ON THE ECONOMICS OF REMANUFACTURING A WIDGET

by

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Abstract

This paper provides a framework for defining an efficient remanufacturing procedure of a generic durable good at the end of its useful life. For many materials, the recycling technology (material recovery) is broadly available. However, the design of most products does not favor the recovery of the value-added in the good. Products designed for optimal marketing and ease of manufacturing are not necessarily good candidates for a recovery scheme. Design measures such as recyclability, disassemblability and reusability are clearly defined and used as the basis of the product recovery framework. I apply this framework and the design measures to a bicycle to illustrate their application and managerial relevance.

Keywords: *remanufacturing, recycling, disassembly, material recovery, product recovery, asset recovery, product design, design for the environment, waste reduction, resource conservation.*

1. Introduction

With the purpose to develop environmentally conscious production processes, many thinkers have adopted the three R's banner: *reduce, reuse, recycle*. The three R's is an intuitive decision process intended to preserve the environment. *Reduce* the consumption of materials and energy, through the design of more efficient processes and products. *Reuse* goods, assemblies and parts whenever possible. *Recycle* the materials from goods, assemblies and parts that cannot be reused otherwise.

Remanufacturing results from the combination of the three R's in a single activity. It is the process of making renovated products or assemblies with some components or subassemblies that have previously been used. Remanufacturing requires the disassembly of the used widget, selection of parts that can be reused, inspection and renovation of critical components, and reassembly into the final product, the remanufactured widget. The machines or "widgets" in this discussion are the result of a serial manufacturing operation. In this paper, I analyze a generic widget, trying to understand what makes it a strong or weak candidate for the development of a remanufacturing operation. Usually, when one says remanufacturing, we think about final products such as an automobile, a computer or a refrigerator. However, the concept is also applicable to a subassembly or module: a tire, a hard disk drive or a diesel engine. In principle, any of these products may be remanufactured, with different levels of success.

In many industries, firms have implemented "take back" schemes for their used products, as illustrated by Thierry et al. (1995) and Ferrer(1994). Firms in the automobile and the electronic industries have established pilot disassembly and recycling operations for returned used goods to learn efficient ways of dealing with them [1, 2]. These firms have discovered that products designed for optimal marketing are not necessarily good candidates for remanufacturing. In what follows, I develop a framework to analyze how remanufacturable a generic product is. Roughly speaking, the profitability of a widget remanufacturing operation depends on the value saved from the major parts reclaimed from the used widget. Moreover, the remanufacturability of a product increases with the disassemblability of its major modules.

Most products offered as remanufactured are also offered new, either by the same company or by a competitor. The customer usually has an alternative that is perceived to be of a quality that is higher than that of the remanufactured version. Hence, the remanufactured good has to include some additional advantages over the new widget in order to be successful in the market. This requires an operational efficiency that allows reaching a significant cost advantage.

A word about recycling: one cannot dissociate recycling from remanufacturing. A successful remanufacturing operation is always coupled with a recycling operation. Back in 1978, Ginter and Starling proposed the establishment of a national materials policy in the United States. It would address the potential shortage of material, the increased dependence on foreign supply and the increasing generation of solid waste [3]. They described the salvage industry in the US as composed of 10,000 firms, extremely small and of limited scope. Sixteen years later, Biddle (1993) addresses the profitability of the recycling ventures in the nineties. Many large companies are involved in recycling, but customers still refrain from consuming products made of recycled materials or containing recycled components [4].

Successful recycling has some of the same requirements as remanufacturing, such as an efficient collection system. Complex products must be easy to disassemble to be profitably recycled. Penev and de Ron (1994) address this issue when they describe the development of a disassembly line for recycling the materials in refrigerators [5]. Conceivably, under appropriate market conditions, a recycling operation could be transformed into a remanufacturing process.

The problem of design for remanufacturing complements that of design for environment, which is object of a number of studies [6, 7, 8, 9]. Loosely speaking, a product is designed for the environment when all activities concerning its production process, its usage and its disposal are considered environmentally friendly. When two similar products are competing for a given application, it may be useful to evaluate their respective impact on the environment. The US EPA (1993) issued a guidance manual to help the designer to introduce Design for the Environment (DFE) in its new products. According to this manual, life cycle design should meet five goals: resource conservation, pollution prevention, environmental equity, ecological sustainability and economic viability. Likewise, Kriwet et al. (1995) developed a set of guidelines for integrating end-of-life aspects into product design, such that the materials can be more easily recycled and parts cannibalized for use as spares. With the same purpose, Bendz (1993) described actions taken by a number of corporations that have profited from adopting DFE.

Brennan et al. (1994) list several technical and operational problems in the area of disassembly, including disassembly scheduling, product design and reverse logistics. They consider that the most critical requirement is the development of a scheduling methodology. Hence, they anticipate that algorithms and heuristics are the most likely approaches to solve this family of problems, in order to address the variety of events that a single disassembly line may face [10]. The disassembly procedure and objectives are not sufficiently covered in that study.

I recognize that the profitability of remanufacturing depends on the economics of external processes, such as collection, transportation and product demand. Likewise, inventory, scheduling and capacity decisions have significant effect on plant performance. However, the purpose of this paper is to understand how the design can affect the recovery potential and how to suit the process to an individual product type.

This paper contributes in this literature in two fronts: it develops economic-based measures of *recyclability*, *disassemblability* and *reusability*, and it provides a framework for determining the remanufacturing process of a generic widget. The design measures are the building blocks of the proposed framework. Moreover, these measures can be useful in the comparison of the recovery potential of two assembly designs. The framework attempts to produce an economically sustainable remanufacturing process that requires limited information about the used widget. The framework indicates how to identify assemblies that should be inspected and, of those not inspected, which should be renovated for straight reuse, disassembled for parts' reuse, or recycled for material recovery. I illustrate its application with the recovery of used bicycles, in order to assess its managerial relevance.

2. Issues in Design

Typically, when a firm designs a product, it attempts to meet marketing specifications that maximize its economic viability, subject to regulatory restrictions. However, a widget designed for optimal marketing when new is not necessarily a strong candidate for remanufacturing. In the simplest case, the firm might be interested in solving the problem

maximize (unit price - unit cost) (first sale + repeat business)

In this illustration, the firm attempts to balance cost and quality parameters designing the product that provides the largest profit. The decision making process might address other issues such as production sites, distribution channels, advertising and competition. Unfortunately, this simplified approach is indifferent to the remanufacturing option and, as such, is not likely to ensure a successful product recovery process.

There is legislation affecting the environmental impact of certain production processes, and there is also some regulation on energy consumption of certain durable goods. Several firms have adopted even more stringent rules, in order to gain marketing benefits. Others have performed some sort of "life-cycle" analysis to evaluate the cradle-to-grave environmental impact of their products. Measuring the suitability of a widget for remanufacturing presents several difficulties. However, it is not necessary to take a holistic approach. It suffices to restrict the analysis to the latter stages of the production process and of the product design. Certain design characteristics play major roles:

- ease of disassembly of modules subject to wear
- ease of repair or substitution of wearable parts
- design longevity of components and assemblies
- design flexibility allowing interchangeability
- commonality of parts across product line
- commonality of parts across generations

Some of these characteristics are addressed in section 3. Disassembly cost, recovery cost and component value are some of the proxies used to represent them.

A widget cannot be successfully remanufactured unless it is easy to disassemble. In fact, if a widget is designed for disassembly, it is likely that it can be easily maintained, repaired, recycled, remanufactured and, if too many parts are damaged, cannibalized.

Some authors have addressed the problem of optimal disassembly processes for a specific good. Johnson and Wang (1995) designed a four-level approach to the disassembly problem for material recovery [11]. Their objective is to maximize the revenue by means of the optimal disassembly sequence, constrained by the reclamation value of the component, disassembly costs and disposal cost. Penev and de Ron (1996) present a similar work where a disassembly sequence is developed to recover the value-added to products, in order to avoid increasing disposal cost [12]. Both approaches require a complete search of all feasible disassembly sequences to identify the most profitable alternative. Under simple assumptions, both schemes achieve an optimal solution. However, their applicability is quite limited given the complexity of the typical durable product considered for remanufacturing. The heuristic in section 4 foregoes optimality, but ensures an efficient recovery of the value-added of even the more complex products.

When the widget was originally produced, the assembly process was optimized with the choice of materials and connectors that would minimize assembly time and cost. In many occasions, the connection is easily reversed: design for ease of assembly and design for disassembly may coincide. Unfortunately, however, some of the most efficient assembly processes (bonding, welding, riveting, joint stamping) cannot be reversed without damaging the original components. Thus, these products are not consistent with DFE. For example, if the connection between two components cannot be undone without damage, the remanufacturer faces one of these options:

- Consider the two components as one. They are jointly inspected and, if the assembly is worth reusing, it is recovered for reassembly. Otherwise, it is recycled. The recycling process may be inefficient if the two materials are not compatible.
- Recover the more valuable component. The connection, as well as the less valuable component is destroyed. Inevitably the number of recoveries under this situation is limited, because the structure of the most valuable component deteriorates with each separation procedure.

The next section describes a generic widget. It could be a camera, a copier, an air-conditioner, a TV-set, an automobile or a mainframe computer. The section starts with a sequential analysis of successive assemblies in the widget, based on the fact that, in general, the value-added in the final stages of the production process represent most of the value of a finished good. Based on this assumption, I develop measures of *recyclability*, *disassemblability* and *reusability*. These are the building blocks of the remanufacturing heuristic suggested in section 4.

