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Integration and optimisation of product design for ease of disassembly

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1. Introduction

Disassembly is the process of removing the connectivity of parts in a product and it is prerequisites for efficient maintenance and recycling. Disassembly is environmentally conscious approach that allows the removal of malfunctioning components for replacement, thereby extending the life-span of products; it facilitates the recovery of useful components for reutilisation and separation of decontaminated materials for reprocessing. Disassembly therefore not only accommodates maintenance and repairs, but also helps to maintain the purity of materials for reprocessing and facilitates the safe isolation of hazardous substances as well. Optimisation of disassembly is necessary, in order to make the disassembly process efficient and economically a viable option. The Optimisation of disassembly can be only achieved in two main areas; 1- the integration of ease of disassembly into product design and development phase and 2- obtaining an efficient disassembly process plane and finding an optimum disassembly sequence, in order to disassemble a given product efficiently.

In this work due to space constraint, the first part of the disassembly optimisation will be addressed and the focus here will be only on the integration of ease of disassembly into product design and development processes. The integration into product design phase is essential, because product attributes are mainly fixed at the design stage and most of the disassembly problem should be tackled at the design phase. It is in the design stage that designers decide about the structure of a product, the components constructions, materials to be used, accessibility, joining techniques and fastening methods. The integration of design for ease of disassembly into design processes, therefore can lead to the correct identification of design specifications for disassembly and guarantees efficient and cost-effective disassembly operations. In this work, design for ease of disassembly criteria have been established and comprehensive design guidelines for ease of disassembly have been developed, so that designers can use to assess and evaluate the impact of their design decision and make the necessary changes to ease the problems associated with disassembly. The design criteria and the guidelines have been validated through a case study and the obtained results clearly demonstrate the application and effectiveness of the purposed methodology.

2. Literature Review

The current relevant literature review shows that considerable research effort has been channelled to the area of disassembly sequence planning (DSP), but the work in the area of the design for ease of disassembly is limited. Ishii et al. (1994), address the methodology to design product for retirement using hierarchical semantic network of components. Bylinsky (1995), gives examples of various products that can be torn apart into reusable pieces and sold for profit. The main focus of the paper is on Design for Disassembly (DFD) and the main principles are: Use fewer parts and fewer materials, and use snap-fits instead of screws. Other authors e.g. (Dowie et al. 1996) and Rose et al.2000), were also studied the disassembly problem and introduced some guideline for DFD, similar to those of Bylinsky. Chen et al. (1996) conducts a cost-benefit analysis to determine the amount of efforts that need to be put in disassembly and recycling of a product and a car's dashboard has been used as an example in this study and the analysis is centred on the following two scenarios: 1) The removal of only one part - the radio, and 2) Complete disassembly and the results show that while the recycling method yields a profit, but complete disassembly can lead to losses. The paper proposes that if two factors were changed, therefore there would be a substantial improvement in net benefit. The factors are: 1) Joint type and material combination and 2) Disassembly operation method. The study also indicates the disassembly time is one of the key factors affects the net benefit and for that the result of sensitivity analysis shows that there is a linear relationship between mean value of the net benefit of dashboard and time of disassembly. A mathematical model to assess design for optimal return from the disassembly of products has been developed by Motevallian et al., (2003). The model is the only one of the kind in the reported literature that can be used by designers to assess their design for optimum return from the disassembly and take the necessary corrective action in order to improve the design and maximise the return from the disassembly of their design.

2.1 Discussions and Significance

It is evident from the literature review that there is no an established frame work to assess design in an integrated form at the early stage of product development phase, in order to ease the problems associated with disassembly and to obtain a design that guarantees an efficient disassembly operations. In addition there are very limited numbers of DFD guidelines are reported in the literature and these guidelines certainly by no means are comprehensive. Further more there are no DFD criteria for assessing a design in order to ease the disassembly problems at the design stage. Those therefore are essential tools, so that designers can use to asses and evaluate their design decisions and take the appropriate corrective actions and make the necessary changes, in order to ease the problems associated with disassembly at the design phase. There are certainly a great need for such tools and methodologies that this study has addressed, developed and presented in this work.

3. Product Design Practices

In order to integrate design for ease of disassembly into product design and development process, the traditional design practice and Design for Assembly (DFA) approach are discussed in the following sections and the best available design practice is selected and used for the integration purpose.

3.1 Traditional Design Process

Traditionally, the attitude of designers has been "we design it, you build it." (Boothroyd et al., 1994). The traditional design process usually begins with the recognition of a need (Krishna, K,. 1997), involving "*the realisation by someone that a problem exists for which some corrective action can be taken in the form of a design solution*" (Groover 1987). The need is then translated into functional or design requirements (conceptual design) which details in precise terms what the product should be able to do including the service conditions under which it would perform. This list of requirements could also pertain to the various product life cycle phases, such as planning, design, manufacturing, marketing, maintenance, and use. Conceptual design is high level of design abstraction consists of different types of information including technical, economical, and legal. Figure 1, (*Stoll, W.H.,* 1991), shows the traditional design process.

