6 Consideration of Reuse, Recycling and Remanufacturing

6.1 INTRODUCTION

The traditional manufacturing process is referred to as linear manufacturing or cradle-to-grave manufacturing. It consists of extracting raw materials from the natural environment, processing it into finished products and disposing of it at the end of its useful life. They are disposed of in landfills. We have seen repeatedly throughout the course of this book that this practice is inherently not sustainable. It is essential to close the "loop" on the manufacturing process. Doing so would transform the system of linear manufacturing into cyclical manufacturing.

Cyclical manufacturing is also referred to as the cradle-to-cradle approach to manufacturing. In this approach, the material that was introduced into the system at the beginning never leaves that system. It stays in it because it is reused, recycled or remanufactured. Reuse, recycling and remanufacturing constitute the so called end-of-life (EOL) options. They answer the question: "What is to be done with all these products when they reach the end of their lives?" If the goal is to conserve the environment and prevent the landfills from being overexploited, then the only feasible alternative is to reuse, recycle or remanufacture end-of-life products. Figure 6.1 demonstrates how the loop can be closed on material flows.

However, this is easier said than done. It is not so simple to recycle a product or to reuse or remanufacture it. But aren't old cars shredded all the time? Shredding a car is not the same as recycling it intelligently. In order to truly conserve material and energy, it is essential to design the product for a particular end-of-life option. This is done by taking specific actions during the design stage itself. A designer can truly embrace the idea of sustainable product design and development only by making sure that a product is "destined" for one of the three end-of-life options. What does this mean? It means that the product has been designed in such a manner that when its time comes, it is easy to be either recycled, reused or remanufactured. Thus, the design of such a product would be substantially different from its counterpart that is destined for the landfill. The difference can lie in the choice of material, types of fasteners and joints, product structure and so on.

The goal of this chapter is to introduce the reader to design decisions that must be made early in the product lifecycle (particularly in the design stage) to make an environment-friendly product.

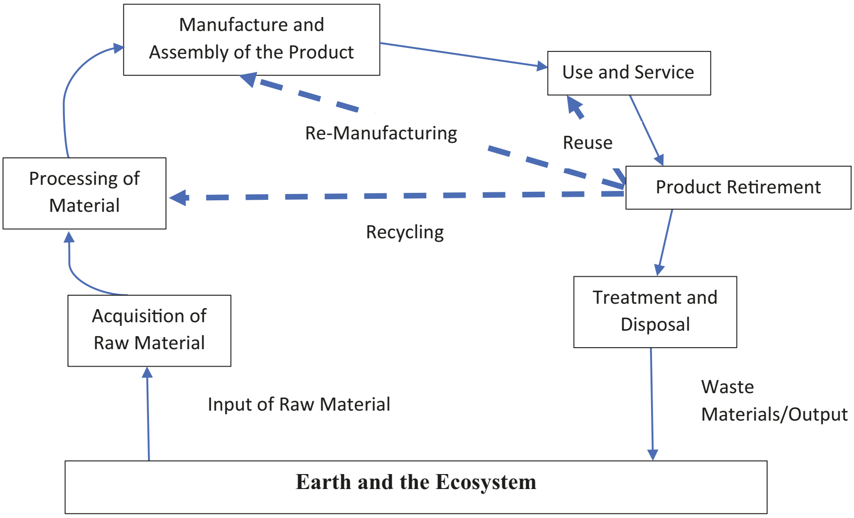

FIGURE 6.1 Closed loop material flow (Adapted from Nasr and Thurston, 2006).

6.2 WHAT IS PRODUCT REUSE?

Reusing a product implies using the product again for the same purpose or for a different purpose at the end of its useful life. This is clearly distinguishable from the concept of recycling wherein the product is broken down to its most basic material form.

If a product is destined to be reused at the end of its useful life, it is necessary to adopt proper quality assurance measures of used parts (Kimura et al., 1998). The reliability of the product throughout the entire life cycle should also be checked (Hata et al., 2000).

From the design point of view, a product that is destined to be reused must be designed and manufactured differently from other products. A different idea about the life cycle needs to be adopted in order to design products for ease of reuse. This section of the chapter will present some of the design principles that facilitate product reuse.

Many different types of products are routinely designed for reuse. For instance, in the case of single-use cameras, mechanical units are completely reused many times over and across successive generations of products (Tanaka, 2000). In the case of photocopiers, on the other hand, comprehensive systems are designed to facilitate product take back. Also design concepts such as product modularization and standardization of parts are used when designing the photocopier.

6.3 PRODUCT MODULARIZATION FOR EASE OF REUSE

Modularization is a design principle commonly used in product design to facilitate reuse. In its most basic form, a module can be defined as a building block of any product structure. Modular design has been used for thousands of years. In more recent times, it is necessary for a module to possess something more than merely being a building block. It should also possess a considerable amount of functionality. In an industrial context, such functionality should be strong enough that it can be tested independently. For instance, the power supply module in a printer has enough functionality and it can also be considered a building block of the printer (Miller and Elgard, 1998). We have already examined the role played by product functionality in chapter 1 of the book.

Traditionally, whether to adopt a modular product structure has been determined by several factors as follows (Kimura et al., 2001):

- Commonality among products, also referred to as standardization.
- Functional independence.
- Product cost.
- Ease with which product can be manufactured.
- Ease with which product can be maintained.

It is obvious that some of the above factors can have conflicting effects of the actual design of the module. Thus, it is necessary to make design tradeoffs based on their relative importance. However, since the goal of this section of the chapter is to examine product modularization to enhance ease of reuse, we will focus on that objective.

In order to enhance the possibility of reuse, the following modular characteristics are important:

- Stability of technology.
- Ability to upgrade functionality.
- Longevity of the part.
- Ease with which quality assurance can be achieved.
- Ease with which the part can be cleaned, repaired and so on.

These considerations are at odds with traditional thinking in terms of modularizing parts. The modularizing procedure with the sole aim of enhancing product reusability is delineated stepwise as follows (Kimura et al., 2001).

1 Functional dependency: During this step, the modules and/or parts of the products being designed are described by means of a graph structure. The nodes of the graphs are modules/parts and the functional or other relationships are depicted by means of arcs. The design requirements dictate the level of detail of the graph structure. During the early design stage, only functionally important components are identified. The graphs are then superimposed with identification of same or similar nodes as those that existed in part products with similar functionality. Multiplicity of superimposition with respect to each arc is counted for the next step.
2 Commonality: During this step, the number of multiplicity of arcs is identified. The number of multiplicities is referred to as weight. If the difference in values of arc weight is within a specified parameter value, say “L,” then the

nodes that are connected by those weighted arcs are combined together in the form of a module. If the parameter L has different values, it leads to different module structures. A larger value of L implies less importance to structural commonality within modules.

3. Module types: In terms of types of modules, two different types can be identified as follows:
    - Component swapping modules: In this type of modules, several different exchangeable (swappable) modules are connected with a component to create a variety of products.
    - Component sharing modules: In this type of modules, various modules that share the same basic component are responsible for creating different variants of the product.

    Swappable modules and/or shared modules are combined to create new modules.
4. Dividing the modules: Modules that have similar property are combined by dividing different portions from the main parts. This is done for pairs of parts/modules that exhibit component sharing modularity. Such an operation results in decreasing the total number of modules. The aforementioned steps are repeated in order to achieve a stable product structure.

Although reusing parts has several advantages, there are some disadvantages associated with the process. For instance, rapid technological advancement can render old parts obsolete whereby they can no longer be reused. It could also be quite difficult to collect, clean and refurbish old parts. This could make it prohibitively expensive to reuse old parts.

6.4 WHAT IS RECYCLING?

The Environmental Protection Agency (EPA) defines recycling as “the process of collecting and processing materials that would otherwise be discarded as trash.” Instead these materials are turned into new products by further processing the underlying raw material. According to the Europe 2020 strategy, “the quality of our life and the functioning of the global economy is underpinned by natural resources.” This implies that human civilization is entirely dependent on natural resources for sustenance. Thus, it is essential to obtain reliable access to critical raw materials as well as make smarter use of natural resources. Recycling aims to close the loop of materials and components. It accomplishes this by reusing/utilizing them for new products.

Recycling, as a rule, is performed at the material level. It is rarely, if at all, beneficial to recycle the entire product. The main goal of recycling is to maximize the amount of recycled resources while investing the least amount of effort (Kriwet et al. 1995). We will examine the minute differences between terms such as recycling, remanufacturing, refurbishing and so on later in the chapter, specifically when we discuss the concept of product remanufacturing. In this section of the chapter, we will take a deeper look into the concept of design for recycling and pertinent rules and principles.

6.5 TYPES OF RECYCLING

Recycling activities can occur in three distinct loops in a product lifecycle (Kriwet et al., 1995).Two more concepts related to recycling plastic are also discussed They are described as follows.

