

## Chapter 2

# General Disassembly Process

**Abstract** The economic feasibility of the disassembly process is a main issue restricting its implementation in industry practice. Much research in the planning of disassembly processes and operations has been conducted in order to increase its economic feasibility. This chapter presents various aspects of the disassembly process including product representation, disassembly sequence planning (DSP), and dismantling techniques. This general knowledge is not limited to manual disassembly, but is also useful in automatic disassembly, which is presented in the following chapter.

### 2.1 Disassembly Process Planning (DPP)

The disassembly process is generally economically infeasible due to the difficulties in the process. Designing products according to Design for Disassembly (DfD) guidelines [1, 2] is expected to resolve this problem by making the disassembly process easier. However, few products nowadays are actually designed according to DfD. Therefore, the disassembly process remains difficult for the majority of products. Hence, this book focuses on the means of improving the economic feasibility of disassembly apart from DfD.

Dufloy et al. [3] summarise the factors that influence profitability of the disassembly process. Two major factors which are further explained in this book are the (a) *completeness of disassembly* and (b) *degree of autonomy* of the process. The desired completeness or depth of disassembly is a question addressed in disassembly process planning and disassembly sequencing, and is further explained in Sect. 2.2. The degree of autonomy can vary from complete manual disassembly to semi-automatic disassembly and fully-automatic disassembly. Since automation is a major theme of this book, an overview is explained in Chap. 3, with other details presented throughout the rest of the book.

This chapter gives an overview and literature review regarding disassembly process planning.

### 2.1.1 Difficulties in Disassembly

The disassembly process cannot be considered as the reverse of assembly. This is largely due to increased uncertainties: the disassembly process deals with unpredictable characteristics in both the quality and quantity of EOL products. This causes disassembly to be more difficult than assembly in the following aspects.

#### Uncertainties within models

Gungor and Gupta [4] summarise the physical uncertainties that can be found in EOL products manufactured under the same model. These uncertainties result from (a) *component defects*, (b) *upgrading or downgrading during usage* and (c) *damage during the disassembly operation*.

*Defective main or connective components* can result in difficulties during the removal operation which range from undesirable to dangerous. Examples include chemical leakage from batteries and broken fasteners that cannot be disestablished using common disassembly tools.

*Upgrading and downgrading of the product during the usage stage* can result in a change in product and component configuration. This situation is commonly found in devices containing exchangeable modules such as the personal computer (PC). Repairs and upgrades, e.g. involving the installation of random access memory (RAM) or graphics card, are common during the usage stage.

*Damage in the disassembly process* potentially occurs when the returned product is fragile. The disassembly process may need additional steps or a change in the disassembly sequence when certain parts are likely to break during the process.

#### Model-related variations

Products are manufactured into different models within the same product family. Different models contain variations in characteristics, including material, size and internal configuration. The same model may also be sold under different brands. Optimally, model information should be obtained from a product design database, taking the form of well-documented product specifications or a Computer-Aided Design (CAD) model. Unfortunately, this information is usually unavailable by the time EOL products are returned. Therefore, the disassembly process needs to deal with incomplete product information, some of which is only revealed during the disassembly process. The challenge is to develop a disassembly plan that is general enough to deal with these uncertainties [5].

#### Difficulty of operations

Kroll et al. [6] define the term *disassemblability* to quantify the ease of product disassembly. A product is assessed for disassemblability according to the difficulty of the disassembly operation, by assessing it against five major criteria: (a) *component accessibility*, (b) *precision in locating the component*, (c) *force required to perform tasks*, (d) *additional time*, and (e) *special problems* that cannot

be categorised in the other areas. Mok et al. [7] summarise the characteristics of an ease of product disassembly as follows:

- Minimal force exertion;
- Quick operation without excessive manual labour;
- Simple mechanism of disassembly;
- Minimal use of tool: ideal disassembly should be performed without tools;
- Minimal part repetition: parts easy to identify at each state of disassembly;
- Easy recognition of fasteners;
- Simple product structure; and,
- Avoidance in usage of toxic material.

Gupta and McLean [8] state that the development of optimal disassembly plans relies on four key phases: (a) *product analysis*, (b) *assembly analysis*, (c) *usage mode and effect analysis* and (d) *dismantling strategy*. Firstly, the product must be analysed and represented systematically. Options regarding the disassembly process can be generated from or represented using the product structure. The process can be considered at two levels, which are the *sequence plan* and the *operation*. The completeness of disassembly is considered a part of the sequence plan.