3. The Remanufacturable Widget

In order to evaluate the remanufacturing potential of a widget, it is imperative to understand how it was originally manufactured. Without loss of generality, the widget is the assembly of several modules, as shown in Figure 1. It is assumed to have a modular architecture, including

- a casing or a frame
- functional modules
- functional connectors (cables, hoses, tubes, belts, chains)
- structural connectors (nuts, bolts, rods, rivets)

Furthermore, each module has a similar architecture, including a number of assemblies, functional connectors and structural connectors. The same architecture is adopted in the assemblies, subassemblies and so on. The definition of final product is somewhat subjective. A final product for one manufacturer (for example, a diesel engine) may be just an input in the production of a more complex product (for example, a truck). With this in mind, the number of transformation steps can vary enormously, from product to product. Let's consider the final assembly: normally, the sum of values of the individual inputs is less than the value of the final product. This is so because assembly is a value adding operation. Table 1 introduces the notation. The value of the final product can be decomposed as

$$V_0 = U_0 + \sum_{i=1}^{n} V_i \qquad (1)$$

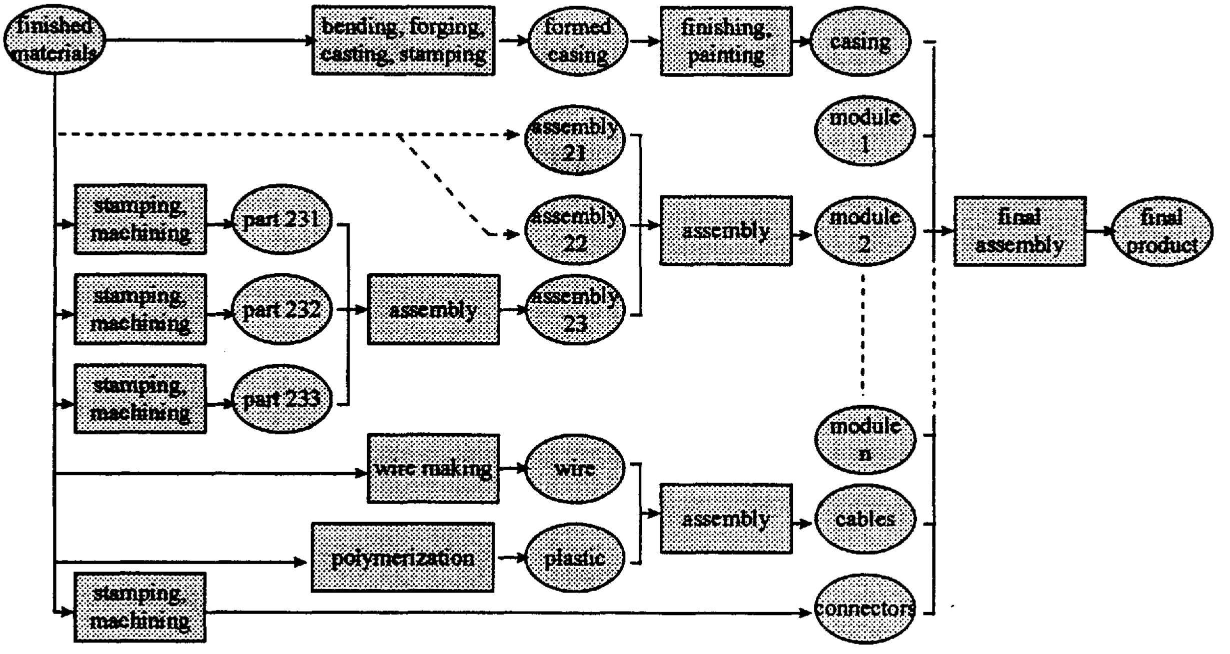

Figure 1 - A multilevel assembly process

where V_0 is the value of the finished widget, U_0 is the value added by final assembly and V_i is value of the ith component in the assembly. Identifying the value (V_i) of each individual module is not a simple matter, especially when there is not a stable market. In this analysis, I consider the internal value of the module, that is the cost to make it or to acquire it. Module i is composed of m_i components. The production of each module is a value-adding activity. Hence, the internal value of each module i can be expressed as

$$V_i = U_i + \sum_{j=1}^{m_i} V_{ij}$$

where V_{ij} is the value of the jth component of the ith module and U_i is the value added by the operation that completes the ith module. (Parts can be considered as degenerate modules that cannot be subdivided.) Hence, one can express the value of the product as the sum of the value of individual components, the value added to assemble them into modules and the value added to assemble these modules into the product. For a two-level product we have

$$V_0 = U_0 + \sum_{i=1}^{n} U_i + \sum_{i=1}^{n}\sum_{j=1}^{m_i} V_{ij} \tag{2}$$

Equations (1) and (2) provide two ways to disaggregate the value of V_0. In the latter formula, the value-added corresponds to a larger fraction of the total than in the former. One may continue decomposing the value of the product as far back into the production chain as desired. The further the product is disassembled into simpler subassemblies, the larger is the value-added, and the smaller is the material value.

Clearly, the number of assembly levels can be fairly large. In the absence of a reasonable framework to limit the scope of the analysis without jeopardizing the quality of the decision, the search for the optimal recovery procedure becomes a daunting task. The remainder of this section develops the building blocks for such a framework.

Table 1: Notation

V_0	value of final product	U_0	value added by final assembly
V_K	value of module or component K	U_K	value added by the operation generating component K
$R3_K$	revenue from recycling component K	$C3_K$	cost and losses in recycling component K
$R2_K$	revenue from disassembly of component K	$C2_K$	cost and losses in disassembly of component K
$R1_K$	revenue from reusing component K	$C1_K$	cost and losses in reusing component K

3.1 Design measures for product recovery

The production process depicted in Figure 1 starts with the finished materials used to produce the simple parts and their successive assembly into the final product. However, when the parts are recycled, one cannot recover the finished material suitable for the production of the same part again. For example, recycling the body of an automobile will provide scrap steel valued much less than the sheet metal required to stamp new automobile parts again. This scrap steel is melted and, after a series of costly processes, it will become sheet metal again. At this point, it is interesting to build a common vocabulary of product recovery. Strictly speaking, there are only two recovery approaches for any product or component: they are *material recovery* and *value recovery*. These concepts are defined as follows:

Material recovery: The process of recovering the raw material value in the product. It is a destructive process with complete loss of all functions and all information embodied in the product. In this work, the term *recycling* is strictly used to define a material recovery process.

Value recovery: The process of recovering usable components or subassemblies from the product. The material value of the recovered component and the value-added in the production of the individual component are saved. There are several value recovery processes, including *cannibalization*, *retrofitting* and *remanufacturing*. In this paper, recycling is not considered a value recovery process, because the value added to the parts and subassemblies by earlier manufacturing processes is destroyed.

According to these definitions, disassembly is not yet a recovery process. Indeed, disassembly as such does not recover either the material or the value-added of the disassembled item. It defers the recovery decision to a lower assembly level. Figure 1 illustrates the case: Module 2 results from the assembly of Assembly 21, Assembly 22 and Assembly 23. This module may be reused, after some cosmetic recovery, or may be shred and recycled. Eventually, the decision between material and value recovery is deferred to the next level through disassembly. Subsequently, Assemblies 21, 22 and 23 are subject to the same decision process. At the next level, the value at stake is lower than the value that could possibly be recovered at the higher level. The remanufacturer incurs two losses during disassembly: the disassembly cost, and the value-added loss. Hence, disassembly should take place *only if the component cannot be reused nor renovated as a whole*. Moreover, disassembly should not occur if the parts obtained from it are not of sufficient value.

Each recovery alternative generates a different revenue (eventually negative). This leads to the formal measures of product design used in this paper: recyclability, disassemblability and reusability. These measures contain the costs and revenues that depend on the product design and occur within the plant boundary. The design measures follow:

Recyclability is the measure that answers the question: "How economically efficient is it to recycle this unit, if it is the only recovery alternative?" One simple way to measure this efficiency is to equate the recyclability of a component with the return-on-investment (ROI) of the respective operation. That is the ratio between the net gain from recycling and the recycling cost. Hence, the recyclability of component Z is measured as

$$\text{Recyclability}_Z = \frac{R3_Z - C3_Z}{C3_Z} = \frac{R3_Z}{C3_Z} - 1 \tag{3}$$

where $R3_Z$ is the revenue obtained from recycling and $C3_Z$ is the sum of costs and losses related to recycling.[1] If the recyclability is negative, it means that recycling that part is not a profitable operation. That is, $R3_Z < C3_Z$. Now, I introduce another measure of design efficiency regarding product recovery:

Disassemblability is the measure that answers the question: "How economically efficient is it to disassemble this unit, given the opportunity to recycle it instead?" One could measure disassemblability as the ROI of the disassembly operation, to obtain an expression analogous to equation (3). However, the purpose of this measure is to identify whether a given component should be disassembled, given the recycling opportunity. This requires comparing the marginal revenue (beyond that provided by recycling) with the disassembly costs. Hence, the disassemblability of a component Z is expressed as

$$\text{Disassemblability}_Z = \frac{(R2_Z - R3_Z) - C2_Z}{C2_Z} = \frac{R2_Z - R3_Z}{C2_Z} - 1 \tag{4}$$

where $R2_Z$ is the revenue obtained from reusing the parts obtained from disassembly, and $C2_Z$ is the sum of costs and losses incurred during disassembly. The numerator includes the value recovered with disassembly, net of the material value that can be recovered from recycling the same component. It is a positive number, as long as component Z contains any value added beside its material value. If the item has a negative measure of disassemblability, it follows that the marginal revenue provided by disassembly is less than the disassembly cost. Hence, a decision system would recommend it to be recycled or, if reused, any renovation is performed without further disassembly. Finally, there is the formal measure of reusability.

