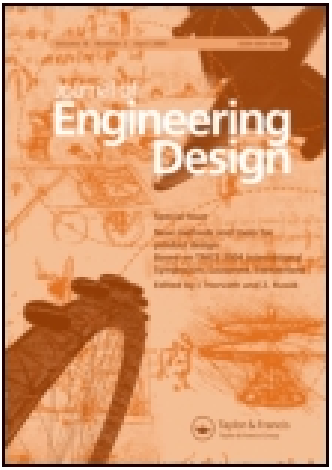

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Evaluating the unfastening effort in design for disassembly and serviceability

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and SANCHOY DAS‡

Disassembly is the process of physically separating a product into its parts or subassemblies. Recently, product designers are being challenged to address the concept of ‘ease of disassembly’ while configuring new designs. This is driven by the need for new products to undergo a design for disassembly and serviceability (DfDS) analysis. DfDS promotes design features and attributes, which reduce the subsequent disassembly costs. The disassembly process commonly involves an unfastening action. In this paper we present the unfastening effort analysis (U-effort) model, which helps designers to evaluate and select their fastener options. The U-effort model was developed from an experimental investigation of the most common fastener types used in industry. For each fastener type, the U-effort model identifies several causal attributes, and uses these to derive the U-effort index for a given case. From our experiments, we found that the most significant causal attributes are usually related to fastener size, shape or operational characteristics. The U-effort model is easily integrated into DfDS analysis schemes. The disassembly times generated from the U-effort model can be used to perform economic analysis of product service and/or end-of-life disassembly operations.

1. Introduction

Product designers have traditionally been concerned with optimizing the functionality of a product. Subsequently, the objectives of reducing the manufacturing effort and cost have become increasingly important. This led to the development of the concept and research area of design for manufacturability. Recently, product designers are being challenged to also address the concept of ‘ease of disassembly’ while configuring new designs. This is motivated by both economical and environmental reasons. Disassembly is the process of physically separating a product into its parts or subassembly pieces. There are three primary reasons why disassembly is practiced: (i) to service or repair a product during its useful life, (ii) end-of-life separation to recover valuable parts and/or materials, and (iii) the removal of hazardous or toxic parts and/or materials. The disassembly process involves either an unfastening action, which involves removal of a fastening element, or a destructive action, which involves breaking a fastener joint. Typically, a destructive action is not viable when service or repair is the purpose. The purpose of a design for disassembly and serviceability

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(DfDS) analysis is to promote design features and attributes, which reduce the subsequent disassembly costs. While the total cost of disassembly includes several components (logistics, material handling, etc.), a key component is the cost and effort associated with the actual disassembly action. In this paper we specifically address the unfastening process, and present a model for estimating the unfastening effort for common fasteners. While the proposed model is applicable is for all three disassembly reasons, our focus is primarily on end-of-life disassembly.

Traditionally, product disassembly was only done to service or repair a part. But the disassembly of a product at the end of its useful life is slowly growing into a common and worthwhile industrial practice. End-of-life disassembly facilitates part re-use and more efficient material recycling, and thus helps 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 Printed Circuit Boards (PCBs), mercury from electrical switches, starters and alternators from automobile engines, plastic resin from computer housings, and power supply units from electrical equipment. In Europe a variety of current and pending legislations requires manufacturers to address to end-of-life issues during the design process. The lack of an effective DfDS analysis could result in significant economic penalties to the manufacturer, in the context of the regulations.

While the process of disassembly does not generally require any special worker skills, it is invariably a labour-intensive process. Discrete fasteners and integral attachments can usually be unfastened or detached with manual tools. Given that the revenue streams from a disassembled product are relatively small, the economics of the disassembly process are quite fragile. As a result the vast majority of products do not enter a disassembly process, and consequently have little opportunity for an environmentally friendly disposal. It is well recognized that the majority of factors, which determine the economics of product disassembly, are made during the design phase. The unfastening effort is a key factor in the disassembly economics. In the ideal case the consumer would be able to appropriately disassemble the product prior to disposal. Most products are assembled from several components with the help of various types of fasteners or through bonding. Some of the bonding processes are use of adhesives, welding, soldering and brazing, and so on. Generally the adhesive and energy bonding can be disassembled only in a destructive way such as sawing and cutting, and so on. Destructive disassembly processes will not be included in this research.

Almost all product disassembly involves the removal of one or more fasteners. This removal process includes accessing the fastener, unlocking or releasing it, and finally extracting it. The total effort required to execute this sequence of actions is a function of (i) the type of fastener, and (ii) several situation-specific attributes. From a design perspective, therefore, if several functionally equivalent fastener options were available, and product disassembly was an end-of-life goal, then the designer would want to select the fastener with the greatest ‘ease of disassembly’. In this paper we present the unfastening effort analysis (U-effort) model, which helps designers to evaluate and select their fastener options. The U-effort model was developed from an experimental investigation of the most common fastener types used in industry.

For each fastener type, the U-effort model identifies several causal attributes, and uses these to derive the U-effort index (UFI) for a given case. The U-effort model is easily integrated into DfDS analysis schemes.

2. Related research

Research on product disassembly is a relatively new topic, but even then quite an extensive body of research has been generated in the past few years. A review of various aspects and models of product disassembly is provided by Moyer and Gupta (1997). 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 to 2.5 s for a wide variety of operations, including screw removal, cutting, and snap-fit release. 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. 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. Das *et al.* (2000) 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 is derived from seven factors: time, tools, fixture, access, instruct, hazard, and force requirements.

In the DfDS area, one of the earliest works is reported by Navin-Chandra and Prinz (1993) who address engineering design issues from an environmental and economic perspective. Several design for recycling rules, which can reduce the cost of recycling, are presented and integrated with a cost–benefit analysis model. Following on their work several other groups have presented 'guideline style models'. Lankey *et al.* (1997) present the development of an environmental attributes matrix and a product specification sheet to be used during the design process. Newcomb *et al.* (1998) have developed a prototypical computer-aided design (CAD) system for assessing demanufacturability. This system is able to semi-automatically generate disassembly processes containing a disassembly sequence, a tool change sequence, and disassembly paths of components. Scheuring *et al.* (1994) and Coulter *et al.* (1998) propose a re-manufacturability metric that is similar in format to traditional design for assembly analysis. Shyamsundar *et al.* (1997, 1998) report on the development of a CAD tool for the design of mechanical and electro-mechanical products, so that they can be disassembled and the materials and components in them can be effectively recycled. They propose algorithms to perform virtual disassembly including selective non-destructive disassembly and destructive disassembly. Sonnenberg and Sodhi (1998) present common disassembly tools for certain fastening methods, and discuss potential unfastening problems. Almost all of the reported DfDS models would benefit from a direct evaluation of the unfastening actions, and hence can incorporate the U-effort model.