In summary, the uncertainties and variations found within returned products leads to uncertainties in the disassembly process. Uncertainties and variations of the disassembly process are summarised in Table 2.1.

**Table 2.1** Summary of variations and uncertainties in the disassembly process

Category	Specific issues
Uncertainty in EOL condition	• Modification of product during usage phase
	• Condition of product
	• Condition of main component
	• Condition of connective component
Diversity of the supplied products	• Main product structure
	• Physical appearance of components
	• Quantity of components
	• Location of components
	• Variation in manufacture (quality)
Complexity in process planning and operations	• Disassembly sequence plan
	• Disassembly operation plan (considering prior actions)
	• Disassembly process parameters
	• Capabilities and limitations of detection technique
	• Precision of robot's sensors—actuators
External factors	• Technology and design changes
	• Market driven factors

### 2.1.2 Representation of Product Structure

The structure of a product consists of (a) *components* and (b) *connections* [9]. A *component* is an element that keeps its extrinsic properties, i.e. functionality and material properties, after being detached from the product. A component cannot be further dismantled without using destructive disassembly methods. The *connection* or *liaison* is a relation that physically connects two components to restrict the motion between them. The task of disassembly is to disestablish these relations in order to separate the relevant components.

#### Fasteners

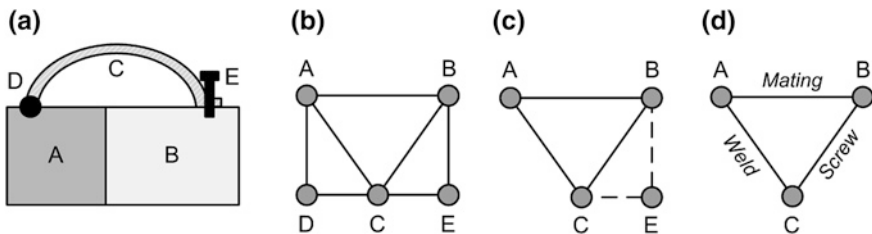
A fastener is a component or design element that serves the purpose of connecting other (main) components. Fasteners that are insignificant to the goal of disassembly may be modelled separately to the main components. Lambert and Gupta [9] considers such fasteners as *quasi-components*, which can be discrete components (e.g. screws, rivet, cable, etc.) or part of the main component (e.g. snap-fits). Connection-establishing elements, such as solder and weld joints, that do not form a component in themselves, can be considered *virtual components*.

#### Product structure

The structure of a product can be represented in many ways, of which two will be detailed here: the *connection diagram* and the *disassembly matrix*.

First, the *connection diagram* (liaison diagram) graphically represents the complete product structure using an undirected graph. The components are represented by nodes and the connections by arcs. According to the level of detail, the graph can be shown in three different forms: (a) *extended form* (b) *reduced form* and (c) *minimal form* (see Fig. 2.1).

In Fig. 2.1a, the product is a composition of three main components—A, B, and C. A and B are connected by mating. B and C are connected with a screw E which is considered a quasi-component. C and A are connected by a weld D which is a virtual component. The *extended form* shows full details of the product with every component and fastener. All fasteners, including virtual connections, are modelled (see Fig. 2.1b). The *reduced form* represents the structure more concisely by hiding the virtual components and using dashed lines for quasi-components. In this case,



**Fig. 2.1** Connection diagram [9]. **a** Product assembly. **b** Extended form. **c** Reduced form. **d** Minimal form

the connections associated with the virtual component, D–A and D–C, are removed. As a result, only connection A–C is retained representing the weld (see Fig. 2.1c). The *minimal form* shows the structure of the product in the most compact way by hiding both virtual and quasi-components. This form represents the product in the simplest way while preserving the information regarding the main components (see Fig. 2.1d).

