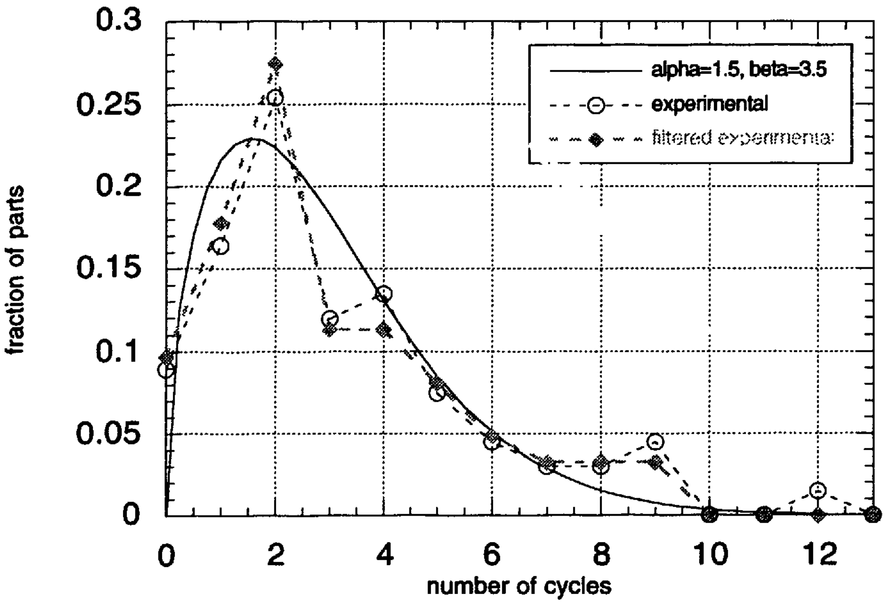


Fig. 3.11a. Comparison of sample cycles-to-failure histogram and closest Weibull distribution (3)

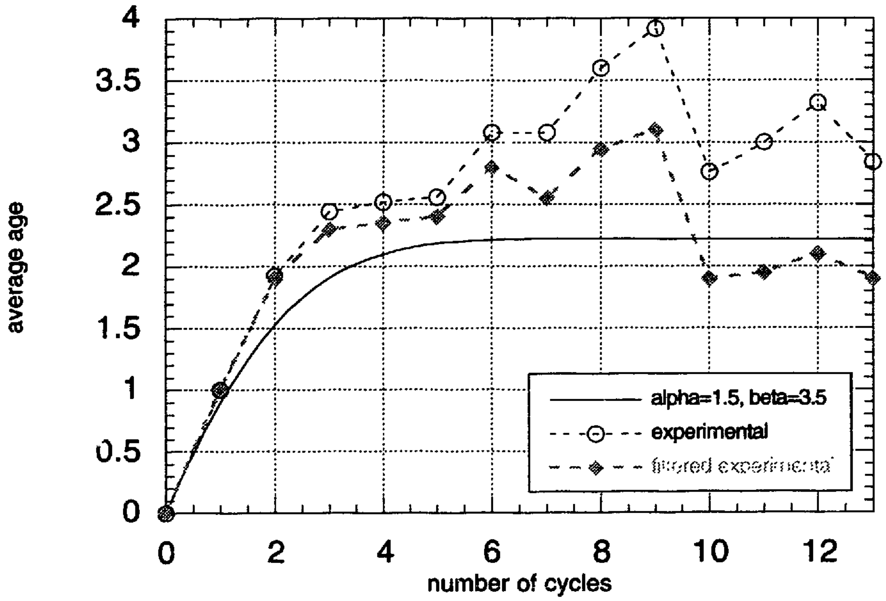


Fig. 3.11b. Average age determined experimentally vs. through simulation (3)

3.6.3.5. Experiment 4

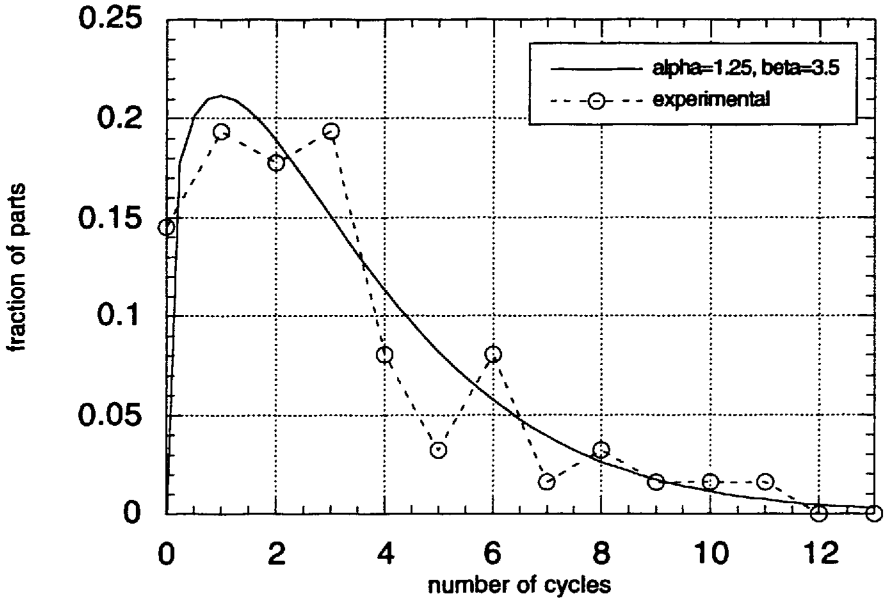


Fig. 3.12a. Comparison of sample cycles-to-failure histogram and closest Weibull distribution (4)

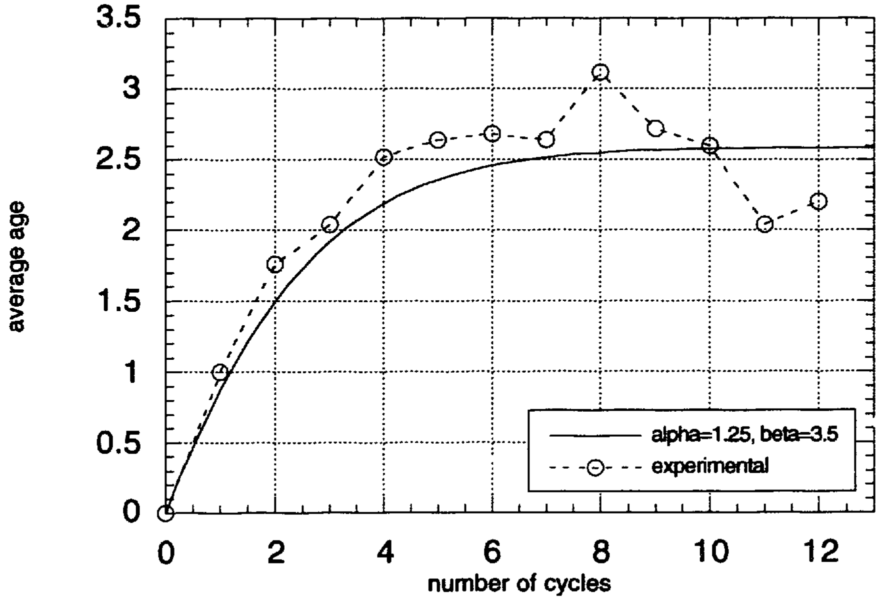


Fig. 3.12b. Average age determined experimentally vs. through simulation (4)

3.6.3.6. Experiments 3 and 4 Combined

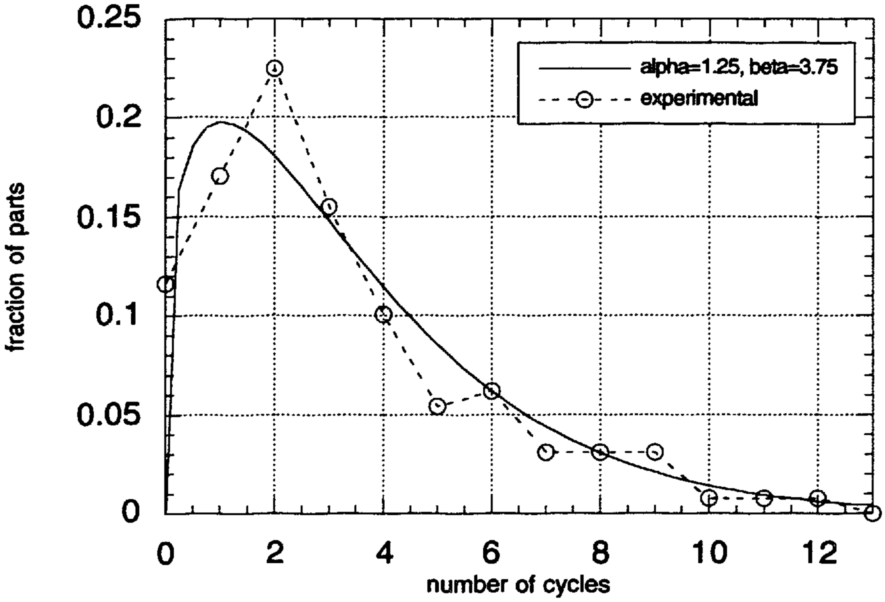


Fig. 3.13a. Comparison of sample cycles-to-failure histogram and closest Weibull distribution (3 & 4)