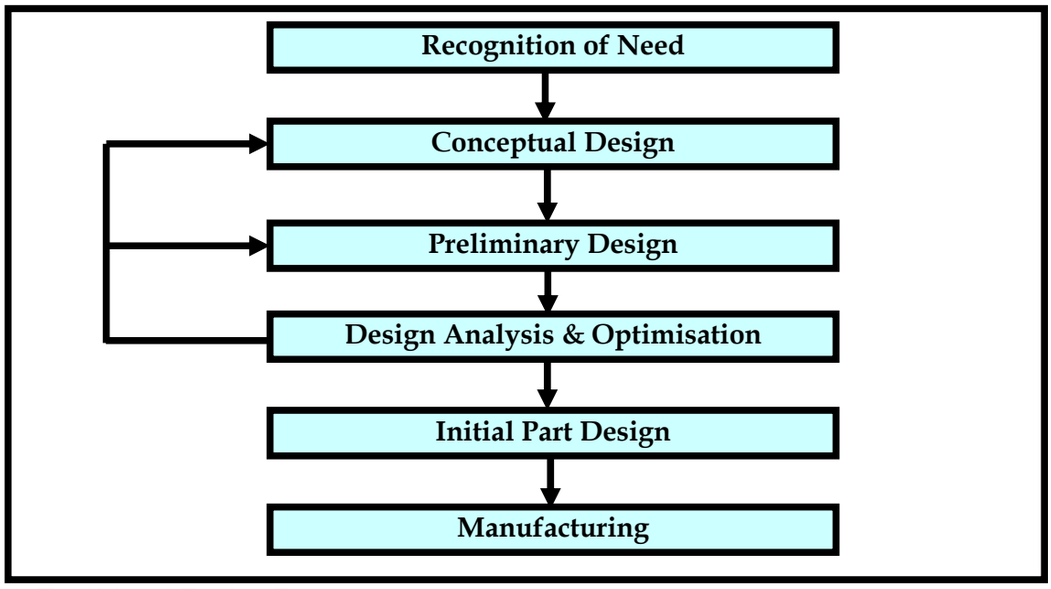


Fig. 1. Traditional Design Process

In preliminary design phase, the geometry and configuration of the part is developed based on the functional specifications. The part design will include the detailed specification of geometry, dimensions, materials, tolerances, and surface finish. The design analysis and optimisation phase performs various analyses of the part with respect to its ability to meet the functional requirements. Finally, if no further product revisions are needed in the design and analysis phase, the initial part design is provided for manufacturing.

3.2 Designs for Assembly and Manufacturing

Assembly can be defined as joining and fastening of parts in a specified sequence into a complete product or a unit that is part of a product. Boothroyd and Dewhurst (1983), showed that if product was designed specifically for assembly, the manufacturing cost could fall by up to 40% and assembly productivity could rise by up to 200%. Since then a large number of publications have given design guidelines and have provided methods to be used when designing for assembly and manufacturing (DFMA), in which many of them now are in regular use by designers, such as Lund, et al. (1985), Bralla, J. (1986), Boothroyd,

et al. (1987), Holbrook, et al. (1988), Stoll, H. (1988), and Leaney et al. (1992). Design for assembly method given by Boothroyd and Dewhurst involves design being assessed at the early stage of design to calculate the assembly time, the theoretical minimum number of parts and the assembly costs. The areas of the design which need to be changed are clearly highlighted via elimination of unnecessary parts and the integration of some of them into necessary ones. The result should be the reduction of costs and assembly times.

3.3 Designs for Ease of Disassembly

Product attributes are mainly fixed at the design stage; therefore most of the disassembly problem should be tackled at the conceptual design phase. That is because designers decide about the structure of the product, its components, materials and joining techniques. The designer's decision, therefore affects significantly on disassembly operations and its associated costs. According to Hoth (1990), the design cost of a product is approximately 5% of the total product costs, but the design usually determines more than 70% of the manufacturing costs. It influences 60% of the product quality and 50% of the manufacturing lead-time Bloo (1989). Moreover design also determines 80% of the disassembly costs Seliger et al. (1997). Studies by Carter and Baker (1992), considering the costs associated with a product life cycle, have demonstrated that from 60 to 95% of these costs are determined during the design phase. The authors conclude; it is during the design stage that the best savings can be achieved and the earlier the improvements are made the greater is the cost reduction. The purpose of the above studies are to demonstrate the importance of the design and designer's decisions' at the early stage of product design and development phase, to ensure that the decisions that are made during the design phase is to result in minimum overall costs during and/or end of the product life cycle. Those studies therefore clearly highlights' the influence of design on disassembly operations and thereby necessitate the integration of design for ease of disassembly into product design and development phase, in order to obtain a design that guarantees an efficient disassembly operations, which is economically a viable option and environmentally an effective one. That is because the aim of the DFD is to increase the use of common reusable materials, choose detachable and removable fasteners and joint types, improve accessibility, minimise the complexity of structure and the layout of products by modularisations in order to improve the disassembly operations and achieve the most efficient and effective way of performing the disassembly, in order to reduce the disassembly time and increase the environmental benefits. To achieve that design for ease of disassembly therefore need to be integrated into product design and development process. The following sections explain the advantages of the DFD and briefly indicate the benefits that generate and provide a way and the method in which DFD can be integrated into product design and development process.

3.3.1 The Benefits of DFD

The integration of design for ease of disassembly into product design and development phase not only eases the problems associated with disassembly, but it also has many other benefits and advantages, including the followings:

1. Meets regulatory compliance/ environmental obligations and International Standards "ISO-TC207" (Fiksel et. al. 1994).
2. Reduces the potential risk of contaminations and accommodates the safe isolation of hazardous substances.

3. Minimises disposal and handling of wastes, thereby reduces those potential costs and contributes positively to environmental benefits.
4. Facilitates maintenance and repair, thereby extends products useful life.
5. Prevents contaminations and facilitates the recovery of materials for reprocessing.
6. Reduces risk of damages and facilitates recovery of components for re-use.
7. Accommodates accessibility, thereby makes it easier to reconfigure a system or to make adjustments to system/ sub-system.
8. Simplifies disassembly steps and accommodates failure-mode/end-of-life analysis.
9. Facilitates re-designs or relocation of parts and/or grouping parts (modularity design) with similar end of life strategies.
10. Through design for disassembly, parts connectivity information will be readily available and easily accessible.
11. Simplifies the disassembly steps, thereby eases the automation of disassembly.
12. Increases the disassembly operations efficiency, thereby reduces the disassembly times and its associated costs.

3.3.2 The Integration of DFD into DFMA

In order to integrate design for ease of disassembly into product design and development phase, design for assembly and manufacturing (DFMA) by Boothroyd et al., has been chosen for the integration purpose. That is because DFMA process is now commonly used in manufacturing industries and research institutes alike. Figure.2 below, (Boothroyd et al. 1994), shows the DFMA process that has been modified and design for ease of disassembly (step 3) has been incorporated into the framework.