3. Modelling the unfastening process

During the assembly of a product, the fastening process is usually facilitated by fixtures and other feeding devices. Since disassembly tends to be a relatively low volume activity, it usually only involves a human operator and an unfastening tool. Unfastening may therefore be defined as the process of separating components or sub-assemblies from each other by removing fasteners or by detaching parts with integral attachments manually with or without the use of a tool. There are several types of fasteners or attachments commonly used in product assembly. Fasteners may be discrete fasteners, which are separate elements that are used to connect two or more parts with each other, or integral attachments, where the fastener is a part of the component itself. There are two groups of discrete fasteners, threaded fasteners and non-threaded fasteners. The threaded fasteners could be screws, nuts and bolts, studs, hooks, spring toggle bolts, turnbuckles, and so on. The non-threaded fasteners include nails, tacks, rivets, keys, pins, staples, clips, retaining rings, zippers/Velcro, snap-type fasteners, quick release fasteners, and so on. In this research we studied a total of 10 fasteners, and these are introduced later in section 4.

There are considerable differences in the disassembly effort associated with each fastener type, and even the attributes or factors that influence this effort. These attributes typically relate to one or more physical features of the fastener itself. Our research therefore indicates that it is not possible to develop a common unfastening analysis model for all fastener types. Rather, the U-effort model uses a common effort indexing scale, but a fastener specific effort calculator. Figure 1 identifies the sequence of steps in the U-effort model. For a given design, we would first list all the fasteners that need to be removed, and then analyse each fastener independently through the corresponding effort calculator. The output from this is the UFI for the specific fastener. The UFI for all fasteners in the design can be summed to get a cumulative assessment of the design. The UFI scale is defined in the 0–100 range, with 100 representing the most difficult case.

3.1. The UFI calculator

For each fastener type the calculator is described by a corresponding linear effort equation that derives the UFI score. This equation consists of a scalar lower bound, which is summed to a coefficient weighted score for each attribute. Let i represent the code for a fastener type, then the general format of the equation is:

$$\mathrm{UFI}_i = \Psi_i + \beta_a A_i + \beta_b B_i + \beta_c C_i + \beta_d D_i$$

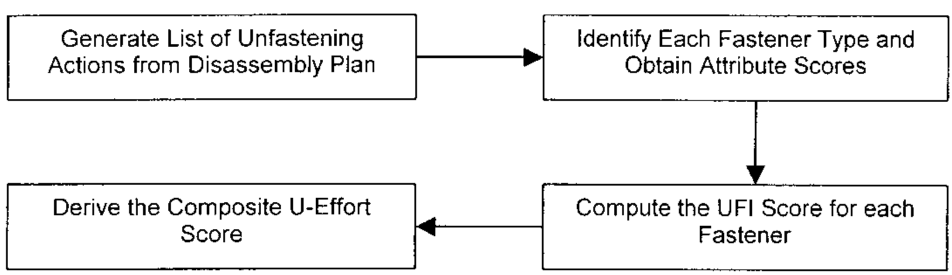


Figure 1. Steps in the U-effort model.

where Ψ_i is the lower bound on the unfastening effort, A_i, B_i, C_i, and D_i, are the unfastening complexity scores for each attribute in a specific case, and β_a, β_b, β_c, and β_d are the significance coefficients for each attribute. Ψ_i is representative of the minimum effort expended in removing a fastener type, or in other words the easiest case for that fasteners. It also indicates the relative disassembly ease of each fastener type. This equation generates a UFI score in the Ψ_i–100 range. We found that the lowest UFI scores are generated for a Velcro-type fastener. To give a practical relevance to the UFI scores, it is necessary to relate it to unfastening times. The UFI score is upper bounded at a value of 100, which represents about 400 s of direct labour time. From our experiments we formulated the following correlation between the UFI score and the estimated unfastening time by an average worker:

$$\text{Unfastening time (s)} = 5 + 0.04(\text{UFI})^2$$

Figure 2 plots this relationship. From the graph we observe the rapid escalation in unfastening times as the UFI increases. Our experiments indicate that 5 s is the typical lower bound for removal of any fastener. As part of their DfDS analysis a designer would attempt to modify the fastening system so as to reduce the UFI scores and consequently the unfastening time.

3.2. *Experimental analysis*

To derive the UFI calculator for each fastener type a series of experiments were conducted. These experimental activities occurred in three stages:

Stage 1. Physical experiments to isolate and model the causal attributes that have a significant impact on the removal effort for that fastener.

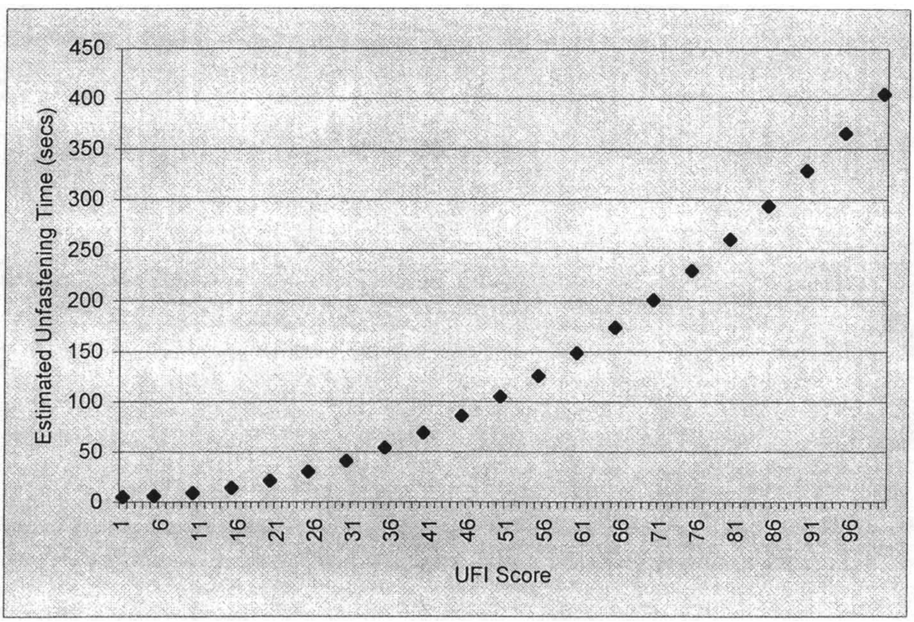


Figure 2. The UFI to unfastening time relationship.