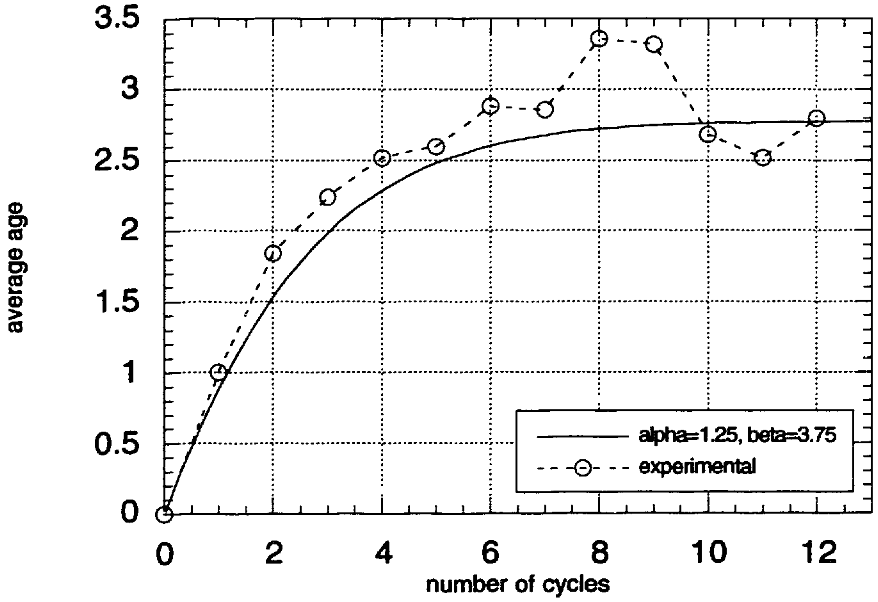


Fig. 3.13b. Average age determined experimentally vs. through simulation (3 & 4)

3.7. Simulation of System Modification

The preceding simulation results and experimental verification were for the replacement of failed parts with parts of the same type. As explained earlier, repairs during remanufacture often change the reliability characteristics of a system by replacing failed parts with components of a different type. The remaining parts of the system can either stay the same or be reconfigured to accommodate the replacement component. Similar experimental verification of this behavior could involve using, in the first hole of each row, screws with thread densities different from the screws used in the remaining holes of each row. The different thread density will result in a different distribution of disassembly and reassembly cycles-to-failure for identical holes. In the remanufacture of toner cartridges, when a plastic boss is stripped, a larger or coarser-thread screw is often used in place of the original screw.

The simulation results for the replacement of failed parts with a different type of components follow. Subsequent failure of replacement components results in replacement by the same type of components, i.e., parts of the original type are not reintroduced into the population.

Figures 3.14a and 3.14b chart the replacement of an initial population of parts with Weibull parameters $\alpha=3$, $\beta=10$, hereon denoted (3,10), with components of Weibull parameters $\alpha=10$, $\beta=10$ denoted (10,10). Subsequent replacements of failed (10,10) components are with the same (10,10) components. For reference, replacement of an initial population of (3,10) parts by the same (3,10) parts and replacement of an initial population of (10,10) parts by the same (10,10) parts are also plotted. Of interest in the average age and part-replacement cost plots (Figs. 3.14a and 3.14b) are the phase shift and reduced oscillation of the (3,10)-to-(10,10) curve relative to the (10,10)-to-(10,10) curve. An original population of (3,10) parts fail earlier and with more spread between time of failures than an original population of (10,10) components. Therefore the first replacement batch of (10,10) parts appear earlier and more staggered over time than the first replacement batch for the population that began with (10,10) components. The effect of this initial difference carries over to subsequent oscillations.

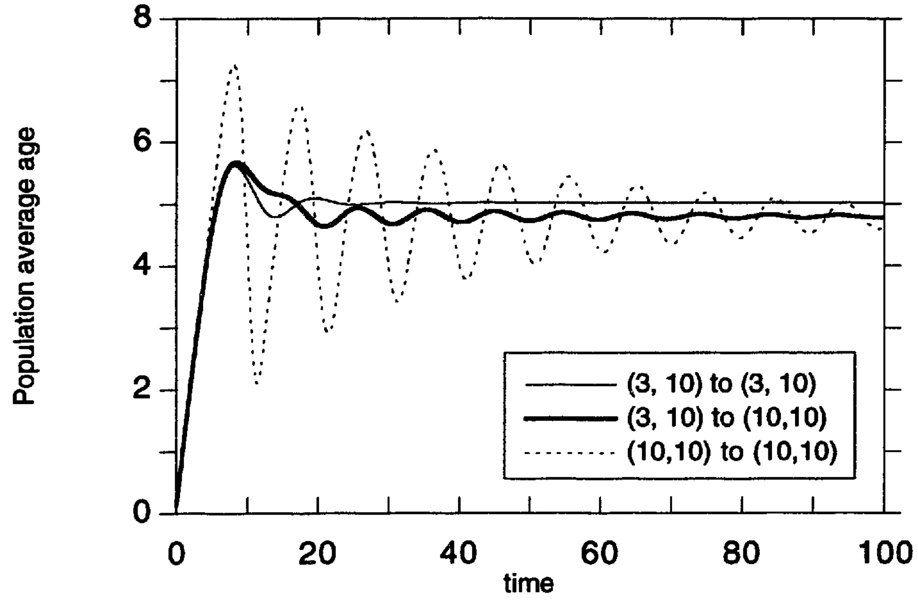


Fig. 3.14a. Population average age of system modification

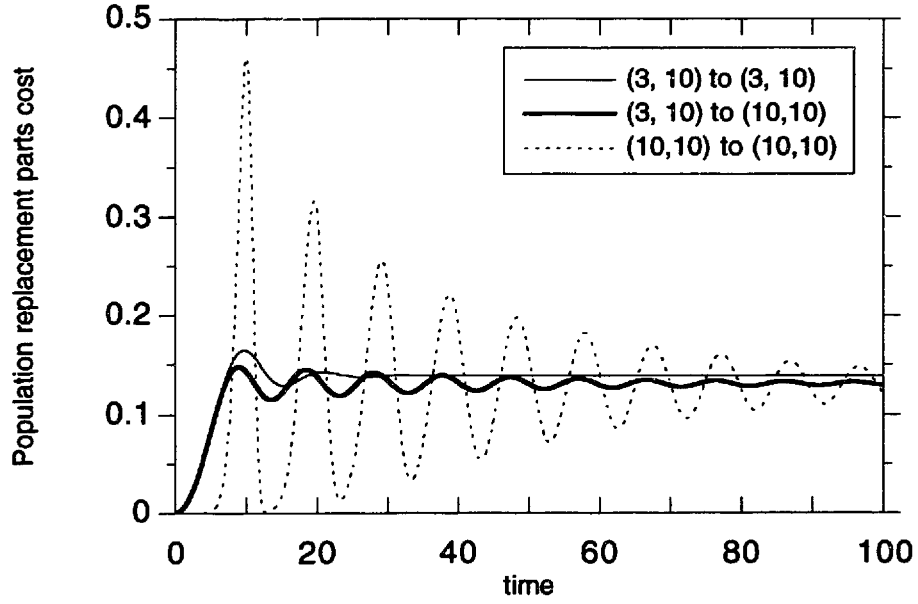


Fig. 3.14b. Population replacement parts cost of system modification

3.8. Series System Behavior

The previous sections described the model behavior for single populations of parts. This section illustrates how the system reliability is obtained from the reliability of the constituent parts in series. In a series system, the failure of any one of the constituent parts results in system failure.

For series systems, the failure rate of the system is the sum of the failure rates of the components:

$$\lambda_{sys}(x) = \sum_{i=1}^{N} \lambda_i(x) \qquad (3.8)$$

The reliability of a series system is the product of the reliability of the components:

$$R_{sys}(x) = 1 - F_{sys}(x) = \prod_{i=1}^{N} 1 - F_i(x) \qquad (3.9)$$

From (3.4), the failure density of a series system whose parts have Weibull failure densities is:

$$\begin{aligned} f_{sys}(x) &= \lambda_{sys}(x) R_{sys}(x) = \sum_{i=1}^{N} \frac{\alpha_i x^{\alpha_i - 1}}{\beta_i^{\alpha_i}} \prod_{i=1}^{N} e^{-(\frac{x}{\beta_i})^{\alpha_i}} \\ f_{sys}(x) &= \sum_{i=1}^{N} \frac{\alpha_i x^{\alpha_i - 1}}{\beta_i^{\alpha_i}} (e^{-\sum_{i=1}^{N} (\frac{x}{\beta_i})^{\alpha_i}}) \end{aligned} \qquad (3.10)$$

For example, consider a system composed of two components in series, each with a density of time to failure that is described by a Weibull distribution with parameters, $\alpha=3$, $\beta=10$:

$$f_1(x) = f_2(x) = \frac{3x^2}{10^3} \exp\left[-(\frac{x}{10})^3\right] \qquad (3.11)$$

The density of time to failure for this system is:

$$f_{sys}(x) = 2(\frac{3x^2}{10^3}) \exp\left[-2(\frac{x}{10})^3\right] \qquad (3.12)$$

The probability of system failure can be obtained by integrating (3.12). For a two-component system, the probability of failure can also be computed by:

$$F_{sys}(x) = F_1(x) + F_2(x) - F_1(x) F_2(x) \qquad (3.13)$$

where the probabilities of part failure are obtained by integration of the corresponding part-failure density functions.

