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An approach for estimating the end-of-life product disassembly effort and cost

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Disassembly is the process of physically separating a product into its parts or subassembly pieces. The overall economics of the disassembly process, and in particular the cost to disassemble, is still not well understood. In this paper our goal is to introduce a methodology that will support and facilitate the economic analysis of the disassembly activity. We present a multi-factor model to compute the disassembly effort index (DEI) score, which is representative of the total operating cost to disassemble a product. The DEI score can then be compared against the projected market value of the disassembled parts and subassemblies to get an economic measure. To develop the DEI model we surveyed a variety of commercial disassembly facilities. Based on these surveys we propose a multi-factor weighted estimation scheme. The seven factors are (i) time, (ii) tools, (iii) fixture, (iv) access, (v) instruct, (vi) hazard, and (vii) force requirements. The DEI scale is defined in the 0 to 100 range. This range is assigned on a weighted basis to each of the seven factors. For each factor, an independent utility scale is formulated, using the assigned range as anchors. Using a conversion scale the DEI score is used to derive an estimate of disassembly cost and the disassembly return on investment. An example is presented.

1. Introduction

Disassembly is the process of physically separating a product into its parts or subassembly pieces. Traditionally, product disassembly was only done to service or repair a part. However, the disassembly of a product at the end of its useful life is slowly growing into a common and worthwhile industrial practice. There are several reasons for this, including, (i) the recovery of valuable and reusable parts or subassemblies, (ii) product separation to facilitate the downstream material recovery process, (iii) the removal of hazardous or toxic materials, (iv) to remanufacture the product for another useful life, and (v) to destroy the proprietary parts or subassemblies. In combination, these reasons also help reduce the environmental and ecological detriments associated with product disposal. At the very minimum, disassembly reduces the occupied landfill space. Several large companies such as IBM, Digital/Compaq, and Phillips have initiated in-house disassembly operations. In other cases, such as in the automobile industry, independent third-party companies have established disassembly and recovery facilities. In the majority of cases the disassembly is limited to the highest value components or the bulk parts that are easily recycled. Examples are precious metal from PCBs, mercury from electrical

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switches, starters and alternators from automobile engines, plastic resin from computer housings, and power supply units from electrical equipment.

The process of disassembly tends to be predominantly manual, and the overall economics is still not well understood. There is much reported research on the life cycle analysis (LCA) of products (Carnahan and Thurston 1998). These LCA models attempt to capture all costs associated with production, usage, and disposal of the product. They usually account for a disposed product's costs either as a whole or in parts. However, since the cost to disassemble the part is not obvious, disassembly is not easily justified in these models. The lack of an effective approach for estimating the product end-of-life disassembly effort is one of the primary reasons limiting a more widespread interest in product disassembly. As a result, products with a good number of reusable/recyclable parts are disposed of or recycled in their entirety. For example, in the case of computers and copiers, parts such as CRT glass, keyboard caps, drive motors, transformers, and steel casings, could all be given a new life if they could be disassembled efficiently. In recent years though, some progress has been made and several companies are setting up cooperative disassembly centres. For instance, Xerox expects to reuse 60% of the parts in the 4 million copiers discarded annually.

Clearly, product disassembly is important both from an environmental perspective and a corporate strategy. In this paper, our goal is to introduce a methodology that will support and facilitate the economic analysis of the disassembly activity. We present a model to compute the disassembly effort index (DEI) score, which is representative of the total operating cost to disassemble a product. The DEI score can then be compared against the projected market value of the disassembled parts and subassemblies to get an economic measure. The model is applicable in manual disassembly cases. To develop the DEI model we surveyed a variety of commercial disassembly facilities. Based on these surveys we propose a multi-factor weighted estimation scheme. The facilities studied included the product take-back and disassembly centre of a large computer manufacturer, several facilities of a major automobile recycling franchise, two facilities specializing in the disassembly of electronic products, and a disassembler of office equipment.

One may question why a detailed costing analysis is not done, so as to get a precise estimate of the disassembly cost. Several approaches for such an analysis exist and are commonly used to estimate assembly costs. The disassembly process and industry is characterized by several features that preclude the economic application of these approaches. The primary reasons are (i) disassemblers lack a detailed knowledge about the design of a product, (ii) disassembly process plans are more general as compared to assembly process and are not readily amenable to work measurement analysis, (iii) disassemblers process a wide variety of products and models and typically gross margins are relatively tight, which makes it difficult to justify a detailed analysis of each product, finally (iv) the available decision-making time in disassembly is relatively short and the disassembler must quickly decide whether the product provides a profit opportunity. Our objective is to develop a tool that works in such an environment.