Stage 2. The use of expert analysis to formulate the UFI calculator equations.
Stage 3. Validation of the UFI calculator.

Figure 3 sketches the logical flow on which the UFI derivation is based, and this was used in the design and set-up of the experiments. It is important to note that DfDS analysis tends to be approximate in nature since it represents a secondary objective (as compared with cost and functionality), and the goal is to easily derive and assess the product so it can be readied for re-use and recycling. Our goal in the experiments was therefore to isolate the primary causal attributes and provide a tabular scheme for quick derivation of the UFI.

Stage 1 represents the key data gathering process and involved a large number of unfastening experiments. These experiments involved the set-up of example cases, in which each fastener was repeatedly analysed in the context of tools commonly used to remove them. Fastening industry handbooks were used to identify the common variety seen in each fastener type. These were used to set-up a series of experiments, and each participant was required to repeat the entire range of experiments for a fastener type. There were 25 participants (replications) for each fastener type. The unfastening times for the experiments were recorded and at the end each participant indicated the relative difficulty of experiment on a score of 1–10.

Stage 2 involved an analysis of the experimental data in combination with expert opinion from a variety of commercial disassembly facilities. These disassembly experts were knowledgeable about a variety of products including automobiles, personal computers, mainframe computers, telecom equipment, and Cathode Ray Tubes (CRTs). Based on the Stage 1 data, a scored list of the casual attributes for each fastener type was derived. The expert opinion was then used to refine this list and delete attributes of low significance. The selected attributes are introduced in section 4. We found that the most significant causal attributes are related to fastener size, shape or operational characteristics. For each fastener we limit the model to a maximum of four causal attributes. The expert assessment data and the experimental data were then used to derive the Ψ_i values. Table 1 summarizes the derived values and the list of final attributes. The next activity in stage 2 involved deriving β_a, β_b, β_c, and β_d, the significance coefficients for each attribute. This was done by analysing the experimental data, along with force and tooling analysis of each disassembly. The unfastening force type was classified in terms of increasing effort as follows: axial, torsional, orthogonal, leverage, low impact and high impact. This analysis was extended to also derive the scales for A_i, B_i, C_i, and D_i, the case-specific unfastening complexity scores. A key component of this derivation was relating the recorded unfastening times to figure 2. The scales for each case are also introduced in section 4.

The effectiveness of our model will depend upon how reliably these attributes can be used to project the unfastening effort. During the stage 3 validation process we confirmed the significance of the listed attributes. The UFI scores for three sample

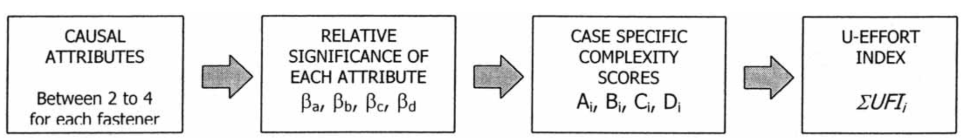


Figure 3. The UFI derivation process.

Fastener	Fastener type	Ψ_i	Unfastening causal attributes
1	Bolt	30	(i) Bolt head shape, (ii) bolt length, (iii) bolt diameter, (iv) use of washers
2	Cantilever snap-fit	20	(i) Beam length, (ii) retention angle, (iii) number of concurrent snaps
3	Cylindrical snap-fit	36	(i) Joint diameter, (ii) retention angle, (iii) wall thickness
4	Nail	15	(i) Nail length, (ii) nail diameter, (iii) shape of the nail head
5	Nut and bolt	40	(i) Nut head shape, (ii) nut diameter, (iii) use of washers, (iv) unfastening torque
6	Releasable clips	10	(i) Access to release trigger, (ii) clip size
7	Retaining rings	25	(i) Ring position, ring size, (ii) ring type
8	Screw	25	(i) Screw head shape, (ii) screw length, (iii) screw diameter, (iv) use of washers
9	Staple	20	(i) Tool access, (ii) staple length, (iii) staple hold
10	Velcro/zippers	0	(i) Access to edge length, (ii) contact area or edge length

Table 1. UFI calculator attributes for different fasteners.

products (a portable cassette tape recorder, a business telephone, and an inkjet printer) were derived. In an experimental set-up, seven participants were asked to repetitively unfasten these products. The recorded times matched closely with the estimated times.

4. A multi-attribute unfastening effort model

In this section we present the detailed UFI calculator for several common fastener types. As noted earlier, each calculator model is unique for a particular fastener type. There are several physical conditions that influence the unfastening process. In order to determine the unfastening effort of different fasteners, a key issue is the disassembly motion. Certain types and directions of motions are used to disengage or remove specific fasteners in order to take a product apart. The assembly motion is a set of simple movements that describes the last motion the fastener or the part makes as it is attached to the base or the other component. The part separation is usually accomplished by reversing one of the simple assembly motions. The access available to impart such motion greatly influences the degree of difficulty and hence access is one of the important factors in our study. It is usually possible to unfasten discrete fasteners and integral attachments. However, there are cases where unfastening should be possible, but due to certain reasons it becomes very difficult (e.g. environmental exposure). The environmental exposure may cause damage to the screw and bolt heads, creating difficulty in the unfastening of such fasteners. Thus the shape of the unfastening trigger is a leading attribute affecting the unfastening effort.

Another key issue in unfastening is the tooling requirement. The selection of the tool needed depends on the fastener type and on the condition of the fastener. Usually, if standard tools were used for the fastening process, then the same standard tools would often be sufficient for unfastening. Sometimes regular tools are not able to access the fasteners and special tools for unfastening are needed. The location of the fasteners also plays an important role in determining the unfastening effort. Table 1 provides a list of the causal attributes that are modelled in each of the UFI calculators.

In the following subsections each UFI calculator is individually presented. From table 2 we see that the number of causal attributes range from 2 to 4 for the different fasteners. Each UFI calculator model is supported by a UFI complexity score table (tables 2–11), which is used to obtain the unfastening complexity scores for each attribute. Each table provides a range of A_i, B_i, C_i, and D_i, values corresponding to standard configurations of that fastener type. These values were derived using the experimental process described in section 3.1.