1. Recycling of production scrap: During this process, residues emanating from traditional manufacturing processes such as punching, injection molding and so on are recycled at the material level so as to be used in new products.
2. Recycling during product usage: This involves continuing to use the product after it has been reused or remanufactured.
3. Recycling after product has been used: This involves the process when a product is recycled at the end of its useful life. Different recovery options are available at the end of life of most consumer products such as household appliances, automobiles and so on. These products have a complex product structure and composition. In such cases, other product recovery processes must take place prior to the actual process of recycling, namely disassembly, shredding and separation.
4. Closed loop recycling for plastics: Plastics constitute some of the most commonly recycled material. In closed loop recycling, the recycled plastics are used to produce the same product from which they were recovered. The new product could contain only recycled plastic, or it could be a combination of virgin plastic and recycled plastics (Ragaert et al., 2017). In the latter case, the product can continue to be recycled in the future and the material recovered from it can be added at the same rate. This is very commonly done in the case of PET (Polyethylene terephthalate).
5. Open loop recycling for plastics: In the case of open loop recycling, the recycled plastic is used in a different product. This means that the new product is unlike the old product from which the plastic was originally recovered. The new application is not necessarily of lower value. Manufacture of textile fibers from bottle (PET) or printer components from water bottle carbonates are examples of open loop recycling (Kunststofindustrie, 2015).
6. Steps in the mechanical recycling process: The process of mechanical recycling of plastics consists of the following steps, each of which can occur anywhere between not at all and multiple times in the sequence (Ragaert, 2017):
    - Separation and sorting: This step occurs based on shape, density, chemical composition, size or color.
    - Bailing: On the basis of physical location where the plastic is sorted, bailing takes place. If the processing occurs at a different location than the sorting, the plastic is bailed in between to facilitate transport.
    - Washing: The plastic is washed to remove organic contaminants.
    - Grinding: This step reduces the size of the plastic product to flakes.
    - Compounding and pelletizing: This is an optional step. During this step, the flakes are reprocessed into a granulate. The granulates are easier to use in converters.

As far as product disassembly is concerned, we have already examined this process in detail in a previous chapter of this book. But insofar as recycling is concerned, disassembly enables decomposition of the product into subassemblies or individual components, which retain their original form and characteristics.

Shredding and separation are processes that are characterized by decomposition of components and parts into random, minute pieces which can then be separated using a variety of different methods, mostly in accordance with individual material properties.

6.6 COMPONENTS OF A RECYCLING SYSTEM

The recycling system can be construed to comprise designers, recyclers, suppliers and consumers. We have already discussed the role of the designer and examined the overall product design process in the first chapter of this book. The role of recyclers to that process needs to be added.

Recyclers perform the function of dismantling the product and provide waste management services. This function can be provided by original equipment manufacturers (OEMs), an independent recycler or a contract recycler (very similar to the types of operators in remanufacturing). In this overall system, the designer controls the network and provides recycling data and assesses different decisions.

Different types of data interchange occur between the entities named above within the overall recycling system that are relevant to the end-of-life stage. The following information exchange occurs between each pair of entities.

1 Between designer and recycler:
  - Data concerning different modes of collecting, transporting ad storing the products at the end of their useful life.
  - Data concerning availability of different recycling methods.
  - Information pertaining to different markets for materials.
  - Information on properties of different materials in order to facilitate ease of sorting and separation.
  - Information concerning the existence of reusable components and their specific location, materials, whether they are harmful or valuable and information regarding how best to disassemble the product.

2 Between designer and consumer:
  - This information exchange involves tracking the exchange of parts of the product during the repair or upgrading process. The objective of this exchange is to reduce the uncertainties inherent in product recovery.

3 Between designer and suppliers:
  - Information exchange concerning the use of recovered materials in new parts, the particular specifications or reuse components.
  - Information exchanges about markets for particular materials.
  - Information about properties and quality of recycled materials and their reliability.

6.7 DESIGN FOR RECYCLING

When making a decision regarding the end-of-life options that a product is destined for, it is up to the designer to decide this early during the product life cycle. When making such a decision, the designer needs to take into account the requirements of recycling processes that may lie 15–20 years in the future. A study of relevant literature indicates the general absence of formalized rules for designing a product for recycling. As a result, a set of guidelines have been formulated based on heuristics and are presented as follows (Kriwet et al., 1995).

6.7.1 Criteria Applicable to Individual Components

- Use of hazardous and material that is otherwise environmentally harmful should be avoided.
- Standard processes such as crushing are used to recycle materials. If a material is incompatible with standard recycling processes, its use should be avoided.
- If a material can be reutilized easily, it should be given preference over other materials that are more difficult to be reutilized.
- The product should be structured in such a way that it allows for the use of recycled components. This principle will be discussed in more detail in the section on product remanufacturing.

6.7.2 Criteria Applicable to Subassemblies

- When designing subassemblies, design for recycling is facilitated by clustering materials with similar utilization compatibility.
- As with individual components, subassemblies should be designed so that the use of recycled subassemblies is feasible.

6.7.3 Criteria Applicable to Disassembly Operations

Recycling is usually performed on individual components and rarely on entire products. For instance, the steel for an automobile body is recycled. In order to perform the recycling process, it is essential to selectively disassemble the components that are destined for material recycling. Thus, the body panels of a car need to be selectively (also referred to sometimes as nondestructive disassembly, as we have already examined in the chapter on design for disassembly) disassembled from the rest of the car prior to being recycled. Thus, the disassembly process is an integral part of the recycling operation. The criteria applicable to disassembly are as follows:

- If subassemblies consist of dissimilar materials, use of joining materials that are easy to disassemble should be incorporated.
- Joining elements that are easily accessible should be designed and used for the purpose of assembly. This is a design principle that is also important when designing products for remanufacturing.

- As we have already studied in the chapter on design for disassembly, joining elements that do not require special tools are preferred to those that require special tools.
- Joining elements that are corroded pose various problems. First, they take longer to disassemble because they need to be cleaned thoroughly prior to the actual disassembly. Second, they can pose a health hazard to the person performing the disassembly. Such joints are also more difficult to access.
- Since the material is being recycled, it is not necessary to always resort to nondestructive disassembly (unlike remanufacturing). Components can be separated using destructive disassembly as well. However, this process should be avoided if it produces sharp edges.

6.7.4 Criteria Applicable to the Entire Product

- In order to improve the recyclability of the entire product, it is preferable to minimize the overall variety of materials used in the product.
- The number and variety of joining elements used in the products should be minimized.
- If there are any harmful materials and/or components used in the product, the product needs to be designed to allow easy access to them.
- Precedence relationship between parts should be avoided in order to improve accessibility.
- Paints and laminates should be avoided where possible. The product should be built along planes to facilitate access and ease of separation.

6.7.5 Criteria Applicable to Recycling Logistics

- The product should be designed in such a way that it allows for predisassembly. This makes it easy to transport after usage.
- Information about the advantages of recycling should be widely propagated. This will occur through educating the public about them. This will encourage consumers to begin recycling the products thus initiating the recycling process.
- Information pertaining to recycling should be made easily available. This includes information on material content, disassembly procedures, recycling processes and options that are available and so on.

6.8 ASSESSING RECYCLABILITY

A study performed in 1996 assessed the recyclability of automobiles (Coulter et al., 1996). Three vehicles were disassembled and the factors that influenced their recyclability were determined. The recyclability of the automobiles was based on two ratings for the various components of the cars. Specifically, these ratings were termed as recyclability rating and material separation rating. These ratings are presented the following tables. The recyclability rating is presented in Table 6.1 and the material separability ratings is presented in Table 6.2. In Table 6.1, examples of individual parts that can be recycled are graded on a scale of 1 through 6. A score of 1 represents

TABLE 6.1
Recyclability ratings for automobiles with examples of parts

Rating	Description	Examples
1	Part is remanufacturable	Starters, alternators
2	Material in the part is recyclable with a clearly defined technology and infrastructure	Most metals Catalytic convertors
3	Technically, it is feasible to recycle the material, but the infrastructure to recycle the material is not available	Most thermoplastics Glass Seat foam
4	Technically, it is feasible to recycle the material, but further processes and material development are required	Armrests Steering wheels Airbag modules
5	Material can be used for energy recovery because it is organic but cannot be recycled	Headliners Wood products
6	Material is inorganic with no known technology that can be used for recycling	Heated glass Fiberglass headliners

Source: Coulter et al. (1996).

TABLE 6.2
Ratings for material separability

Rating	Description	Examples
1	Material may be disassembled with ease manually; it takes approximately one minute to achieve disassembly	Cover of lower steering column
2	Material may be disassembled manually, but with some effort; it takes approximately one to three minutes to achieve disassembly	Instrument cluster, radio
3	Material may be disassembled with some effort and requiring some mechanical means or shredding Mechanical means are required to separate component materials (*the process for doing so has been fully proven*)	Engines, sheet metal
4	Material may be disassembled with some effort and requires some mechanical separation and shredding; mechanical means are required to separate component materials, *but the process is currently under development*	Instrument panels
5	It is not possible to disassemble the materials; no known process exists to achieve separation	Heated backlights

Source: Coulter et al. (1996).

a part that is remanufacturable and a score of 6 represents a part that cannot be recycled at all. As far as recycling is concerned, the highest score that a part can possibly achieve according to this grading system is a “2.” Examples include most metals and catalytic convertors.

6.9 MANUAL MATERIAL SEPARATION VERSUS MECHANICAL SEPARATION

It is obvious from Tables 6.1 and 6.2 that when products are designed so as to facilitate manual material separation, they are easier to recycle as compared to when material separation has to be performed mechanically. Recovery of metal from the vehicle as a whole is an example of mechanical material separation. In this case, it is possible to easily recover the steel after having shredded the vehicle. But doing so manually would be quite difficult. The distinctly different requirements of manual material separation and mechanical material separation are described here.

- Manual material separation: If the design goal is to simplify the process of material separation to the point that it can be performed manually, it requires more effort on the part of the product designer. This is because it requires more effort to improve the disassembly and sorting process. Manual separation is facilitated by reducing the amount of time required to separate and identify the material. This makes the process economically more feasible. To put it succinctly, design guidelines for this process should suggest different ways by which manual disassembly effort is reduced. Design guidelines that result in being able to more easily identify the material visually should also be included.
- Mechanical material separation: If the product is being designed with the ultimate goal wherein the materials can be easily separated mechanically, the assembly or component should be designed such that they can be separated easily and quickly into pure material streams. These material streams are based on material properties. The material properties should be distinctly identifiable. Thus, although disassembly effort and visual identification are not that important, material selection is critical (Coulter et al., 1996).