2. Disassembly economics

There are several cost elements in the disposal and disassembly process. Figure 1 illustrates the associated flow process and from this we can categorize the operational costs into the following: (i) collection of products; (ii) sorting into

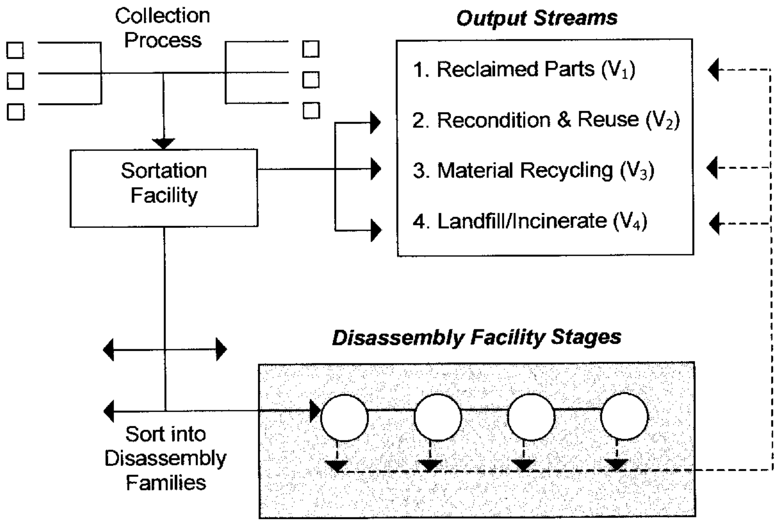

Figure 1. The disposal and disassembly process.

disassembly families; (iii) product handling; (iv) disassembly worker training and instructions; (v) product disassembly; and (vi) part and material handling. The DEI scoring model presented here only considers categories (iii) to (vi). Collection costs are usually quite significant. However, this is an unavoidable cost, since collection to a sorting location must occur regardless of whether disassembly occurs or not. Sorting costs, though, are considered in our economic analysis.

In figure 1 we show four output streams. Typically, the value of these streams is decreasing as we go down the list, with landfill/trash actually being a cost. Observe that a key economic decision at the sorting facility is whether to send the product directly to one of the output streams, or to enter it into a disassembly channel. When the product can be effectively reconditioned and there is a demand for such products, then the second stream is an attractive option. When a product has significant quantities of valuable materials (e.g. aluminium, precious metals), then the most common direct disposal path is to send it to a material recycler. Disassembly provides an opportunity to increase the net value of the output streams. This, however, can only be justified if the disassembly cost is relatively low. Low *et al.* (1998) presents generic financial models for comparing three end-of-life options (resale or reuse, re-manufacturing, and disassembly and recycling). They provide some parametric equations that could be used to estimate sorting costs, and landfill or scrap costs. Das and Matthew (1999) provide a list of common material outputs from disassembly operations, and estimates of their market value.

After disassembly, the outputs will enter either streams 1, 3 or 4. Let V_1, V_3 and V_4 be the projected values of the output streams after disassembly, note that one or more of these could be negative. Let W be the maximum value if the product is directly disposed. In direct disposal we assume that the product enters one of output streams 2, 3 or 4, and W is the maximum of the direct disposal value of V_2, V_3 and V_4. Let C_s be the cost to sort into disassembly families plus the logistical cost of moving the inventory. This includes any special material handling costs such as the crushing of automobiles. Let C_d be the disassembly cost. Then we propose the following measure of return:

$$\text{Disassembly Return on Investment} = R_d = \{[(V_1 + V_3 + V_4) - W]/(C_s + C_d)\} - 1.$$

For a given scenario one could determine a threshold level for R_d, and that could be used to make the direct disposal versus disassembly decisions. In the above equation the variable cost values are obtained from market data, while the cost C_s is projected from costs at existing recycling centres. Possibly, C_s could be a pre-defined constant for all disassembly families. In this paper we provide a model for estimating the cost C_d.

The concept of disassembly families needs some discussion. Most disassembly facilities tend to be specialized in the type of product they will accept and can process. For instance, a facility may process only small to medium sized computing equipment, or only household appliances, or only automobiles. There are several reasons for this restriction, including: (i) the need for product specific tools and fixtures; (ii) the disassembler's knowledge and expertise about the product's design and its components; and (iii) the need to generate critical masses of recoverable parts and/or material types. A disassembly family may therefore be defined as a group of products that have sufficient commonality, such that they can be efficiently disassembled in the same facility. In the development of our DEI model we assume that the facility is restricted to processing a single disassembly family or a set of related families.

3. Related research

Research activity in the disassembly area is a relatively recent event. Models and methods are typically restricted to a small class of products or material types. During the last 4 to 6 years researchers have begun to address and devise general and standard solutions for many aspects of product disassembly. In an effort to standardize disassembly operation times, Dowie and Kelly (1994) conducted a series of disassembly experiments with simple operations. They recorded times ranging form 0.2 s to 2.5 s for a wide variety of operations, including screw removal, cutting, and snap-fit release. These exclude any access issues or execution problems. They expect the real-life times to be 10 to 20 times more. Kroll (1996) and Kroll *et al.* (1996) developed a method for estimating the ease of disassembly using work measurement analysis. The relative difficulty of each disassembly task was evaluated in four categories: accessibility, positioning, force, base time, and special. Using the MOST work measurement system, standard evaluation charts for several tasks (e.g. unscrew, cut) were developed. These charts provide scores in the '1' (no difficulty) to '4' (considerable difficulty) range. No scales are provided to assist the user in the difficulty evaluation. Using these scores the disassembly design efficiency is calculated. Theirs is a part-by-part analysis, with each part represented by a row in their evaluation worksheet. Similar to the DFA method (Boothroyd and Dewhurst 1987), this method also considers the theoretical minimum number of parts in calculating the efficiency, and is thus intended as a tool for product designers. They report testing their method on a variety of small appliances, and concluded that current designs have generally low disassembly design efficiencies. Vujosevic *et al.* (1995) also used a work measurement tool to estimate disassembly times in developing a simulator for maintainability analysis. One drawback in applying work-measurement based methods is the need for precisely defined motions. In disassembly operations, process planning data are typically limited, and in the DEI scheme we attempt to stay within this assumption.