System failure can result in either partial or complete replacement of the system. Figs. 3.15a and 3.15b compare the average age and replacement-part cost for replacement of only the failed part versus system replacement. As expected, the average system age is higher if only the failed part is replaced, and the replacement cost is lower if only the failed part is replaced. Components of a system are sometimes arranged or joined in a manner that requires the replacement of more than one part upon the failure of a single part. Also, part consolidation often results in single components containing multiple features, the failure of any one of which would require part replacement. The cost curves of Fig. 3.15b suggest the advantages of making failure-prone features separable, so that failure of a small portion of a component does not require the replacement of a largely unaffected and possibly expensive part.

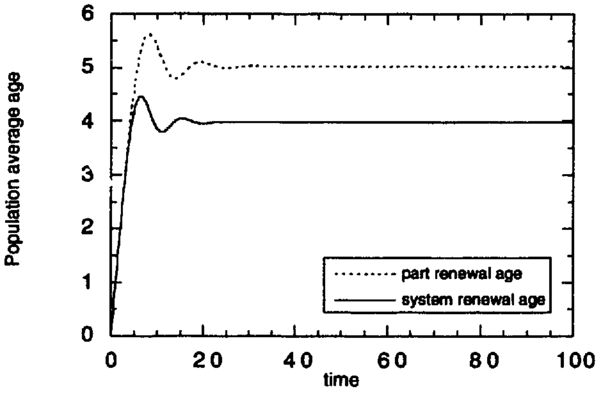


Fig. 3.15a. Average age: part vs. system renewal

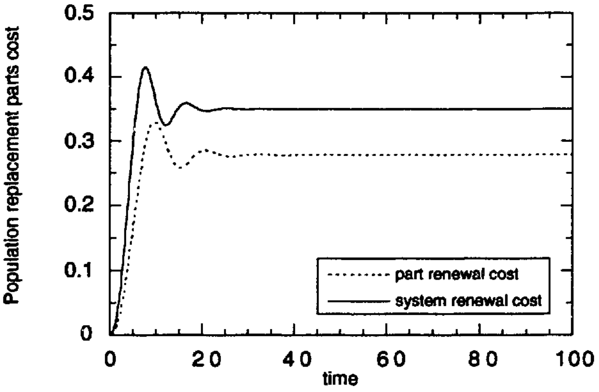


Fig. 3.15b. Part cost: part vs. system renewal

3.9. Series Mechanical Systems

This section presents additional considerations for application of the model to mechanical systems. The model is then applied to an example mechanical system to compare life-cycle part-replacement costs for various combinations of component selection.

Wear and failure of mechanical components often occur due to relative motion between parts, and thus the reliability of many mechanical components depends on the interaction with the component with which it is coupled. For example, a gear may have different failure characteristics depending on the gear with which it meshes. Therefore, failure characteristics are defined as interactions between components.

For example, consider the driver-shaft-and-bevels assembly and driven bevel pinions illustrated in Fig. 3.16. The interactions between the driver and driven bevels, as well as the material and geometry characteristics of each gear, prescribe the gear failure parameters. Tables 3.2 and 3.3 contain hypothetical gear failure characteristics as α and β of the Weibull distributed time-to-failure density. Table 3.2 contains failure density functions of driver-assembly bevels made from three different materials as a function of the material of the meshing driven bevel pinion. Table 3.3 contains the corresponding failure characteristics for the driven bevels. The trend assumed by the tables is that a softer material wears faster when meshed with a harder material.

If the entire driver assembly is replaced as a unit upon failure of either driver bevel, the assembly has two simultaneous interactions. The resultant failure density of the assembly due to the failure of either driver bevel can be found using (3.10).

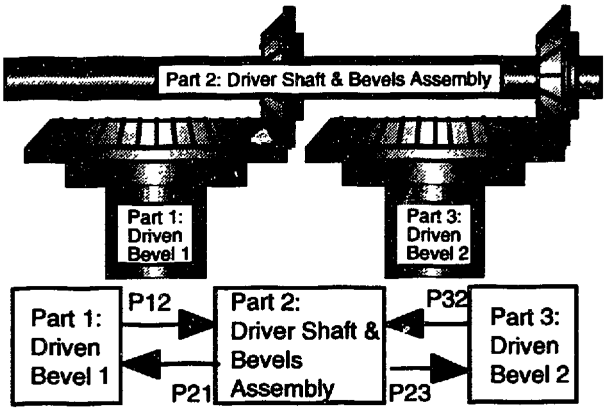


Fig. 3.16. Failure characteristics representation for mechanical elements in series

Table 3.1. Gear costs used in simulation

Gear material	Driven Bevel 1	Driver shaft/bevel Assembly	Driven Bevel 2
Polished steel	20	50	20
Brass	15	40	15
Nylon	5	15	5

Table 3.2. Failure distributions of driver assembly bevels for various material combinations

Driver bevel material	*Driven bevel material*		
	Polished steel	*Brass*	*Nylon*
Polished steel	α=6, β=8	α=7, β=12	α=8, β=16
Brass	α=3, β=4	α=4, β=8	α=5, β=12
Nylon	α=1, β=1	α=2, β=2	α=2, β=3

Table 3.3. Failure distributions of driven bevels for various material combinations

Driven bevel material	*Driver bevel material*		
	Polished Steel	*Brass*	*Nylon*
Polished steel	$\alpha=6, \beta=16$	$\alpha=7, \beta=24$	$\alpha=8, \beta=32$
Brass	$\alpha=3, \beta=8$	$\alpha=4, \beta=16$	$\alpha=5, \beta=24$
Nylon	$\alpha=1, \beta=2$	$\alpha=2, \beta=4$	$\alpha=2, \beta=6$

The part cost and failure data of Tables 3.1 through 3.3 are used to compare life-cycle part-replacement costs for four combinations of part selection. These combinations are: steel driver-assembly bevels with steel driven bevels, steel driver-assembly bevels with brass driven bevels, brass driver bevels with nylon driven bevels, and nylon driver bevels with nylon driven bevels. In each combination, both the driver bevels are of the same material, as are both the driven bevels.

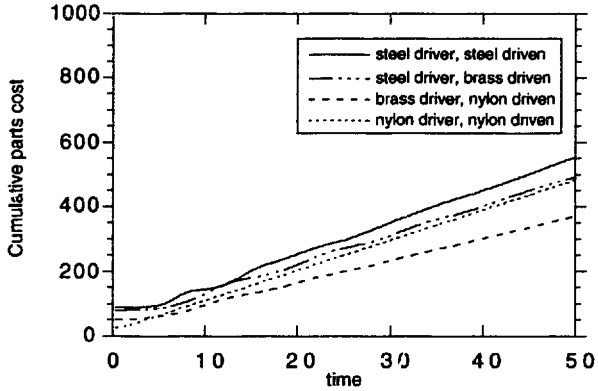


Fig. 3.17. Cumulative part-replacement costs: No labor included

Several simplifications over typical practice are made. The effects of the attachment between the bevels and the shafts are neglected. Meshing gears are usually both replaced when either is to be replaced, but here only the failed component is replaced, and the failure characteristics of one gear are assumed independent of the age of the meshing gear. The driver-shaft-and-bevels assembly is counted as one component and replaced as a unit.

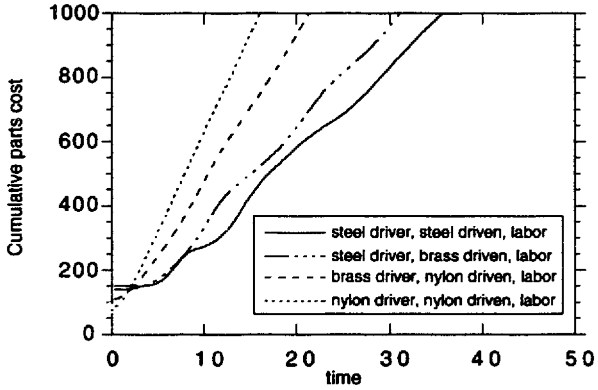


Fig. 3.18. Cumulative part-replacement costs: Labor included

The cumulative part costs for the above material combinations, shown in Fig. 3.17, suggest that the use of cheaper components is more cost effective. However, the cumulative cost included only part costs, not labor cost, nor the cost of disruption while the failed part is being replaced. Fig. 3.18 plots the total population replacement-part costs obtained by adding a uniform cost of 60 to the part costs in Table 3.1. This additional cost can either represent a labor cost incurred each time a component is installed or replaced, or make up for an initial underestimate of component costs. The results are then reversed: the most cost effective combinations are those that incur a larger part cost, but also last longer. This confirms that the labor and disruption costs associated with replacing a component, in addition to the cost of the component, should drive initial component selection. Figs. 3.17 and 3.18 also suggest that the interaction between part cost and reliability makes it difficult to predict from intuition alone the combination of component selection that will yield the lowest life-cycle cost.

3.10. Summary

This chapter presented a reliability model which estimates life-cycle costs of systems that are remanufactured. These reliability-based, life-cycle costs can be used to compare design alternatives.