6.10 DESIGN GUIDELINES FOR MATERIAL SEPARATION

We have examined the critical role played by material separation in designing products for ease of recycling. Material separation can be facilitated by adhering to the following design guidelines.

- Whether or not a complex assembly can be economically recycled depends upon the extent to which it can be separated into pure material streams.
- As we have examined in the previous section, both manual material separation and mechanical material separation have their respective advantages and applications.
- Materials should be manually separated only if significant value is retained in a part.
- Depending on whether manual separation or mechanical separation will be adopted, different design techniques should be used. This will lead to distinct designs (Coulter et al., 1996).

6.11 APPLYING MATERIAL SELECTION GUIDELINES TO DIFFERENT SCENARIOS

Most products comprise two main constituents, namely individual components and fasteners. Each of these is made of some type of material, which is our primary interest when designing product for ease of recycling. The aforementioned design rules are applied to various parts of a product in accordance with the type of material that was selected for that part. Thus, material selection plays a critical role in incorporating design features into a part. This section provides specific examples of such design decisions.

1 Component design: Modern automobiles incorporate large number of electronic items such as radios, instrument clusters, climate control units, engine control units and so on. Most of these items, by themselves, are very difficult to disassemble manually. There is one exception though. The housing for such items constitutes the largest volume of material that can be recycled. Thus, mechanical disassembly of the housing can be accomplished easily if the right material is chosen.

2 Fastener design: If a casing is made from thermoplastic, it would be advisable to use snap fits or even a few screws if the goal is to separate it manually. If, on the contrary, the same casing was to be separated mechanically, it could be welded together sonically. In this instant, the case would be shredded prior to separating the material (Coulter et al., 1996).

3 Material selection: Of the different types of plastic, thermoplastics are separated based on material density. This type of plastic is often used in automotive instrument panels. If such a panel is to be disassembled manually, it could utilize a top spin substrate composed of a blend of polycarbonate and ABS (specific gravity of about 1.1). This could be used together with a module case made from glass-filled polypropylene with the same density (Coulter et al., 1996).

If the goal was to separate the instrument panel mechanically, it would not be possible for the above materials to be separated. Also, the polypropylene and ABS are incompatible for recycling. This would render both component unrecyclable (Coulter et al., 1996). Thus, it would be necessary to select some other material combination that is compatible for recycling.

6.12 WHAT IS REMANUFACTURING?

Remanufacturing can be defined as a process that involves restoration of old, broken products to “like new” condition by rebuilding and replacing their component parts. It involves a considerable amount of restoration. The “like new” state is not only aesthetic but also functional in nature. The process is also referred to by the more popular term: “Reman.” The old, broken products are referred to as “cores.”

The definition of remanufacturing is sometimes extended based on the end use of the remanufactured product or component. If new features are built into the product during remanufacture, the process is referred to as upward remanufacturing.

Succinctly, the process is defined as disassembly, cleaning, inspection, repair, replace and reassembly of the components of a part or product. The goal is to return it to “as new” condition and structure it into a new or “next generation” system (Nasr and Thurston, 2006). The distinction between upward remanufacturing and remanufacturing is quite clear.

The process of remanufacturing involves the collection of reasonably high volumes of similar products in a central place. These products are then disassembled and treated to be reused or upgraded (Sundin, 2004).

While remanufacturing has been widely practiced in the US and Europe, it is beginning to gain in importance in countries such as China. One of the reasons for this phenomenon is the fact that the number of vehicles on Chinese roads has seen a dramatic increase in recent years (Hatcher et al., 2013). Also, it has been shown that manufacturing generates more than 60% of annual nonhazardous waste (Nasr and Varel, 1996). End-of-life processes such as remanufacturing help alleviate the detrimental environmental impact of products and manufacturing processes. For instance, landfill can be reduced by requiring producers to recover used products by resorting to practices such as remanufacturing.

A very broad spectrum of products is remanufactured every year. This industrial process can be readily applied to the following disparate types of products, to name a few:

- Personal computers.
- Photocopiers.
- Cathode ray tubes.
- Industrial robots.
- Vending machines.
- Construction equipment.
- Medical equipment.
- Heavy duty engines.
- Aircraft parts and military vehicles.
- Cellular phones.
- Automobile parts.

It should be obvious from this list of products that the process of remanufacturing is almost universally relevant in our everyday life. Many companies in the automobile component remanufacturing sector often use the term “rebuilding” instead of remanufacturing. Tire manufacturers refer to themselves as “re-treaders” and companies remanufacturing laser toner cartridges refer to themselves as “rechargers” (Sundin, 2004).

Remanufacturing contributes to environmental sustainability by being less harmful to the environment than conventional manufacturing. It can also be profitable. Environmental sustainability is achieved by reducing landfill and levels of virgin material, energy as well as specialized labor used in the manufacturing process (Lund, 1984; Lund, 1996; Guide, 1999; Hormozi, 1996; McCaskey, 1994).

In order to restore a used product to “like new condition” through remanufacturing, a variety of subprocesses need to be adopted. They are delineated as follows.

1. Inspection: The used product needs to be thoroughly inspected for signs of wear, corrosion and so on.
2. Disassembly: The used product needs to be either partially or totally disassembled in order to access worn out and/or obsolete components. These components can then be repaired or replaced in order to return the product to "like new" condition. Please refer to the chapter on product disassembly for more detailed information on this topic.
3. Cleaning: The used product needs to be cleaned of grease and grime to further upgrade its condition.
4. Reprocessing: The used worn out and/or obsolete components are replaced and reprocessed. This is a critical step in the remanufacturing process. It should be borne in mind that only some components can be repaired; it is not possible for all components to be repaired. In such cases, they will have to be replaced with new components. In such cases, the remanufactured product may be sold at a lower price than its new counterpart. Even so, it is still offered with an equal warranty as a new product (Amezquita, 1996).
5. Reassembly: During this stage, the product is put back together or reassembled. This is important in order to ensure the functionality of the product as intended. Please refer to the chapter on product assembly for more detailed information on this topic.
6. Testing: No matter how well the product has been repaired, reprocessed, cleaned and reassembled, it still needs to be tested in order to verify that it does indeed function as intended and as close to a new product as possible. This is ensured by the testing phase.

6.13 COMPARING PRODUCTS THAT HAVE BEEN REMANUFACTURED, RECYCLED, RECONDITIONED AND REPAIRED

While remanufactured products are everywhere and the advantages of the process are seemingly numerous, it is still important to put the process in perspective. Remanufacturing is not the same as recycling. The two processes are substantially different. Remanufacturing is often preferred to recycling. The reason for this is because remanufacturing adds value to waste products by returning them to working order. Recycling, on the other hand, breaks down the used product to its raw material value (Ijomah et al., 2007). .Assuming that the product being remanufactured is in keeping with the production characteristics for the process, the amount of energy required to remanufacture a product is substantially less than that required for recycling (Lund, 1996).

Remanufacturing is also often confused with the term reconditioning. It should be remembered that while a remanufactured product has a warranty equal to that of a new product, a reconditioned product does not offer a similar warranty.

A remanufactured product is also substantially different from a product that has been "repaired." In the case of a repaired product, specific faults in the product have simply been repaired. Although a remanufactured product often requires more work and thus higher level of upfront energy, expense, effort and time than a reconditioned or repaired product, it results in an end product that exhibits better quality and an extended useful life (Hatcher et al., 2013).

Thus, when compared to other end-of-life processes such as recycling, reconditioning and repair, remanufacturing results in greater amount of energy savings and is considered more cost effective (Amezquita, 1995).

6.14 WHAT TYPE OF PRODUCTS CAN BE REMANUFACTURED?

We have discussed the obvious advantages of the remanufacturing process. So, is it possible to remanufacture every product when it reaches the end of its useful life? Not quite. In principle, in order to be remanufactured, a product should exhibit a high degree of durability. Technically speaking, it should exhibit the following properties:

- In order to be remanufactured, a product should be able to withstand multiple lifecycles. In other words, it should be durable enough that it can be reused, albeit in modified form. An automobile engine is an example of such a product.
- A remanufacturable product should contain high value parts. A value part is defined as a part that is worth investing in. An aircraft engine with its turbines (part of high value) is an example of such a product.
- In order for a product to be remanufactured, it is important that there is market demand for such a product. Examples of remanufactured products on the UK include automotive products, pumps and compressors and off-road equipment (Berko-Boateng, 1993).
- Efficiency of the remanufacturing process also depends to a large extent on design variables. We have already discussed the importance of such variables in chapters on design for assembly and disassembly. Design variables are defined as variables that are largely within the control of the designer. Attributes and design features such as product architecture, choice of materials, choice of fastening and joining methods and so on directly impact constituent processes such as disassembly, reprocessing, reassembly. This understanding has led to the formulation of design for remanufacturing (DfRem) guidelines. In spite of this, very few companies currently use these guidelines or actively design their products for ease of remanufacturing (Fiksel, 1996).
- In general, the following four properties are found to be the most technically relevant and important for remanufactured products and its parts (Sundin 2004):
    1. Accessibility: This property refers to the ease with parts can be accessed. Better accessibility implies greater ease of manufacturability. This is a design feature. Please refer to the chapter on design for disassembly to further understand this concept better.
    2. Ease of identification: This property refers to the ease with which parts can be identified. Greater ease of identification generally results in greater ease with which products can be remanufactured.
    3. Wear resistance: This property refers to the fact that a product or a specific component can withstand greater degrees of wear during use. As such, such products tend to have a greater longevity and are ideal candidates for remanufacturing.

TABLE 6.3
Relationship between generic remanufacturing process steps and preferred product properties

	Remanufacturing step						
Product property	**Inspection**	**Cleaning**	**Disassembly**	**Storage**	**Reprocess**	**Reassembly**	**Testing**
Ease of identification	X		X	X			X
Ease of verification	X						
Accessibility	X	X	X		X		X
Ease of handling			X	X	X	X	
Ease of separation			X		X		
Ease of securing						X	
Ease of alignment						X	
Ease of stacking				X			
Resistance to wear		X	X		X	X	

Source: Adapted from Sundin (2004).