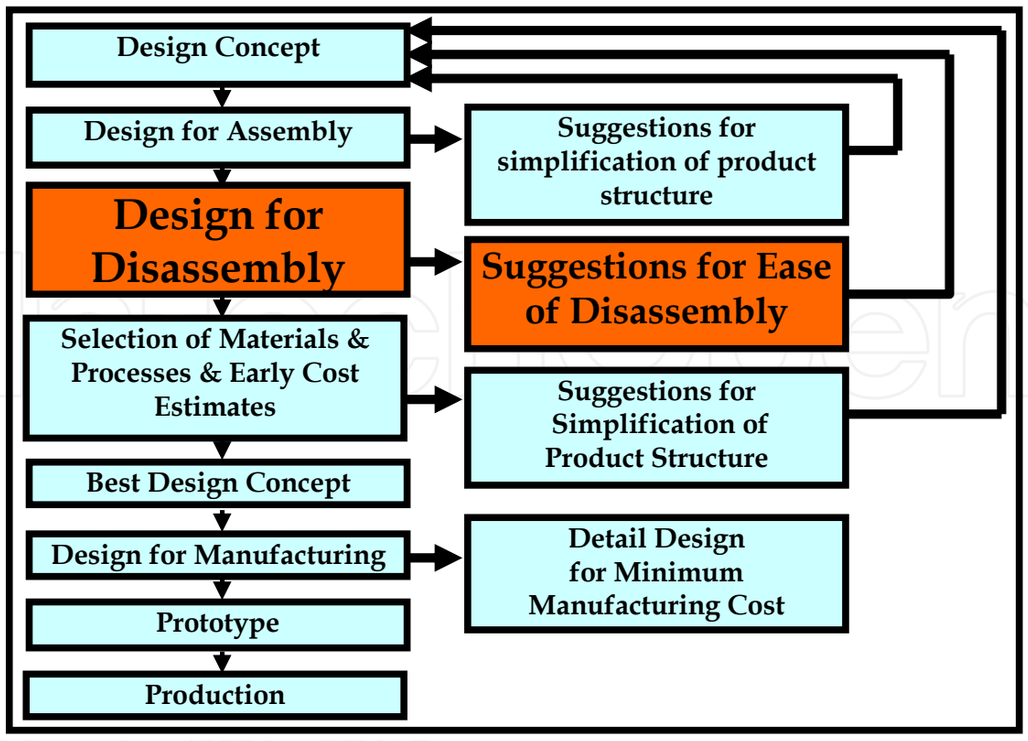


Fig. 2. Integration of DFD into DFMA Process

In Design for Assembly by Boothroyd, et al. (1987), each part as added to the product is examined against the following three criteria, to determine the necessity of its existence;

1. **During operation of the product, does the part move relative to all other parts already assembled?**
2. **Must the part be made of different material than or be isolated from all other parts already assembled?**
3. **Must the part be separate from all other parts already assembled?**

In Design for ease of Disassembly there are also three main areas that need to be taken into consideration and each part of a product to be assessed for those areas through the following criteria;

1. **Is the part accessible to be disassembled easily?**
2. **Are the fastening methods of the part easy to undo? (Such as snap fit)?**
3. **Does the material of the part recyclable and does it need to be incompatible with adjacent part?**

In the evaluation and assessment process for DFD, if there is any negative/ no answer to any of the above criteria, then designer needs to take corrective actions inline with the following DFD Guidelines.

3.3.3 Design for Ease of disassembly Guidelines

After assessing each part of a product by the provided DFD criteria, product designers need DFD guidelines, so that they can use at the design phase to ease the problems associated with disassembly, which are discussed and presented in the following sections.

The structure of a product and its layout (the way it is built) significantly affect the disassembly operations. A product consists of different parts/ components, modules and/or subassemblies, in which all connected by several joints/ joining techniques as shown as an example in Figure 3

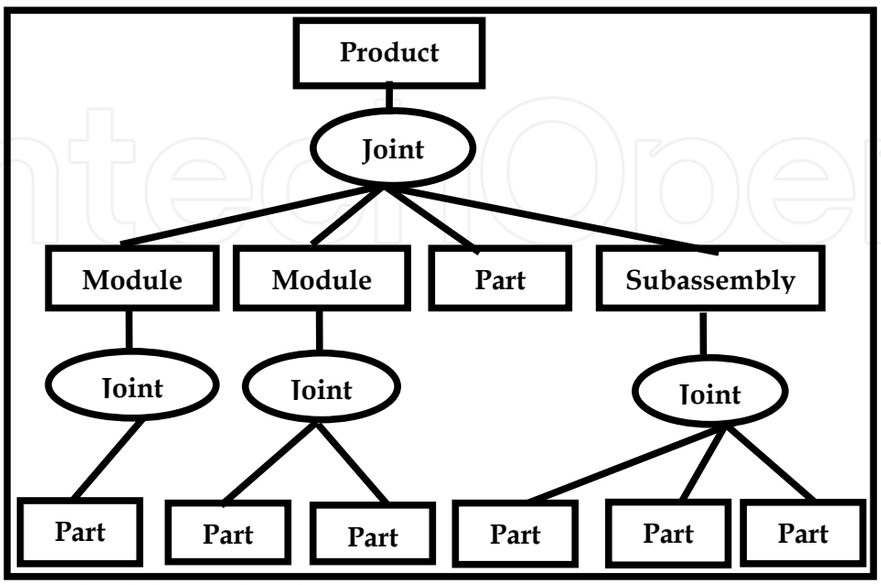


Fig. 3. An Example of the Product Structure

The figure 3 illustrates the product structure and shows a product could consist of parts, modules and subassemblies. A part consists of one single material and a subassembly consists of more, a module could be a part or parts that functions independently. These parts, modules and subassemblies, are generally made of a variety of different materials and are usually joined together with different joining techniques. These joints have to be disconnected in disassembly operation non-destructively in order to separate parts and materials. Several factors will affect the efficiency of the disassembly operations, e.g. the number of joints, the ease of disconnection of joints, the location and standardisation of joints and accessibility to parts and its joints. Furthermore; factors such as the life span of parts/components and their standardisation, maintenance and servicing requirements play a major role in disassembly operations, therefore these kinds of factors/ requirements needs to be taken into considerations when designing a product for ease of disassembly. These requirements/factors are grouped in six categories as; Product Structure and Layouts, Parts, Materials, Joins, Accessibility, and Ease of Disassembly Efforts, as illustrated and presented in Figure 4.