Reusability is the measure that answers the question. "How economically efficient is it to renovate this unit for immediate reuse, given the risks of sub-standard performance, and the opportunity to recycle or to postpone the recovery decision until after further disassembly?" Analogous to disassemblability, it is not a straight ROI measure. Reusability is defined as the ratio between the marginal revenue (beyond that provided by disassembly) and the renovation costs. Hence, the reusability of component Z is measured as

$$\text{Reusability}_Z = \frac{(R1_Z - R2_Z) - C1_Z}{C1_Z} = \frac{R1_Z - R2_Z}{C1_Z} - 1 \tag{5}$$

where $R1_Z$ is the potential revenue for reusing component Z after minor recovery, and $C1_Z$ is the sum of costs and losses incurred because component Z is reused. The numerator is necessarily a positive number, as long as assembly is a value-adding operation. Nonetheless, if renovation is sufficiently expensive, the whole expression is negative, suggesting that the item is not reused as a whole.

The material flow in Figure 2 summarizes the remanufacturing routine proposed in this paper. The figure is divided in three distinct areas. The upper area includes the components that still have to be recovered,

[1] Some authors define recyclability as the weight fraction recovered by recycling the original machine. For the purpose of this work, it is more useful to adopt economic-based measures of design efficiency.

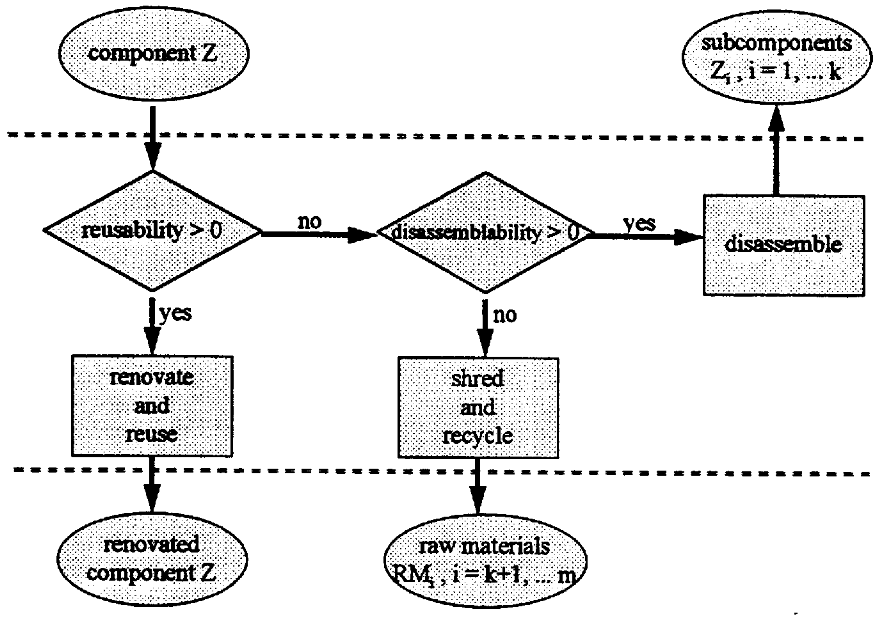

Figure 2: The Remanufacturing Routine

that is: those that have not been processed and those that were obtained from disassembly. The central area corresponds to the decision and recovery processes, where the recovery of the used component is decided. The lower area corresponds to the material that has been fully processed; that is: those that are ready for reuse, and those that are ready for recycling.

3.1.1 Measuring the revenue and costs from different recovery processes

When a used component enters the remanufacturing shop, it may follow four paths: immediate reuse, disassemble, recycle or inspect before deciding the best procedure for that individual component[2]. Figure 3 shows these alternatives. The path starts with the decision to inspect the used component or not. Inspection may not be necessary if the recovery decision is usually the same for all such components. For instance, the component is always disassembled because the more sensitive parts are at a lower assembly level. If a component is routinely inspected, it is because it may be subjected to more than one recovery process. The decision to inspect or not depends on the component complexity and on the inspection cost. It is assumed hereafter that the number of units considered for product recovery is large enough to permit some statistical analysis. I propose the following classification of components, according to the usage pattern:

1. The wear state is predictable

Usually, these components are easy to classify: they are well within the envelope of allowability, or not. In the latter case, they are worn out. Hence, all components with predictable wear follow a predetermined recovery routine. They are removed and substituted by an entirely new part or reused after a minor renovation, such as washing, cleaning or lubricating. Eventually, the component is disassembled, if the recovery decision requires reaching a component at a lower level.

2. The wear state is not predictable

[2] Incinerating is another alternative. If the energy is recovered, it is simple to show that it can be analyzed the same way as recycling, after appropriate change in the parameters.

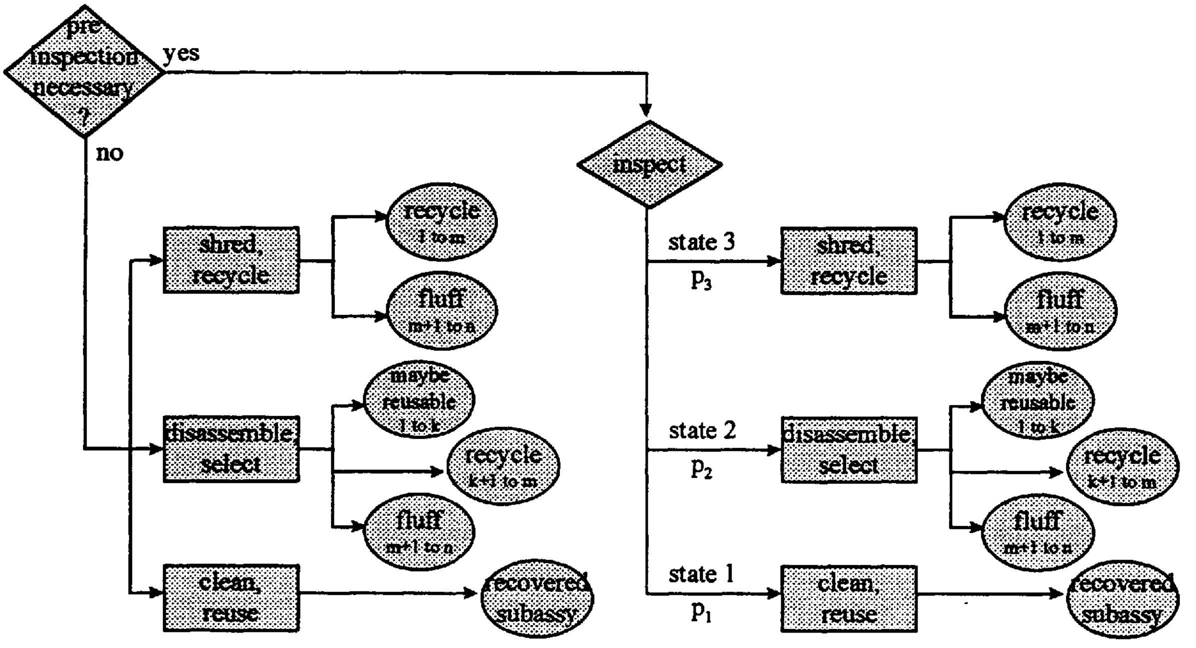

Figure 3: Possible Recovery Paths for a Given Assembly

Assemblies with unknown wear are subject to degradation that is not observable by the remanufacturer. The remanufacturer needs to inspect the component before identifying its state. Some components do not have a pre-determined routine: they are recovered according to the inspection results. Eventually, inspection is too costly relative to the value-added of the recovered component. In such a case, a predetermined routine is determined according to the stochastic value of disassemblability and reusability. Section 3.2 elaborates this matter.

Assume that module Z results from the assembly of parts and/or subassemblies. Without loss of generality, these subassemblies and parts belong to one of three categories shown in Figure 3:

- Parts 1 through k are generally robust. Most of them can be reused after minor renovation, subject to a probability distribution. The disassembly process identifies the actual state of the parts making up each component. If they are reused, the value-added is saved after some renovation. Otherwise, they are recycled.
- Parts k+1 through m are recycled, either because they do not survive the disassembly process or because reusing these parts might jeopardize the final performance. Their embodied value cannot be recovered.
- Parts m+1 through n make up the fluff, the "soft" material that is not recovered in the shredding or disassembly process because of difficult separation for recycling. Typically, they are the small parts made of plastic, rubber, paper, cloth, glass or clay.

If the component is not subject to inspection, there are three recovery paths (recycle, disassemble or reuse). Table 2 adds some notation. Each recovery path is associated with the following gains:

Option 1: Shred and recycle.