Second, the product structure can be represented by a *disassembly matrix*, which a computing approach (e.g. Linear Programming (LP) or Integer Programming (IP)) can be used to solve the disassembly planning problem. The disassembly matrix is an  $N \times N$  connectivity matrix where  $N$  is the number of the components. Each element of the matrix represents the existence of a connection between two corresponding components: “1” if a connection exists, and “0” if it does not. This information is completely represented by the lower left part of the matrix, since the matrix is symmetric and the elements on the diagonal axis are non-applicable. From this matrix, it is clear that the maximum number of connections is  $\frac{1}{2}(N)(N-1)$ . The disassembly matrix of the example product in Fig. 2.1a is shown in Eq. (2.1).

$$\text{Disassembly Matrix} = \begin{array}{c|ccccc} & \text{A} & \text{B} & \text{C} & \text{D} & \text{E} \\ \hline \text{A} & & & & & \\ \text{B} & 1 & & & & \\ \text{C} & 1 & 1 & & & \\ \text{D} & 1 & 0 & 1 & & \\ \text{E} & 0 & 1 & 1 & 0 & \end{array} \quad (2.1)$$

### 2.1.3 Disassembly Process Representation

The steps of the product disassembly process and their corresponding relationships can be schematically represented in many ways. Lambert and Gupta (2005) [9] summarise these approaches as follows:

#### Disassembly precedence graph

The disassembly precedence graph expresses sub-tasks of the disassembly process connected and constrained by precedence relationships. This can be represented in two forms: as a *component-oriented* or *task-oriented* graph (see Fig. 2.2). The arrows communicate the ordering in which tasks must be performed. This technique was originally used for assembly process representation and assembly line-balancing problems. Gungor and Gupta [10] introduce this to the disassembly process due to its simplicity. However, a major disadvantage is that a complete disassembly sequence cannot be expressed in one graph [11].

#### Disassembly tree

The disassembly tree expresses all possible choices for disassembly sequences, and is derived from a table containing all possible sequences sorted by level and

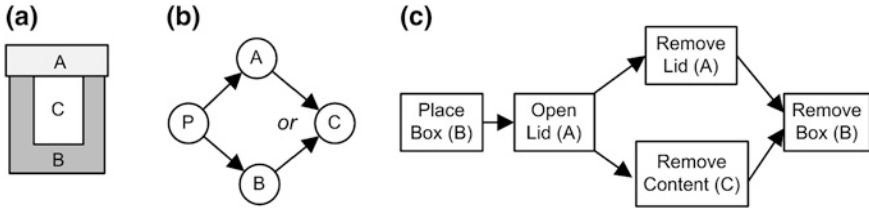


Fig. 2.2 Disassembly precedence [9]. **a** Assembly. **b** Component-oriented. **c** Task-oriented

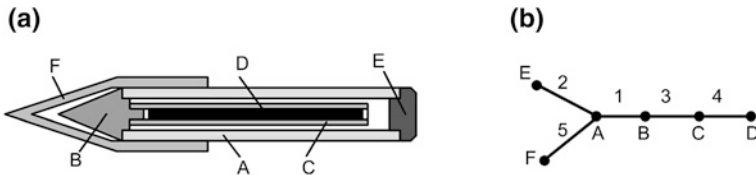


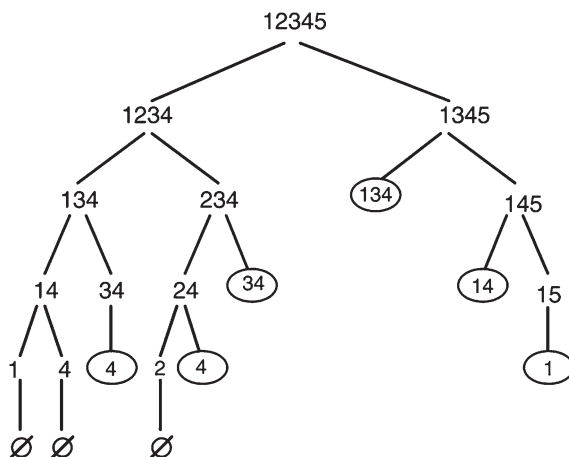
Fig. 2.3 Example product Bourjault's ballpoint [9]. **a** Assembly. **b** Connection diagram

operation type. A widely-used example is the *Bourjault tree* [12]. Two major drawbacks are the complexity arising in complex products and difficulty in representing parallel operations. Figure 2.4 shows a Bourjault tree representation of the disassembly process of a sample product, the Bourjault's ballpoint, which is shown in Fig. 2.3. This product will also be used to demonstrate the representation methods described in the following sections.