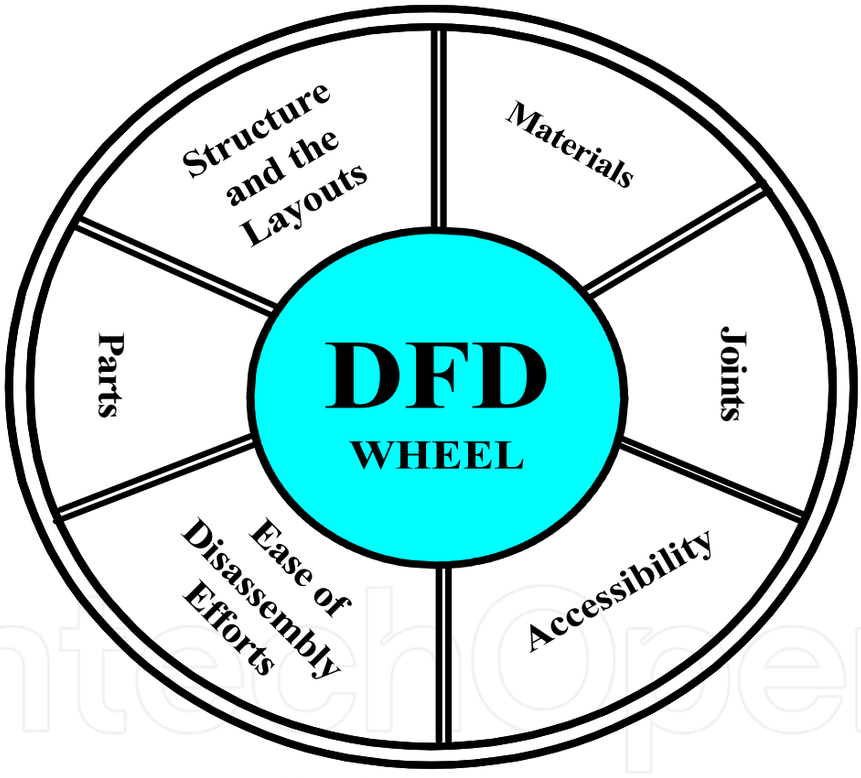


Fig. 4. Design for Ease of disassembly Wheel

In the following sections each of the above factors in the disassembly wheel are explored and briefly discussed and a set of design guidelines for each factor is developed and presented in a table respectively, (these guidelines by no means are exhaustive and some of which may have already been appeared in different forms in the literature). These DFD guidelines need to be used by designers after assessing each part by those of provided three DFD criteria to ease the problems associated with disassembly at the early stage of product design and development phase.

Factor 1: Product Structure and the Layouts

Product structure (dimensional constraints) and layouts (spatial constraints) both play an important role in disassembly operation and has a direct impact on costs and quality of retrieved components and materials. Simplification of product structure and its layout offers significant opportunities to reduce costs and maintain the quality of retrieved components and materials. As product structure and its layout are simplified, the required operations will be simplified and fewer disassembly steps will be required. Designers therefore need to evaluate and design as such that component positions in product layout favours disassembly to provide opportunity to dismantle products efficiently and without damage to other parts or contaminations. Designers should also design "robustness" into products to compensate for uncertainty in product's disassembly. That is because products can go through various changes and substantial variations during their useful life, variation could result from deterioration, maintenance and use. A robust design reduces the risks and thereby reduces the uncertainty during disassembly operation. Robust design can be achieved when designers understand the potential sources of variations and take steps to desensitise the product to the potential sources of variations. Robust design also can be achieved through "brute force" techniques of added design margin or through "intelligent design" (Boothroyed et. al. 2002), by understanding which design parameters are critical to achieve a performance characteristic whilst minimising the sources of variations.

Moreover modular design is another way that can help to reduce the complexity of the product, which reduces the complexity of the disassembly operations. In modular design each module is functionally separate from the other modules, which facilitates grouping parts/ components with similar end of life strategies. Designers should therefore design products as modular as possible, so as to open up the service/upgrade/recycle options. A modular structure makes it possible to revitalise a product from a technical point of view. It allows the benefits of a new technology to be incorporated into an older product and as a result a modular product may undergo through several upgrades in components over its lifespan, thereby extending the product useful life. Designing in modules will also allow the reduction in diagnoses and problems findings as well, since each module has separate functions the problem will be isolated to a particular module. Moreover the modular design can also minimise the number of parts, therefore the total number of items to be manufactured will be minimised, thereby reduces the inventory, assembly and disassembly processes. Modules can be manufactured and tested before final assembly; therefore the short final assembly lead-time will result in a wide variety of products being made to order in a short period of time without having to stock a significant level of inventory. Production of standard modules can be levelled and repetitive schedules established. Through standard product modules and by establishing design retrieval mechanisms and embedding preferred manufacturing processes in the preferred part list, the design, production, assembly and disassembly efficiencies will be enhanced greatly. A wide variety of products can be assembled and disassembled from a more limited number of modules, thereby simplifying the design and disassembly processes. Utilising a modular design therefore will reduce the complexity of the product; thereby simplifies the disassembly processes. Designers should also design the layout in such a way that valuable parts can be located in easily accessible places; because the more these parts are remain in the product there will be risk of damage, therefore if they are easily accessible and they can be removed safely, then

their economic benefits will be realised sooner rather than later. Furthermore designers should also put parts that have same/or similar lifespan in close proximity, because these parts are likely to wear out at the similar time, therefore they can be easily removed and replaced simultaneously. The table below provides design for disassembly guideline for the product structure and the layouts.