Outcome: The component continues into some sort of secondary raw material recovery. Typically, this procedure generates some fluff. If inspection is not performed, the revenue and costs from recycling equal:

Table 2 - Additional Notation

Sh_K	shredding cost of component K for recycling	RM_K	value of the raw material required to make component K
D_K	disassembly cost of component K	P_K	probability that, once disassembled, component K is successfully recovered
Rec_K	cost of a minor recovery of component K	α	fluff disposal cost per raw material value
F_K	probability that, once approved for recovery and reuse, component K fails	L_K	monetary loss if, once approved for recovery and reuse, component K fails in the field

$$\begin{aligned} R3_Z &= \sum_{i=1}^{m} RM_{Z_i} \\ C3_Z &= \alpha \sum_{i=m+1}^{n} RM_{Z_i} + Sh_Z \end{aligned} \tag{6}$$

where Sh_Z is the operating cost of the shredder and α is the unit cost of disposing of the fluff. For simplicity, the fluff disposal cost is assumed to be proportional to its raw materials value. This simplification excludes the existence of harmful or hazardous materials. It is implicit in equation (6) that the material recovered from shredding module Z is worth as much as the virgin material. This may not always be true. For example, the metal scrap originated from a shredding processes may still be more valuable than the virgin material because it has already seen a refining stage. Conversely, the additives to enhance physical or chemical properties of the raw material, used in its original production, limit the range of applications for the recycled raw material. Hence, the recovered scrap is not worth as much as the respective raw material. In what follows, such differences are not considered because the raw material value plays a small role in the valuation of the disassemblability and the reusability of the components. However, the analyst should be careful about this limitation when evaluating the recyclability of a complex machine.

Equation (6) gives an immediate measure of the revenue and costs of recycling module Z. Using the definition in equation (3), the recyclability of Z is given by the expression

$$\text{Recyclability}_Z = \frac{\sum_{i=1}^{m} RM_{Z_i}}{Sh_Z + \alpha \sum_{i=m+1}^{n} RM_{Z_i}} - 1 \tag{7}$$

If recyclability is positive, it only means that it is a profitable alternative, but not necessarily the most profitable alternative. One should consider the value recovery opportunities before committing to recycling. Notice that, even if recycling is not profitable (that is, recyclability is negative), one may have to incur this loss if the other recovery alternatives are not viable.

Option 2: Disassembly for component recovery.

Outcome: Disassembly delays the recovery decision to lower assembly levels. It may generate some fluff, assumed to be identical to that when module Z is shred. Hence, if inspection is not performed the expected revenue and costs are equal to:

$$
\begin{aligned}
R2_Z &= \sum_{i=1}^{k} P_{Z_i} U_{Z_i} + \sum_{i=1}^{m} RM_{Z_i} \\
C2_Z &= \sum_{i=1}^{k} P_{Z_i} \operatorname{Rec}_{Z_i} + \alpha \sum_{i=m+1}^{n} RM_{Z_i} + D_Z
\end{aligned} \tag{8}
$$

where Rec_{Z_i} is the recovery cost of part Z_i, P_{Z_i} is the a priori probability that part Z_i is reusable and D_Z is the disassembly cost. The terms in the left summations refer to the value-added in the individual parts and the cost of recovering them. Hence, the success of disassembly is due to two components: the existence of some recoverable parts (providing a significant revenue) and a low disassembly cost. If these conditions are satisfied, one may say that the component was designed for disassembly, and conversely.

Definition: ***Design for Disassembly***

A component is designed for disassembly if the sum of the value-added in the recovered parts, net of the respective recovery costs is larger than the component's disassembly cost

The definition is quite intuitive, but needs to be quantified. Equation (8) gives a measure of the economic value of disassembly. Considering that the widget is not disassembled unless the resulting parts are worth more than the raw material recovered by recycling, the disassemblability of Z is given by:

$$
\text{Disassemblability}_Z = \frac{\sum_{i=1}^{k} P_{Z_i} U_{Z_i}}{\sum_{i=1}^{k} P_{Z_i} Rec_{Z_i} + \alpha \sum_{i=m+1}^{n} RM_{Z_i} + D_Z} - 1 \tag{9}
$$

Equations (4) and (5) are quite convenient. The subtraction in the respective numerators are responsible for a substantial reduction in the data collection necessary to evaluate product design. This is reflected in the expanded expression above, and in the reusability expression that follows.

Option 3: Reuse after minor renovation.

Outcome: The component is reusable after appropriate cleaning or painting, or some other simple operation. This option is selected if the probability that the component can be readily reused is very high. Here, the expected revenue and costs equal:

$$
\begin{aligned}
R1_Z &= V_Z = U_Z + \sum_{i=1}^{n} \left(U_{Z_i} + RM_{Z_i} \right) \\
C1_Z &= F_Z \left(L_Z + V_Z \right) + \operatorname{Rec}_Z
\end{aligned} \tag{10}
$$

where F_Z is the a priori probability that the component fails, L_Z is the loss incurred if it fails in the field and Rec_Z is the recovery cost without disassembly. It is worth noting that in some situations the loss incurred in case of failure can be very high. Making use of equations (5), (8) and (10), the reusability of module Z is expressed as

$$
\text{Reusability}_Z = \frac{U_Z + \sum_{i=1}^{k} \left(1 - P_{Z_i}\right) U_{Z_i} + \sum_{i=k+1}^{n} U_{Z_i} + \sum_{i=m+1}^{n} RM_{Z_i}}{F_Z \left(L_Z + V_Z \right) + \operatorname{Rec}_Z} - 1 \tag{11}
$$

where P_{Z_i} is the a priori probability that, following disassembly, part Z_i can be reused. Many parameters influence the reusability of a given component. In words, the reusability increases with the following conditions:

- the value-added in the final production step U_Z is high
- the value-added in parts that cannot be recovered by disassembly ($i = k, \dots n$) is high
- the recovery cost is low
- the probability of failure of the recovered components is low
- the raw material value of what would become fluff otherwise ($i = m, \dots n$) is high

Module Z is reused whenever reusability is positive. In other words, the module is not reused unless its recovery without further disassembly is feasible, and the recovery procedure reduces the risk of failure to an acceptable level. Moreover, recovering a module should be less costly than remaking it from scratch.

3.1.2 Recovering simple parts

The valuation in the previous section was dedicated to assemblies containing several parts with a variety of raw materials. In the case of simple parts, the decision process is slightly different because the disassembly alternative does not exist, and there is just one type of raw material. This facilitates the recycling process, and eliminates the shredding and the fluff disposal cost. Now, consider component X, a simple part made of a single finished material. Many connectors as well as some complex mechanical or electronic elements are like this. Only two recovery alternatives are available for such components: recycle or reuse. They are valued as follows

Option 1a: Recycle (single part).

Outcome: If the part is recycled, the net revenue is simply the raw material value, RM_X. There is no shredding cost and no fluff disposal cost because the part is made of a single material. It can be mixed with the other inputs in the production of the corresponding finished material.

Option 3a: Reuse after minor renovation (single part).

Outcome: If the part is reused after appropriate cleaning or painting, or some other superficial operation, the recovered value is the same as the value of the original manufactured part. This alternative is selected if the probability that it can be reused is very high. The expected revenue and cost equal:

$$R1_X = V_X = U_X + RM_X$$
$$C1_X = F_X(L_X + V_X) + Rec_X$$

where F_X is the probability that the component X will fail in the field, and L_X is the cost of such a failure. The reusability of a single component is measured against the alternative recycling process. In the case of simple parts, recycling is the only one available.

$$\text{Reusability}_X = \frac{U_X}{F_X(L_X + V_X) + Rec_X} - 1 \tag{12}$$

If the reusability of component X is positive, the component is reused instead of recycled.

Table 3 - Final notation

$G_{K,s}$	probability that used component K is in state s	$Insp_K$	inspection cost of component K
s	wear state (1, 2 or 3)		

3.2 Assemblies of unpredictable wear state

Perhaps the greatest challenge in the product recovery shop is the variability in the wear state of the returned products. It is tempting to replace all components with unpredictable wear. However, if these assemblies happen to have high value added, and low cost of failure in service, this might be an unwise decision. On the other hand, 100% inspection of all assemblies at each stage is generally too expensive. The widget may be in a wide range of possible states but only three recovery routines are envisaged (shred and recycle, disassembly or reuse). Consequently, it is possible to define all states subject to the same recovery procedure as one.

Inspection only makes sense if it might result in significant increase in the recovery gains. For example, if there is a significant probability that the component may be reused without further disassembly, or if the potential loss for not reusing a component that could be reused is large. Consequently, some assemblies require inspection before choosing the most appropriate recovery procedure while others allow by-passing inspection.

If the inspection is performed, the wear state becomes known. After inspection, the problem is identical to the one where inspection is not necessary. For each state, one can calculate the disassemblability and the reusability of the selected component (notice that the recyclability is invariant with the state). However, if inspection is costly it is important to identify these measures before incurring any expense. Finally, if the wear state is unpredictable but the component is not inspected, the recovery alternative is determined based on the statistical expectation of the design measures.

3.2.1 Measuring the revenue and costs of inspected components

Inspection has two purposes: (1) it avoids reusing a component that might fail in the field and (2) it avoids the value destruction that occurs when a component is disassembled or recycled unnecessarily. If there is a significant probability that these losses might occur, and if these losses are significant, inspection is strongly recommended. If inspection is performed, and it identifies that component Z should be recycled, it is in state 3 (see Figure 3). In this case, the net revenue is smaller than in equation (6), as follows

$$R3_Z - C3_Z = \sum_{i=1}^{m} RM_{Z_i} - \alpha \sum_{i=m+1}^{n} RM_{Z_i} - Sh_Z - Insp_Z$$

Likewise, if inspection identifies that component Z should be disassembled, it is in state 2. Hence, the expected revenue and costs from disassembly when inspection occurs equal

$$R2_{Z,2} = \sum_{i=1}^{k} P_{Z_i,2} U_{Z_i} + \sum_{i=1}^{m} RM_{Z_i}$$

$$C2_{Z,2} = \sum_{i=1}^{k} P_{Z_i,2} Rec_{Z_i,2} + \alpha \sum_{i=m+1}^{n} RM_{Z_i} + D_Z + Insp_Z$$

where $P_{Zi,2}$ is the probability that part Z_i can be recovered if component Z is in state 2 (suitable for disassembly), and $Rec_{Zi,2}$ is the recovery cost for part Z_i if component Z is in state 2. Finally, if inspection identifies that component Z should be reused, it is in state 1. The expected revenue and costs from reuse equal

$$R1_{Z,1} = U_Z + \sum_{i=1}^{n}\left(U_{Z_i} + RM_{Z_i}\right)$$
$$C1_{Z,1} = F_{Z,1}\left(L_Z + V_Z\right) + Rec_Z + Insp_Z$$

where $F_{Z,1}$ is the probability of failure when the component is in state 1. It is assumed that the cost of minor recovery is not sensitive to the wear state. The cost and revenue expressions suggest that, in a standardized recovery process, the few assemblies subjected to inspection satisfy the following conditions:

- the value-added is very high (large U_Z)
- there is a significant probability that the component occurs in more than one wear state (no $G_s \rightarrow 1$)
- the inspection cost is relatively small ($Insp_Z / (L_Z + V_Z) \rightarrow 0$)

If these conditions are not satisfied, there is little risk in making the recovery decision without inspection.