4 Ease of handling: This property refers to the ease with which a product or component can be handled. Once again, this is a design feature and is a function of design attributes such as shape and size of the product/component, its material and so on. Please refer to the chapters on design for assembly and disassembly to gain a better understanding of these attributes. A product/component that is easy to handle is also, in many cases, easier to remanufacture. Table 6.3 illustrates the correlation between different product properties and different steps inherent in the remanufacturing process.

6.15 CONDITIONS NECESSARY FOR REMANUFACTURING TO BE PROFITABLE

Although it is possible to remanufacture products exhibiting the technical characteristics enumerated in the previous section, the profitability of the process depends on a different set of variables. Some of these variables are related to those presented in the above section (such as nature of cores), while others are different. They are described here.

- For a remanufacturing process to be profitable, it is necessary that the product contains a core, which is not consumed, discarded or is not functional (Lund, 1996).
- Remanufacturing can be profitable only if the product can be restored to its original state by using currently prevailing technology.
- It is difficult for remanufacturing to be profitable if it must rely on single-part manufacturing processes. The ability to be mass produced in a factory contributes significantly to the profitability of remanufacturing.

- After the product has been remanufactured, it is important that its value is close to the original product's market value. This is crucial for the profitability of the remanufacturing process.
- One of the key processes inherent in the remanufacturing process is the collection and acquisition of discarded and failed products. The profitability of remanufacturing depends on the extent to which such products can be acquired at relatively low cost. The acquisition cost should be low relative to the market value of the remanufactured product.
- The product design should be relatively unchanged if remanufacturing is to be profitable. Similarly, the underlying technology responsible for manufacturing should not be subject to rapid changes. If product design and/or technology changes constantly, it is quite difficult to keep pace with such changes resulting in reduced profitability.

6.16 TYPES OF REMANUFACTURERS

Given that remanufacturing is primarily a process that occurs at the end of life of a product, remanufacturing companies are variously related to the original product manufacturer. Original product manufacturers are also referred to as OEMs. Depending on their relationship with the manufacturer of the original product, remanufacturers are further subdivided into three categories. They are described in detail as follows:

- Original equipment remanufacturers (OEM): They are OEMs that remanufacture their own products. They are also referred to by the acronym OERs. Products that arrive from service centers, trade-ins from retailers and end-of-lease contracts are remanufactured by the OEM/OERs. The reason for this is because the process of remanufacturing is profitable for such companies. They can also offer a wider price range of products to their customers. Another distinct advantage that OEM/OERs possess is that they already have access to all relevant information pertaining to product design, service knowledge and logistical information such as availability of spare parts.

  In the case of OEM/OERs, the remanufacturing process could either be integrated with the original manufacturing process or it could be distinct from it. Product could either be entirely remanufactured or parts from the remanufactured products could be used in manufacturing. Examples of OEM/OERs include companies such as Caterpillar and FUJI Film. In the case of Caterpillar, several products such as engines (which the company manufactures) are also routinely remanufactured. In the case of FUJI Film, on the contrary, the company remanufactures its own single-use cameras at the same facility that it manufactures them (Sundin, 2004).
- Contracted remanufacturers: Contracted remanufacturers are companies that remanufacture products for other companies under contract. While the OEM manufactures the product, the remanufacturing is performed by a different company. After the remanufacturing has been accomplished, the remanufactured products are available for sale albeit at a lower price. As far

as the remanufacturer (independent company in this case) is concerned, the process offers several advantages. For instance, the remanufacturing operation signifies a predictable and stable revenue stream characterized by a considerably lower requirement for working capital. The OEM often assists the remanufacturer in the process by providing assistance in the form of replacement parts, tooling as well as design and testing specifications (Lund, 1983). Our-Way Inc., a refrigeration compressor remanufacturer based in Atlanta, is an example of a contracted remanufacturer.

- Independent remanufacturer: Independent remanufacturing companies are distinguished from contracted remanufacturers in that they have very little contact with the OEM. Such companies receive compensation from the previous owner or distributor to collect end-of-life products (Jakobsson, 2000). It is imperative for such companies to purchase spare parts for the products that they are remanufacturing. Independent remanufacturers often rely on an integrated operation that is characterized by purchasing cores, remanufacturing cores and marketing finished products either under its own name or under the private label of some other company. Relationship between independent remanufacturer and OEMs is mostly nonexistent and is not projected to not likely row in the future (Hammond et al., 1998). 24 Hour Toner Services, a toner cartridge remanufacturer based in Toronto, is an example of an independent remanufacturer. It should be mentioned at this juncture that a remanufacturer could contract some of its products with OEMs. For instance, Electrolux AB—a household appliance manufacturer based in Sweden—remanufactures two types of appliances. First, they remanufacture their own appliances. They also remanufacture appliances for a Danish leasing company L'Easy under contract.

It is clear from Table 6.4 that unlike manufacturing operations, used products are not necessarily owned by the company remanufacturing them (remanufacturer). To quote an example, from a 1983 investigation, 127 remanufacturers were asked, whether the "used product" was owned by them, the "product user," the OEM or by someone else. The question was asked across different market segments such as automotive, industrial and commercial. Table 6.4 depicts the responses to this question based on market segment.

It can be observed from Table 6.4 that if the remanufacturer has a contract with the OEM or if they are somehow related to the OEM, the OEM usually retains ownership of the product. Thus, money accrued as a result of building up the inventories of remanufactured parts is retained by the OEM. On the other hand, if the part has been remanufactured by a contract remanufacturer, the money retained by stored parts and work in process (WIP) is connected to the OEM. On the basis of the laws of extended producer responsibilities, the manufacturer of the product is responsible for end-of-life treatments, not the remanufacturer.

6.17 GUIDELINES FOR DFREM

DfRem can be considered to be part of a larger design for environment (DfE) approach, which has been defined by Dewberry and Goggin (1996) as an approach to design

TABLE 6.4
Remanufacturing product ownership based on market segment

Market segment	Remanufacturer (%)	Product user (%)	OEM (%)	Other (%)	Total number
Automotive • Includes automobiles, trucks, buses, motorcycles and their parts	94	4	2	0	54
Industrial • Includes all types of equipment and machinery used in manufacturing or construction.	64	25	6	5	45
Commercial • Includes all equipment used in trade or service type businesses	51	39	6	4	28
					127

Source: Sundin (2004).

wherein all environmental impacts of a product over its useful life are considered. Manufacturing companies can substantially reduce their impact on the environment using DfE strategies. The DfE approach is based on the design for X (DfX) philosophy. In order to better understand DfRem guidelines, it would be appropriate to first consider the DfX method stepwise. The different steps of DfX are presented in a bulleted format as follows (Huang, 1996):

- Collect and present facts pertaining to product and processes.
- Analyze extant relationships between products and processes.
- Gauge performance.
- Identify and analyze strengths and weaknesses and compare alternatives.
- Analyze a design from the point of view of redesigning it.
- Analyze design tradeoffs and “what if” effects.
- Implement design improvements.
- Perform iterations in the design process in order to optimize the design for the particular X under consideration.

The major DfRem considerations are described succinctly as follows:

1 Material selection: Selecting the appropriate material is at the core of any process involving product design and development. We have already discussed this at some length in chapter 1 of this book. Material characteristics play a crucial role in remanufacturing processes as well. For instance, consider the example of an engine block that is being remanufactured. Such a product could undergo several processes throughout its entire life cycle. This means it could be remanufactured several times using different processes. In order to successfully perform such operations, it is important that the block be

made from a durable material that also exhibits other characteristics such as high resistance to corrosion, resistance to wear as well as satisfactory fatigue resistance (Yang et al., 2016).

2 Type of material joining method: Material joining method implies the manner in which different materials and components are joined and connected together. This typically involves fasteners such as nuts, bolts, rivets, screws, staples, retaining lugs, adhesive joints, welds, crimps, magnets and so on. This is a very important design feature especially from the perspective of remanufacturing. This is because products are remanufactured at the end of their useful lives. The type of material used in the joining method plays an important role in deciding end-of-life options. The manner in which parts are joined together has a crucial bearing on whether the product can be reused, recycled or remanufactured. It is generally not desirable for any valuable component to inadvertently undergo damage during disassembly since it may render the part and sometimes the entire product unusable. For instance, consider two parts that have been joined using a built-in spat fit. We have already seen in the chapter on design for assembly that snap fits reduce assembly time significantly and are thus being increasingly used to join distinct parts together. However, the situation is quite different when the product is destined for remanufacturing at the end of its useful life. Although snap fit may provide fast assembly and disassembly, a failed or broken snap fit cannot be salvaged very easily and renders the part in question unfit to be reused.

3 Design of product structure: Remanufacturing of complex products is a challenging task. As we have seen before, this process involves several individual processes such as disassembly, cleaning, reassembly and so on. It is important to resort to nondestructive disassembly in order to separate components. Component design characteristics such as the number of components, design tolerance, component shape and their positioning also directly impact the efficiency of other remanufacturing processes such as cleaning, inspection, reconditioning and so on (Yang et al., 2016). For instance, a part that needs to be replaced on a frequent basis but is located deep inside the product structure and is difficult to access will have a detrimental impact on the efficiency of the remanufacturing process.