Contrary to many other system reliability models, this model describes repair during remanufacture or maintenance as leaving the system in neither same-as-new nor same-as-old states. Furthermore, this model accommodates system modification, in which failed parts are replaced with components with different failure characteristics. This feature portrays more accurately many instances of component replacement during remanufacture or maintenance. Replacement components may have different failure properties from the original components due to different suppliers of replacement parts, and system upgrade or reconfiguration.

The model represents a population of systems as a collection of populations of the constituent parts. Part failure can result in replacement of the part with a component of the same or different type, or in replacement of the system. When only a portion of the system is replaced, the remaining parts of the system either remain unchanged or are reconfigured to accommodate the replacement component. The age distribution of each part population determines the failure characteristics of the corresponding part. Currently, this model describes series systems in which the components have densities of time to failure that can be represented by the two-parameter Weibull distribution.

The basic model behavior simulates replacement of failed parts with components of the same type; this fundamental behavior was experimentally verified. Since it is common practice in remanufacture to replace failed parts with components of a different type, this situation was also modeled. Reliability theory necessary to predict system failure from the failure characteristics of the constituent parts in series was outlined. Finally, the model was applied to a mechanical series system to compare life-cycle costs of various combinations of component selection.

Chapter 4. Genetic-Algorithm Based Optimization of Life-Cycle Fastening and Joining Costs

The results from the case studies of Chapter 2 showed that fastening and joining methods which facilitate assembly and recycling do not necessarily facilitate remanufacture. For example, installation of an insert during original manufacture may involve extra cost for both assembly and recycling, but the extra effort may reduce the remanufacture cost significantly. Also, snap fits may be ideal for assembly and disassembly for recycling, but a part with a failed snap fit may be difficult to reuse. 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. In remanufacture, the probability and consequence of fastener and part damage, in addition to disassembly and assembly time, are important.

Chapter 3 introduced a reliability model to describe the effect of remanufacture on a population of systems. The current chapter applies the reliability model to joint systems. Primary factors are identified that affect life-cycle fastening and joining costs in products that are remanufactured. These factors are inputs to the reliability model and can be combinatorially optimized. The life-cycle costs of each possible solution of an illustrative sample search space are calculated to identify trends in life-cycle costs. A larger search space would require the use of optimization methods to minimize life-cycle cost. A genetic-algorithm based representation for fastening and joining plan optimization has been implemented. This chapter closes by describing this implementation that will be used for larger search spaces to be developed in the future.

4.1. Factors Affecting Remanufacture Cost of Fastening and Joining

Collaboration with remanufacturers identified three primary factors that affect the life-cycle fastening cost of remanufactured products. These factors are the original fastening or joining method, disassembly and reassembly method used during remanufacture, and the repair policy.

The general class of methods, e.g., separate mechanical fasteners, integral fasteners, adhesive bonding or welding, determines the nominal suitability for disassembly and the degree to which damage during disassembly can be controlled and isolated. For example, it is unlikely that an ultrasonic-welded joint can be separated without considerable damage to at least one of the parts joined. The method class also determines the available set of disassembly methods, as well as available repair options in the event of failure.

The specific embodiment of the fastening method, e.g., particular type and size of threaded fastener, determines the exact geometry and material properties of the fastening elements, and the cost of implementing or replacing joints fastened with this method. The specific embodiment also determines the number of disassembly and reassembly cycles that the joint can survive based on a nominal disassembly and reassembly method and various part materials.

The disassembly and reassembly methods chosen during remanufacture significantly affect the cost of remanufacture as determined by the fastening or joining method. The disassembly and reassembly method prescribes both time and skill needed, and likelihood of damage, during disassembly and reassembly. Faster methods may save labor cost, but result in increased part damage. Even subtleties within a method, such as the specification of the torque to be used on a power screw driver, may affect the amount of part damage.

Finally, the repair policy determines the consequent cost of damage incurred during disassembly and reassembly. Failure of a part may result in replacement of the failed part with a new part of the same or different type. For example, a damaged screw can be replaced with another screw. A stripped boss may result in system reconfiguration, such as the installation of an insert into the boss. This installation alters the system reliability characteristics by increasing the number of disassembly and reassembly cycles the joint can survive over that achievable by a new joint of the original type. Reconfiguration of the fastening method during remanufacture is not uncommon. Some products, such as copier parts, are designed with backup fastening methods. In these parts, snap fasteners are the primary fastening system, but bosses molded during original manufacture facilitate use of threaded fasteners should the snaps fail. In toner cartridges where disassembly is not planned by design, heat stakes are drilled out during disassembly, and threaded fasteners are used for reassembly. Finally, the entire system may be replaced with a new one of the same or different type, either upon failure, or uniformly without inspection, due to system upgrades, experience with past reliability problems, or even aesthetic reasons.

4.2. Reliability Representation for Joints

When parts are reused, in either remanufacture or maintenance, the reliability of the part is very important. The above factors directly affect the reliability and thus the life-cycle cost of a joint in a product that is remanufactured.

The elements of a joint may be represented as a series system, such that failure of any part of the system will constitute joint failure. Failure of mechanical elements often results due to relative motion between elements. In joints, this relative motion can occur during product operation, but most certainly during assembly, disassembly and reassembly. This relative motion can be either intended or unintended. For instance, loosening a screw may also loosen an insert.

With mechanical series systems, the failure characteristics, for a given set of operating conditions, of one part are determined not only by that part's material and geometry but also by the interactions with the part with which it meshes. For example, the likelihood that a given boss will strip depends heavily on the type of screw used with it. Therefore, it is useful to define failure characteristics of one part based on its interaction with other parts. In Fig. 4.1, the screw imposes a certain failure characteristic, f_{sb} on the boss, and the boss imposes f_{bs} on the screw.

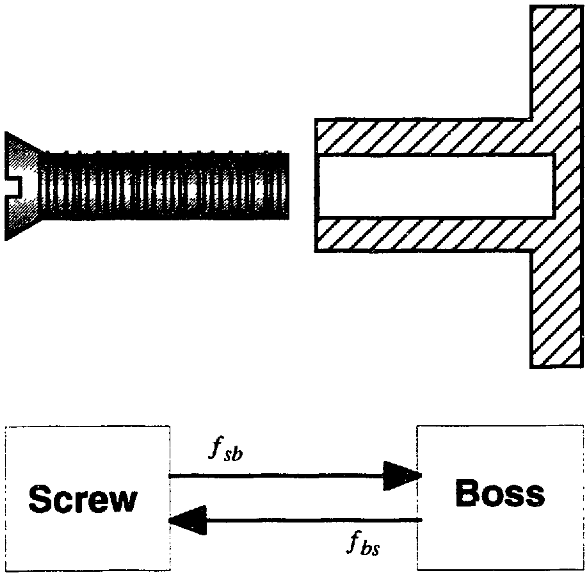


Fig. 4.1. Interaction-based failure characteristics

Focusing on failure that occurs during disassembly and reassembly, failure characteristics of joint elements are represented as cycles-to-failure density functions. For example, a certain boss-screw combination may average 3 or 4 disassembly and reassembly cycles.

A part often interacts with more than one neighbor. In Fig. 4.2, the part with the hole and the part with the boss impose failure characteristics, f_{hs} and f_{bs} respectively, on the screw. Likewise, the screw imposes f_{sb} and f_{sh} respectively on the boss and the hole.

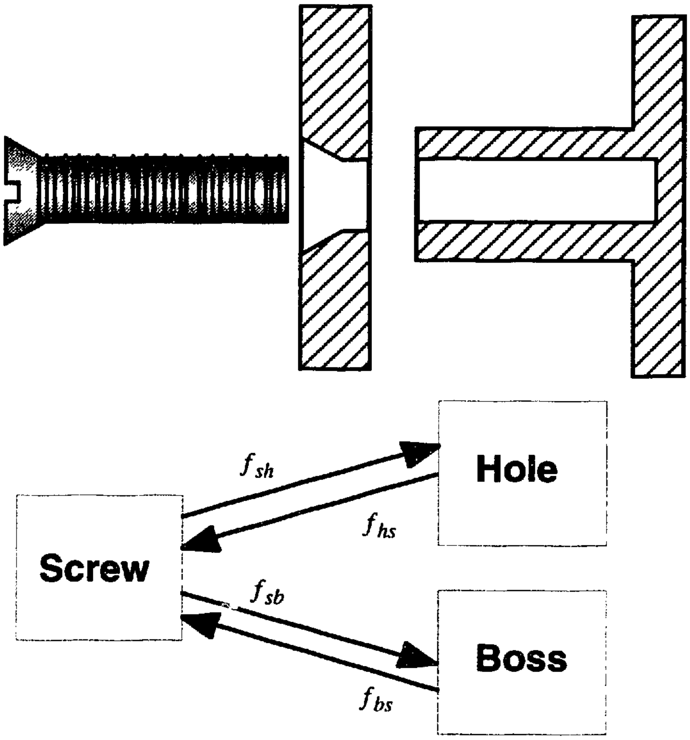


Fig. 4.2. Simultaneous interactions between neighboring parts

The resulting probability density function from the combined effect on the screw can be found using series system reliability theory presented in Chapter 3. If the method involves point fasteners, all the elements of the same type are lumped into one part that has the equivalent failure characteristics of the multiple parts in parallel. Point fastening systems are those where fastening occurs at discrete points along the joint interface and include methods such as spot welding, threaded fasteners, rivets, etc. If the joint uses multiple nuts and bolts for example, all the nuts would be lumped together as an object with the equivalent failure characteristics of the number of nuts used in parallel, and the bolts would be treated similarly.