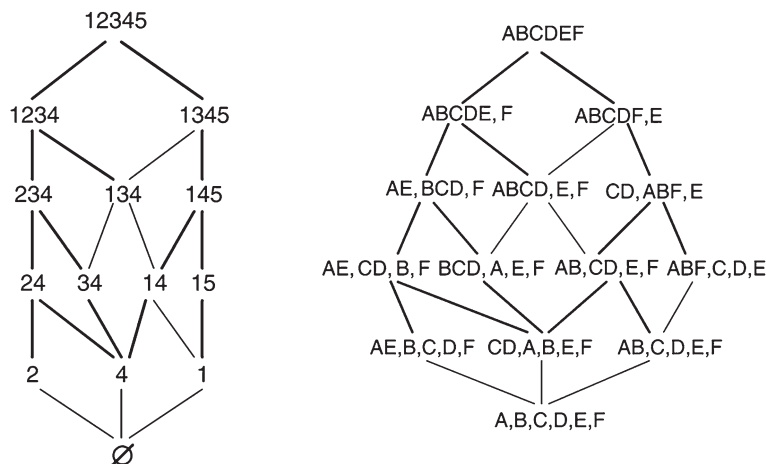
### State diagram

The state diagram represents the disassembly sequence as an undirected graph, where each node represents a state of disassembly. This can be categorised into two approaches: (a) *connection-oriented* [13] and (b) *component-oriented* [14, 15] (see Fig. 2.5). All possible combinations of connections are represented by the nodes. Each edge represents the establishment or disestablishment of a connection. The major advantages are that the disassembly sequence of the complete product can be demonstrated in one diagram, and the diagram is compact even for complex products. However, state diagrams are unable to show how the disestablishment of some connections cannot be done individually without affecting a combination of related connections.

Kara et al. [16] used a connection-oriented state diagram representation to develop a graphical representation method, the *disassembly-sequence diagram*, for representing the disassembly sequence to and from different stages of the process for selective disassembly. This diagram can be automatically generated from the liaison and precedence relations. An example is shown in Fig. 2.6.



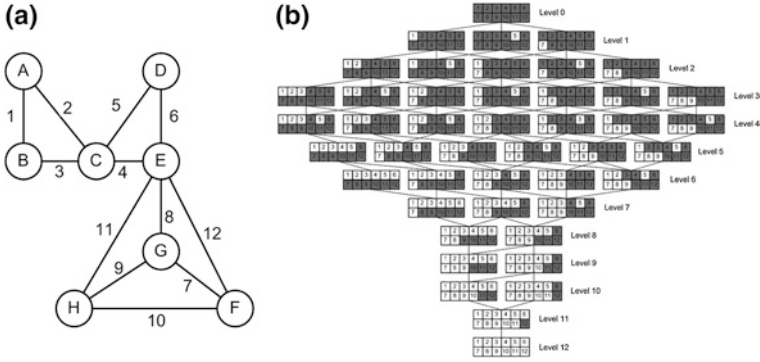
**Fig. 2.4** Disassembly tree of the Bourjault's ballpoint [9]



**Fig. 2.5** State diagram of the Bourjault's ballpoint [9]

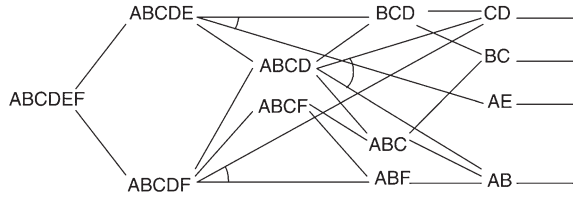
### AND/OR graph (Hypergraph)

This graph represents disassembly sequences based on subassemblies. A process is represented by multiple-arcs (hyper-arcs) pointing from a parent to its child components (subassemblies) (see Fig. 2.7). This overcomes the drawback of the state diagram. However, a major drawback is the complexity of the visual representation, which may become difficult to read when the number of components increases. Lambert [17] proposes a simplified version of this graph named the *concise AND/OR graph*. Further developments, aimed at representing the product model and its constraints more accurately, include the arborescence with hyper-graph [18], Petri net [19], and Hybrid graphs [20].



**Fig. 2.6** Disassembly-sequence diagram [16]. **a** Liaison diagram. **b** Disassembly-sequence diagram

**Fig. 2.7** AND/OR graph of the Bourjault's ballpoint [9]



### 2.1.4 Disassembly Sequence Planning (DSP)

A disassembly sequence is a procedure for the disestablishment of connections and detachment of parts in the disassembly operation. The initial state is defined as the complete product, and the final state, as a state where all desired components or subassemblies have been separated. The main purpose of disassembly sequence planning (DSP) is to find the optimal sequences of disassembling products with respect to certain factors, e.g. cost-effectiveness, material return, component recovery, and duration of operations. Theoretically, the number of possible sequences increases exponentially according to the number of components. Therefore, finding the optimal solution is considered an NP-complete optimisation problem [4].