4 Surface coatings: Surface coatings are generally used when a substrate material has been selected for its bulk design characteristics. These characteristics are in contradiction to its surface design properties. Surface coatings are applied to the substrate in order to meet those requirements (Yang et al., 2016). The requirements can include properties such as wear, corrosion, aesthetic purpose or surface fatigue resistance. If a surface coating method is improperly selected, it can increase the frequency at which the product fails due to material wear or corrosion. It can also make the product remanufacturing process especially burdensome. This is because a very smooth surface coating is likely to take a substantial amount of effort to be restored to a “like new” condition. Conversely, if the coating is too coarse, it is likely to act as a dirt trap and unnecessarily complicate the cleaning process.

Table 6.5 illustrates design features that affect the ease with which a product can be remanufactured. A score of 1 implies that the design feature (such as using screws or rivets) has a low impact. A score of 4, on the other hand, points to a design feature that has a high impact.

High-level designs for remanufacturing guidelines are presented in Table 6.6. These are based on findings collected from literature and case studies. Product

TABLE 6.5
Design features that affect ease of product remanufacture

1 Low-impact	**2**	**3**	**4 Very high–impact**
Design features	**Problems identified**	**Impact severity**	**comments**
Type of assembly		1–4	Assembly type may hinder disassembly, an essential and initial activity that could altogether hamper remanufacturability
	Screws	1	Time consuming but does not make remanufacturing impossible
	Rivets	2	Time consuming but does not make remanufacturing impossible
	Welding	3–4	Difficult if not impossible to disassemble; depends on the type of weld
	Strong adhesive such as epoxy	4	If the adhesive is very strong, it can completely prohibit disassembly
Complexity of products		3	
	Many components	2	Many components require more resources for testing and remanufacture
	Product dimension	2	Size and weight can impede remanufacturing by obstructing access to damaged components
	Arrangement of internal components	2–3	Spatial arrangement of internal components may lead to wear due to friction between parts; also, parts, especially damaged ones may be difficult to access, thus hindering the ability to remanufacture the product: Could be caused due to ineffective communication between end user, remanufacturer, manufacturers and designers
	Coatings	2	Remanufacturing can be hindered due to ineffective and unnecessary coating, for instance, Teflon coating that flakes may result in debris that causes damage to components
Materials		4	It is not possible for nondurable materials to be remanufactured; banned materials will also hamper remanufacturing.
Design cycle		3	Resources need to be expended to stay abreast of current trends

Source: Ijomah et al. (2007).

TABLE 6.6
High-level guidelines for product remanufacturing

	Characteristics of product/design		
Process activities	**Material**	**Technique of assembly**	**Structure of product (dimensions, internal arrangement and external features)**
Product disassembly	If components are to be reused, it should be ensured that their materials are sufficiently durable to survive disassembly	Assembly methods that allow disassembly without damaging components should be used	Components should be arranged to achieve easy disassembly
	The material of the fasteners should be similar or at least compatible with that of the base material, which would limit the opportunity to damage parts during disassembly		Total number of parts should be reduced
			Complexity of disassembly should be reduced, for instance, by using standardized fasteners
			Complexity of disassembly can be reduced by using modular components, thus reducing the different types of assembly techniques
			Components should be arranged in a manner that allows for easy access and identification of separation joints
			Number of joints should be minimized
			The number of redundant parts should be reduced and/or eliminated
			Component fits should be simplified and standardized
Cleaning components	Cleaning material that would survive cleaning processes should be used, for example, material whose melting point is higher than cleaning process temperature should be used	Only those assembly methods that allow disassembly to the point that internal components can be accessed during cleaning should be used	All parts to be cleaned should be easily accessible
	The number of material types per part should be limited		Redundant parts should be reduced or eliminated

(*continued*)

TABLE 6.6 (Cont.)

	Characteristics of product/design		
Process activities	**Material**	**Technique of assembly**	**Structure of product (dimensions, internal arrangement and external features)**
	Components requiring similar cleaning procedures and cleaning agents should be identified		Components should be arranged so that all can be accessed for effective cleaning
			It should be ensured that product surfaces are smooth and wear resistant
Remanufacturing components including test components	Only materials that are at least durable enough to withstand the remanufacturing process should be used	Assembly methods should be used that allow disassembly at least to the point that internal components and subsystems requiring work can be accessed	Redundant parts should be reduced or eliminated
	Materials that do not prevent upgrade and rebuilding of the product should be used	Only use assembly methods that do not prevent the product from being upgraded	Product should be structured to facilitate ease of product upgrade
	Component material should be identified	Joining methods should be used that allow disassembly at least to the point that internal components and subsystems that require it can be accessed for testing pre- and postrefurbishment.	Components should be arranged so that parts prone to damage are easily accessible
		Fault tracking devices should be incorporated	Standardized parts should be used
			Structure of the product should allow for determining component condition easily
			Product structure should allow for sequential testing: Reassembly order should be mirrored

			Disassembly level required to effectively test components should be minimized
			Test procedures should be standardized
			Component load limits, tolerances and adjustments should be clearly identified
Product assembly	The number of different materials should be limited	Components requiring similar assembly tools and techniques should be identified	Structural complexity should be reduced
		Assembly methods should not prohibit disassembly without damage to reusable components	Sequence of component assembly should be identified
		Assembly methods should simultaneously facilitate easy disassembly without damage to reusable components	Redundant parts should be reduced
		Design for assembly methods should be used: These methods should not prevent disassembly and should not damage components	Parts should be standardized
		Complexity of reassembly should be reduced by taking actions such as standardizing fasteners	Product should be structured to facilitate access to parts that have a short life and are prone to breakdown easily
			Modular structure should be adopted in such a way that obsolescence occurs with components and not the entire product

Source: Ijomah et al. (2007).

design characteristics are clearly enunciated for each type of activity inherent in remanufacturing (such as disassembly, cleaning, assembly and remanufacturing).

DfRem consideration from the perspective of material selection, joining method, product structure and surface coatings is depicted in Table 6.7.

6.18 BENEFITS OF REMANUFACTURING

As far as the OEM is concerned, remanufacturing offers the following benefits:

- Given the fact that the OEM manufactured the original product, it has complete access to the product's design content and specifications. Thus, it is also in the unique position to estimate not only the durability but also the reliability of the product. Access to the aforementioned information enables the OER to appropriately plan the remanufacturing process. Decisions pertaining to the nature of material that can be recovered from the product, how the material and product can be modified as well as the disassembly process inherent in remanufacturing are facilitated. The same can be said for decisions on the level of required maintenance.
- After having manufactured the product, the OEM sells it. As such, an established network for the distribution of the original product is easily accessible to the OEM. Since the OEM is also the OER, the same can be said for the OER. Thus, the OER also has access to the same network for the distribution of the remanufactured product. It can also access the network for the collection of discarded products. The OER is also able to build a relationship with the customer. The information obtained through this relationship can be used in the remanufacturing operation in terms of the nature of end-of-life products, the relevant schedule and quantities.
- In order to manufacture its products, the OEM needs to first establish a supplier network to enable it obtain original parts. The OER can also rely on the same network to obtain original parts for the remanufactured product. These parts would be difficult to procure from other vendors in the absence of the supplier network. It should be mentioned that such is the condition of independent remanufacturers who do not have access to a similar network. They must depend on replicas of parts and components or purchase them directly from the OEM.
- It is also possible for the OEM to leverage the knowledge gained from its supply chain network to better understand its customers. This information provides valuable insight into user patterns and can be used to evaluate residual value in discarded products.
- Information gained from its customers also enables the OEM to market its products better. One of the advantages lies in the fact that the market size can be determined more accurately. This can in turn enable the OEM/OER to remanufacture products based on demand that has been more accurately estimated. The remanufactured products can also be better marketed to a segment of the market that is more receptive to such products.

TABLE 6.7
DfRem considerations

	Material	**Material Joining method**	**Product structure**	**Functional and decorative surface coating**
Durability	• Corrosion resistance • Wear resistance • Fatigue resistance	• Corrosion resistance		• Wear/corrosion/fatigue resistance: Functional coating • Fingerprint/scratch resistance: Decorative coating • Adhesion
Ease of disassembly and assembly		• Nondestructive disassembly (including fastener/joint) • Nondestructive disassembly (excluding fastener/joint) • Destructive disassembly (for recycling) • Ease or reassembly	• Modularity for easy separation • Accessibility to valuable and reusable components	
Ease of cleaning	• Ease of removing impurity and deposit • Resistance to cleaning		• Avoid intricate or unnecessary concealed design form	• Ease of removing contaminants (coating removal not required) • Potential damage to the substrate (coating removal is required)
Ease of restoration and ease of upgrading	• Ease of machining • Ease of receiving additive process • Ease of receiving conditioning process • Reliability of the reconditioned part		• Accessibility to the failure prone parts • Tolerance design for multiple cycles • Modularity for replacement/upgradability	

(*continued*)

TABLE 6.7
(Cont.)

	Material	Material Joining method	Product structure	Functional and decorative surface coating
Environmental health and safety	• Recyclability • Air emissions and waste disposal • Toxicity • Scarcity of raw material • Laws and regulations	• Compatibility with other parts • Toxicity		• Air emissions and waste disposal • Recyclability • Law and regulation
Cost	• Cost of raw material	• Labor cost • Capital cost		• Labor cost • Material and energy consumption • Capital cost
Complexity	• Number of materials	• Number of fastener/joint types • Number of fasteners/joints • Tool standardization • Accessibility to fastener/joint	• Number of parts and components • Standardization of parts and components	

Source: Yang et al. (2016).