The given fastening method determines the objects in the system, and the failure characteristics imposed by their neighbors should the corresponding interface separate. For example, an insert may seriously damage a boss if it were to separate from the boss, although this is not intended to occur frequently.

The disassembly method determines the probabilities with which interfaces between parts will separate. For example, in Fig. 4.3, the probability that a given disassembly method will separate the boss from the insert is denoted P_{ib}. The disassembly method also scales the nominal probability of damage to each part specified by the fastening method. In Fig. 4.3, the disassembly-method scale on the probability of damage imposed by the screw on the hole is denoted S_{sh}. Finally, the disassembly method imposes other damages due to contact between the disassembly tool and a part, that may or may not result from separation of an interface. For example, a nut may be stripped without being removed from the bolt.

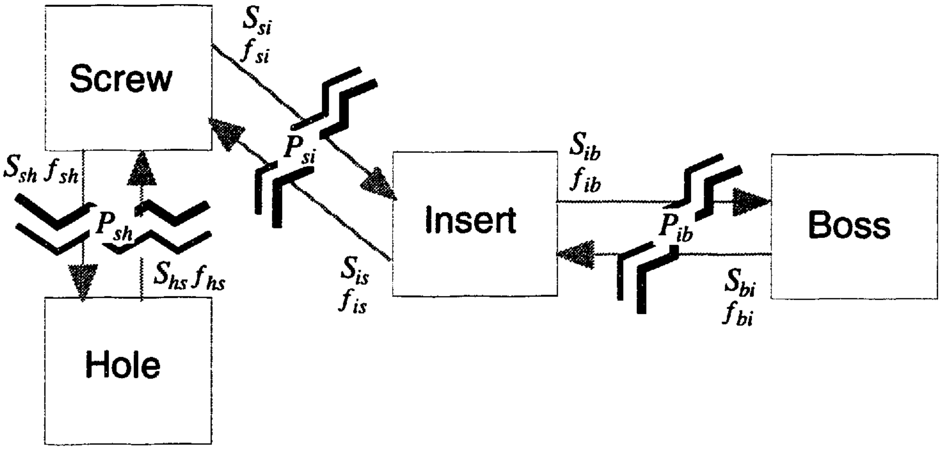


Fig. 4.3. Effect of disassembly method on reliability

4.3. Disassembly and Reassembly Cost for Remanufacture

The remanufacture portion of the life-cycle fastening and joining cost includes the cost of disassembly and reassembly, and the consequential cost of part damage incurred during disassembly and reassembly. It is assumed that the joint of interest must be disassembled to enable other remanufacture activities such as cleaning, testing or part replacement.

4.3.1. Example Calculation

An example calculation will be performed for a population of snap-fit joints pictured in Fig. 4.4, where both parts of the snap fit are described by the Weibull distribution with α and β equal to 3

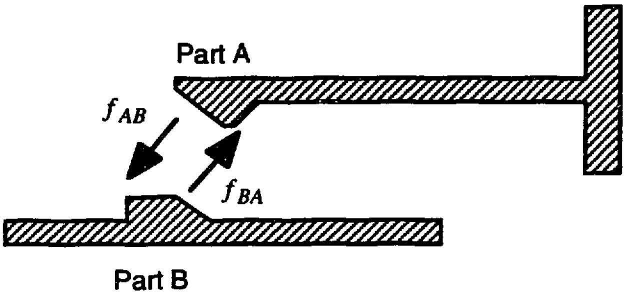


Fig. 4.4. Interaction-based failure characteristics for snap-fit joint

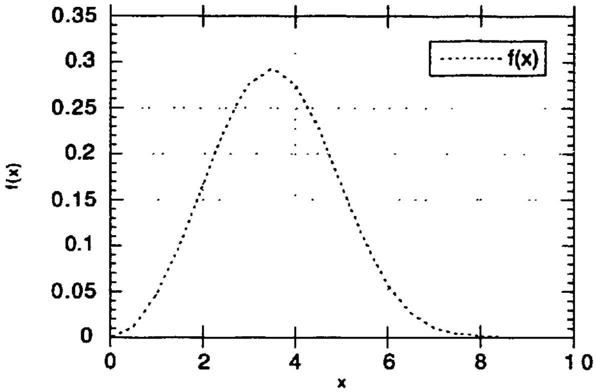


Fig. 4.5. Time-to-failure density for Weibull Distribution with parameters α=3, β=4

and 4 respectively. Assuming that both parts have the same distribution is an approximation to simplify this example.

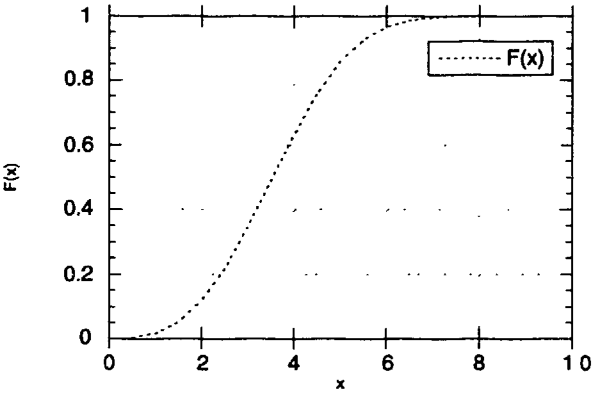


Fig. 4.6. Probability of failure for Weibull Distribution with parameters α=3, β=4

The product with this joint will undergo a total of 2 remanufacture cycles. The remanufacture portion of the life-cycle cost as determined by the fastening and joining method is calculated as follows for both parts A and B.

At the first remanufacture cycle, the portion of the population of parts that fails and must be replaced is determined by integrating the density of time to failure from 0 to 1 time step. The remainder of the population survives and ages by one time step. The cost of disassembly and reassembly is approximated by assuming that one disassembly and reassembly operation is performed on the entire population. There may actually be more than one disassembly and reassembly operation performed on some of the systems with failed parts, since the failure may occur on reassembly, which will then require an extra disassembly and reassembly operation.

Specifically for α and β equal to 3 and 4 respectively, the integral of the Weibull distribution evaluated from 0 to 1 is 0.0155. This is the portion of the population that fails and must be replaced by new parts. Therefore the cost for this cycle is 0.0155 times the population replacement-part cost, plus the cost of disassembly and reassembly performed on the population.

At the second remanufacture cycle, the portion of the population installed initially that fails during this cycle can be found by integrating the density function from 1 to 2. For this particular distribution, this value is 0.1175-0.01550 or 0.1020. This only includes the parts that were installed initially. There are also the parts that were installed as replacements during the first remanufacture cycle. The relative proportion of these parts that fail is 0.0155, and the absolute proportion of the total part population that fail from this category is 0.01550 x 0.01550 or 0.00024. Therefore, the remanufacture cost at the second cycle is determined by summing the cost of one disassembly and reassembly operation performed on the population and the cost of replacing 0.10224 of the parts.

4.4. Sample Search Space

This section will present an illustrative search space to examine how various combinations of the previously identified factors affect life-cycle fastening and joining costs. The two fastening classes used for this example are threaded fasteners and snap fits. Table 4.1 shows hypothetical data used for cost calculations. For each fastening class, two embodiments of the method, one more failure-prone than the other, are defined. The failure characteristics in Table 4.1 are represented as a pair of numbers that correspond to α and β of the Weibull distribution describing the number of disassembly and reassembly cycles to failure.

For each fastening method class, there are two disassembly and reassembly methods, one that is faster but has a higher probability of causing damage and another that is slower with a lower probability of causing damage. The effects of the disassembly and reassembly method are represented as scaling factors for the parameters of the Weibull distribution. Recall that higher values of β result in a higher average time to failure, and higher values of α result in a higher proportion of the population failing at time β. The repair policies for each class are, replace only the failed part with a new part, or treat the failure by system reconfiguration to use a coarse-thread