Several groups have developed methods for generating a 'recovery plan' for a given design. These methods typically attempt to balance the value of the reclaimed parts with the disassembly costs. One of the first methods was ReStar developed by Navinchandra (1993). For a given product design and composition, the method provides the user with an assessment of the recyclability and disassembly strategy. Zussman *et al.* (1994) even consider the uncertainty of future costs and values, in projecting a recovery plan at the time of design. There is a growing body of work on mathematical models for developing disassembly sequences for a recovery plan. Pnueli and Zussman (1997) and Penev and de Ron (1996) have used and/or graphs to prescribe a disassembly plan and hence compute the end-of-life value of a product. Gungor and Gupta (1997) propose a disassembly sequence generation heuristic, which then selects a near optimum solution. Lambert (1997) presents a method for determining the optimal disassembly sequence under varying objectives. Most of these models will use a disassembly cost or effort parameter to be associated with each disassembly arc or branch. One set of models assumes a constant disassembly cost per step (Johnson and Wang 1995, Gungor and Gupta 1997). The objective then is to minimize the number of steps needed to retrieve the most valuable assets. Other models (Penev and Ron 1996) require the disassembly cost for each component or operation to be input. Lambert (1997) suggests this cost should include labour, equipment, and energy costs for each operation. The method presented in this paper will provide an estimate of this cost parameter, and thus support the application of the above models.

4. The disassembly process

Our approach is to visualize disassembly as a multi-step process or plan. At each step one or more parts with certain commonalties are separated or removed. The separated element could be a partial part, an entire part, or a sub-assembly of parts. This removal process and its associated logistics are the primary determinants of the disassembly effort. A separated subassembly may be further disassembled; hence, the disassembly plan can be represented by a diverging network, with some steps occurring in parallel. Commonly, the term 'disassembly tree' refers to the network that includes all possible disassembly plans. For a given product, multiple plans can be generated, with each having a different R_d value. It should not be assumed that the disassembly plan is simply an inverse of the bill-of-materials tree. Our industrial observations indicate that this is rarely the case. Each disassembly step involves one of two classes of processes: (1) the unfastening process, where a fastening device is removed which, in effect, reverses the original assembly fastening action; (2) the disassembly processes; that is, all other activities that facilitate the separation of the product into its parts. An example disassembly action would be cutting or impact breakage. Within each class there are several specific process types. From an empirical review of present and future disassembly practice, we were able to identify 13 unfastening processes and 16 disassembly processes. These are listed in table 1. Reclaimed parts typically constitute the most valuable output from a disassembly process, and unfastening processes are key to removal of reusable parts. Shu and Flowers (1995), using case studies, illustrate how design changes can significantly lower the unfastening cost and increase the reusable part yield. Using a

Unfastening Processes (removal of the following)	
1. Nail	8. Spring toggle
2. Rivet	9. Zippers and velcro
3. Screw	10. Cantilevered snapfit
4. Retaining ring	11. Center lug snapfit
5. Staple	12. Crimp or seam
6. Nuts and bolts	13. Adhesive tape
7. Push on fastener	
Disassembly Processes	
1. Self removal of part	9. Crushing and bending
2. Axial part pull out	10. Chemical dissolution
3. Levered part removal	11. Shredding
4. Hammered part pull removal	12. Impact breakage
5. Adhesive separation	13. Suction and drainage
6. Shearing cut	14. Paint Removal
7. Saw cutting	15. Drilling
8. Flame cutting	16. Weld and solder breakage

Table 1. Common disassembly activities.

cost analysis, they show how high part and fastener failure rates during disassembly could render the operation economically unattractive.

A disassembly plan is described by the sequence of processing steps, the part or parts worked on each step, and the part portions, parts, and subassemblies remaining at the end. Each of these end components will enter one of the output streams introduced in section 2. Typically, as we progress down the disassembly plan we will observe three phases. In the first phase, the disassembler attempts to improve the accessibility to different parts of the product. As a result, no value is directly released in this phase. In the second phase, valuable parts and sub-assemblies are reclaimed. Finally, in the third phase, separation is done so as to facilitate downstream material recycling processes. This ensures a higher grade of input purity to the material shredder, and consequently results in a better quality recycled material. In some cases there is also a fourth phase, in which parts and subassemblies are forcefully destroyed in an effort to protect their proprietary content. Typically, the incremental value released decreases as we move from phase to phase. Often, a disassembler will discard the product after phase two, with the knowledge that the marginal cost benefit of further disassembly is not attractive.

An important element in the way a product is disassembled, is the nature of the facility itself. We find that, in general, disassembly facilities are one of two kinds, (A) those operated by the original manufacturer either directly or indirectly, and (B) those operated by a third party with little or no OEM connection. The cost structures for the two facilities tend to be different, primarily because of the differentiating features noted in table 2. An indirect Type A facility is one where a contractor operates the facility for the OEM. We observed such a situation in a Hewlett-Packard facility.