- Since the OER is essentially the OEM, the OER can leverage the reputation of the OEM for producing high-quality products. This can go a long way in convincing customers of the reliability of the company's remanufactured products.
- For all practical purposes, the process of remanufacturing consists of reversing some part of the processes inherent in manufacturing products. As such, the infrastructure necessary for the manufacturing process is already in place. All the OER needs to do is reverse pertinent parts of the manufacturing process in order to accomplish remanufacturing. This reduces the need for additional investments. Readers will appreciate that the same cannot be said for independent remanufacturers.
- Generally, the manufacturing process involves much higher quantities than remanufacturing. As such, it allows for greater amount of investment in advanced equipment that can be used for remanufacturing as well.
- From the economic perspective, it is possible for the OEM to earn a higher profit margin due to the remanufacturing process. This is because parts recovered as a result of remanufacturing can also be used in the manufacturing process. This can provide a higher rate of return than if the parts were to be sold individually.
- From the design perspective, it would be to the designers' advantage to carefully monitor how well their designs perform during use as well as end-of-life phases. Doing so would enable them to modify their designs with the objective of making the product easier to remanufacture. This is, after all, the gist of DfRem.
- An OER generally tends to exhibit a higher worker productivity attributable to its factory methods. It also tends to make efficient use of its facilities, equipment and energy.
- Also, production volumes at such companies tended to be large enough that machines with at least a partial degree of automation could be utilized. Such machines are usually more expensive, and their higher cost can only be offset by producing in large quantities. The advantage of using such machines is that they can do away with a large degree of skilled labor.
- By its very nature, remanufacturing consists of salvaging more material. This reduces the need for virgin material and can do away with the higher cost of new parts (Lund, 1983).

Whether or not a company should remanufacture a product is always a management decision. Management decisions can be classified as strategic, tactical or operational in nature. They are described in more detail here. Examples are provided as appropriate.

- Strategic decision: Strategic decisions constitute decisions that are made to shape the long-term future of a business. From the point of view of remanufacturing, these decisions assess whether adopting the decision to remanufacture is strategically beneficial for the company. It is obvious that such a decision must be taken prior to the establishment of remanufacturing activities (Goodall et al., 2014). Remanufacturing decisions have been successfully incorporated into a business in a variety of scenarios such as:

1. The decision to remanufacture an entire product was taken in the case of single-use cameras. The remanufacturing was performed by independent third-party remanufacturers.
2. Automotive spare parts are often remanufactured in the form of aftermarket spare parts. The remanufacturing is performed by OEMs and licensed third-party remanufacturers.
3. Electronic game consoles are remanufactured under warranty (OEM or licensed third party).
4. Wind turbine gearboxes are remanufactured as a product/part service system. This means that the remanufacturing process is performed by an independent third-party remanufacturer.
5. Photocopiers are remanufactured as a product service system.

- Tactical decision: Tactical decisions are primarily medium term by nature. The objective of tactical decisions is to provide a method to implement the strategy that was picked by decision makers. From the point of view of remanufacturing, tactical decisions consider which products should be remanufactured (Goodall et al., 2014). The tactical decision is based upon specific product types and models in particular. It is important to develop general rules and heuristics at a tactical level in order to arrive at a logical decision as to which products to remanufacture. This is an important consideration because a typical remanufacturer routinely receives a range of cores for remanufacturing. These cores represent a large variety of product models and OEMs. Remanufacturers that deal with high value and low quantity products tactically assess products on a per product basis.
- Operational decision: Day-to-day decisions are characterized as operational decisions. In the context of remanufacturing, these decisions focus on evaluating individual products and components. Operational decisions made inside a remanufacturing facility are largely based on inspection operations. The main goal of an inspection operation is to weed out components and products that are not suitable to be remanufactured. We have already considered the different factors that contribute to the remanufacturability of a product. It is important to inspect products and components against such metrics in order to conserve precious resources by not resorting to unnecessary processing. Inspection decisions typically occur at different steps of the remanufacturing process. Different types and degrees of information are gained at each step. Inspections can range from virtual inspection to specific inspections. Virtual inspections rely on a pretty sophisticated infrastructure consisting of embedded sensors and conditional monitoring networks to collect and analyze information (Jun et al., 2007). Visual inspections, on the contrary, are the most widely used form of inspection. It is a quick and inexpensive form of inspection that is typically performed early in the remanufacturing process, mostly by operators who are trained to identify specific faults. Operators are trained to quickly assess the remanufacturability of products through visual inspection. Examples of specific inspection methods include those relying on metrological measurements and physical testing.

TABLE 6.8
Decision stages to assess feasibility of remanufacturing

Decision stage	Purpose	Information contained with description of product	Potential users
Strategic	Provide an early feasibility analysis of adopting remanufacturing within a business strategy	General product type	High-level management, senior and middle management
Tactical	Analyze and evaluate a product strategy for remanufacture	Specific model, product structure and bill of materials could be included	Middle management, operational management and design engineers
Operational	Evaluate a particular product for remanufacture, which can occur remotely or during inspections at a remanufacturing facility	Detailed product structure including information about product condition; other process information such as inventory levels and factory capacity may also be included	Idle management and operational management

Source: Goodall et al. (2014).

The decision stages for assessing the feasibility of remanufacturing are presented in Table 6.8.

There is a high level of uncertainty associated with the returned product cores. This introduces a significantly higher uncertainty and therefore risk in remanufacturing operations as compared to traditional manufacturing. The uncertainty is attributable to lack of information flow between early life cycle phases and the remanufacturer.

In particular, the uncertainty pertains to three factors as follows:

- The condition of product returns.
- The design and physical structure of product returns.
- The timing and quantity of product returns.

The effect of each source of uncertainty on decision making and its possible solution is presented in Table 6.8. For instance, if the condition of returned core is the source of uncertainty, Table 6.9 illustrates the impact it has on the different levels of decision making and proposes possible solutions to the problem.

The different factors affecting DfRem are encapsulated in Table 6.10.

6.19 METRIC DEVELOPMENT FOR ASSESSING REMANUFACTURABILITY

A remanufacturing metric was designed by Bras and Hammond (1996) to assess product designs for ease of remanufacturability. The metric focuses on issues that are directly affected by mechanical aspects of product design. For this reason, market issues such as core and parts availability are excluded from the metric. Core and parts

TABLE 6.9
Sources of uncertainties in remanufacturing, their effects and solutions

Source of uncertainty	Effect on decision making			Solutions
	Strategic	Tactical	Operational	
Condition of returned core	Added complexity in identifying the effect of long-term decision factors	Assessing the impact of uncertainties upon performance metrics including cost, quality, time and environmental impact	Measure and quantify quality of core accurately	Incorporation of multiple inspection stages Obtaining middle of life (MoL) product information
Type of returned product and design information			Determine the evaluation criteria	Important to establish links with OEM to obtain product information Need to obtain store product information obtained from experience
Quantities and timing of returns			Note inventory and production planning issues are complicated	Establish contacts with core suppliers. Offer cash back for cores.

Source: Goodall et al. (2014).

TABLE 6.10
Various factors affecting DfRem

Technical factors	Market factors	Operational factors
Ease of disassembly	Customer perceptions	Management
Ease of assembly	Product life cycle thinking	Customers
Ease of identification	Design for upgrade	Design process
Stackability		Knowledge and understanding
Accessibility		Suppliers
Resistance/durability		Cooperation
		Motivation

Source: Adapted from Hatcher et al. (2013).

availability is important to the ability to remanufacture a product (as we have already discussed at length in this chapter); however, since these are logistical issues, they are beyond the scope of the metric under consideration.

The remanufacturing metric is based on the following generic remanufacturing processes:

- Product assembly.
- Product disassembly.
- Product testing.
- Product repair.
- Product cleaning.
- Inspection of products and components.
- Product and component refurbishing.
- Component replacement.

The reader can observe that overlap of area often happens between the aforementioned processes. These areas of overlap must be eliminated so that each process can be assessed independently. This is achieved by combining or partitioning the processes into independent criteria. The list of top-level issues is refined into categories for which a set of metrics were developed. The categories are enumerated as follows:

- Cleaning.
- Damage correction: This category comprises metrics such as repair, refurbishment and replacement.
- Quality assurance: This category comprises metrics such as testing and inspection.
- Part interfacing: This category comprises metrics such as disassembly and assembly.

This categorization is presented in Table 6.11. The table depicts the composition of the remanufacturing index developed by Bras and Hammond (1996).

The structure of each of the metrics and categories is described as follows.

1 Metrics for assembly and disassembly (parts interfacing category)

The processes of assembly and disassembly are quite similar in nature. When products are being remanufactured, the disassembly sequence is often the opposite of the (re)assembly sequence. Very similar tools, techniques and fixtures are used in both processes. However, there are some design issues that are a source of complication. For instance, design features that optimize assembly do not necessarily optimize disassembly and vice versa. They could in fact serve to hinder the other process. An example is the use of snap clips in the place of screws and other threaded fasteners. The snaps can help speed up assembly times but removing them is not as easy. Thus, it is preferable to quantify assembly and disassembly separately. On the contrary, since they are so closely related, it is still desirable to consider them simultaneously when assigning weights for combination with other metrics (Bras and Hammond, 1996).

In order to compute the metrics for assembly and disassembly, it is essential to first determine the assembly and disassembly times. Next, it is important

TABLE 6.11
Composition of a remanufacturing index

Metric	Weight (%)	Index	Category	Weight	Index	Index	
Replacement (key)						Level 1	**Remanufacturing Index (Level 1 + Level 2)**
Disassembly	30		Interfacing	30			
Reassembly	70						
Testing	80		Quality assurance	5			
Inspection	20					Level 2	
Replacement	20		Damage correction	40			
Refurbishing	80						
Cleaning			Cleaning	25			

Source: Adapted from Bras and Hammond (1996).

to determine the theoretical minimum number of parts (also referred to as the number of ideal parts). In keeping with the Boothroyd and Dewhurst method, 3 seconds are allocated to each ideal part for reassembly. Sometimes, disassembly is much faster than the assembly process. In such cases, a value of only 1.5 seconds is allocated per ideal part for the process of disassembly. The metrics for assembly and disassembly efficiency are depicted in the following equations.

$$\text{Disassembly efficiency} = (\text{Number of ideal parts})\ (1.5\ \text{seconds}) / \text{Disassembly time.}$$

$$\text{Assembly efficiency} = (\text{Number of ideal parts})\ (3\ \text{seconds}) / \text{Assembly time.}$$

2 Metrics for testing and inspection (quality assurance category)

It is essential that remanufacturers maintain quality of their products. This is important especially in view of the lackadaisical impression that customers often seem to have about “remanufactured” products in spite of their lower cost. This concern largely is a result of the impression that remanufactured products are less capable than brand-new products. However, 100% inspection is often necessary to ensure that defective parts are not reused in the remanufactured product. This inspection practice also allows the remanufacturer to confidently issue a warranty on the product.