1.a	Simplify product structure (geometrical constraints) and the layouts (spatial constraints), to reduce the complexity of the disassembly process
1.b	Design robustness into product and its components (to allow components to be disassembled and removed in one piece as intended)
1.c	Make design as modular as possible to facilitate grouping parts with similar end of life strategies to allow replacement of modules during maintenance
1.d	Design the structure of parts such that its position in layout favours disassembly
1.e	Design the component such that allows clear paths for removal
1.f	Design in such a way that valuable parts can be located in easily accessible places (so that they can be disassembled easily and removed safely)
1.g	Put parts that are likely to wear out in close proximity (so that they can be easily removed and/or replaced simultaneously during maintenance)

Table 1. DFD Guidelines on Product Structure and Layouts

Factor 2: Ease of Disassembly Efforts

One of the ways to facilitate the ease of disassembly efforts is to design as such to minimise the need for alignment operations during disassembly, because it takes time and required efforts to align a part in a confined space to separate and remove. In many cases the problems of alignment can be significantly reduced through small design modification. If however, alignment operations are necessary then locating and aligning features should be used, to reduce the required recognition times. In addition designers should indicate on the product the starting point of disassembly and how it should be opened non-destructively, e.g. where and how to apply leverage with a screwdriver to open the snap connections, and so on. This saves time and also reduces the risk of damage.

Designers should also design for ease of handling and cleaning of components that would allow a part to be grasped and picked-up when separated, because additional time and efforts are required to remove a part that is difficult to grasp, handle and clean. Accurate sorting of materials is also essential if purity of materials is to be maintained and maximum recycling value is to be achieved. One of the ways that can help to accurate sorting is labelling the parts and materials that accommodate identification and sorting, which in turn saves time and reduces the unnecessary required efforts. If the parts are also hazardous and/or contaminated with hazardous substances, then they should be clearly marked for identification purpose and

to be accessed easily for removal, to ease the efforts and to avoid the risk of contaminations and putting in danger the health and safety of workers and workplace. The table below provides design for disassembly guideline for ease of disassembly efforts.

2.a	Label/mark all parts and materials to ease identification and separation/sorting
2.b	Avoid the need for alignment operations, but if it is necessary, then locating and aligning features should be used (There is a recognition phase and efforts required for alignments, therefore it should be minimised)
2.c	Design for ease of handling and cleaning of components (design parts, which are not sharp and sticky, so that they can be easily grasped and picked-up)
2.d	Indicate on the product how it should be opened and/or which parts must be cleaned and maintained in a specific way.(e.g.: colour-coded lubricating points)
2.e	Hazardous parts should be clearly marked for quick and safe removal (to eliminate the risk of contaminations)

Table 2. DFD Guideline on Ease of Disassembly Efforts

Factor 3:Parts

The number of parts in a product has direct correlation with disassembly time and costs. As the number of parts increases, so do the steps of the disassembly operation. A product, therefore should be designed to have as few parts and components as are necessary to perform its intended function. This can be achieved by means of integration and/or by using parts with multiple functions, the complexity of a product and the number of unnecessary disassembly steps will be reduced/ eliminated. In that way there will be a fewer parts to disassemble and thereby the time of assembly and manufacturing processes will be reduced and as a result the total cost of manufacturing, fabrication, assembly and disassembly goes down. In addition costs related to purchasing, stocking and servicing will also goes down as well. Inventory and work-in-process levels will be reduced and then since a fewer parts need to be handled and processed, so that automation becomes easier. Furthermore designers should avoid designing a part that need to be supported, constrained or held down while undoing operation need to be performed. That is because; supporting a part during disassembly operation requires additional tools and manual effort to carry out the operation and therefore avoiding it will speed up the disassembly process and improves the disassembly efficiency. Designing parts that nests/ tangles should also be avoided. That is because nesting/tangling creates problems for maintenance and consumes unnecessary disassembly time and complicates the disassembly process. That is not suitable for selective disassembly and requires many more operations to reach to the target components. Additionally minimising flexible parts can also minimise the disassembly time; that is because flexible parts have a tendency to move about during disassembly operations and usually require special tooling, therefore avoiding it improves the disassembly operation. Consideration should also be given to minimising the use of force, to reduce the risk of damage, but some parts may exert some sort of resistance to release, if that is the case, the force should be minimised. Furthermore a self-locking part (a part that holds itself in

location after it has been positioned, e.g. press fitting), should be avoided, that is because excessive force need to be used to separate the part, which increases the potential risk of damage to parts and also consumes disassembly time. In addition designing parts for re-orientation should be avoided, to minimise the unnecessary manual effort and avoid ambiguity in orienting a part for removal. That is because there is a recognition phase require by humans for every orientation and additional time and efforts require orienting a part for removal. Volume/weight of a component can also play an important role in disassembly efficiency. For example, removing a screw is easier than removing an engine, therefore designing heavy parts should be avoided where possible, since it slows down the disassembly process and increases workers fatigue and as a result potential risk of injuries. In-addition, facilitating design activities through standardisation and utilisation of common parts also provide the opportunity to reduce the number of parts, which in turn facilitates the standardisation of tooling requirements and reduces the need for frequent tool changes as a result. In standardisation however, since less variety is used in configuration of a product and common components are utilised and used that simplifies the product design and results in significant operational efficiencies. The table below provides disassembly guideline for designing parts.