To develop the DEI model we surveyed a variety of commercial disassembly facilities. The purpose of this was twofold, (i) to document what resources and the variety of resources that were utilized in the disassembly process, and (ii) to document management opinion about the disassembly effort and cost for different products. Both type A and type B facilities were included in the survey. In both types there was a need for a tool to estimate R_d quickly and easily. The facilities were

Type A Disassembly Facility	Type B Disassembly Facility
1. Smaller variety of product input, typically restricted to their own products	1. Higher product variety, possibly handling two to three different disassembly families
2. Greater degree of disassembly, often 100%	2. Limited degree of disassembly with a focus on few assets
3. Detailed design knowledge of the product structure and its components	3. Design knowledge as gained from experience, with no knowledge for first time products
4. Low inventory levels both on the input and output side	4. High input inventory levels (due to asset value uncertainty), and high output inventory levels (in order to accumulate minimum transportable quantities)
5. Primary goals are environmental concerns, retrieval of reuseable assets, and destruction of proprietary products/parts	5. Primary goal is profitability

Table 2. Type A and B disassembly facilities.

unable to predict up front the likely disassembly cost. Consequently, only products in which there was a high likelihood that the R_d would be attractive were disassembled. This was more pronounced in type B facilities. One important feature that we noted was that a part-by-part analysis is not readily applicable in these facilities. The reason being that the disassembly usually results in a few whole parts, plus several subassemblies of similar materials, and a mixed waste stream. Further, in many cases, a single part is cut or broken into two or more pieces. We therefore constructed a DEI model that is step focused as opposed to part focused.

5. A multi-factor disassembly cost and effort model

In our research, we found that the disassembly effort and cost were a function of several factors, much like an assembly process. We thus concluded that we would need to develop a multi-factor model for computing the DEI score. Using an activity-based costing approach we surveyed both line managers and line workers at the different disassembly facilities, with the objective of identifying the factors in our model. We concluded that the model should consist of the following seven factors: time, tools, fixture, access, instruction, hazard and force requirements. Disassembly is, for the most part, a manual activity, and the disassembly time is a direct measure of the labour cost. It is important to note that there are several pilot attempts to build automated disassembly lines, and these could, in the future, enter the main stream. An example would be the NEUROBOT initiative, which is concerned with the development of an autonomous robot cell for the disassembly of automotive components (Tuominen *et al.* 1995). The DEI model will need to be modified prior to application in these settings. In addition to time, we found that several other factors contribute to an indirect activity cost or effort. These will influence worker fatigue, worker skill, material handling effort, set-up effort, and the yield rate or output quality. The six factors listed above are representative of the indirect cost or effort in a disassembly operation.

Multi-factor or multi-criteria models are effective tools for representing the true performance of a given problem. However, their validity is dependent on ensuring that each factor is effectively transformed to the common scale and is appropriately represented on that scale. Rosenthal (1985) provides recommendations for the formulation of multi-criteria objectives and we follow these here. In our model we evaluate each step in the disassembly process independently. Thus, our approach requires that either all possible steps be known, or a specific disassembly plan be available. Our plan is to evaluate each factor for each step on a cost/effort indexing scale. This permits us to develop a robust model that is widely applicable. Later, in section 6.8, we show how this scale is transformed into a cost value for a specific case.

The cost effort index scale is defined in the 0 to 100 range. This range is assigned on a weighted basis to each of the seven factors. This is a common practice in multi-attribute utility theory and is often referred to as the amalgamated utility model. A key assumption, which follows from this approach, is that we know the minimum and maximum cost/effort per step for a given case. Our premise is that this assumption is valid at the step level. At the facilities we studied, process planners were clear on what the maximum cost/effort would be for their facilities. To assign the range the relative importance of each factor was studied and discussed with management at the different facilities. The final allocation was as follows: time—25%; tools—10%; fixture—15%; access—15%; instruction—10%; hazard—5%; and force—20%. For each factor, an independent utility scale can now be formulated, using the assigned range as anchors. Note that the DEI method considers the operating cost associated with each factor, and not the capital costs. Operating costs include maintenance, skill, and set-up costs. When a tool, fixture, or hazard gear appears in several steps, they would still need to be scored in each step. Clearly, though, the relative effort will be less with usage in multiple steps, and the model is handicapped in its inability to model this effect.

6. Estimating the disassembly cost and effort for each factor

In this section we develop the cost/effort or utility scale for each of the seven factors. The scales were designed such that a user could rapidly generate responses for a specific design. Apart from the time and force factors, there are no obvious scales for measuring the other factors. To develop these scales we recorded the possible outcomes for each factor, and then scaled them on the basis of their relative difficulty. In manual disassembly operations, the set of possible outcomes is not very large and is thus amenable to such a scaling procedure. Clearly, converting a non-numeric factor to a numeric scale provides room for error. In an attempt to minimize the error we iteratively applied the scales to benchmark products in the different facilities. At the amalgamated level each facility will assign a different cost value to the scales and, in section 6.8, we illustrate how this is modelled. The factors and their associated scales are described below. Figure 2 illustrates a scoring card for implementing the proposed estimation scales. For each step, the user enters the appropriate score from the scale. The scores are added to give the DEI score for that step. Finally, the DEI scores for all steps are summed to give the overall DEI score. In many instances there may be more than one response to a factor. For instance, two tools may be used in a step.