3.2.2 Decision making without inspection

The previous section restricts inspection to a small group of modules or subassemblies. In general, it is better not to inspect a component that could be in different states, if the expected loss for making a wrong decision is small. If the component is always recycled, the expected revenue and costs are the same as in equation (6) because of their independence on the wear state. If component Z is always sent to disassembly, the expected revenue and costs are expressed as

$$\begin{aligned} E_s R2_Z &= \sum_{s=1}^{3} G_{Z,s} \sum_{i=1}^{k} P_{Z_i,s} U_{Z_i} + \sum_{i=1}^{m} RM_{Z_i} \\ E_s C2_Z &= \sum_{s=1}^{3} G_{Z,s} \sum_{i=1}^{k} P_{Z_i,s} Rec_{Z_i,s} + \alpha \sum_{i=m+1}^{n} RM_{Z_i} + D_Z \end{aligned} \tag{13}$$

where $G_{Z,s}$ is the probability that component Z is in state s, $P_{Zi,s}$ is the probability that part Z_i can be recovered if component Z is in state s, and $Rec_{Zi,s}$ is the recovery cost for part Z_i if component Z is in state s. Notice that equation (13) converges to equation (8) if any of the values $G_{Z,s}$ (s = 1, 2 or 3) is close enough to 1. The disassemblability expression is easily adapted to evaluate components with unpredictable wear:

$$E_s Disassemblability_Z = \frac{\sum_{s=1}^{3} G_{Z,s} \sum_{i=1}^{k} P_{Z_i,s} U_{Z_i}}{\sum_{s=1}^{3} G_{Z,s} \sum_{i=1}^{k} P_{Z_i,s} Rec_{Z_i,s} + \alpha \sum_{i=m+1}^{n} RM_{Z_i} + D_Z} - 1 \tag{14}$$

If the part is robust enough, it may be reused without undergoing any inspection. In this case, the expected revenue and costs from reusing component Z is

$$\begin{aligned} E_S R1_Z &= U_Z + \sum_{i=1}^{n}\left(U_{Z_i} + RM_{Z_i}\right) \\ E_S C1_Z &= Rec_Z + \left(L_Z + V_Z\right)\sum_{s=1}^{3} G_{Z,s} F_{Z,s} \end{aligned} \tag{15}$$

where $F_{Z,s}$ is the probability of failure when the component is in state s. Notice that equation (15) converges to equation (10) if any of the values $G_{Z,s}$ is close enough to 1. The reusability expression can be easily adapted to calculate the expected reusability of a component with unpredictable wear.

$$E_s\text{Reusability}_Z = \frac{U_Z + \sum_{i=1}^{k} U_{Z_i}\left(1 - \sum_{s=1}^{3} G_{Z,s} P_{Z_i,s}\right) + \sum_{i=k+1}^{n} U_{Z_i} + \sum_{i=m+1}^{n} RM_{Z_i}}{Rec_Z + (L_Z + V_Z)\sum_{s=1}^{3} G_{Z,s} F_{Z,s}} - 1 \quad (16)$$

The expected reusability and the expected disassemblability expressions require the knowledge of some parameters that are generally not available, or have to be estimated based on a small number of observations. Hence, one should limit these evaluations to assemblies satisfying the following conditions:

- the value-added is very high (large U_Z)
- the loss in case of failure is low (small L_Z)
- there is a significant probability that the component occurs in more than one wear state (no $G_s \rightarrow 1$)
- the inspection cost is relatively high ($Insp_Z / (L_Z + V_Z) >> 0$)

These characteristics define the profile of the components for which the expected reusability and expected disassemblability are worth measuring. In these cases, the recovery decision is then made without performing an inspection. Figure 4 illustrates the conditions under which the component is inspected or not. The graph in the left applies to components with predictable wear state while the graph in the right applies to components of unpredictable wear. Each component is located in the graph based on two parameters: the relative inspection cost and the value-added in the final process, defined as follows:

$$\text{Value Added} = V_Z - \sum_{i=1}^{n} V_{Z_i}$$

$$\text{Relative Inspection Cost} = \frac{Insp_Z}{(L_Z + V_Z)\sum_{s=1}^{3} G_{Z,s} F_{Z,s}}$$

The purpose of these graphs is to allow the analyst to intelligently limit the number of inspections and calculations to the few components where such an effort would bring the greatest contribution. The boundary lines in the figure are not exact, but an indication of the decision criterion.

The relative inspection cost is small in two situations: (1) if the inspection cost itself is low (small $Insp_Z$); (2) if the expected cost due to the occurrence of a hazardous event is significant (large $F_{Z,s}$ and large L_Z). In both situations, inspection is well justified and it becomes even more important if the value added in the component is high. Consider the lower-right region in the both graphs. This area corresponds to the components with largest value-added and relatively low inspection costs. In this region, one should certainly inspect, even if the wear state is predictable, keeping in mind that the wear state is *never* so predictable that renders inspection useless.

In short, if the inspection cost is high and the wear state is not predictable, only the components with high value-added are inspected. As the value-added decreases, the component becomes less interesting from a recovery viewpoint. In the intermediate range (zone b in the graph), the product is analyzed using the disassemblability and reusability expressions in this section, equations (14) and (16). Finally, as the value-added falls below a certain threshold (zone a in the graph), the analysis can be approximated using the disassemblability and reusability expressions developed in section 3.1.1, equations (9) and (11), by using the

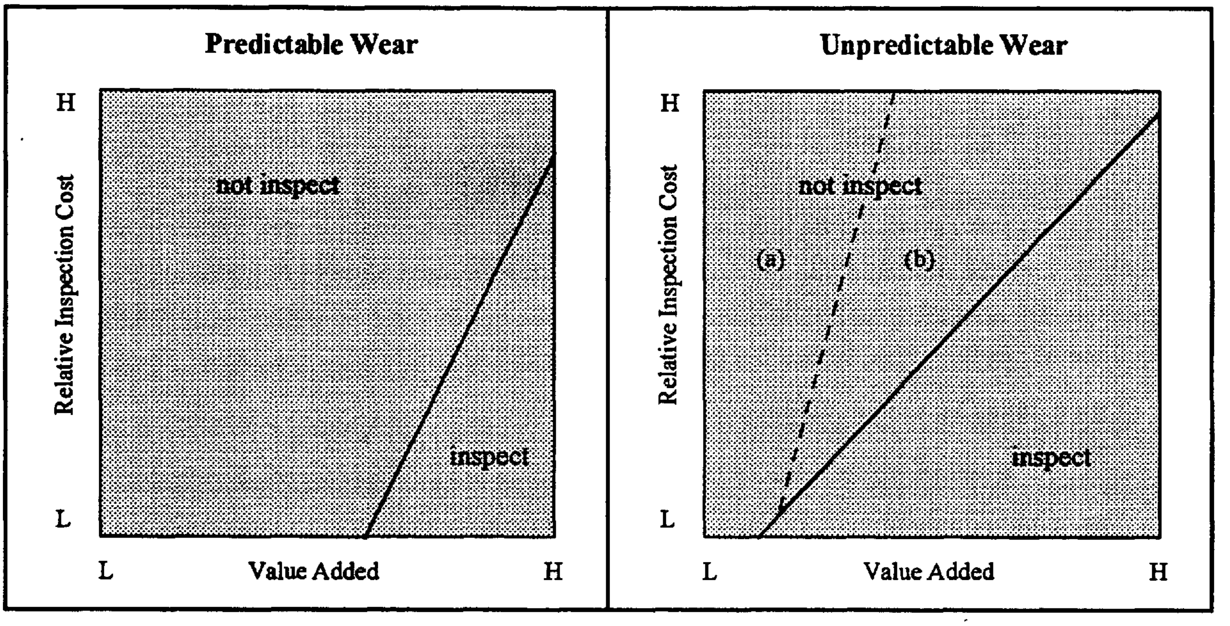

Figure 4: Inspection decision based on the value added, inspection costs and predictability of wear state

most likely values for each recovery parameter (P_{Zi} and Rec_{Zi}). Consequently, the parameters that have to be identified describe the assemblies that are not inspected but still have significant value-added to be recovered.

One of the difficulties in this procedure is to draw the line separating high and low value-added components, low and high inspection costs. It is an accepted rule-of-thumb that in any inventory system containing a reasonably large number of stock keeping units (50 sku's or more), 20% of the sku's are responsible for 80% of the inventory turnover. Consequently, 80% of the stock keeping units are responsible for just 20% of the inventory turnover. It is likely that this phenomenon occurs among the components of the widget: approximately 20% of the components used in the assembly of the final product are responsible for the 80% of the value-added of inputs. These are the ones that deserve more careful analysis and, by this criterion, they are inspected. In the next section, I develop a generalized decision process for recovery of a complex machine.