4.1. Bolt

Bolts are commonly used to assemble metal parts where high bonding strength is required. For this situation, our research has established that there are four causal attributes (table 2). The shape of the bolt head is the primary factor for this case. Factor c_1 has been given values based on the shape of the bolt head. We found that a countersunk bolt is the most difficult to unfasten and therefore scores $A_1 = 1.0$, whereas a hook bolt requires no tooling and thus scores $A_1 = 0$. We also found that the time for unfastening increases with the bolt length and bolt diameter. The length and diameter are modelled in progressively longer intervals. The presence of washers or other auxiliary devices was found to complicate the unfastening process, and is therefore included in the model. The corresponding UFI calculator with $\Psi_1 = 30$ therefore is:

$$\mathrm{UFI}_1 = 30 + 20A_1 + 12B_1 + 8C_1 + 5D_1$$

4.2. Cantilever snap-fit

The use of snap-fit type fasteners as an integral attachment has become an increasingly popular design practice due to its manufacturing efficiency and ease of assembly. Cantilever snap-fits are almost always made from a polymer material; consequently, unfastening involves a deformation process. We found that three attributes have the most effect on the unfastening of these devices (table 3): the beam length, the retention angle and the number of concurrent snaps. We do not include the material physical properties since the range is to wide, but this may play an important role. The longer the beam length the more flexible and requires a lower release force. The greater the retention angle, the greater the unfastening force. Note that an angle of 90° makes the connection permanent. Where multiple snaps are used concurrently, the unfastening effort can increase significantly, since they must all be disengaged simultaneously. The corresponding UFI calculator with $\Psi_2 = 20$ therefore is:

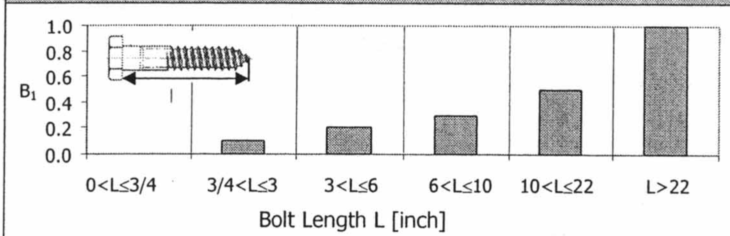
$$\mathrm{UFI}_2 = 20 + 15A_2 + 16B_2 + 19C_2$$

4.3. Cylindrical snap-fit

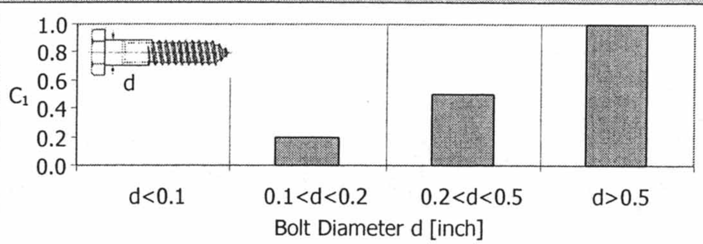
The use of cylindrical or annular snap-fits as an integral attachment has become an increasingly popular design practice. These snap-fits are commonly used to assemble flat parts such as door panels in automobiles. Cantilever snap-fits are also made from a polymer material, and unfastening therefore involves a deformation process. We found that three attributes have the most affect on unfastening of these devices (table 4): the joint diameter, the retention angle and the wall thickness. The grater the joint

FACTOR A: Bolt Head Shape	
SHAPE TYPE	A_1
Square	0.2
Hexagonal	0.2
Round (Carriage)	0.8
Countersunk	1.0
T-Head	0.5
Askew	0.6
Eyebolt	0.0
Hook Bolt	0.0

FACTOR B: Bolt Length



FACTOR C: Bolt Diameter



FACTOR D: Use of Washers/Devices	
WASHER/DEVICE TYPE	D_1
No Washer	0
Flat Washer	0.2
Split Lock Washer	0.6
Shake Proof Lock Washer	1.0

Table 2. UFI complexity scores for a bolt.

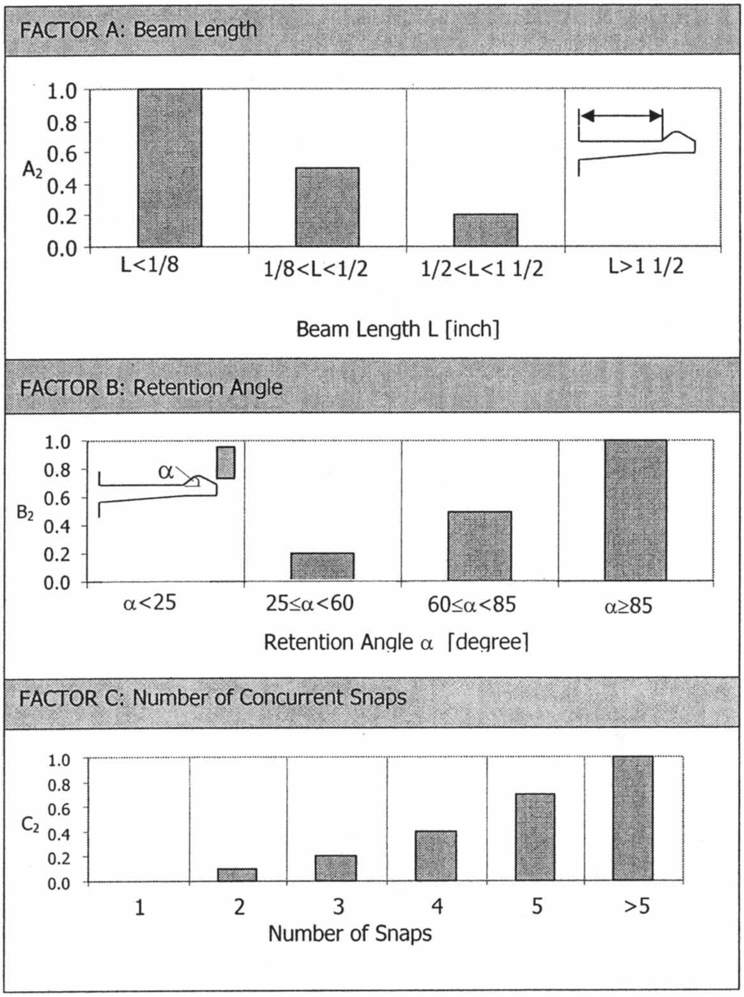


Table 3. UFI complexity scores for a cantilever snap-fit.

diameter, the more rigid the cylinder becomes resulting in a higher unfastening force. The flexibility in the outside cylinder (tube) is also related to its wall thickness. A thin tube is more flexible it is and can be more easily unfastened. The corresponding UFI calculator with $\Psi_3 = 36$ therefore is:

$$\text{UFI}_3 = 36 + 23A_3 + 15B_3 + 26C_3$$

4.4. Nails

Nails are commonly used to assemble wooden parts or sheet metal parts. To unfasten a nail, a linear force is typically applied in the direction of the nail axis to overcome the frictional force between the nail surface and mating surface. We found that three attributes have the most effect on unfastening of nails (table 5): the nail length, the nail diameter, and the shape of the nail head. The nail length is usually measured in penny