Inspection is not limited to visual inspection only. It is necessary that parts and/or assemblies can perform certain functions (functionally fit) within a specified set of parameters. This is where testing is important. Testing, as a rule, is more quantitative than inspection. This is because the product should perform functionally within specified limits. For instance, automotive water pumps are pressure/vacuum checked to make certain that the system is watertight (Bras and Hammond, 1996).

Inspection is defined as the qualitative inspection of parts for damage. It is usually performed during the process of disassembly or immediately after cleaning. Each part is inspected for visual damage. It is important to do so to ensure that none of the parts that goes back into the remanufactured product is visually damaged. Frequently, parts are damaged due to improper use on the part of the user, abusive environments, corrosion and so on. These are examples of sources of damage that are unexpected. In general, the inspection process examines the product beyond wear and any other damage that is usually anticipated during product design.

Whenever checking the condition of a part involves a significant investment of time and resources, such checks are like testing and are counted as such. An example would be inspecting an iron casting for cracks through the process of magnafluxing. The total number of parts that need to be inspected is designated as the total number of parts less the number of parts that are replaced. In such cases, the ideal number of inspections is the theoretical minimum number of parts that do not need to be replaced during refurbishing. The metric for inspection is given by the following equation:

Inspection efficiency = (Number of ideal inspections)/
(Number of parts–parts replaced).

Testing a product involves checking the functionality of a product. This is achieved by checking the performance of a product or subassemblies against a set of predetermined criteria. Products that are manually assembled or disassembled are also presumed to be capable of undergoing manual testing. This implies that they can be picked up and manipulated by the person in charge of doing the testing without requiring the aid of a machine. The total idealized time for testing is computed by multiplying the total number of tests by 10 seconds. The metric for testing is given by the following equation:

Testing efficiency = (Number of tests) (10 seconds)/(Testing time)

3 Metric for cleaning

Cleaning is defined as any process that involves removing foreign objects that may be present in any part. A foreign object is defined as any object that is not intended to be present in the part under consideration. The process also involves removing substances like oil and grease, which would prevent any remanufacturing processes such as painting or applying protective coatings from being performed. Parts should be designed such that markings on parts should be able to withstand cleaning. Also, surfaces to be cleaned should be smooth and resistant to wear. Part design should also enable a rational design of the cleaning line. The important thing to remember is that all deposits, impurities and other materials should be removable without causing any damage to the parts (Hundal, 2000).

It is obvious that cleaning is an important process within the overall context of remanufacturing and requires a major commitment from the remanufacturer. A major portion of the investment deals with the need to conform to environmental legislations of waste disposal requirements. Some parts such as engine heads and carburetors can also require extensive amount of cleaning. In such cases, the process can involve large amounts of time and capital expenditure. Several different subprocesses are involved in the overall process of cleaning. These can be further categorized as loose debris, dry adhered debris, oily baked debris and oily washed and dried debris (Bras and Hammond, 1996). The cleaning metric is quantified by assessing the resource requirement for each cleaning process.

Table 6.12 depicts a prioritization matrix wherein the amount of investment required for each method is compared with other methods in order to determine their relative importance. The calculated importances are rounded off wherein they constitute a set of approximations to the true relative importances. The approximations are then scaled such that the one with smallest investment is assigned a score of "1." The scaled set is used as the cleaning score for each process. The total cleaning score is computed by adding up the scores for the individual parts.

TABLE 6.12
Prioritization of different cleaning processes

	Blown	Abraded	Baked	Washed	Score	Relative importance (%)	Approximate cleaning score	Usable cleaning score
Blown	1	0.3	0.2	0.2	1.7	7	1.00	1
Abraded	3	1	0.3	0.3	4.7	18	2.69	3
Baked	5	3	1	1	10.0	38	5.77	6
Washed	5	3	1	1	10.0	38	5.77	6
					26.4	100	15.23	

Source: Bras and Hammond (1996).

The first step in creating a metric for cleaning involves development of an idealized score. One of the most basic ideal situations for cleaning constitutes blowing, brushing clean all parts of a product. This is an ideal situation since it requires the least amount of effort. A more ideal case would involve only cleaning the minimum number of parts. These parts would need to be blown free of loose debris. Thus, the metric for cleaning constitutes a comparison of the total cleaning score of each part and the ideal number of parts. This formula is given below:

Cleaning efficiency = (Number of ideal parts) (1)/(Cleaning score).

4 Metric for part refurbishing

The process of part refurbishing consists of two parts. On the one hand, it involves repair of damage to the part and application of protective and aesthetic coatings. The refurbishing process is not concerned with when the part was damaged, but only whether the damage can be rectified or undone in order to return the product back to its original capabilities. If the original capabilities cannot be restored, the part must be replaced.

Ideally, no parts should require refurbishment. This implies that in the ideal case, all parts in the product would go back into the product without having to be refurbished. As the parts that do not need to be refurbished approach the total number of parts, they approach the ideal situation. The formula for refurbishing efficiency is given below:

Refurbishing efficiency = [1 − (Number of refurbished parts)/
(Total number of parts)].

5 Metric for part replacement

As we have already seen in the previous section, it is not always possible to refurbish every part. Thus, parts that cannot be refurbished or reused need to be replaced. If a very large number of such parts need to be replaced, it renders the remanufacture of the product impossible. This is because it entails a substantially large financial investment to replace all such parts. The metric for replacement is split into two: namely, a metric for replacing key parts and another for replacing nonkey parts. The key parts are construed to be essential to the functionality of the product whereas the nonkey parts are not essential.

Once again, as with part refurbishing, the ideal situation would involve not having to replace any parts at all. The metric for key part replacement is given in the following equation:

Key part replacement efficiency = [1 – (Number of key parts replaced)/
(Total number of key parts)].

The remainder of the parts that are considered key parts are referred to as basic parts. Once again, ideally none of the basic parts should require replacement. The metric for basic part replacement is given below:

Basic part replacement efficiency = [1 – (Number of parts replaced–
Number of key parts replaced)/
(Total number of parts).

6 Structure of the combined index

The criteria from the preceding discussion are combined into one index that gauges the ability to remanufacture a product. This index satisfies the following criteria:

- The magnitude criterion: The goal of this criterion is to make sure that the remanufacturability index is not significantly larger or smaller than the metric indices. Since the metric indices have been normalized, they have a maximum value of 100%. Thus, the value of the remanufacturability index should not exceed 100% either.
- The idealization criterion: This criterion states that if all the individual indices had an ideal score of 100%, the score of the remanufacturability index should also be 100%. Given that the individual metrics were developed by normalizing them against an idealization, the index will also take on the form of comparison of actual to ideal situations. This implies that as the remanufacturability of the product approaches the ideal case, the value of the index will approach a value of 100%.
- The annihilation criterion: According to this criterion, if the value of one of the metrics approaches 0, the value of the remanufacturability metric will also approach the value of 0. This will be independent of how well the other metrics perform. This way, if a significant problem were to occur that would render the product incapable of being remanufactured, it would not be outdone by excellent performance by other metrics.
- The weighting criterion: We have already recognized the fact that the metric indices do not contribute equally to the total outcome, namely the formation of the remanufacturability index. Thus, it is necessary that each metric be weighted in keeping with the extent to which it contributes to

the overall index. This implies that a combination technique must rely on a weighting system to form the composite score.

In order to weight the different individual metrics, the authors have used the technique of inverse weighted addition. This way, each of the aforementioned four goals can be achieved.

The inverse weighted addition technique uses a nonlinear additive approach. The equation for calculating the efficiency of remanufacturability using this approach is as follows.

$$\text{Efficiency of remanufacturability} = \Sigma\ (W/\mu)^{-1}$$

Key part replacement is more important than basic part replacement as we have already discussed. For this reason, key part replacement is considered a "level 1" metric. The remainder of the metrics is considered to be "level 2" metrics. These are combined using the weighted inverted addition method. They are then combined using direct manipulation. The total combination is depicted by the following equation:

$$\text{Efficiency of remanufacturability} = (\text{Key replacement efficiency})/(\Sigma\ (W/\mu)$$

The weights for the different categories are set up using the prioritization matrix depicted in Table 6.13. The weights for the individual metrics contained in each category are presented in Table 6.11.

To sum up this discussion, the remanufacturability assessment is performed by adhering to the following steps:

1 Efficiency of each of the individual metrics is obtained by following the procedure described earlier.
2 The category indices are evaluated by combining the appropriate metrics. This is accomplished by using the weighted inverted addition.
3 The second level index is evaluated by combining the category indices using weighted inverted addition.

TABLE 6.13
Prioritization of metric categories.

	Interfacing	Damage	Quality assurance	Cleaning	Score	Exact importance (%)	Approximate importance (%)
Interfacing	1	0.2	10	5	16.2	32.5	30
Damage	5	1	10	5	21	42.1	40
Quality Assurance	0.1	0.1	0.1	0.1	1.3	2.6	5
Cleaning	0.2	0.2	1	1	11.4	22.8	25

Source: Bras and Hammond (1996).

4. The remanufacturing index is evaluated by multiplying the first level (corresponding to key part replacement) and second level (corresponding to base part replacement) and thus combining them.