4. A Generalized Recovery Decision Process

Section 3 evaluated the recovery processes for simple assemblies. The design measures in that section are the building blocks for developing a recovery heuristic useful even for complex machines, provided that information about the value added in the major components is available. Given the loss of value-added at each successive disassembly step, it is very unlikely that any machine would ever be disassembled more than a few levels. Consequently, the recovery process does not require complete information about all parts in the machine but of the major components. It suffices to understand the product architecture as well as the bill of materials for each module, down to a small number of levels (possibly two or three). The analysis follows these steps:

Start

Step 1. Produce a three-level bill-of-materials: final product, modules into final product, components into modules.

Placing the components in the inspection decision graph

Step 2. For each module Z in the third level, calculate the value added in the production process to make them (U_Z) and identify L_Z, V_Z and $Insp_Z$ to calculate their relative inspection cost.

Step 3. Any complex product will have several dozens of components in the third level of the bill of material. Produce two graphs similar to those in Figure 4, one for assemblies with predictable wear and the other for assemblies with unpredictable wear.

Drawing the boundary lines in the inspection decision graph

Step 4. In the graph of assemblies with predictable wear, 20% of them are inspected. Select them from the assemblies in the lower-right corner of the graph (high value added and low relative inspection cost). The inspection will confirm the wear state and, consequently, the most appropriate recovery procedure (recycle, reuse or disassemble to next level).

Step 5. The graph of assemblies with unpredictable wear, is split in three areas.
Inspection zone: The assemblies closer to the lower-right corner (approximately one-third of them) are inspected to determine their wear state and define the most appropriate recovery procedure.
Zone a: The assemblies closer to the upper-left corner (approximately one-third of them) are not worth inspecting. Their reusability and disassemblability are estimated using the most likely values of each recovery parameter (P_{Zi} and Rec_{Zi}) in equations (9) and (11).
Zone b: The remaining assemblies lie along the diagonal from the lower-left to the upper-right corner. They are not inspected. Their reusability and disassemblability are estimated using equations (14 and (16).

Recovery decision based on reusability and disassemblability

Step 6. Assemblies that are not inspected are subjected to pre-determined recovery routines. All those with positive reusability are renovated without being disassembled (cleaning, painting, lubricating, polishing, etc.). Recycle the components with negative reusability and negative disassemblability. Disassemble the components with negative reusability and positive disassemblability.

Inspection and recovery decision of lower-level components

Step 7. The components disassembled in step 6 generate a number of parts and assemblies. Calculate their value-added and relative inspection cost of all assemblies. Locate them in the inspection decision graph produced in step 3.

Step 8. Repeat steps 4 through 7 as many time as necessary until the recovery routine for all assemblies is defined.

Recovery decision for simple parts

Step 9. Each disassembly procedure produces simple parts, along the assembled components. Calculate the reusability of these simple parts. Renovate and reuse whenever positive. Recycle otherwise.

End

Once the recovery routine is defined, the remanufacturing plant is capable of efficiently recover value from a continuous flow of used products with similar design. If the components are interchangeable, the products are remanufacturable. This 9-step product analysis does not pretend to provide the optimal solution to the product recovery problem. It is a practical method for recovering value from complex durable products, requiring limited information about the used widget. The heuristic attempts to recover the value-added from the original assembly whenever renovation is feasible without further disassembly. It requires that the renovation process is financed by the incremental revenue from reusing the respective component, while the disassembly operation is financed by the incremental revenue from reusing the disassembled components. Consequently, if most of the product's value is added in the final stages of the production process, this heuristic provides a recovery scheme that is close to optimality.

4.1 An application to a real product

In this section, this 9-step analysis is applied to an actual product, the 20-inch children bicycle, model BMX. The objective is to underscore the usefulness and difficulties of implementing such analysis in real life. Two used bicycles were available for this analysis. No documentation was available for either of them. Both of them show the sign of wear, but can still be ridden. Their difference lies in the different styles (girls' model and boys' model) which dictates the type of embellishments and colors.

Several manufacturers produce bicycles based on the BMX design, probably the most common among children bicycles. Most of the differentiation is in the choice of colors or accessories and does not preclude the interchangeability among units of different brands. The bicycles examined contain a small number of parts. They ride at a single speed (no gear system) and have just the coaster brake (no cable and caliper brake system). However, it contains a small number of safety features required for the children market, such as special retainers to prevent the loss of the front or the back wheel while riding. Although the sample size is small (only two units were studied) their examination offers an idea of the production decisions faced by a hypothetical remanufacturer dealing with this product.

The product results from the assembly of six subassemblies, the main fork-crankshaft-frame assembly, and a number of embellishments and accessories, as shown in the breakdown in the appendix. Some design features supported the impression that the bikes were consciously designed for ease of assembly. For example, the crankshaft is held with a single pair of bolts on the same side of the frame. The product breakdown is detailed down to three levels. A fourth level exists but is not considered. A priori, I expect that the analysis might end before the need for further disassembly arises, which might not be true in more complex machines.

The product recovery starts with the first level disassembly. Table 4 shows the recovery parameters of the main modules in the bicycle. It includes some estimation that in practice should be obtained with the examination of a larger sample. The value-added (U) and the relative inspection cost (RIC) are located in the graph to identify which modules should be inspected or not. See Figure 5. At this level, it is safe to affirm that the fork-frame-crankshaft assembly should be inspected before any recovery takes place, and that the pedals and the seat assembly are not worth being inspected. Hence, the analysis proceeds to include the modules in the next level of assembly.

Table 5 shows the parameters for the evaluation of modules and subassemblies of unpredictable wear state. The value-added and the relative inspection cost are graphed. It turns out that the recovery of five components requires inspection. One of them is the frame-fork-crankshaft assembly, already identified as requiring inspection. The others are the crankshaft, the back wheel, the back wheel assembly and the front wheel. The graph indicates that the value of the other components in the bicycle do not justify the respective inspection costs. Notice that the seat is on the edge between parts worth inspecting or not. The seat and the parts subject to inspection are identified in Figure 6.

Table 6 repeats the analysis with modules and subassemblies of predictable wear. Here the purpose is to identify the components with very low inspection cost, compared to the value-added at stake. The analysis clearly shows that the frame is one such a module: although it is quite robust, the value-added (U) of that item is very high and the inspection cost (Insp) is low compared to its total value (V) or to the loss in case of failure (L). Hence it is worth inspecting it, even if the result of the inspection is quite predictable. Notice that the chain is also an outlier. One might wonder if it is worth inspecting as well. Actually, the relative inspection cost of the chain is high, when compared with the components of unpredictable wear. Hence, it is probably not worth inspecting it. Figure 7 locates these subassemblies in a graph.

Now, I calculate the reusability of all modules that are not inspected. Table 7 shows the procedure. The calculation requires the evaluation of several costs that would normally occur in the remanufacturing setting. The most sensitive to errors is the renovation cost (Rec). The renovation has different meaning depending on the component. For a reusable bearing assembly, it is just a new coat of grease. For a crankshaft with a hidden bearing assembly, the renovation cost may not include lubrication because of lack of access if there is no further disassembly. Once the table is complete, I identify the components with positive reusability. This is the case with the pedals, the handle-bar assembly and the chain. The disassemblability of those with negative value is calculated. In this level, the front-wheel assembly and the seat assembly have negative reusability but positive disassemblability, so they are disassembled.

Among the components that were inspected, the best alternative for some of them might be to disassemble, depending on circumstances. Hence, the next step is to identify which recovery procedure should be adopted for the subassemblies obtained from second level disassembly. Although the reusability of the front wheel is positive, it cannot be readily recovered. It must be inspected to ensure that it is fit to be reused or should be further disassembled. The inner tube is not reusable and the tire not even worth evaluating: it is replaced. All subassemblies in the seat assembly are reused.

In the same step, I calculate the reusability of the subassemblies in the back-wheel assembly and in the frame-fork-crankshaft assembly. It turns out that the rear axle and the fork assembly are the only subassemblies that are clearly reusable. The back wheel, the crankshaft and the frame are subject to inspection. The inner tube and the tire are discarded. The analysis is ended. No more reusability or disassemblability needs to be calculated.

The analysis results in a recommendation of the following recovery process for the bicycle:

1. Disassemble the bicycle to the modules level. Separate the accessories.

2. Renovate and reuse the rear reflector, the chain protector, the pedals, the handle-bar assembly and the chain.

3. Substitute the bike stand.

4. Disassemble the front wheel assembly. Inspect the front wheel for eventual reuse or further disassembly. Substitute the tire and the inner tube. Reuse the front axle.

5. Inspect the back wheel assembly. If disassembly is suggested, inspect the back wheel for eventual reuse or further disassembly. Substitute the tire and the inner tube. Reuse the back axle.

6. Disassemble the seat assembly. Renovate all part for reuse.

7. Inspect the frame-fork-crankshaft assembly. If disassembly is suggested, inspect again the crankshaft and the frame separately. Reuse the fork assembly.

8. Reassemble.

5. Conclusion

In this paper I developed a framework for determining the remanufacturing routine of a generic widget. It attempts to balance the need for an optimal product recovery scheme with the difficulties in obtaining comprehensive information about the value and the wear state of the many components processed in a remanufacturing plant. The framework is based on two design measures: the *reusability* and the *disassemblability* of the used machine. Whenever the reusability of a component is positive, it should be renovated and reused without further disassembly. If the reusability is negative but the disassemblability is positive, the component should be disassembled one level and its sub-components are evaluated, separately.