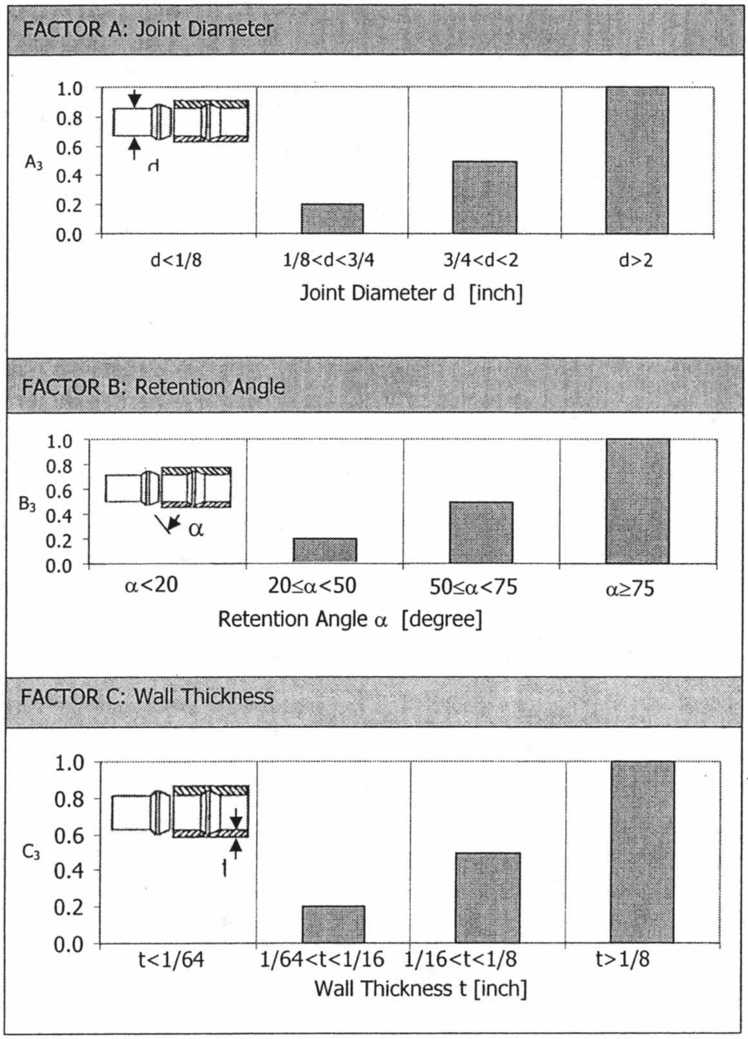
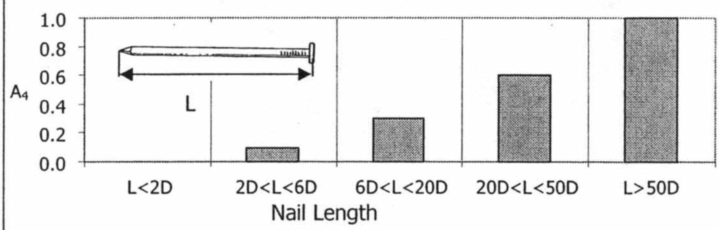


Table 4. UFI complexity scores for a cylindrical snap-fit.

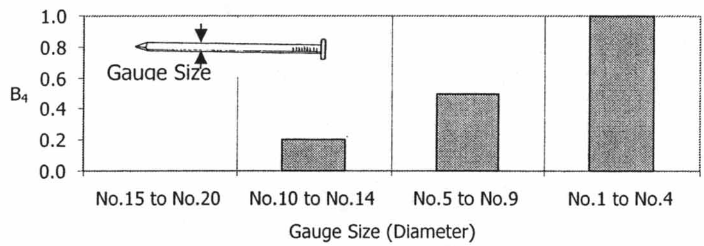
size. As the length increases, the extraction motion becomes longer. The resistance of a nail to extraction also increases directly with its diameter; if the diameter of the nail is doubled, the holding strength is doubled, similarly increasing the unfastening effort needed. Nail diameters are measured in wire gauge numbers. As the wire gauge numbers go down, the diameter of the nail goes up. The shape of the nail head affects the clearance of the head, thus influencing the access available to use an unfastening tool. We found that if the head size is very small, the unfastening is more difficult as compared with for a bigger nail head. A bigger nail head can be grabbed easily with pliers. If the head of a nail is sunk in, the unfastening is more difficult than if it is not sunk in. The corresponding UFI calculator with $\Psi_4 = 15$ therefore is:

$$\mathrm{UFI}_4 = 15 + 8A_4 + 17B_4 + 25C_4$$

FACTOR A: Nail Length



FACTOR B: Nail Diameter



FACTOR C: Shape of the Nail Head

Head Shape - C_4	Head Shape - C_4
Flat – 0.1	Round – 0.2
Double Headed - 0	Casing – 0.9
Button – 0.2	Oval – 0.3
Curved – 0.6	Cup Head – 0.8
Sinker – 0.9	Projection – 0.4
Cupped Oval – 0.3	Oval Countersink – 0.9
Countersink – 0.9	Headless – 1.0
Hook Head – 0.1	Slotted 0.5

Table 5. UFI complexity scores for a nail.

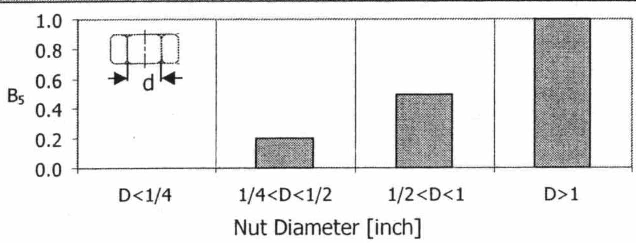
4.5. *Nut and bolt*

A nut and bolt combination is usually used to assemble metal parts where the strength of the clamping is important. It is one of the most common fastening devices used in serviceable parts, since no damage is done during the unfastening process. We found that four attributes have the most effect on unfastening of nails (table 6): the shape of the nut, the nut size, the use of washers and the unfastening torque. There are many different types of nuts. The nut shape determines whether standard tools or special tools have to be used. Each nut type has a standard set of dimensions. The inside diameter of the nut determines the thickness of the nut, and also the threaded length that influences how many turns are needed to unfasten the nut from