Table 4.1. Sample search space

SCREWS		SNAP FITS	
fine-thread screw	medium-thread screw	failure-prone snap	failure-resistant snap
piece 1 (boss) cost: 4.5 piece 2 (screw) cost: 0.10 piece 3 (hole) cost: 4.0 f_{2-1}: (2, 2) f_{1-2}: (5, 50) f_{3-2}: (5, 50) f_{2-3}: (2, 8)	piece 1 (boss) cost: 4.5 piece 2 (screw) cost: 0.10 piece 3 (hole) cost: 4.0 f_{2-1}: (3, 4) f_{1-2}: (5, 50) f_{3-2}: (5, 50) f_{2-3}: (3, 16)	piece 1 cost: 5.0 piece 2 cost: 5.0 f_{2-1}: (1, 2) f_{1-2}: (1, 2)	piece 1 cost: 5.0 piece 2 cost: 5.0 f_{2-1}: (3, 8) f_{1-2}: (3, 8)
fast, more-failure (un)screw	slow, less-failure (un)screw	(un)snap without fixture	(un)snap with fixture
S_{2-1}: (1.0, 0.5) S_{1-2}: (1.0, 0.5) S_{3-2}: (1.0, 0.5) S_{2-3}: (1.0, 0.5) Time$_{dis}$: 3.0s Time$_{asb}$: 7.3s	S_{2-1}: (1.0, 1.0) S_{1-2}: (1.0, 1.0) S_{3-2}: (1.0, 1.0) S_{2-3}: (1.0, 1.0) Time$_{dis}$: 4.3s Time$_{asb}$: 7.3s	S_{2-1}: (1.0, 0.5) S_{1-2}: (1.0, 0.5) Time$_{dis}$: 1.8s Time$_{asb}$: 2.2s	S_{2-1}: (1.0, 1.0) S_{1-2}: (1.0, 1.0) Time$_{dis}$: 2.5s Time$_{asb}$: 2.2s
replace part that fails	reconfigure to use:	replace part that fails	reconfigure to use:
	coarse-thread screw piece 2 (screw) cost: 0.10 f_{2-1}: (5, 10) f_{1-2}: (5, 50) f_{3-2}: (5, 50) f_{2-3}: (5, 20) *disassembly & reassembly* S_{2-1}: (1.0, 1.0) S_{1-2}: (1.0, 1.0) S_{3-2}: (1.0, 1.0) S_{2-3}: (1.0, 1.0) Time$_{dis}$: 4.3s Time$_{asb}$: 7.3s reconfiguration cost: 0.10 (cost of screw)		*coarse-thread screw* piece 2 (screw) cost: 0.10 f_{2-1}: (5, 10) f_{1-2}: (5, 50) f_{3-2}: (5, 50) f_{2-3}: (5, 20) *disassembly & reassembly* S_{2-1}: (1.0, 1.0) S_{1-2}: (1.0, 1.0) S_{3-2}: (1.0, 1.0) S_{2-3}: (1.0, 1.0) Time$_{dis}$: 4.3s Time$_{asb}$: 7.3s reconfiguration cost: 0.75 (drill hole, screw, possible part damage during drilling)

screw. Specifically, the stripping of the boss or hole will result in replacement of the screw with one that has a coarser thread. The failure of one or both parts of the snap fit would result in drilling a hole and installing a coarse-thread screw.

Table 4.1 yields 16 possible combinations of fastening plans. A life-time that includes 5 disassembly and reassembly cycles was used to calculate the life-cycle fastening cost for each possible solution. The life-cycle cost includes the manufacture and first assembly, disassembly and reassembly for remanufacture, and disassembly for recycling costs. In Chapter 2, only the part of the manufacture cost directly determined by the fastening or joining method was included in the first cost to highlight the effect of the fastening method. The manufacture cost was modeled to consist of the basic part cost, constant for all fastening methods, and the cost of implementing the particular fastening method. Here, the entire part cost is included in both the first and replacement cost calculations.

Table 4.2 lists the life-cycle joint costs for all 16 combinations. These costs reveal a number of trends. First, for this example, reconfiguring the system by either using a different screw or drilling a hole to accommodate a screw is cheaper than replacement of the failed part. In practice, the use of a different screw with a stripped boss is precluded when screw size consistency across the product is a priority. Transforming failed snap-fits to accommodate screws is more likely to take place when the joint is located in an inconspicuous location. Original equipment remanufacturers are less likely to reconfigure a system upon failure, as opposed to uniformly, particularly if the rebuild line is integrated with the new-build line. Independent remanufacturers, however, have more flexibility and are frequently more creative in their efforts to salvage parts, since spare parts are rarely made available by the original equipment manufacturer.

With the particular cost and failure parameters of Table 4.1, it is occasionally cheaper to use a slower, but less part-damaging disassembly method since the cost of part replacement or reconfiguration is included in the life-cycle cost. Again, this would be particularly true when

Table 4.2. Ranked fastening plans

Rank	Life-cycle cost	Fastening method	Disassembly/assembly method	Repair policy
1	9.835	medium-thread screw	fast, failure-prone unscrew	reconfigure upon failure
2	9.849	medium-thread screw	slow, less-failure unscrew	reconfigure upon failure
3	9.854	fine-thread screw	fast, failure-prone unscrew	reconfigure upon failure
4	9.862	fine-thread screw	slow, less-failure unscrew	reconfigure upon failure
5	10.86	failure-resistant snap	unsnap with fixture	reconfigure upon failure
6	11.52	failure-resistant snap	unsnap w/o fixture	reconfigure upon failure
7	11.76	failure-prone snap	unsnap with fixture	reconfigure upon failure
8	11.81	failure-prone snap	unsnap w/o fixture	reconfigure upon failure
9	12.65	failure-resistant snap	unsnap with fixture	replace part that fails
10	14.09	medium thread screw	slow, less-failure unscrew	replace part that fails
11	19.34	medium thread screw	fast, failure-prone unscrew	replace part that fails
12	19.75	failure-resistant snap	unsnap w/o fixture	replace part that fails
13	20.16	fine-thread screw	slow, less-failure unscrew	replace part that fails
14	29.42	fine-thread screw	fast, failure-prone unscrew	replace part that fails
15	30.14	failure-prone snap	unsnap with fixture	replace part that fails
16	42.01	failure-prone snap	unsnap w/o fixture	replace part that fails

replacement parts are scarce. Finally, note that the life-cycle cost rankings of the two classes of methods are interspersed, suggesting that it is inappropriate to assume that one class of fastening methods is consistently better even for one particular application.

While the size of the above search space does not justify the use of optimization methods, the next sections will describe an optimization implementation, which will be applied to significantly larger search spaces in the future.

4.5. Choice of Genetic Algorithms as an Optimization Method

Murty (1995) details a number of combinatorial optimization methods, one of which is the branch and bound approach. The branch and bound approach is used to approximate an optimum without enumerating and evaluating every possible combination. The fastening plan can be represented for the branch and bound approach as shown in Fig. 4.7. The objective function to be minimized is the life-cycle cost, which is additive at each level of the tree. A strategy for pruning, which makes a partial enumeration possible, involves calculating the life-cycle cost accumulated at the final level for a particular path down the tree. This value is then used as a criterion to prune other branches that exceed this cost before reaching the final level. For example, if the implementation cost alone of a fastening method exceeds the implementation, disassembly and repair costs of the criterion path, there is no need to further evaluate the remaining life-cycle costs for that fastening method.

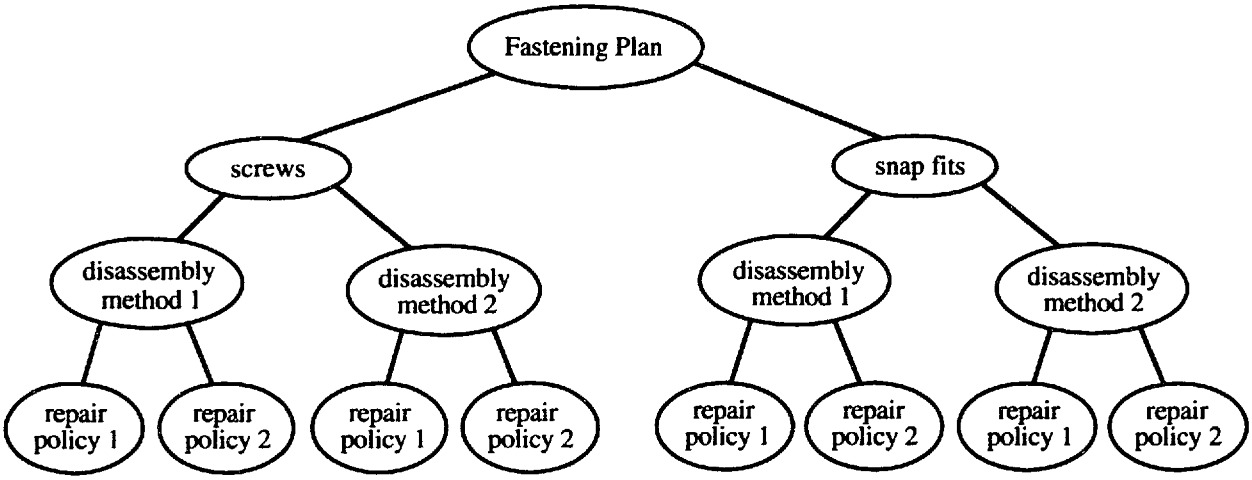


Fig. 4.7. Branch and bound representation of fastening plan.

However, as identified in Chapter 2, the fastening methods that are cheap to implement and assemble and disassemble once, may be those that cost the most in the long run for products that are remanufactured. Therefore, the applicability of this type of pruning, which enables a more efficient search than complete enumeration, would be limited. Also, the search tree is not deep enough to significantly benefit from pruning.

Genetic algorithms were selected as a method to optimize life-cycle fastening costs. A major advantage of genetic algorithms is the parallel search among multiple solutions, instead of the optimization of a single solution characteristic of the branch and bound approach. A brief overview of genetic algorithms follows.

Genetic algorithms simulate the evolution of design solutions. A design solution is represented as a single chromosome. Multiple solutions exist as a population of chromosomes that is evolved toward superior solutions. Superiority of a solution is determined by an objective function that represents a quantity to be minimized or maximized.

An initial population of solutions is created upon startup of the genetic algorithm. Evolution is executed through a process of selection, crossover and mutation of members of the population. First, chromosomes are selected based on fitness to be parents for the following generation. Fitness is a scaled value of the chromosome's objective function value. Crossover of two parent chromosomes involves combining parts of the parents to yield chromosomes representing new design solutions. Mutation involves a random alteration of part of a particular chromosome and is performed to maintain diversity in the population. The original population is replaced in part or whole by new chromosomes yielded by these operations. This process continues until either a number of generations or some convergence criterion on the objective function has been achieved.