3.a	Reduce the number of parts/components (fewer parts/components, translates to a fewer disassembly operation)
3.b	Minimise flexible parts such as belts, cables and gaskets (flexible parts have a tendency to move about during disassembly operations and usually require special tooling for handling and increases the part's susceptibility to damage)
3.c	Avoid designing heavy parts (difficult to handle as slow down the process)
3.d	Utilise standard/common parts where possible
3.e	Avoid designing parts that need to be supported or held while undoing operation is performed
3.f	Avoid designing parts that nests and tangles (complicates the disassembly)
3.g	Avoid designing parts for a self-fix-Turing; e.g. press fitting (they prolong and complicate the disassembly operation)
3.h	Avoid designing parts that need re-orientation for removal (there is a recognition phase required for every orientation, therefore time can be saved and unnecessary manual efforts can also be minimised)
3.i	Design parts for stability (a product can go through a variety of variations and changes during its life-cycle, therefore designing for stability can minimise the negative aspect)
3.j	Design parts with minimum resistance to release (if parts exert resistance to release, the force therefore should be minimised to reduce the risk of damage)

Table 3. DFD Guideline on Parts

Factor 4: Materials

The type of materials and its variety that are used to make up the product has direct influence on disassembly operation. A product whose components are made of different materials necessitates further disassembly operation that is because materials in a product need to be separated and sorted out prior to recycling to maintain its purity. In order to reduce unnecessary disassembly operations, the use of mixed and incompatible materials that requires exhaustive disassembly operations and manual efforts should be avoided. If the number of different types of materials are minimised and common recyclable materials are utilised then the disassembly operation time will be reduced and additional costs of separating and sorting materials goes down. In addition the potential risks of contaminations of materials will be reduced and thereby the purity of materials will be maintained for reprocessing and reuse (for example copper can contaminates steel that reduces the purity of steel, thereby reduces its value). Additional consideration should also be given to the use of toxic materials and hazardous substances (such as mercury, asbestos, cadmium, etc) to prevent decontaminations and maintain the safety of disassembly operations. Further to that, care needs to be taken on the selection of the ways in which metals are finished, i.e. (Plating, Painting, Oxidation, etc.). A good material marking system should be put in practice, to accommodate material recognition and ease the sorting process, which speeds up the disassembly operation. The table below provides design for disassembly guidelines for the use of materials.

4.a	Use materials that can be recycled
4.b	Avoid using toxic materials and other hazardous substances (such as mercury, asbestos, cadmium, etc.)
4.c	Avoid using composite materials (such as added fibreglass, etc.)
4.d	Use compatible materials and eliminate incompatible labels (e.g. if the material of a part is steel, then use the same for the label, to reduce the unnecessary operation of separating and sorting out the materials)
4.e	Avoid combinations of materials, which contaminates one another (such as copper and steel in which copper contaminates steel and therefore reduces the purity of the steel, thereby its value)
4.f	Avoid using mixed materials and utilise common materials
4.g	Avoid metal reinforcements in plastic parts (moulded-in metal inserts)

Table 4. DFD Guideline on Materials

Factor 5: Accessibility

Accessibility to components in a product is a critical factor in disassembly operation and has a direct impact on disassembly time and costs. Accessibility therefore must be given thorough thought and be taken into series consideration in the product design and development phase in order to accomplish the disassembly tasks successfully and efficiently. If the potential accessibility of disassembly is large, then the cost of disassembly will be reduced; that is because such conditions increases flexibility and makes it is easier to

use the required tools in the most convenient way to conduct disassembly operation and remove the desired parts. In addition, it is equally important that one should have an appropriate access to be able to see and observe the disassembly point in order to asses the condition of the joints to decide how the disassembly operation should be conducted. In disassembly, also the range of disassembly directions indicates the ease with which a component can be disassembled. Because, if there are two components in which one of them has only a single axis direction and the other has three or four axis directions, then the latter is easier to be disassembled and therefore is the preferred one that is because components with larger range of disassembly directions generally consumes less disassembly time and are easier to disassemble. Where in contrast in assembly a complex orientation and assembly movements in various directions should be avoided by utilising a simple patterns of movement to minimise the axes of assembly. The accessibility to drainage points is another feature that must be taken into consideration in order to remove Liquids easily. The table below provides design for disassembly guideline for accessibility.

5.a	Design to increase the potential extraction directions of disassembly
5.b	Provide visual access (one need to be able to see the joints and asses the condition to determine how the disassembly operation should be carried out)
5.c	Provide space and allow clear paths for removal of parts (to avoid collision and damage)
5.d	Design easy access drainage points, so that liquids can be removed
5.e	Fastening points should have easy access, to use hands/tools to perform the disassembly operation

Table 5. DFD Guideline on Accessibility

Factor 6: Fasteners/ Joints

Fasteners are critical factors in disassembly operations and have a direct impact on recovery and disassembly operations. It is important to reduce the number of fasteners in order to reduce the disassembly operation time and associated costs, because the reduced number of fasteners translates to the reduced number of disassembly steps and ultimately the disassembly operation time and cost. The types of fasteners have also influence on disassembly operation; for example screws are time consuming tasks and therefore their use should be minimised and/or avoided as much as possible, but if they are necessary, then using uniform screw-types can minimise the tool-changing time, thereby reduces the disassembly operation time and costs. In addition conventional techniques of permanent fasteners such as welding and gluing should also be avoided as much as possible and be replaced by mechanical snap fittings that can be easily detached and removed. Furthermore position of the joints is also an important issue and has direct influence on disassembly operations and for that joints should be positioned in such a way that minimises the unnecessary movement of product (the product need not to be turned or moved as much during disassembly operations that is because such movements consumes time and also increases the risk of damage to product). Complex joining methods in various directions should also be avoided and designers should evaluate if there is an alternative way to

accomplish the joining tasks. That is because; simplification of the joining activities and minimisation of the joining directions simplifies the disassembly operations and offers opportunities to improve the disassembly operation efficiency. Furthermore, if parts are to be exposed to harsh environments then rust proof joints should be used, because when a joint is rusty it will require more efforts and consumes more time to undo the given joint non-distractively and that adds to disassembly operation time and also increases the risk of damage to parts. The table below provides design for disassembly guideline for joints.