In such situations the higher score is always entered. Note that the additive effect of the multiple tools is represented in the time scale. In many instances the scales will not describe the situation in a given case. In such cases the user will select the appropriate score by relating the cases to the anchors provided. For instance, in

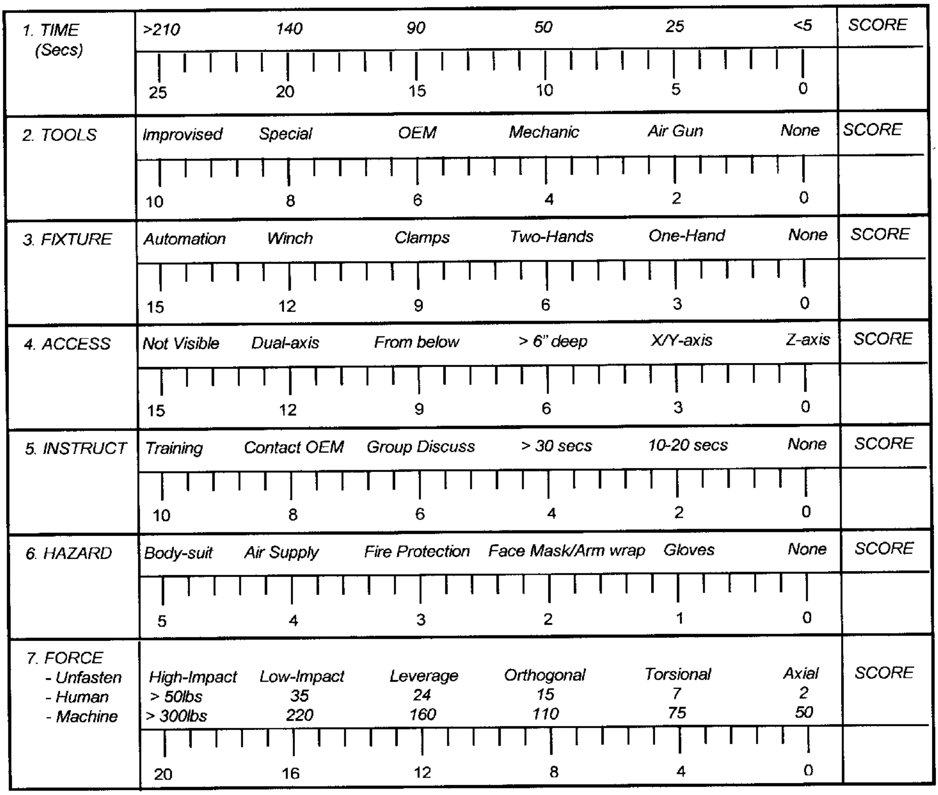

Figure 2. The DEI scoring card.

hazard we may need elbow guards, but this is not listed on the scale. On the basis of the anchors provided the user may conclude that a score of 1.5 is applicable.

6.1. *Time*

The per step disassembly time includes set-up time, handling time and the actual hands-on disassembly time. Set-up time includes tooling and equipment prep time. For an unfastening operation, it includes the time to unlock, loosen and remove the fastener. In the DEI scale the per step disassembly time ranges from between 5 s to greater than 210 s. Since most disassembly activities are manual, the disassembly time is a direct measure of the associated labour cost and hence the profitability of the activity. We observed that, in most disassembly facilities, management projects a maximum allowable total disassembly time ($D_{\max}$). Note that this is the sum of all per step disassembly times. Beyond this time it is unlikely that the activity will be profitable, and hence disassembly is not pursued. In the auto recycling industry $D_{\max}$ is between 270 to 320 minutes per vehicle, while at IBM's Endicott disassembly operation $D_{\max}$ for PCs is 5 minutes. We were unable to find any sound relationship between $D_{\max}$ and the original assembly time of the product, since profitability is a function of part and material content.

In general, as $D_{\max}$ increases, the number of disassembly steps also increases. As a result, the average per step disassembly time tends to be the same across products. We find this time to be between 15 to 20 s, while the ideal time is about 10 s.

Furthermore, operation times in excess of 210 s are rare, and tend to be bottlenecks when they do exist. The non-linear penalty scale shown in figure 2 is thus anchored from these times.

6.2. *Tools*

Tools include all electromechanical equipment, plus any associated handling devices needed to execute the disassembly action. Since disassembly facilities handle a variety of products they have, in contrast to an assembly facility, a non-homogeneous input stream. Thus, as the tooling requirements become more specialized the capital costs tend to be amortized over a smaller portion of the input volume. In many cases we observed that disassemblers would simply avoid a disassembly if an uncommon tool was required, or use a destructive process to achieve the same result. The airgun, hammer, and handsaw were the three most common tools used by the disassemblers.

The primary anchors in the tools scale are described as follows. None—when no tools are needed; that is, the disassembly is performed by hands. An example case would be when parts have easily accessible integral fasteners. Airgun—a hand-held pneumatically driven screw driver or wrench. A common problem in disassembly is the variety of head types and sizes used in the same product. Some airguns are equipped with universal heads, but these do not work well in high torsion cases. Mechanic's tools—these are tools commonly found in a mechanic's toolbox, and include screw drivers, wrenches, spanners, ratchet spanners, hacksaws and pliers. OEM tools—tools that need to be procured from the OEM. Such tools are commonly used in the product servicing industry, but are rarely used by disassemblers. The exception being when such tools are needed for unfastening proprietary or security fasteners. Special tools—these are unique and are fabricated for a specific application. These include heavy duty tools such as crushers, torsional twisters, and heavy sledgehammers. An example would be the crushers used to compress the chassis at the end of an automobile disassembly. Improvised—this is when there are no defined tools and a special tool cannot be built. The user then has to improvise a tooling solution using available resources. Tooling costs in disassembly tend not to be high, tools therefore have a relatively low weighting (10%) in the proposed effort scale.