FACTOR A: Nut Head Shape

SHAPE TYPE	A_5
Square	0.3
Hexagonal	0
Jam	1.0
Castellated	0.9
Wing	0.1
Cap Or Acorn	0.5
Thumb	0.0
Stop	0.9
Lock	1.0

FACTOR B: Nut Diameter



FACTOR C: Use of Washers/Devices

WASHER/DEVICE TYPE	C_5
No Washer	0
Flat Washer	0.2
Split Lock Washer	0.6
Shake Proof Lock Washer	1.0

FACTOR D: Unfastening Torque

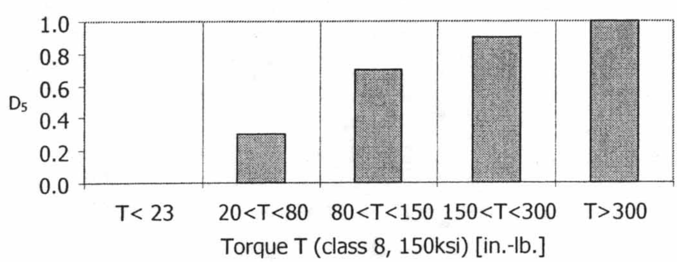


Table 6. UFI complexity scores for a nut and bolt combination.

FACTOR A: Access to Release Trigger	
SHAPE TYPE	A_6
Straight Line Z-Axis (manual)	0
Straight Line X-Axis or Y-Axis (manual)	0.2
Dual Axis (manual)	0.6
Straight Line Z-Axis (tool support)	0.5
Straight Line X-Axis or Y-Axis (tool support)	0.7
Dual Axis (tool support)	1.0

FACTOR B: Clip Size

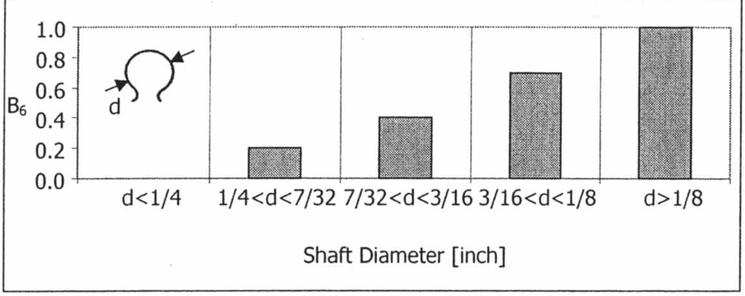


Table 7. UFI complexity scores for a releasable clip.

the bolt. The use of washers also makes the unfastening process more difficult. We found that typically the unfasten torque tends to be greater than the fastening torque. The unfastening torque is a key attribute in the removal of a nut and bolt combination. The corresponding UFI calculator with $\Psi_5 = 40$ therefore is:

$$\mathrm{UFI}_5 = 40 + 20A_5 + 9B_5 + 6C_5 + 20C_5$$

4.6. Releasable clips

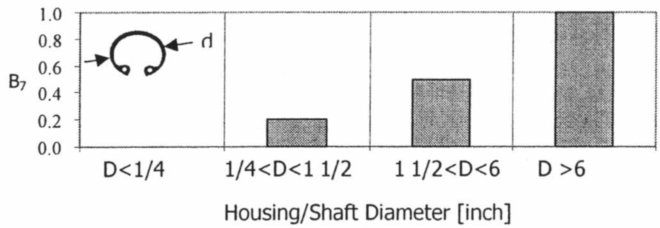
Fastening through a releasable clip involves snapping a ring into an annular groove on a shaft or pin with ends projecting beyond the shaft surface. It is a common fastening device used in the assembly of electrical parts, and hence they often need to be removed during service or disassembly. We found two attributes have the most effect on unfastening of releasable clips (table 7): the access to the release trigger, and the size of the clip. In evaluating the access we differentiate between a manual release and a tool (e.g. pliers) supported release. We found that the larger the clip size the easier it is to grasp and unfasten. The corresponding UFI calculator with $\Psi_6 = 10$ therefore is:

$$\mathrm{UFI}_6 = 10 + 15A_6 + 15B_6$$

4.7. Retaining rings or circlips

Retaining rings or circlips are commonly used for locking and retaining components on shafts or in housings and bores. The rings generally are made of materials

FACTOR A: Ring Position	
Position Type	A_7
Radial retaining rings – orthogonal to shaft	0
Axial retaining rings –parallel to shaft	1.0
FACTOR B: Ring Size	



FACTOR C: Special Tools	
RING TYPE	C_7
E ring, Spring clip, Crescent Ring	0
Bowed Ring, C Ring	0.4
Internal Axial Ring	0.6
External Axial Ring	1.0

Table 8. UFI complexity scores for a retaining ring.

having good spring properties, so the fasteners may be deformed elastically to a considerable degree and still spring back to their original shape. We found three attributes have the most effect on unfastening of retaining rings (table 8): position of the ring on the shaft, the diameter of the ring, and need for special unfastening tools. Retaining rings are available in a very wide range of sizes. The unfastening effort increases with the size of the retaining ring. In the most cases, it is necessary to use special tools to unfasten the retaining rings. The use of the tool needed will depend upon the type of retaining ring used. The corresponding UFI calculator with $\Psi_7 = 25$ therefore is:

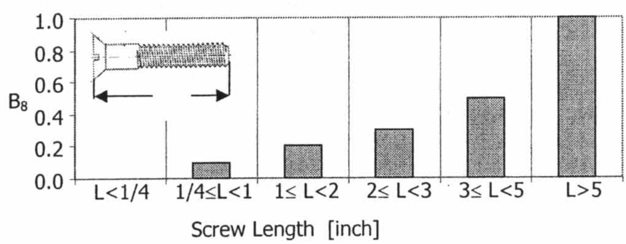
$$\mathrm{UFI}_7 = 25 + 8A_7 + 17B_7 + 20C_7$$

4.8. Screws

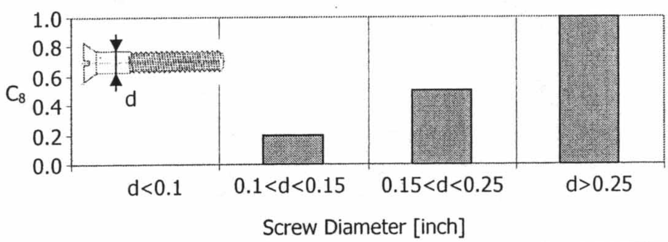
We consider only screws used to assemble metal parts. Screws are the most common fastening devices in use, and usually several have them to be removed during a disassembly or service activity. We found four attributes have the most effect on the unfastening of screws (table 9): the shape of the screw head, the length of the screw, the screw size, and the use of washers. Screws come in many forms, which include machine, cap, set, thumb, socket, lag, miniature, and self-tapping screws. Like bolts, screws are classified by their head type. We found that the unfastening effort varied