6.a	Simplify the joints and minimise the joining directions
6.b	Use joints that are easy to undo (such as snap fits)
6.c	Minimise the use of threaded fasteners and screws (they are time consuming)
6.d	Reduce the number of fasteners (to reduce the disassembly time)
6.e	Use rust proof joints if parts are to be exposed to harsh environments
6.f	Use standardised joints; same size and the same system (to minimise tool-changing time during disassembly)
6.g	Avoid using joining elements that are difficult to undo (such as weld, permanent glue or solder connections)
6.h	Position joints to minimise the movement of product during disassembly
6.i	Use fasteners whose materials are the same with the parts connected.
6.j	Avoid incompatible adhesives and heat staking between non-compatible parts (such as steel with copper)
6.k	Identify joining points and mark the location of snap fits, so that they can be identified quickly for separation

Table 6. DFD Guideline on Joints

3.4 Discussions

The above section discussed and provided the way in which DFD should be integrated into early stage of product design and development phase. Since it is in the design phase that product attributes are mainly fixed and therefore most of the problems associated with disassembly should be tackled and dealt with at the design phase. In this work 3 main criteria for assessing DFD were provided and a set of guidelines for the ease of disassembly presented. The main aim is to communicate disassembly improvement priorities to product design and development team and provide the information, knowledge, and the necessary tools to identify design changes for better product attributes and obtain a design that guarantees efficient disassembly operations. To validate the methodology and demonstrate the applicability, an industrial size product is chosen as a case study for redesign analysis and presented in the following section.

4. A Case Study

To demonstrate the application of the DFD criteria and the guidelines, an existing product-Videotape Recorder (VCR)-Toshiba is chosen for redesign analysis. This product was made in 1990's in Japan with the karaoke system for television broadcasters and that was a major development of the time, because News and other TV programs could be recorded and broadcasted later. This VCR has two main functions to perform; it must deal with the tape– an extremely thin, fairly fragile and incredibly long piece of magnetised plastics and also it must read the signals of the tape and convert them to TV signals that can be broadcast. The descriptions of this VCR and its materials contents are presented in the following sections.

4.1 The Product Descriptions

This Toshiba VCR system is fairly heavy in weight and has been designed with two motors and two electric plates to run and perform its functions. The components of this VCR are presented in table 4.1, which also provides information regarding material types and their weights. Figure 4.1, illustrates the exploded views of the original design of the VCR and figures 4.2-4.4 illustrate the different views of the angles of the VCR

Parts No.	Quantity	Components Name	Material	Weight kg
14	1	Base	Steel	2.638
13	1	VCR runner	Steel	0.975
			Plastics	0.85
15	3	Screws runner	Brass	0.021
11	2	Electrical Components (EC)	Motor	2.482
16	1		Mixed	2.367
12	1		Power Supply	1.869
10	12	Screws (EC)	Steel	0.24
9	1	Bracket	Steel	0.295
8	1	Bracket screws	Steel	0.08
7	1	Front Cover (FC)	Enforced Plastics	0.383
6	1	Tighten bar (TB)	Steel	0.922
5	3	F C & T B screws	Brass	0.024
4	1	Upper Cover (UC)	Enforced Plastics	1.85
3	4	U C screws	Steel	0.032
2	1	Bottom Cover (BC)	Steel	3.78
1	5	B C screws	Steel	0.040

Table 4.1. The Components Information of the Original Design

The figure 4.1, below illustrates the exploded view of the original design of the VCR and figure 4.2, illustrates the view from the bottom of the right-back of the original design.