These design measures were developed with the explicit objective to support the choice of the appropriate recovery process of a given widget. Their valuation depends on the technological capabilities of the remanufacturing shop, and on the quality (wear state) of the average widget arriving at the site.. Hence, they should be updated whenever these capabilities or the profile of the incoming widgets changes.

The framework is driven by the value-added in the final operations in the widget production. It attempts to avoid the value destruction that occurs when a component that could otherwise be reused is recycled or disassembled. The framework recognizes the stochastic aspect of used components. Therefore, a comparative criterion was developed to identify which components should be inspected, or not. It is based on the relative inspection cost (RIC) of the major components in the widget, and their value-added. Components with lower RIC and high value-added should be inspected before any recovery decision takes place. Components with high RIC or low value-added are spared of inspection. Their reusability and disassemblability are calculated based on the distribution of the different wear states in which they may occur, and these measures are used to select the appropriate recovery process.

I illustrated the framework with the development of a remanufacturing routine for a bicycle model. Although bicycles are simpler than many other products worth recovering, this application shows some of its advantages as well as some of its limitations. In our illustration, inspection was reduced to about 1/6 of all assemblies and subassemblies in the bicycle. Regarding the assemblies that are not worth inspecting, these are subjected to uniform recovery processes. To define these processes, limited information about the assembly is required. It is not necessary to evaluate the "last bolt" in the product. On the contrary: the evaluation is limited to the first few assembly levels , including the value-added, material values, expected wear and the loss in case of bad decision.

However, the disassemblability and reusability measures depend on the interaction of many parameters, including the value of intermediate assemblies, and the determination of cost effective disassembly and renovation processes. Ideally, the product recovery should be performed with the concurrence of the original equipment manufacturer. Otherwise, these parameters have to be determined empirically: the remanufacturer will need to examine a large sample of similar widgets in order to obtain reliable information. This underscores the importance of design for environment: widgets abiding to DFE will be disassembled and renovated more easily. The recovery alternatives will be simpler to evaluate and the operation more likely to be profitable. More research is necessary to ground the parameter collection process, and the valuation of used parts or assemblies.

Table 4 - Recovery parameters of major assemblies

PN	Component	a or p	Wear predictability	G1	G2	G3	F1	F2	F3	Insp	V	L	U	RM	RIC	Inspect
	Bicycle	a	n	0.10	0.20	0.70	0.10	0.10	0.40	5.0	100.0	20.0	15.00	20.3	0.13	
1.	Accessories		n	0.20	0.10	0.70	0.10	0.10	0.40	0.5	2.5	2.0	1.00	0.4	0.36	
2.	Right pedal assy.	a	n	0.60	0.35	0.05	0.05	0.05	0.80	0.1	0.9	3.0	0.30	0.2	0.29	n
3.	Left pedal assy.	a	n	0.60	0.35	0.05	0.05	0.05	0.80	0.1	0.9	3.0	0.30	0.2	0.29	n
4.	Front wheel assy.	a	n	0.30	0.55	0.15	0.05	0.60	0.90	5.0	9.1	6.0	0.50	1.2	0.69	?
5.	Back wheel assy.	a	n	0.50	0.45	0.05	0.05	0.60	0.90	5.0	12.8	6.0	0.70	1.8	0.78	?
6.	Seat assy.	a	n	0.15	0.75	0.10	0.10	0.15	0.20	0.2	2.9	2.0	0.15	0.7	0.28	n
7.	Handle-bar assy.	a	n	0.75	0.20	0.05	0.02	0.10	0.30	1.0	8.2	4.0	1.50	2.5	1.64	?
8.	Chain	p	y							2.0	5.7	10.0	4.50	1.2	1.27	?
9.	Frame, fork, crankshaft assy.	a	n	0.10	0.70	0.20	0.01	0.60	0.99	5.0	41.9	10.0	4.00	12.1	0.16	y

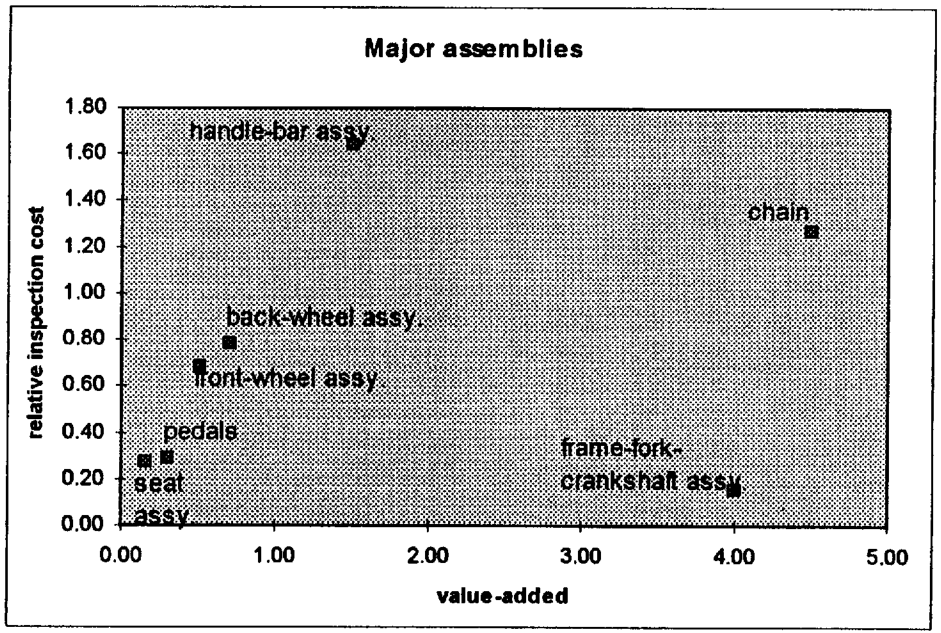

Figure 5 - Inspection decision graph of major assemblies

Table 5 - Recovery parameters of modules and subassemblies of unpredictable wear

PN	Component	a or p	G1	G2	G3	F1	F2	F3	Insp	V	L	U	RIC	Inspect?
1.1.	Rear reflector	p	0.20		0.80	0.10		0.40	0.50	0.72	0.00	0.60	2.04	n
1.3.	Bike stand	p	0.60		0.40	0.10		0.70	0.50	0.36	1.00	0.20	1.08	n
2.	Right pedal assy.	a	0.60	0.35	0.05	0.05	0.05	0.80	0.10	0.92	3.00	0.30	0.29	n
2.3	Reflectors	p							0.00	0.12	0.00	0.10	0.00	n
3.	Left pedal assy.	a	0.60	0.35	0.05	0.05	0.05	0.80	0.10	0.92	3.00	0.30	0.29	n
3.3.	Reflectors	p							0.00	0.12	0.00	0.10	0.00	n
4.	Front wheel assy.	a	0.30	0.55	0.15	0.05	0.60	0.90	5.00	9.13	6.00	0.50	0.69	n
4.2.	Front wheel	a	0.50	0.35	0.15	0.01	0.50	0.90	5.00	4.30	3.00	2.30	2.17	y
4.4.	Inner tube	p	0.30		0.70	0.20		0.60	2.00	0.70	2.00	0.50	1.54	n
5.	Back wheel assy.	a	0.50	0.45	0.05	0.05	0.60	0.90	5.00	12.81	6.00	0.70	0.78	y
5.1.	Rear axle	a	0.50	0.45	0.05	0.05	0.15	0.75	3.00	6.11	6.00	0.50	1.91	n
5.2.	Back wheel	a	0.50	0.35	0.15	0.01	0.50	0.90	5.00	4.30	3.00	2.30	2.17	y
5.4.	Inner tube	p	0.30		0.70	0.20		0.60	2.00	0.70	2.00	0.50	1.54	n
6.	Seat assy.	a	0.15	0.75	0.10	0.10	0.15	0.20	0.20	2.91	2.00	0.15	0.28	n
6.1.	Seat	a	0.20	0.75	0.05	0.01	0.10	0.40	0.10	1.94	2.00	0.50	0.26	?
7.	Handle-bar assy.	a	0.75	0.20	0.05	0.02	0.10	0.30	1.00	8.18	4.00	1.50	1.64	n
7.2.	Handle-bar tilting assy.	a	0.80	0.15	0.05	0.05	0.30	0.70	0.50	0.98	6.00	0.40	0.60	n
9.	Frame-fork-crankshaft assy.	a	0.10	0.70	0.20	0.01	0.60	0.99	5.00	41.90	10.00	4.00	0.16	y
9.1.	Crankshaft	a	0.70	0.25	0.05	0.10	0.50	0.95	5.00	12.55	10.00	1.75	0.91	y