FACTOR A: Screw Head Shape	
SHAPE TYPE	A_8
Round, Slotted	0.2
Countersunk, Slotted	0.3
Phillips	0.3
Torx Drive	0.6
Hexagonal	0.7
Square	1.0
Fillister, Slotted	0.2
Hex-Socket	0.8
Spline Socket	1.0
Thumb	0.0

FACTOR B: Screw Length



FACTOR C: Screw Diameter

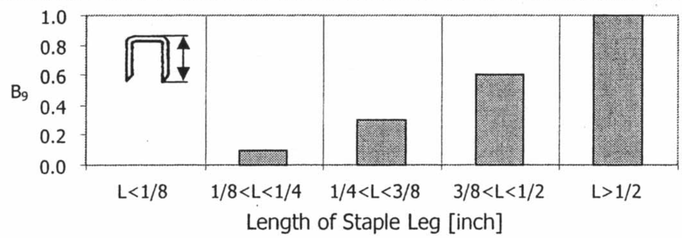


FACTOR D: Use of Washers/Devices	
WASHER/DEVICE TYPE	D_8
No Washer	0
Flat Washer	0.2
Split Lock Washer	0.6
Shake Proof Lock Washer	1.0

Table 9. UFI complexity scores for a screw.

FACTOR A: Tool Access	
SHAPE TYPE	A_9
Straight Line Axis from Top	0
Straight Line Axis from Bottom	0.6
Dual Axis from Top	0.4
Dual Axis from Bottom	1.0

FACTOR B: Staple Length



FACTOR C: Staple Hold	
HOLD TYPE	C_9
Straight	0
Outward-Pointing	0.6
Inward-Pointing	1.0

Table 10. UFI complexity scores for a staple.

considerably between different head types. The screw length is a direct determinant of the unfastening time, since it determines the number of turns required. The use of washers or other auxiliary devices was also found to add to the unfastening effort. The corresponding UFI calculator with $\Psi_8 = 25$ therefore is:

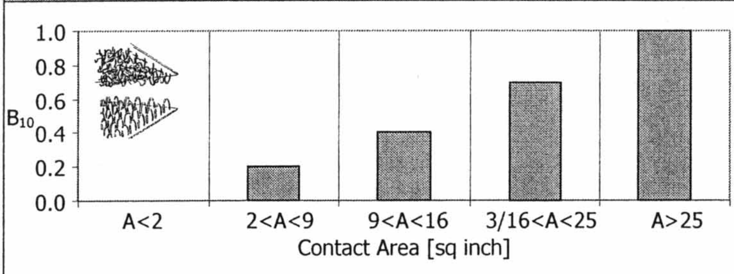
$$\mathrm{UFI}_8 = 25 + 23A_8 + 18B_8 + 12C_8 + 7D_8$$

4.9. Staples

Staples are commonly used to attach sheet material to wood, cork, or similar materials. Where metal sheets are stapled then during disassembly it may be necessary to remove the staples to gain access to other parts. We found three attributes have the most effect on the unfastening of staples (table 10): the tool access, the length of the staple and the staple hold. To unfasten a staple it is necessary to have enough space to use a removal tool such as staple pliers. Some staples can be removed from the same direction they were inserted, but often access from the backside is required. Staples are produced in five standard leg lengths for average use. We found that the shorter the staple leg, the lower the effort to get the staple out. The shape of the staple to hold the parts together can vary with the use of different mechanical staplers, such as a staple gun, hammer tacker, or plier stapler. Unfastening effort needed to remove a

FACTOR A: Access to Edge Length	
Access Type	A_{10}
Clear Access to 100% of length	0
Clear Access to 70%+ of length	0.2
Clear Access to 40%+ of length	0.5
Clear Access to 20%+ of length	0.7
Clear Access to less than 20% of length	1.0

FACTOR B (Velcro Only): Contact Area



FACTOR B (Zipper Only): Edge Length

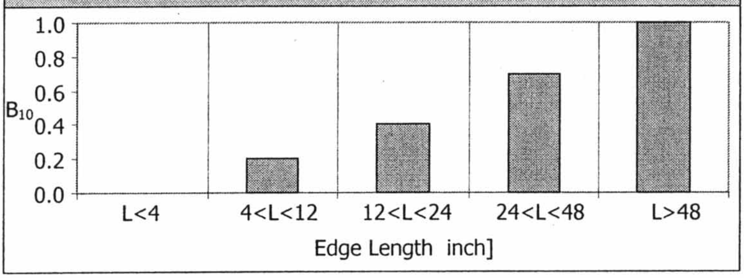


Table 11. UFI complexity scores for velcro and zippers.

staple depends on the shape of the staple hold. The corresponding UFI calculator with $\Psi_9 = 25$ therefore is:

$$\mathrm{UFI}_9 = 20 + 12A_9 + 18B_9 + 20C_9$$

4.10. Velcro and zippers

Both Velcro and zipper fasteners are among the easiest to unfasten, usually requiring a single linear action. On the downside, they have little gripping force and cannot be used in stress situations. These fasteners are being used in a variety of new applications, such as to assemble automobile seat covers, cable harnesses, and flexible pipe assemblies. Both fasteners are typically made from either nylon or polyester. During the unfastening process both Velcro and zippers will be separated into two pieces. We found two attributes have the most effect on the unfastening of these devices (table 11): the edge access, and the size. A long joint characterizes both fasteners, and the manual unfastening force needs to traverse along this joint. Clear access to the entire length makes the unfastening much easier. Velcro tapes are usually available in two widths. The amount of tape that is required for any given job is directly proportional to the holding strength needed. Therefore, greater the Velcro surface, more effort is needed for unfastening. The longer the zipper length, the longer the unfastening time. The corresponding UFI calculator with $\Psi_{10} = 0$ therefore is:

$$\mathrm{UFI}_{10} = 15A_{10} + 15B_{10}$$

Figure 4 illustrates the range of UFI scores for the different fasteners as specified by the presented models. Clearly, a Velcro/zipper fastener needs the least amount of unfastening effort and is upper bounded with a 40 score. The bolt, on the other hand, needs a minimum effort of 30 due to the requirement of a tool for unfastening and the maximum unfastening effort may be 75 on the same scale. We see the cylindrical snap-fit as having potentially the highest score of 100. These fasteners, while quick to assemble are often difficult to disassemble. The nut bolt combination can also have a high score of 95, particularly when the torque is high and locking fasteners are used.