6.3. *Fixture*

Fixturing is the part or product holding activity that is needed to facilitate or even make feasible the disassembly activity. Fixturing would include any specialized equipment used to grip the disassembly carcass as it is moved from stage to stage. Fixturing requirements have been one of the primary impediments to efficient disassembly of large products. For instance, in the case of automobiles, disassembly is done in a single workstation that precludes the economics of a flow process. A Dutch company called De Mosselaar has developed a six-stage automatic disassembly line that fixtures the chassis during the process (Owen 1993). However, this equipment costs close to a million dollars and hence is difficult to justify economically. Another illustration of fixturing costs is the removal of a top-mounted automobile engine, this requires the use of an overhead winch. Conversely, a bottom-mounted engine does not require this fixture and is removed much more easily.

The primary anchors in the fixture scale are described as follows. None—when no fixturing is need. This is possible when the product resists on a conveyor belt or trolley and no product lifting or rotation is requires. One hand—usually applicable for small products and implies the other hand is available for doing the disassembly activity. Two hand—usually implies the product is picked up and oriented into a desired position, and then the disassembly activity is executed. In the disassembly of PCs, most of the steps would fall in this category. Clamps—are tabletop vices and in/out fixtures that are used to hold the part, and include custom-built vices and grippers. Winches—these represent powered fixtures such as an overhead winch. These may also include mechanisms for rotating or moving the product. Automation—represents fixed or programmable automation equipment that is used to fixture and grip the product. This includes robotic equipment. Fixturing costs in disassembly could be significant; fixtures therefore have a relatively moderate weighting (15%) in the proposed effort scale.

6.4. *Access*

Access represents the ease or difficulty with which the part can be accessed. For a fastener, access is evaluated in terms of positioning the toolhead on the fastener, and then executing an unlocking motion. Unlike an assembly process, where parts are generally added layer by layer, in disassembly the parts or points of interest could be anywhere in the product. Disassembly, by sequentially removing only the parts on the product surface, is often not an economical alternative, and is only done when the disassembly would otherwise be infeasible.

The primary anchors in the access scale are described as follows. Z-axis—when access is possible from directly above the product. This is ergonomically the best case for manual disassembly. X/Y-axis—when access is from the side of the part. Greater than 6 inches deep—when the disassembly point is more than 6 inches deep from the product surface. This is applicable only when the access path is tightly restricted; that is, there is less than 7 inches clearance. At depths greater than 6 inches the disassembly worker must insert the entire wrist and at least half an arm. This usually results in a long processing time with difficult manoeuvres. From below—or a negative Z-axis access. This usually requires special fixturing to make the access possible. Dual axis—when the disassembly point is accessed through a flexible or bent tool. For example, when removing the starter in an engine assembly. Not visible—when the disassembly is inside the product and not visible.

6.5. *Instructions*

A disassembly facility must process a variety of products. Even in a facility that focuses on only one disassembly family, every day brings new products. For instance, at IBM's small computer disassembly facility, everything ranging from laptops, to auxiliary power units is processed. Furthermore, the same product may experience internal design changes, implying it may have different disassembly plans. At the other extreme, Type B disassembly facilities often process several related families of products. For instance, at an electronics recycler, we noted the facility handled PCs, copiers, and medical devices. Unlike an assembly line, a disassembly worker must often receive instructions before each product is processed. These instructions could include the disassembly plan for the product, the extent to which it should be disassembled, and what material types are present. Reading and interpreting these instructions slows down the processing rate.

The primary anchors in the instructions scale are described as follows. None—when the next step in the disassembly plan is obvious or apparent. 10–20 s and

> 30 s—the time range for the worker to assess the next step. This could include checking product contents in a manual or computer database. In the case of one facility we observed an information system that provides the user with a list of recoverable parts when the product SKU number is entered. Group discuss—if the worker needs to discuss the situation with others or the line supervisor. Contact OEM—is when OEM documentation needs to be checked before disassembly can continue. Training—due to a difficult disassembly step, special training is needed. Instruction is a common element in disassembly costs but is usually not significant, and therefore has a relatively low weighting (10%) in the proposed effort scale.

6.6. *Hazard protection*

Disassembly operations are characterized by destructive activities and broken parts, coupled with an uncertain input stream. In such situations the potential for a wide range of worker hazards exists. In the extreme, these hazards would include the presence of toxic chemicals or inflammable compounds. Battery acids and gasoline vapours are two examples from the automobile disassembly process, while static charges and mercury in control switches are examples from the electronics industry. Sharp edges from cut metal and broken glass are common in almost all disassembly operations, and are a constant hazard.