Lambert [5] summarises effective methodologies based on a product-oriented approach as follows. As adaptability is required for a flexible automatic disassembly system, the main theme of this book, emphasis is placed on the adaptive planners.

#### Mathematical programming (MP) method

The mathematical programming (MP) method aims to make the internal variables converge to their optimum value without considering the complete search space. The problem model is derived from a hypergraph (AND/OR graph). Costs are assigned to each action (arc) with respect to subassembly components (i.e. parent



and child) and stored in a transition matrix. This can then be effectively solved by mathematical solvers, e.g. using Linear Programming (LP), Mixed Integer Programming (MIP), or Dynamic Linear Programming (DLP). Petri nets are also used in case of a dynamic approach.

### Heuristic methods

Gungor and Gupta [21] present a heuristic algorithm used to find near-optimal solutions to the disassembly sequencing problem. Near-optimal solutions are considered instead of optimal solutions, which are sometimes difficult to find due to the size of the search space. This method requires information of the precedence relationship among each of the components and the difficulty in performing each action. Efficiency is evaluated by the authors based on disassembly time. A case study regarding the DSP of a cell phone using the heuristic method and different search algorithms, e.g. greedy k-best and A\*, is examined by Lambert and Gupta [22].

### Artificial intelligence (AI) methods

Various techniques are used in artificial intelligence to generate and utilise constraints and reduce the size of the search space. Lambert [5] reviews typical AI techniques for disassembly sequence planning, including simulated annealing algorithms, genetic algorithms (GA), fuzzy sets, neural networks, multi-agent systems, and Bayesian networks. Other novel algorithms that have been efficiently applied to DSP include ant-colony optimisation [23], case-based reasoning [24] and rule-based sequence generation on clustering graphs [25].

### Adaptive planner

An adaptive planner generates a disassembly sequence with respect to the uncertainties and unexpected circumstances encountered during the disassembly operation. Due to its particular relevance to automated disassembly, a number of publications relating to adaptive planners have been reviewed in this section. The literature handles the problem at two levels: the (a) *process planning level* and (b) *operation level*.

In the *process planning level*, Tang [26] proposes using a Fuzzy Petri net to model the dynamics of disassembly, including the uncertainties in product condition and human factors. The system is trained with data and feedback from the actual disassembly, and selects the appropriate disassembly plan based on past experience. Turowski et al. [27] presents an implementation of a Fuzzy Coloured Petri Net for balancing a disassembly line. Grochowski and Tang [28] propose a learning approach using a Disassembly Petri Net (DPN) and Hybrid Bayesian network. Veerakamolmal and Gupta [29] propose using case-based reasoning (CBR) to generate disassembly plans for multiple products. The plan for a new product is adapted from existing plans by deriving it from a base case. Gao et al. [30] propose using a Fuzzy Reasoning Petri Net to adaptively generate the disassembly sequence according to the condition of the product observed at each state. Decisions are made based on the estimated value returned, hazard level, and disassembly cost.

In the *operation level*, Salomonski and Zussman [31] propose using a predictive model with DPN to adaptively generate the disassembly process plan according to real-time measurements conducted by a robot arm. Lee and Bailey-Van Kuren [32] address the uncertainties in the operation level by automatically recovering from a visually-detected error. In addition, Martinez et al. [18] propose a dynamic sequence generation method that generates an optimal disassembly plan during operations in response to unpredictable situations, e.g. failure to remove a corroded part, replacement of screws, etc. This system is modelled and controlled by a *multi-agent system* (MAS). ElSayed et al. [33] use GA to generate an optimal disassembly sequence according a supplied bill-of-materials (BOM) and components detected in real time. Relations defined in the original BOM must be preserved.

In conclusion, the existing adaptive planners deal with many types of uncertainty experienced during the disassembly process. The uncertainties relate to variations in the component conditions that deviate from the ideal case. The ability for an adaptive planner to handle these uncertainties stems from its ability to appropriately adapt existing knowledge into a new plan according to sensed information. Machine learning techniques are used to allow the system to improve its performance from past experience. However, the structure of the product, e.g. BOM and CAD model, generally needs to be supplied a priori. A methodology accounting for an uncertainty in the general product structure in real-time has not yet been proposed in any research. In addition, the learning process has only been implemented in the planning level. Hence, learning at the operation level, such as in optimising process parameters, should be further investigated.