5. Illustrative example

We will use an example to illustrate how the presented UFI calculator models can be used to compute the cumulative U-effort score for a given design. The example

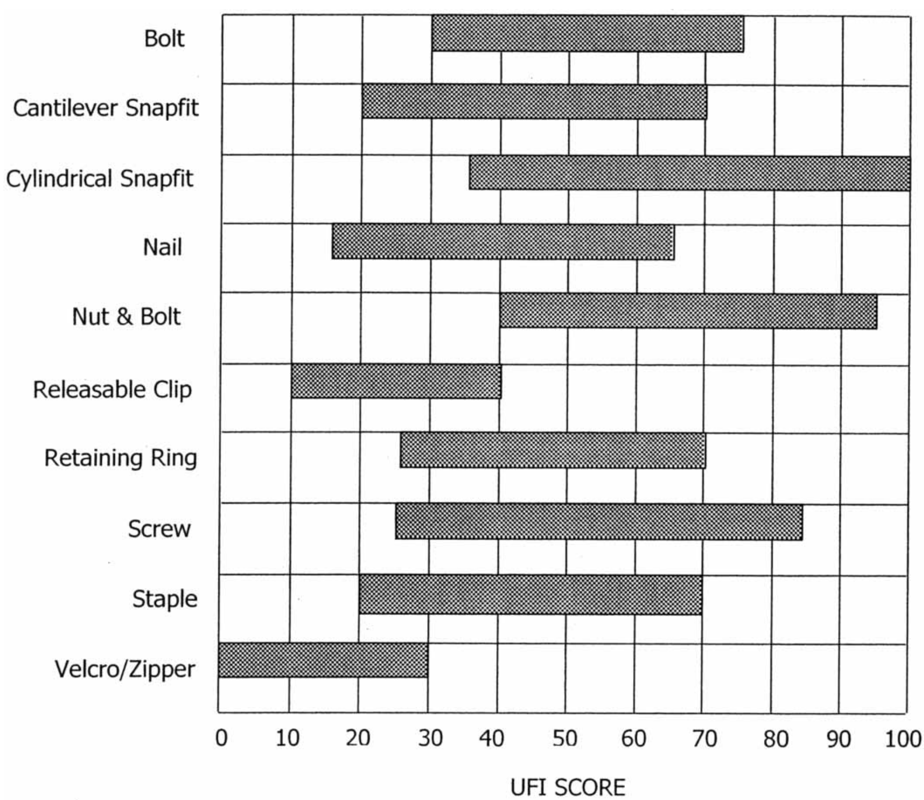


Figure 4. Range of unfastening effort for different fasteners.

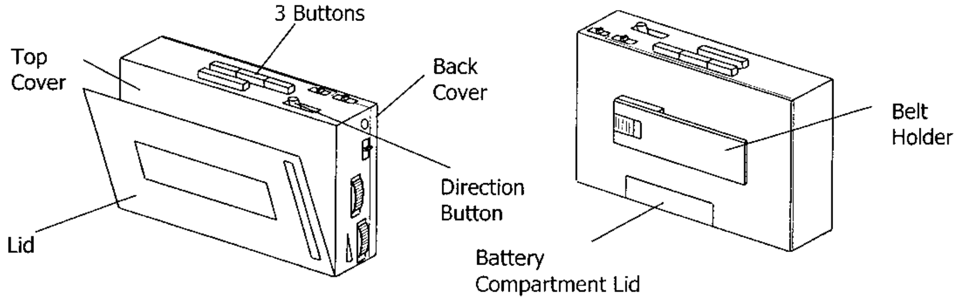


Figure 5. Schematic of the portable recorder.

product is a portable cassette tape recorder, which is shown in figure 5. Disassembly of this product, for either service or disposal purposes, involves the removal of seven different fasteners. The sequence of disassembly steps and the fasteners involved is presented in table 12. The U-effort model results for the recorder are summarized in table 13. Note that disassembly times are computed for a single fastener using the equation introduced in section 3.1, and then multiplied by the number of fasteners.

The total UFI score for the product is 467.4. A design team can use this score to benchmark the current design against alternative designs. Fastener 1 requires the greatest effort on a unit basis, and is a target for a design change. Fastener 3 has 4 units and has the greatest effort on a net basis. Possibly the number of fasteners could be reduced. The projected total disassembly time for the product is 761 s. Where product service is required, a design team can evaluate the service cost (parts and labour) against the replacement cost. Where disassembly for material/part recovery is of interest, the disassembly costs must be evaluated against the retrieved value.

6. Summary

A model for estimating the unfastening effort for common fasteners either as part of an end-of-life disassembly process or product service process has been presented. The U-effort model is applicable on a wide range of fasteners. The attribute driven nature of the UFI calculator models makes the U-effort model readily applicable in a product design setting and is easily integrated with a DfDS analysis tool. The

Disassembly action	Fastener
Remove belt holder by releasing snap-fit	1
Remove battery compartment cover by releasing snap-fit	2
Remove back cover by unfastening four screws	3
Remove spooling assembly by unfastening one screw	4
Remove drive motor by unfastening two screws	5
Remove top cover by unfastening two screws	6
Remove printed circuit boards by releasing two retaining clips	7

Table 12. Disassembly plan for the portable recorder.

Fastener	Type cantilever	A	B	C	D	UFI score	Number	Sum	Disassembly time (s)
1	Cantilever snap-fit	1.0 (1/8″)	0.5 (60–85)	0.1 (2)		44.9	1	44.9	86
2	Cantilever snap-fit	0.5 (3/16″)	0.5 (60–85)	0.0 (1)		37.4	1	37.4	61
3	Screw	0.3 (Philips)	0.1 (5/16)	0.2 (1/8)	0.0 (no washer)	36.1	4	144.4	229
4	Screw	0.3 (Philips)	0.0 (3/16)	0.2 (1/8)	0.6 (split)	38.5	1	38.5	64
5	Screw	0.6 (Torx)	0.1 (1/2)	0.0 (1/8)	0.0 (no washer)	43.0	2	86.0	158
6	Screw	0.3 (Philips)	0.1 (1/2)	0.2 (1/8)	0.0 (no washer)	36.1	2	72.2	114
7	Retaining clip	0.6 (Dual-M)	0.2 (1/2)			22.0	2	44.0	49
Total								467.4	761

Table 13. U-effort results for the portable recorder.

disassembly times generated from the U-effort model can be used to perform economic analysis of product service and/or end-of-life disassembly operations. The results of the U-effort model are presented in tabular format and hence are easily interpreted into design modifications and recommendations.

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