The primary anchors in the hazard scale are described as follows. None—when there are no known hazards and the disassembly can be done without any protection, other than eye guards. Gloves—when hand protection from sharp edges and local chemical hazards is needed. This represents the typical disassembly situation. Face mask and arm wrap—face masks are needed when breathable particles become airborne during the disassembly. This occurs during cutting or grinding operations, in particular when ceramic materials such as fibreglass are processed. Arm wraps are Kevlar coverings used to protect the worker when there are many sharp edges or the disassembly point is deep. At one facility we noted a sharp decline in arm injuries after the introduction of arm wraps. Fire protection—needed when explosive materials are being handled. This could be either a protective apparel or safety/handling equipment. As an example, a new problem in the case of automobiles is the disassembly of airbags. Very often the propellant is released during disassembly, thus causing worker injury. Air supply—when the ambient atmosphere must be cleaned using a special purpose ventilation equipment, similar to an electronics cleanroom. Body suit—when the worker must be fully covered with no skin exposure. This is rare in commercial disassembly, but necessary in weapons system disassembly or products with radioactive contents. Hazard protection can be costly, and for that reason products with such requirements are rarely disassembled on a commercial basis. Our observation was that the maximum permissible hazard costs would be 5%.

6.7. *Force requirements*

Disassembly is inherently a forceful activity, whether one is doing a simple unscrewing activity or a hammering activity, a force must be exerted. The intensity of this force and the manner in which it is applied, determines the disassembly effort. Unlike the other measures, we evaluate force requirements in three scales instead of one, namely, (i) unfastening, (ii) human application, and (iii) machine application. The rational for this is that the same force has different degrees of intensity depending on how it is applied. For instance, when comparing between automobile disassemblers, the first had equipped the workstation with an electric saw, while the second had not. Consequently, many tasks that were viewed as difficult in the second facility were considered easy in the first. The human and machine scales for force requirements are quite straightforward. The anchors for the human force scale are based on conventional ergonomics, which specify a maximum comfortable human force of about 50 lb. In some instances we found workers lifting pieces in excess of 70 lb, but this was the exception. The anchors for the machine scale are based on the relative economic costs (ownership and maintenance) of the corresponding machinery. This gives us a range of 50 to 300 lb. In the case of unfastening we find that the force requirements are typically constant from a cost perspective, as the force is most often applied from an airgun. Instead, it is the application mode that determines the level of effort. The anchors for the unfastening force scale are as follows. Axial—a linear force applied along the primary axis of the tool. Could be used to open some common snap-fit type fasteners. Torsional—a rotational force applied around the primary axis of the tool is torsional. Airgun activities and screwdriver actions are in this category. Orthogonal—this implies the force is perpendicular to the tool, as for example with shear cutting a fastener head. Leverage—this requires a fulcrum to exert the unfastening force. Low impact—this represents a hammering or repetitive force with less than 20 lb intensity. Commonly used to remove rivets, brackets and nails. High impact—a repetitive force with more than 20 lb intensity.

6.8. *Calculating C_d*

A key question is how to convert the DEI score into a cost factor, so as to facilitate economic analysis. Rather than propose a fixed relationship we recommend that the conversion be calibrated for a given application. This accounts for the differences in the operating infrastructure of different facilities. In our discussions with the different facilities, we found that some were interested in costing each factor separately, while others were interested in the aggregate cost only. We propose the following general conversion formula:

$$C_d = \alpha(\textit{Total Disassembly Time}) + \beta(\textit{DEI Score})$$

Here, α represents the labour rate plus other time-based direct costs, while β represents the cost conversion factor. β is representative of the indirect and overhead costs and can be estimated by calibrating the past cost performance of the facility with the DEI scores. For instance, if the indirect and overhead cost for five previously processed products can be estimated, then we can compute the DEI score for these five and subsequently derive a trial β for each. The average of these would then provide a calibrating β. While initially a user may have some difficulty estimating β, we expect that, with time, a reliable estimate would be obtained.

7. An illustrative example

A common computer DeskJet printer was disassembled and evaluated using the DEI scoring model. This class of product has a useful life of 3 to 4 years and is disposed of in relatively large quantities. In the direct disposal route the entire product would be landfilled ‘as is’. A nine-step disassembly plan for this product was formulated for an example Type A facility. As per this plan the disassembly will generate nine output portions or pieces plus several screw fasteners. Figure 3

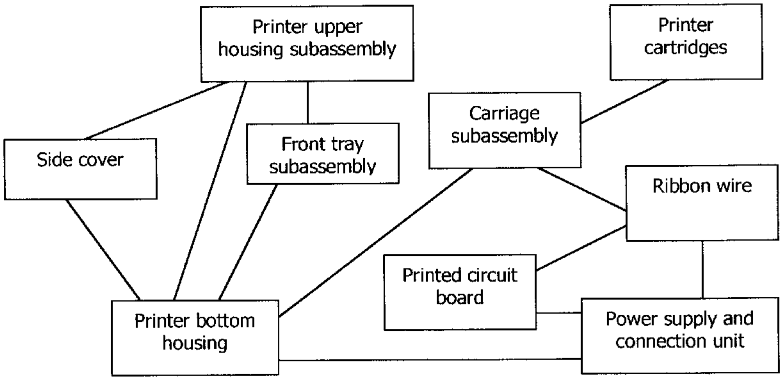

Figure 3. Connectivity graph for the DeskJet printer.

shows the connectivity graph for the different pieces in the printer. The plan and the associated DEI calculation are shown in table 3. Note that other disassembly plans are possible, and could potentially be better than this one. Table 4 lists the pieces and their material compositions. All the plastic pieces are of the same type and would be sent to a plastic recycler, while the circuit board would be sent to a precious metal recycler. The power unit is a reusable asset and, in current markets, is auctioned in bundles. The steel pieces would be sent to a ferrous metal recycler, while the mixed waste would be landfilled.