6.20 CASE STUDY TO EVALUATE PRODUCT REMANUFACTURABILITY

A case study to evaluate ease of remanufacturability of an actual product has been presented in this section (Bras and Hammond, 1996). The product under consideration is a Kodak Funsaver camera. The case study consists of opinions collected from designers in the form of a questionnaire (Table 6.14) and then converting them into metrics, categories and process efficiency as described in the preceding section of this chapter.

The metric calculations are performed as follows:

1. Disassembly and assembly: Column L in Table 6.14 corresponds to the evaluation of designer responses from columns B through E. It evaluates whether each part is considered an ideal part. If any of the criteria in the columns is answered yes (Y), then the corresponding part qualifies as an ideal part and vice versa. The disassembly time is computed for each part (columns B through E in Table 6.15) and reassembly time (columns F through H). If the part is subject to corrosion, the amount of time required to disassemble that part is doubled.
2. Inspection: If an ideal part has to be replaced, it should be excluded from the number of ideal inspections, or else it is added. The total number of parts is computed by adding values in column A. The number of parts is computed from column N.
3. Testing: Column A from Table 6.14 corresponds to the total number of tests. The total testing time is computed by adding the values in column D in the same table.
4. Cleaning: The cleaning score is computed by adding the scores in column K in Table 6.14.
5. Part refurbishment: The total number of refurbished parts is ascertained by adding the value in column M of Table 6.14. This column checks columns H through K to find out whether a part needs to be replaced. The part must be refurbished if either of those columns corresponds to a Y.
6. Part replacement: We have already seen from the preceding discussion that column M checks whether a part needs to be replaced. The number of key parts is computed by summing up the values in column P. If column F has a Y value, the part is considered a key part and vice versa. Column Q checks columns P and N to determine the number of key parts replaced. If both columns show a “non-0” value for the same part, it implies that the part is a basic part that needs to be replaced.

TABLE 6.14
Design questionnaire and results for Kodak funsaver camera remanufacturability

Kodak Funsaver camera		Please answer “Y” or “N” to the following											Questionnaire results					
		Number of parts	Large relative motions?	Different material properties required?	Required to facilitate assembly or Disassembly?	Required to isolate wear?	Significant intrinsic value relative to Assembly?	Does part fatigue?	Will parts require adjustment?	If coated, can coating be reapplied?	If worn, can worn surface be replaced?	If damaged during disassembly, can damage be refurbished?	Theoretical minimum number of parts	Number of refurbished Parts	Total number of replaced Parts	Number of ideal inspections	Number of key parts	Number of key parts replaced
Part no	**Part name**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**
1	Camera body	1	N	N	Y	N	Y	N	N				1	0	0	1	1	0
2	Internal aperture	1	N	N	N	N	N	N	N				0	0	0	0	0	0
3	Firing lever	1	Y	N	N	N	N	N	N				1	0	0	1	0	0
4	Spring—firing lever	1	N	Y	N	N	N	N	N				1	0	0	1	0	0
5	Cam follower	1	Y	N	N	N	N	N	N				1	0	0	1	0	0
6	Trigger catch	1	N	N	N	N	N	N	N				0	0	0	0	0	0
7	Film advance wheel	1	N	N	Y	N	N	N	N				1	0	0	1	0	0
8	Film advance cam	1	Y	N	N	N	N	N	N				1	0	0	1	0	0
9	Film winding wheel	1	N	N	Y	N	N	N	N				1	0	0	1	0	0
10	Film position wheel	1	Y	N	N	N	N	N	N				1	0	0	1	0	0
11	Top cover	1	N	N	Y	N	N	N	N				1	0	0	1	0	0

(*continued*)

TABLE 6.14
(Cont.)

Kodak Funsaver camera		**Please answer "Y" or "N" to the following**											**Questionnaire results**					
		Number of parts	**Large relative motions?**	**Different material properties required?**	**Required to facilitate assembly or Disassembly?**	**Required to isolate wear?**	**Significant intrinsic value relative to Assembly?**	**Does part fatigue?**	**Will parts require adjustment?**	**If coated, can coating be reapplied?**	**If worn, can worn surface be replaced?**	**If damaged during disassembly, can damage be refurbished?**	**Theoretical minimum number of parts**	**Number of refurbished Parts**	**Total number of replaced Parts**	**Number of ideal inspections**	**Number of key parts**	**Number of key parts replaced**
Part no	**Part name**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**
12	Flash assembly	1	N	Y	N	N	Y	N	Y				1	1	0	1	1	0
13	Shutter	1	Y	N	N	N	N	N	N				1	0	0	1	0	0
14	Shutter spring	1	N	Y	N	N	N	N	N				1	0	0	1	0	0
15	External aperture	1	N	N	N	N	N	N	N				0	0	0	0	0	0
16	Lens	1	N	Y	N	N	N	N	N			N	1	0	1	0	0	0
17	Front cover	1	N	N	Y	N	N	N	N				1	0	0	1	0	0
18	Film spool	1	Y	N	N	N	N	N	N				1	0	0	1	0	0
19	Film	1	N	Y	N	N	Y	N	N				1	0	0	1	1	0
20	Back cover	1	N	N	Y	N	N	N	N				1	0	0	1	0	0
21	AA battery	1	N	Y	N	N	Y	N	N				1	0	0	1	1	0
22	Camera wrapping card stock	1	N	N	N	N	N	N	N			N	0	0	1	0	0	0

Source: Bras and Hammond (1996).

TABLE 6.15
Worksheet for the DfRem index

			Disassembly				Reassembly			Cleaning		
Kodak Funsaver camera		Number of parts	If part can corrode, it is protectively coated?	Manual removal time per part	Manual handling time per part	Disassembly time in seconds (a * f(b)* [c+d])	Manual handling time per part	Manual insertion time per part	Operating time in seconds (a*[f+g])	Cleaning code	Cleaning score per part (f(i))	Total cleaning score (a+j)
Part no.	**Part name**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**
1	Camera body	1		1	1			1	1	D	6	6
2	Internal aperture	1		2.1	2.1			1.7	1.7	A	1	1
3	Firing lever	1		1.8	1.8			2.2	2.2	A	1	1
4	Spring-firing lever	1		1	1			1.8	1.8	A	1	1
5	Cam follower	1		1.3	1.3			2.5	2.5	A	1	1
6	Trigger catch	1		0.8	0.8			2.7	2.7	A	1	1
7	Film advance wheel	1		0.8	0.8			1.4	1.4	A	1	1
8	Film advance cam	1		1.2	1.2			3	3	A	1	1
9	Film winding wheel	1		0.5	0.5			1.2	1.2	A	1	1
10	Film position wheel	1		0.5	0.5			1.5	1.5	A	1	1
11	Top cover	1		3.3	3.3			3.7	3.7	A	1	1
12	Flash assembly	1		2.5	2.5			6.2	6.2	A	1	1
13	Shutter	1		2.3	2.3			2	2	A	1	1
14	Shutter spring	1		2.1	2.1			4.5	4.5	A	1	1
15	External aperture	1		0.5	0.5			0.8	0.8	A	1	1
16	Lens	1		0.5	0.5			1	1		0	0

(*continued*)

TABLE 6.15
(Cont.)

			Disassembly				Reassembly			Cleaning		
Kodak Funsaver camera		Number of parts	If part can corrode, it is protectively coated?	Manual removal time per part	Manual handling time per part	Disassembly time in seconds (a * f(b)* [c+d])	Manual handling time per part	Manual insertion time per part	Operating time in seconds (a*[f+g])	Cleaning code	Cleaning score per part (f(i))	Total cleaning score (a+j)
Part no.	**Part name**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**
17	Front cover	1		2.7	2.7			2.8	2.8	A	1	1
18	Film spool	1		2.1	2.1			1.9	1.9	A	1	1
19	Film	1		1	1			15	15	A	1	1
20	Back cover	1		5.6	5.6			4.2	4.2	A	1	1
21	AA battery	1		2	2			3.8	3.8	A	1	1
22	Camera wrapping—card stock	1		4.9	4.9			10	10		0	0
					40.5				74.9			25

Source: Bras and Hammond (1996).

TABLE 6.16
Table depicting scores for different cleaning processes

Type of debris	Process	Code	Score
Loose—Powder dust	Blown/brushed	A	1
Stuck—Paint/corrosion	Abraded/buffed	B	3
Wet—Oil/dirt/debris	Baked	C	6
Wet—Oil/dirt/debris	Wash and dry	D	6

Source: Bras and Hammond (1996).

TABLE 6.17
Summary of metric computation for remanufacturing index case study

Metric	Weight (%)	Index
Replacement (key)		1.000
Disassembly	30	0.758
Reassembly	70	0.832
Testing	80	0.750
Inspection	20	0.850
Basic replacement	20	0.909
Refurbishing	80	0.955
Cleaning		0.720
Category	**Weight (%)**	**Index**
Interfacing (disassembly + reassembly)	30	0.809
Quality assurance (testing + inspection)	5	0.768
Damage correction (basic replacement + refurbishing)	40	0.945
Cleaning	25	0.720

Source: Br and Hammond (1996).

Note
Level 1 index score = 1
Level 2 index score = 0.829
Remanufacturability index = 0.829

6.21 CONCLUSION

In this chapter, we examined the basic concepts of cradle-to-grave and cradle-to-cradle manufacturing systems. We also examined the various end-of-life destinations such as reuse, recycling and remanufacturing that serve to transform a cradle-to-grave manufacturing system into a cradle-to-cradle system through conserving material. The design decisions that need to be taken early on in the product life cycle in order to enable this transformation were discussed in detail. Knowledge of these decisions in conjunction with knowledge gained earlier in the book (regarding design for assembly and design for disassembly) should enable a designer to make distinct headway in designing sustainable products.

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