## 2.2 Completeness of Disassembly

The completeness of disassembly can be categorised into two types: (a) *complete disassembly* and (b) *incomplete disassembly*. A *complete* or *full disassembly* is the process that separates every single component of the product. This is rarely done due to the technical constraints (particularly the complexity and the uncertainties in the operation) and high labour costs. On the other hand, the *incomplete* or *selective disassembly* separates only the desired components or subassemblies, and terminates when the desired depth of disassembly is reached. Disassembly becomes more cost-efficient with a strategic choice of disassembly targets. Reasons for selective disassembly include recovering modules or components for use as spare parts, separating those that contain hazardous substances, and improving the quality and quantity of shredder residue [17].

Figure 2.8 illustrates the situation in maximising the profit in the disassembly process. The disassembly range refers to the completeness of disassembly. The cost of disassembly is due to operation time, varying according to the number and type of connections to be disestablished. This increases with the desired completeness of disassembly. Disassembly is economically feasible when the total profit from treating or recycling all products exceeds the cost of disassembly. The optimal strategy is the point at which the maximum profit can be obtained [34, 35].

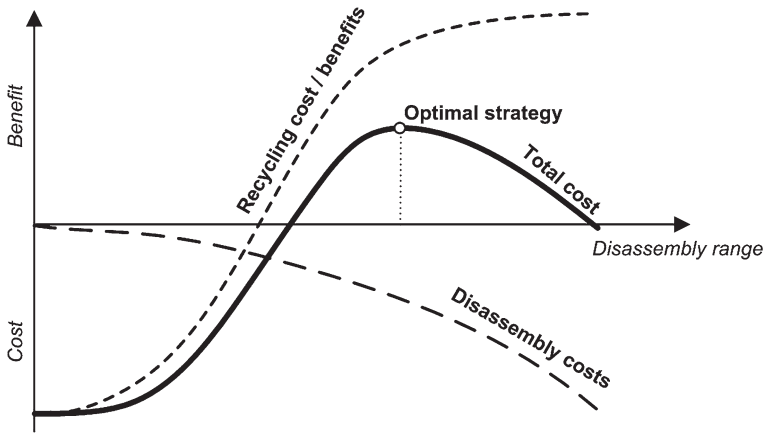


Fig. 2.8 Determination of optimal disassembly strategy [34]

The outcome of selective disassembly can be one of the three following types [9].

- **Homogeneous components:** parts that cannot be physically disassembled.
- **Complex components:** components comprised of a number of homogeneous components, joined together with fasteners, which can only be separated using destructive disassembly.
- **Modules:** sets of components that perform a self-contained function. Modules can be further disassembled via non-destructive or semi-destructive operations. However, maintaining their original condition and functionality can allow reuse of the entire module.

The researchers currently focus on developing a methodology to find optimal disassembly sequences in which the completeness of disassembly is taken into account. Kara et al. [36] propose the methodology of developing the optimal selective disassembly sequence which is the reverse of the methodology for assembly presented by Nevins and Whitney [37]. The disassembly sequences are generated from the product specifications, namely list of parts and subassembly, precedence rules, product representation model, and disassembly sequence diagram. Subsequently, the optimal sequences for removing the selected parts are obtained by removing invalid sequences according to liaison analysis. In regard to this concept, software that automatically generates and visualises optimal sequences of selective disassembly from specified constraints is developed by Kara et al. [16, 38].

## 2.3 Disassembly Operations

### 2.3.1 Types of Fasteners

The disassembly operation is divided into two main tasks: *disestablishing fasteners* and *detaching main components*. The main component is detachable if the associated

**Table 2.2** Disassembly methods according to fastener type

Discrete components	Not deformed	Bundling	Shear cut
		Spring	Deform/pull
		Screw, bolt, nut, washer	Unscrew, drill
	Reversibly deformed	Cotter pin, staple	Pull
	Irreversibly deformed	Rivet	Pry out, drill
		Adhesive: glue, seal	Peel, pry out, break
Parts of components	Reversible connection (semi-reversible)	Surface: mating	Remove
		Surface: press fit	Pull, pry out
		Snap fit	Deform, pry out, pull
	Irreversible connection	Surface: press fit	Pull, pry out
		Surface: mould	Break
		Seam fold	Deform
		Seal	Peel, pry out, break
Virtual components	Irreversible	Solder	Shear cut, break, melt
		Weld	Saw cut, break

connections are located and disestablished. Specific techniques are required for effectively disestablishing different types of fasteners. Lambert and Gupta (2005) [9] categorise the fasteners commonly found in mechanical and electronic-electrical products into 13 types. Different types of fasteners require different disestablishment methods and display different levels of reversibility. A summary of fastener types and their respective disassembly methods is shown in Table 2.2.