Step #	*Description*	*Time*	*Tools*	*Fixture*	*Access*	*Instruc*	*Hazard*	*Force*	*Total*	*Time (sec)*
1	Release snaps and pull out front tray assembly	1	0	3	3	0	0	4	**11**	**8**
2	Use chisel lever to remove side carriage cover	0	4	3	3	9	9	9	**10**	**5**
3	Unscrew and remove top fasteners (×2)	0	2	0	0	0	0	4	**6**	**4**
4	Release bottom snaps and remove printer upper housing	2	4	6	5	2	0	3	**22**	**10**
5	Release latches and remove printer cartridge (×2) from cradle	0	0	0	0	0	1	0	**1**	**5**
6	Unscrew (×3) and remove power supply and connection unit	2	2	3	4	1	0	4	**16**	**10**
7	Using scissors cut out ribbon wire to cartridge cradle	0	3	0	0	0	0	0	**3**	**2**
8	Unscrew (×2) and then use lever to remove circuit board	4	3	6	3	1	1	4	**22**	**20**
9	Use lever to break bottom printer housing from carriage assembly	1	3	3	0	0	0	4	**11**	**8**
								Total	**102**	**72**

Table 3. The disassembly plan and DEI worksheet for the DeskJet printer.

Piece #	Description	Material
1	Front tray subassembly	Plastic
2	Side cover	Plastic
3	Screw fasteners (×7)	Steel
4	Printer upper housing subassembly	Plastic
5	Power supply and connection unit	Reuse Asset
6	Ribbon wire	Mixed Waste
7	Printer cartridges (×2)	Mixed Waste
8	Printed circuit board	Electronic
9	Carriage subassembly	Steel/Plastic
10	Printer bottom housing	Plastic

Table 4. Pieces generated in printer disassembly.

The two key measures generated from the analysis are the DEI score of 102 and the total disassembly time of 72 seconds. Step 8 takes the longest time because of the difficult levering action, while Step 4 has the highest score because of fixturing needs and the associated accessibility. Step 4 is not necessarily bad, since a large mass is released. Steps that have high scores and low mass releases are usually the least cost effective. The easiest step was Step 5, which had a DEI score of 1. A consumer often performs this step, and hence the designers have created an efficient mechanism. Table 3 has several utilities, in addition to providing an estimation of the required effort. First, it could be used by the product design team to focus in on difficult steps and hence improve the disassembly effort. Second, it could be used by the disassembly planner to make planned changes and hence improve the R_d.

In general, the printer has a good design from a disassembly perspective. Potentially all the pieces, except # 6 and # 7, can be recycled or reused. For the DeskJet printer we estimate the following values, on the basis of current market conditions. $V_1 = \$1.90$, $V_2 = \$0.95$, $V_4 = -\$0.05$, $W = \$0.12$ and $C_s = \$1.07$. Furthermore, by calibrating our model for the example electronics recycler. we estimate that $\alpha = \$10.70/\text{hr}$ and $\beta = 0.014/\text{unit score}$. For the printer therefore, $C_d = \$1.67$. These values give a gross profit of \$0.26 per printer and an R_d of 10.75%. Given the projected disassembly volume, the R_d value would not justify disassembly in most facilities. Further, note that in this case R_d is highly sensitive to V_1. A disassembler would only consider this product if they had a confirmed customer for the reusable assets. As a contrast, in a type B facility we would have expected a disassembly plan that would have removed the power supply unit, and disposed of the rest.

8. Summary

The DEI scoring model provides an effective and efficient tool for estimating the disassembly effort and cost. The DEI model does not provide a detailed or highly accurate cost; rather, it provides a reliable estimate that can be used in disassembly decision making. These cost estimates provide valuable inputs to a variety of disassembly related economic models. The DEI model requires the user first to have a disassembly plan, and second the ability to select reliably the corresponding scale values on the scoring card. Our field tests confirm that good and reliable estimates are generated. Further, we find that learning curve effects significantly increase the reliability. These effort and cost estimates can be used (i) to make direct disposal versus disassembly decisions, (ii) to make a bid for the purchase of disposed products, (iii) to levy disposal fees on consumers, and (iv) to improve the disassembly costs at the design stage. In cases where the user requires a precise costing, then an extensive cost analysis should be conducted. The model is amenable to computerization and, in the future, we plan to develop extensions to the disassembly plan, so as to reduce the user input. Further, the model presently uses generally applicable fixed weights for the different effort factors. To increase the multi-factor model accuracy we shall explore the development of weights specific to different disassembly families. For users who wish to develop their own weighting scheme the model is easily adapted.

We can continue to expect that disassembly will become a more widespread activity, and can foresee the construction of large-scale facilities processing high volumes of disposed products. We are already seeing the early phases of this evolution in Europe and the United States. Such an evolution cannot be simply driven from an environmental concern, but must also be profitable and/or cost effective. There continues to be the need for models to predict operational level costs, as opposed to macro level costs. Most of the facilities that we studied were manual operations, but one can expect more automation in the future. The scales in the DEI model would need to be updated as the automation content increases.

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