4.6. Genetic Algorithm Representation of Fastening and Joining Plan

For this application, the chromosome, or possible solution, represents a fastening or joining plan. The plan consists of the initial fastening method, the subsequent disassembly (and reassembly) method, and the repair policy. The objective function to be minimized is the life-cycle disassembly and reassembly cost as determined by the fastening method. This sums the first and assembly costs, costs related to disassembly and reassembly performed during remanufacture, and the disassembly cost for recycling, as previously described.

During initialization of the chromosome, a general class of fastening method is randomly chosen. Based on this class, each part of the chromosome is selected from a predefined, appropriate set of alleles (possible values for parts of the chromosome), as shown in Fig. 4.8. During crossover, the types of methods represented by the parents are checked for compatibility before they are crossed over. This is to prevent nonsensical solutions, an instance of which would combine a snap fit fastening method with an unscrew disassembly method. Both the number and location of crossover points are randomly generated. Fig. 4.9 illustrates crossover for the case of two crossover points yielding one child chromosome. Mutation involves the random selection of one of the three parts of the chromosome and reselecting a value from the appropriate set of alleles, as illustrated in Fig. 4.10.

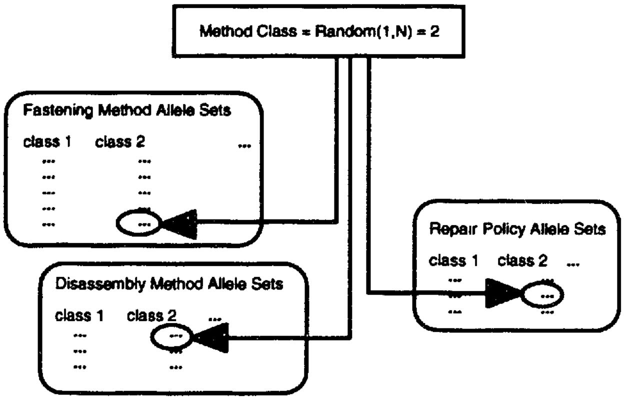


Fig. 4.8. Chromosome initialization

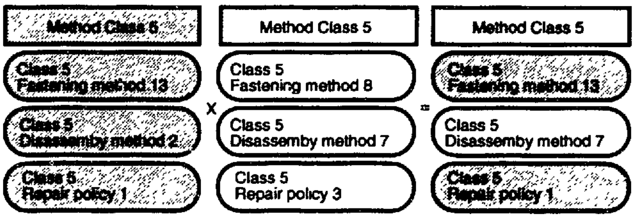


Fig. 4.9. Two-point single-child crossover

This optimization implementation will be used for larger search spaces to be developed in the future. Another attractive feature of genetic algorithms is that of speciation. Speciation in genetic algorithms encourages diversity so that the population will converge to multiple solutions of different types instead of just one

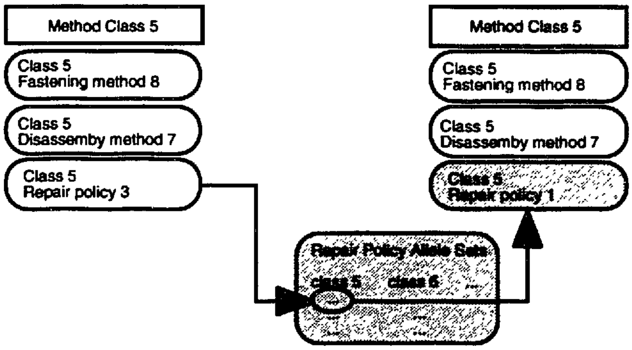


Fig. 4.10. Single-point mutation

single best solution. This feature would be very useful for this problem because it could be used to identify the best plan for different fastening classes. The choice of a particular class of fastening method may be determined by factors such as aesthetics that could be difficult to represent in the objective function. A genetic algorithm with sharing-based speciation was implemented, but the convergence to a single solution was only delayed, not prevented. Other methods that achieve speciation will be explored.

4.7. Summary

Continued collaboration with companies that remanufacture a variety of products identified three primary factors that determine the life-cycle fastening cost in products that are remanufactured. These factors are the fastening method specified during original design, the disassembly and reassembly method specified for remanufacture, and the repair policy which determines the consequence of part damage that occurs during disassembly and reassembly. In products that are remanufactured, the reliability of the part as affected by the above three factors, in addition to time needed for disassembly and reassembly, determine the fastening-related life-cycle cost. The reliability model developed in the previous chapter was applied to predict joint failure due to disassembly and reassembly over a specified number of remanufacture cycles. A small, but illustrative, search space was used to identify trends in life-cycle costs. Finally described was a genetic-algorithm representation for optimization of the fastening and joining plan that will be used on larger search spaces in the future.

Chapter 5. Summary and Future Work

The goal of this research was to enable product design that facilitates remanufacture. Collaboration with companies that remanufacture products yielded several insights on how products can be designed to facilitate remanufacture. An essential aspect of design for remanufacture was found to conflict with other more prevalent design-for-x methodologies, such as design for assembly and design for recycling. Therefore, design for remanufacture was viewed in the context of other design-for-x methodologies. The domains selected for simultaneous consideration were manufacture and assembly, maintenance, remanufacture, and scrap-material recycling. Since fastening and joining issues are common to all these domains, a framework was developed that evaluates the effect of joint design on each of these life-cycle stages. This framework was applied to case studies of joints that did not facilitate remanufacture to estimate the cost of remanufacture relative to other life-cycle costs determined by the joint design. These case studies identified the importance of reliability modeling for remanufacture. A probabilistic reliability model that describes the effect of remanufacture on the reliability of parts and systems was developed and experimentally verified. The various inputs to this reliability model are factors that can be combinatorially optimized using genetic algorithms to minimize the life-cycle cost.

The relationship between the chapters of this thesis is shown in Fig. 5.1. The block representing the contribution of the thesis provides the product designer with a tool that identifies the design solutions with the lowest life-cycle costs from the options that satisfy design requirements. As shown, the optimization is applied to the life-cycle costs calculated from both the multi-domain cost framework and the reliability model.

The reliability model developed in this thesis will be expanded to describe systems with series, parallel, and standby subsystems, where component failure rates can be represented by a variety of

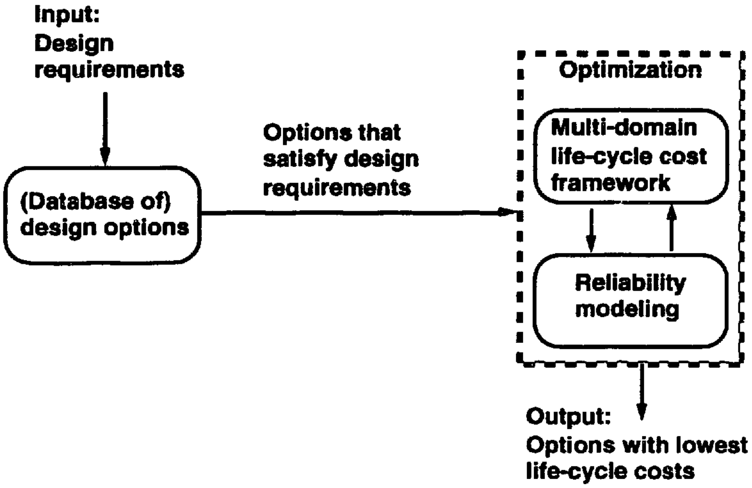


Fig. 5.1. Thesis schema

distributions. Data from industries that perform remanufacture and maintenance will be used to select distributions and parameters for failure rates.

The search space for the genetic algorithm optimization can be increased in several ways. First, data on more fastening methods are required. The optimization of continuous parameters such as those related to snap-fit geometry that determine initial cost, time needed for assembly and disassembly, as well as failure characteristics of the snap fit, is also appropriate. Finally, the consideration of multiple joints and multiple levels of joints within a product would render the search space significantly more complex.

The stochastic nature of the modeling and optimization methods described in this thesis can be used to further combine life-cycle and traditional design requirements, so that consideration of environmental aspects will become an inherent part of the product design process.

Bibliography

L. Alting and J. Legarth, "Life Cycle Engineering and Design," *Annals of the CIRP*, Vol. 44, no. 2, 1995.

T. Amezquita, R. Hammond, M. Salazar, and B. Bras, "Characterizing the Remanufacturability of Engineering Systems," *ASME Advances in Design Automation Conference*, Boston, MA, pp. 271-279, 1995.

H. Ascher and H. Feingold, *Repairable Systems Reliability*, Marcel Dekker, Inc., 1984.

P. Barkan and C. Martin Hinckley, "The Benefits and Limitations of Structured Design Methodologies," *Manufacturing Review*, 6-3, pp. 211-219, 1993.

V. Berko-Boateng, J. Azar, E. de Jong and G. Yander, "Asset Recycle Management - a Total Approach to Product Design for the Environment," *IEEE International Symposium on Electronics and the Environment*, Arlington, VA, pp. 19-31, 1993.