### 2.3.2 Dismantling Techniques

Disassembly operations can be broadly categorised into three types: (a) *non-destructive*, (b) *semi-destructive*, and (c) *destructive* disassembly. The characteristics of each category are explained in detail as follows.

#### Non-destructive disassembly

All outputs of non-destructive disassembly remain undamaged. This is desired for maintenance, component reuse and remanufacture. All fasteners within the product must be reversible or semi-reversible. The dismantling of reversible fasteners (e.g. screws) is generally easier than that of semi-reversible fasteners (e.g. snap-fits). The operation cost is generally high, as high flexibility is required, particularly due to difficulties such as rust and partial damage. Even though a number of tools have been specially developed to facilitate non-destructive disassembly, e.g. for the disassembly of screws [39] and snap-fits [40], the non-destructive approach is still generally economically infeasible [3].

### **Semi-destructive disassembly**

The semi-destructive approach aims to destroy only connective components, e.g. via breaking, folding or cutting, leaving main components with little or no damage. This increases the efficiency of the operation and has been found in many cases to be economically feasible. Many research works relating to automatic disassembly use semi-destructive techniques to overcome the uncertainties in the product condition and geometry. Examples of such techniques include the drilling out of screw heads during the disassembly of electric motors [41], creation of new surfaces allowing torque transmission for unscrewing [34] and cutting off of screw heads using a cut-off wheel [42].

### **Destructive disassembly**

Destructive disassembly deals with the partial or complete destruction of obstructing components. Components or irreversible fasteners, e.g. welds, are destroyed using destructive tools such as a hammer, crowbar or grinder. These operations are fast, efficient and inherently flexible. As a result, destructive disassembly is economically feasible and commonly performed in industry practice. One common application of destructive disassembly is in the opening of a covering component to reach the more valuable components inside. Examples include the breaking of the separating line [34] and using plasma arc cutting to destroy the metal casing of consumer appliances [43].

In summary, semi-destructive and destructive disassembly allow techniques that are more capable of efficiently dealing with the uncertainties in product condition, therefore allowing more economically feasible operation. On the contrary, non-destructive disassembly tends to have high operation costs but may be unavoidable in maintenance or for component reuse. More detail regarding the operations and specially-developed tools can be found in Sect. 3.3.2.

## **2.4 Conclusions**

Disassembly can be a key step in an efficient EOL treatment process, however, is usually economically infeasible due to high operating costs relating to the variation and uncertainties in the products and process, as summarised in Table 2.1. This chapter presents three major considerations which should be addressed to improve the economic feasibility of disassembly.

Firstly, the disassembly plan can be optimised with respect to a goal, which can be operating time or cost. A number of techniques regarding the representation of the product structure and disassembly process are described. With an appropriate representation, an optimal or near-optimal ordering of the disassembly operations can be found via various optimisation strategies described in Sect. 2.1.4. Particularly the adaptive planners are of interest, since they are able to respond to minor uncertainties like product damage. A significant amount of product knowledge, e.g. the product structure or a CAD model, are required before planning.

Secondly, regarding the completeness of disassembly, performing selective disassembly to a certain depth is more feasible than the full disassembly. The optimal disassembly depth should be determined during the planning phase.

Finally, the difficulty of the disassembly operations results from the type of fasteners used, and the product and fasteners' conditions. Different fasteners can be disestablished using different tools and techniques. Semi-destructive and destructive operations are generally preferable due to the shorter operating time and effective operation in spite of uncertainties.

In conclusion, the main source of difficulty in the disassembly process is the need to deal with a high level of uncertainties and variations. If the disassembly is not conducted by the product manufacturers, information regarding the product is generally at first incomplete. Even when the expected outcomes are known, poor product or fastener condition may require deviations to the usual plan. This causes higher operating time in manual disassembly, and is a primary factor hindering the industrial application of automatic disassembly.

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