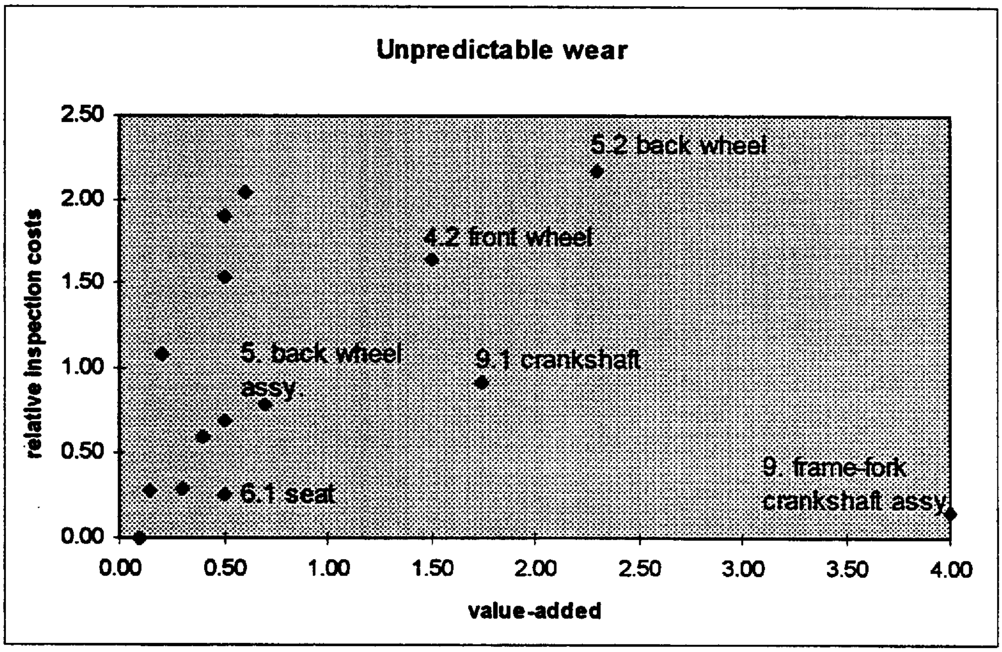

Figure 6 - Inspection decision graph for assemblies of unpredictable wear

Table 6 - Recovery parameters of modules and subassemblies of predictable wear

PN	Component	a or p	F	Insp	V	L	U	RIC	Inspect?
1.2.	Chain protector	p	0.01	0.10	0.46	2.00	0.30	4.07	n
2.1.	Pedal (plastic)	p		0.00	0.25	2.00	0.20	0.00	n
2.2	Axle (iron)	p	0.01	0.10	0.25	3.00	0.15	3.08	n
3.1.	Pedal (plastic)	p		0.00	0.25	2.00	0.20	0.00	n
3.2.	Axle (iron)	p	0.01	0.10	0.25	3.00	0.15	3.08	n
4.1.	Front axle	a	0.10	3.00	2.63	6.00	0.65	3.48	n
4.3.	Tire	p		0.00	1.00	2.00	0.75	0.00	n
5.3.	Tire	p		0.00	1.00	2.00	0.75	0.00	n
6.2.	Rod	p	0.10	0.10	0.50	2.00	0.35	0.40	n
6.3.	Connectors (nuts, bolts)	p	0.10	0.10	0.32	1.00	0.20	0.76	n
7.1.	Handle bar	a	0.01	0.10	3.69	4.00	0.70	1.30	n
7.3.	Steering tube assembly	a	0.01	0.10	2.02	6.00	0.40	1.25	n
8.	Chain	p	0.10	2.00	5.70	10.00	4.50	1.27	?
9.2.	Fork assy.	a	0.05	5.00	10.35	10.00	1.23	4.91	n
9.3.	Frame	p	0.03	0.50	15.00	10.00	9.00	0.67	y

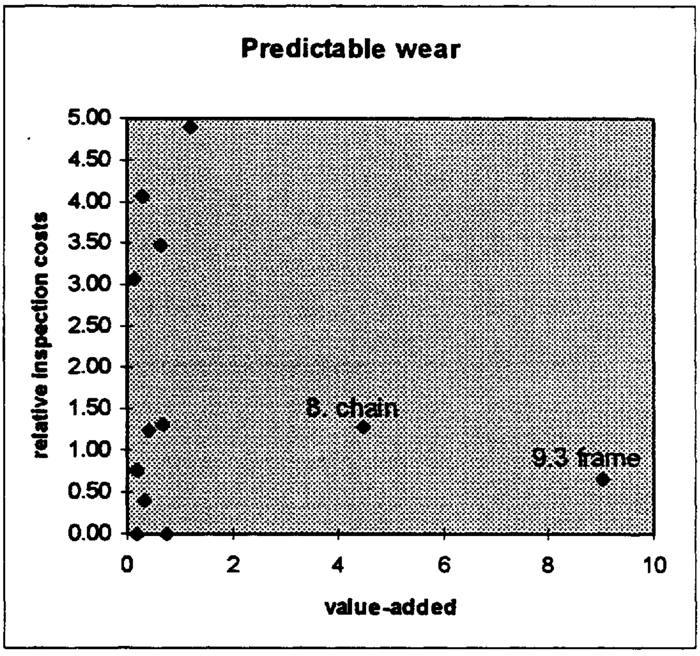

Figure 7 - Inspection decision graph for assemblies of predictable wear

Table 7 - Reusability and disassemblability measures of selected subassemblies

PN	Component	P1	P2	P3	Rec1	Rec2	Rec3	Rec	Dis	Disas-semblabil-ity	Reusabil-ity	Inspect ?
	Bicycle							10.00	5.00		-0.607	
1.1.	Rear reflector	0.70	0.60	0.50				0.10			0.740	no
1.2.	Chain protector	0.60	0.50	0.10				0.20			0.336	no
1.3.	Bike stand	0.60	0.30	0.10				0.10			-0.644	no
2.	Right pedal assy.	0.99	0.95	0.90				0.10			0.433	no
3.	Left pedal assy.	0.99	0.95	0.90				0.10			0.433	no
4.	Front wheel assy.	0.99	0.90	0.60				1.50	1.50	0.779	-0.834	no
4.1.	Front axle	0.99	0.90	0.85	0.01	0.01	0.05	0.02			0.053	no
4.2.	Front wheel	0.99	0.80	0.50	0.01	0.02	0.10	0.05			0.079	yes
4.3.	Tire	0.00	0.00	0.00								no
4.4.	Inner tube	0.90	0.50	0.10	0.01	0.02	0.10				-0.614	no
5.	Back wheel assy.	0.90	0.80	0.40				2.50	2.00	0.357	-0.832	yes
5.1.	Rear axle	0.90	0.70	0.50	0.01	0.01	0.05				0.154	no
5.2.	Back wheel	0.99	0.80	0.50	0.01	0.02	0.10				0.103	yes
5.3.	Tire	0.00	0.00	0.00								no
5.4.	Inner tube	0.90	0.50	0.10	0.01	0.02	0.10				-0.614	no
6.	Seat assy.	0.80	0.70	0.40				0.10	0.75	0.113	-0.678	no
6.1.	Seat	0.99	0.90	0.30	0.05	0.10	0.50	0.10			2.109	no
6.2.	Rod	0.99	0.90	0.85	0.00	0.00	0.00	0.01			0.346	no
6.3.	Connectors (nuts, bolts)	0.99	0.95	0.90	0.00	0.00	0.00	0.01			0.408	no
7.	Handle-bar assy.	0.90	0.70	0.50				0.50			0.561	no
8.	Chain	0.90	0.85	0.75				0.50			1.174	no
9.	Frame, fork, crankshaft assy.	0.95	0.90	0.80				4.00	3.50		-0.859	yes
9.1.	Crankshaft	0.99	0.90	0.20								yes
9.2.	Fork assy.	0.99	0.90	0.40				0.50	0.80		0.499	no
9.3.	Frame	0.95	0.85	0.50				2.00			2.273	yes

6. Appendix: Breakdown of a typical 20-inch BMX bicycle:

1. Accessories
    1.1. Rear reflector
    1.2. Chain protector
    1.3. Bike stand
2. Right pedal assy.
    2.1. Pedal (plastic)
    2.2. Axle (iron)
    2.3. Reflectors
3. Left pedal assy.
    3.1. Pedal (plastic)
    3.2. Axle (iron)
    3.3. Reflectors
4. Front wheel
    4.1. Axle
        4.1.1.Rod
        4.1.2.Bearing assemblies
        4.1.3.Bolts, fasteners, safety retainers
    4.2. Wheel
        4.2.1.Hub
        4.2.2.Spokes and nipples
        4.2.3.Rim
        4.2.4.Reflector
    4.3. Tire
    4.4. Inner tube
5. Back wheel
    5.1. Axle
        5.1.1.Rod
        5.1.2.Bearing assemblies
        5.1.3.Freewheel sprocket
        5.1.4.Coaster brake
        5.1.5.Safety retainer
        5.1.6.Bolts, fasteners
    5.2. Wheel
        5.2.1.Hub
        5.2.2.Spokes and nipples
        5.2.3.Rim
        5.2.4.Reflector
    5.3. Tire
    5.4. Inner tube
6. Seat assy.
    6.1. Seat
        6.1.1.Plastic cover
        6.1.2.Foam cushion
        6.1.3.Plastic base
        6.1.4.Metal structure
        6.1.5.Clips
    6.2. Rod
    6.3. Connectors (nuts, bolts)
7. Handle-bar assy.
    7.1. Handle bar
        7.1.1.Handle bar
        7.1.2.Handles (plastic)
    7.2. Handle-bar tilting assy.
        7.2.1.Mouth
        7.2.2.Tightening bolt
    7.3. Hollow rod assy.
        7.3.1.Hollow rod
        7.3.2.Expander (iron)
        7.3.3.Long screw
8. Chain
9. Frame, fork, crankshaft assy.
    9.1. Crankshaft
        9.1.1.Crank
        9.1.2.Bearing assemblies
        9.1.3.Driving sprocket
        9.1.4.Bolt and retainers
    9.2. Fork assy.
        9.2.1.Fork
        9.2.2.Bearing assemblies
        9.2.3.Bolt and retainers
        9.2.4.Front reflector
    9.3. Frame

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