G. Boothroyd and L. Alting, "Design for Assembly and Disassembly," *Annals of the CIRP*, 41-2, pp. 625-636, 1992.

M. Brown and F. Proschan, *Imperfect Repair*, Department of Statistics, Florida State University, Tallahassee, Stat. Rep. M546, AFOSR Tech. Rep. No. 78-108, 1980.

C. Bryan, C. Eubanks and K. Ishii, "Data Representation for Serviceability Design," *ASME Design Theory and Methodology*, DE-42, Scottsdale, AZ, pp. 301-308, 1992.

R. Chen, D. Navin-Chandra, and F. Prinz, "Product Design for Recyclability: a Cost Benefit Analysis Model and its Application," *IEEE International Symposium on Electronics and the Environment*, Arlington, VA, pp. 178-183, 1993.

E. Cobas, C. Hendrickson, L. Lave, and F. McMichael, "Economic Input/Output Analysis to Aid Life Cycle Assessment of Electronics Products," *IEEE International Symposium on Electronics and the Environment*, Orlando, FL, pp. 273-278, 1995.

J. Cozzolino, "Probabilistic Models of Decreasing Failure Rate Processes," *Nav. Res. Logistics Quarterly*, Vol. 15, pp. 361-374, 1968.

R. D'Amore, *Product Integrity in a Remanufacturing Operation*, SAE Technical Paper Series, No. 840795, 1984.

R. F. de la Mare, *Optimal Equipment Replacement Policies*, National Centre of Systems Reliability, United Kingdom Atomic Energy Authority, Culcheth, Warrington, NCSR R21, 1979.

P. DiMarco, C. Eubanks, and K. Ishii, "Service Modes and Effects Analysis: Integration of Failure Analysis and Serviceability Design," *ASME Computers in Engineering Conference and Engineering Database Symposium*, Boston, MA, pp. 833-840, 1995.

R.F. Drenick, "The Failure Law of Complex Equipment," *J. Soc. Indust. Appl. Math.*, 8, pp. 680-690, 1960.

J. Duda and M. Jakiela, "Generation and Classification of Structural Topologies with Genetic Algorithm Speciation," submitted to the ASME Journal of Mechanical Design, 1995.

J. Gershenson and K. Ishii, "Life-Cycle Serviceability Design," *ASME Design Theory and Methodology*, DE-31, Miami, FL, pp. 127-134, 1991.

D. Goldberg, *Genetic Algorithms in Search, Optimization, and Machine Learning*, Addison-Wesley, Reading, Massachusetts, 1989.

T. Gonzalez, *Remanufacturing Technology*, MIT Department of Mechanical Engineering S.M. Thesis, Cambridge, MA, 1983.

H. Haynsworth and R. Lyons, "Remanufacturing by Design, the Missing Link," *Production and Inventory Management*, 2nd Quarter, pp. 25-28, 1987.

M. Henstock, *Design for Recyclability*, The Institute of Metals, 1988.

H. Holzwasser, "The National Energy, Materials and Pollution Crisis: A Solution from the Garage," Advertisement, OP/Ed Page, *New York Times*, 27 March, 1977.

H. Holzwasser, *Engineering For Remanufacturing*, SAE Technical Paper Series, No. 830549, 1983.

M. Johnson and M. Wang, "Design for Disassembly and Recyclability: A Concurrent Engineering Approach," *10th ISPE/IFAC International Conference on CAD/CAM, Robotics, and Factories of the Future*, Ottawa, Canada, pp. 436-441, 1994.

F. Jovane, L. Alting, A. Armillotta, W. Eversheim, K. Feldmann, G. Seliger, and N. Roth, "A Key Issue in Product Life Cycle: Disassembly," *Annals of the CIRP*, 42-2, pp. 651-658, 1993.

J. Kirby and I. Wadehra, "Designing Business Machines for Disassembly and Recycling," *IEEE International Symposium on Electronics and the Environment*, Arlington, VA, pp. 32-36, 1993.

R. Kutta, *Remanufacture of Durable Products: A Value-Preserving Technology*, MIT S.M. Thesis, Cambridge, MA, 1980.

L. Laperriere and H. ElMaraghy, "Planning of Products Assembly and Disassembly," *Annals of the CIRP*, 41-1, pp. 5-9, 1992.

R. Lund, *Remanufacturing, United States Experience and Implications for Developing Nations*, MIT Center for Policy Alternatives Report, CPA/83-17, Cambridge, MA, 1983.

K. Murty, *Operations Research: Deterministic Optimization Models*, Prentice Hall, 1995.

T. Nakagawa, "Replacement Models with Inspection and Preventive Maintenance," *Microelectronics and Reliability*, Vol. 20, pp. 427-433, 1980.

R. Noller, "Design for Disassembly Tactics," *Assembly*, pp. 24-26, January 1992.

C. Overby, "Product Recycling (Remanufacturing) as a Conservation Option: an International Dimension," in *Advances in Materials Technology in the Americas-1980, Vol. 1 - Materials Recovery and Utilization*, pp. 113-119, 1980.

J. Scheuring, B. Bras, K. Lee, "Significance of Design for Disassembly in Integrated Disassembly and Assembly Processes," *International Journal of Environmentally Conscious Design and Manufacturing*, Vol. 3, 2, pp. 21-33, 1994.

T. Schmaus and M. Kahmeyer, *Design for Disassembly - Challenge of the Future*, Fraunhofer Institute, Germany.

T. Schrader and D. Bawel, *Specification Criteria for Remanufacturing*, SAE Technical Paper Series, No. 840794, 1985.

W. Seaver, "Design Considerations for Remanufacturability, Recyclability and Reusability of User Interface Modules," *IEEE International Symposium on Electronics and the Environment*, San Francisco, CA, pp. 241-245, 1994.

N. Senin, D. Wallace, and M. Jakiela, "Mixed Continuous Variable and Catalog Search Using Genetic Algorithms," to appear in the Proceedings of the ASME Design Engineering Technical Conferences and Computers in Engineering Conference, Advances in Design Automation, Irvine, CA, August 18-22, 1996.

M. Shooman, *Probabilistic Reliability: an Engineering Approach*, Krieger Publishing Company, Malabar Florida, 1990.

L. Shu and W. Flowers, "Considering Remanufacture and Other End-of-life Options in Selection of Fastening and Joining Methods," *IEEE International Symposium on Electronics and the Environment*, Orlando, FL, pp. 75-80, 1995.

L. Shu, "Reliability Modeling in Design for Remanufacture," to appear in the Proceedings of the ASME Design Engineering Technical Conferences and Computers in Engineering Conference, Advances in Design Automation, Irvine, CA, August 18-22, 1996.

M. Simon, B. Fogg, and F. Chambellant, *Design for Cost-Effective Disassembly*, Manchester Polytechnic, U.K.

A. Spicer, M. Wang, "A Software Tool for Analysis of the Retirement Phase of a Product Currently under Design," *3rd International Congress on Environmentally Conscious Design and Manufacturing,* Las Cruces, NM, pp. 439-448, 1995.

A. Subramani and P. Dewhurst, "Automatic Generation of Product Disassembly Sequences," *Annals of the CIRP*, 40-1, pp. 115-118, 1991.

U.S. Congress, *Green Products by Design: Choices for a Cleaner Environment,* OTA-E-541, Office of Technology Assessment, Washington, D.C., 1992.

Z. VerGow and B. Bras, "Recycling Oriented Fasteners: a Critical Evaluation of VDI 2243's Selection Table," *ASME Advances in Design Automation*, DE-Vol 69-2, pp. 341-349, 1994.

VDI, "Konstruieren Recyclinggerechter Technischer Produkte (Designing Technical Products for Ease of Recycling)", VDI 2243, *VDI-Gesellschaft Entwicklung Konstruktion Vertrieb*, 1993.

D. Wallace, M. Jakiela, and W. Flowers, "Design Search under Probabilistic Specifications Using Genetic Algorithms," to appear in *Computer-Aided Design,* 1995.

H. Warnecke and R. Steinhilper, "Designing Products with Built-in Reconditioning Features," *Proceedings of the 6th Annual Conference on Design Engineering,* Birmingham, UK, pp. 241-248, 1983.

C. Whyland, *The Development of a Design for Service Database,* Master of Science Thesis, University of Rhode Island, 1993.

Ziwica, Karl-Heinz. "Problems and Solutions of Recycling at BMW," in *Proceedings of the Second Annual Congress on Environmentally-Conscious Design and Manufacturing: From Best Practices to Profit,* April 18-20, Dearborn, MI, Management Roundtable, Boston, MA, 1993.

E. Zussman, A. Kriwet and G. Seliger, "Disassembly-Oriented Assessment Methodology to Support Design for Recycling," *Annals of the CIRP*, 43-1, pp. 9-14, 1994.

THESIS PROCESSING SLIP

FIXED FIELD: ill. ______ name ______

index ______ biblio ______

► COPIES: [✓ Archives] Aero Dewey [✓ Eng] Hum

Lindgren Music Rotch Science

TITLE VARIES: ►☐

NAME VARIES: ►☐

IMPRINT: (COPYRIGHT)

►COLLATION: 75 l

►ADD. DEGREE: ______ ►DEPT.: ______

SUPERVISORS:

NOTES:

cat'r: date:

page: ► J 150

►DEPT: M.E.

►YEAR: 1996 ►DEGREE: Ph.D.

►NAME: SHU, Lily Hwei-Li