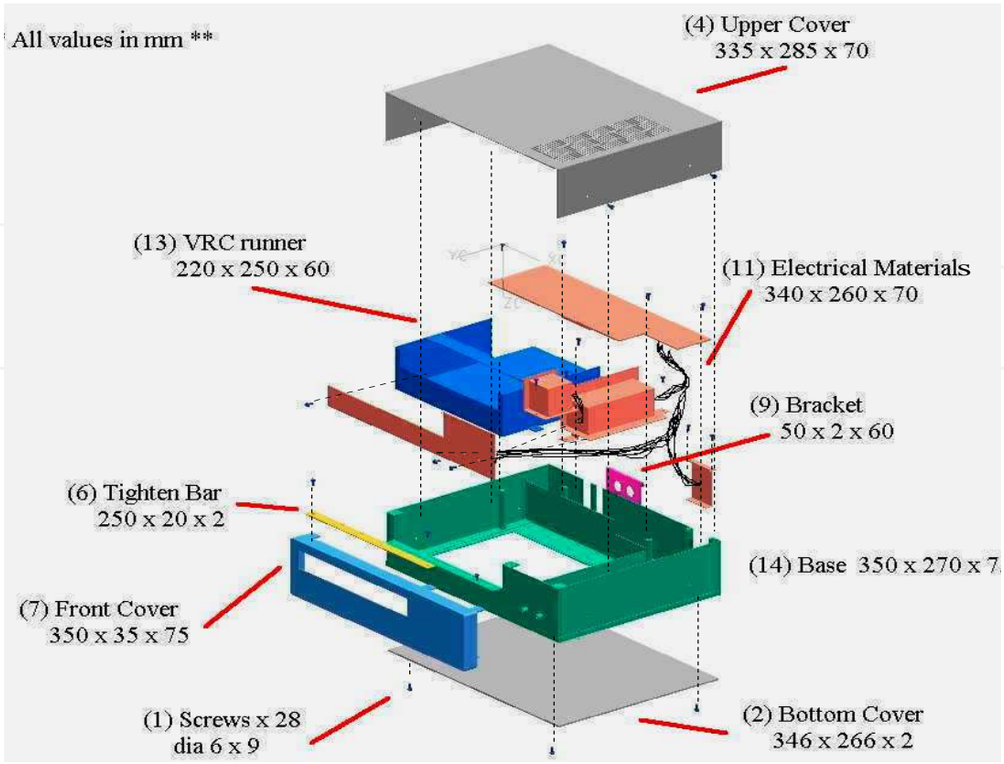


Fig. 4.1. Exploded View of the VCR Original Design

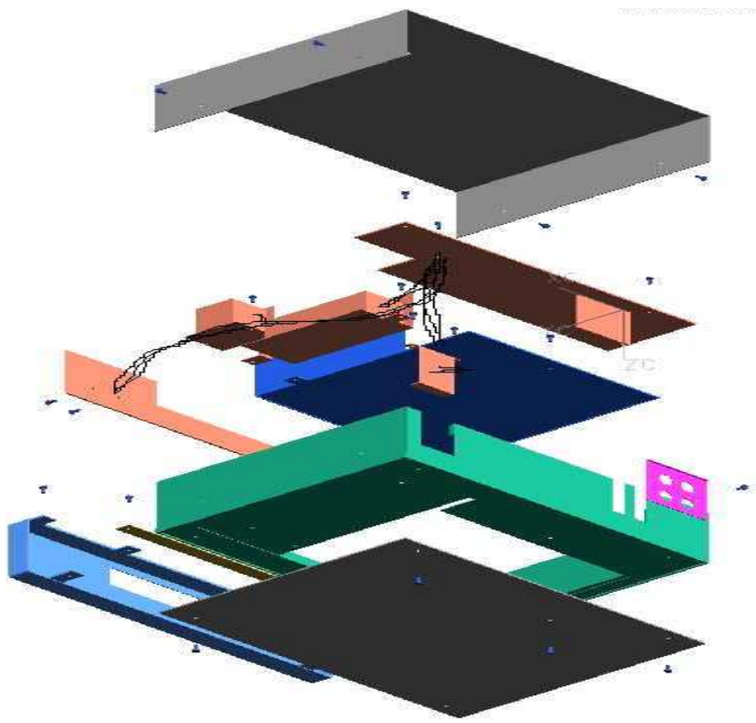


Fig. 4.2. the view from the bottom of the right-back of the original design.

4.2 The Design Analysis of the VCR

This Toshiba VCR system is analysed for its design in an integrated form through those of the DFA and DFD criteria and the provided DFD guidelines. In this process every part of the VCR is assessed and the necessary changes are made based on the DFMA and DFD requirements. The summary of the effect of those applications to each individual part is presented in table 4.2 and the detail explanations are followed subsequently;

Parts Name	Parts No.	Quantity	DFD Criteria	DFA Criteria	Retained	The affects of DFD Criteria
Base	14	1	C3	-	1	HIPS thermoplastics
VCR runner	13	1	C3	Y	1	HIPS thermoplastics
VCR runner screws	15	3	C2, C3	N	0	Integrated Snap-fits
Electrical Parts (EP)	16	1	C3	Y	1	Recyclable
Motor	11	2	C3	Y	1x2	Recyclable
Power Supply	12	1	C3	Y	1	Recyclable
(EP) screws	10	12	C2	N	0	Integrated Snap-fits
Bracket	9	1	C3	N	0	Combined with base
Bracket screws	8	1	C2, C3	N	0	Integrated Snap-fits
Front Cover (FC)	7	1	C3	Y	1	HIPS thermoplastics
Tighten bar (TB)	6	1	C3	N	0	Combined with base
F C & T B screws	5	3	C2, C3	N	0	Integrated Snap-fits
Upper Cover (UC)	4	1	C3	Y	1	HIPS thermoplastics
U C screws	3	4	C2, C3	N	0	Integrated Snap-fits
Bottom Cover (BC)	2	1	C3	N	0	Combined with base
B C screws	1	5	C2, C3	N	0	Integrated Snap-fits
Total		39			8	

Table 4.2. The Analysis of the VCR Original Design

The following sections briefly discuss the affect of the DFD and DFA criteria's on each part of the VCR and shows the necessary changes that required based on those assessments. The provided DFD guidelines have also been applied and the affects are highlighted.

VCR Base, (Part Number 14)

- **DFA Criteria**
  According to DFA criteria, this is the first part and is the base for assembly, therefore it is a theoretically necessary part and that will be retained.
- **DFD Criteria and the Guidelines;**
  Based on DFD criteria, this part should be modified and redesigned, to accommodate the integration of the other parts into the base. This base should also

be made of different kind of materials; such as High-Impact Polystyrene (HIPS) Thermoplastics, which has molecular stability and retains its property under extreme heat, which makes it an excellent recyclable material. Thus modifications and integrations of the other parts and also the change of materials for this part, reduces the number of parts, thereby reduces the disassembly operations time and eases the disassembly efforts for separating and sorting materials out, (meets the requirements of the DFD criteria number 3 and points 3.c, 4.a, 4.d, 4.e and 4.f of the DFD Guidelines).

VCR Runner, (Part Number 13)

- **DFA Criteria**
  According to DFA criteria, since this part moves relative to other parts, therefore it is a theoretically necessary part and that will be retained.
- **DFD Criteria and the Guidelines**
  Based on DFD criteria, this part should be redesigned and modified so that its current fastening methods to be replaced by snap-fits as an integral part of the peace for easy disassembly (meets the DFD criteria number 2 and points 3a, 4a, 4e, 4f, 4g, 6.b, 6.c, 6.d and 6.i of the DFD Guidelines). In addition the materials of this part should also be changed from the combinations of plastics and steel to HIPS thermoplastics. This change will eliminate the combinations of the existing mixed materials and replaces them with materials that are same as the base and recyclable. Thus change therefore not only eliminates the disassembly time, but also abolishes the disassembly efforts for separating and sorting materials out, (meets the requirements of the DFD criteria numbers 2 and 3 and points 3.a, 4.a, 4.d, 4.e, 4.f and 4.g of the DFD Guidelines).

Parts number, (4, 7, 11, 12 and 16)

- **DFA Criteria**
  According to DFA criteria, since these parts are standard subassembly and will be considered necessary separate items, therefore they are theoretically necessary and they will be retained.
- **DFD Criteria and Guidelines**
  Based on DFD criteria, these parts could be redesigned and modified so that their current fastening methods to be replaced by snap-fits as an integral part of the pieces for easy disassembly (meets the DFD criteria number 2 and points 3a, 4a, 4e, 4f, 4g, 6.a, 6.b, 6.c, 6.d and 6.i of the DFD Guidelines). In addition the materials of those parts should also be changed from the combinations of plastics and steel to HIPS thermoplastics, which is an excellent recyclable material. This change not only eliminates the combinations of the existing mixed materials, but replaces them with materials that are same as the base and recyclable. The changes of the materials therefore not only eliminate the disassembly time, but also abolish the disassembly efforts for separating and sorting materials out. (Meets the DFD criteria requirements, numbers 2 and 3 and points 3.a, 4.a, 4.d, 4.e, 4.f and 4.g of the DFD Guidelines).

Parts number (2, 6 and 9)

- **DFA Criteria**
  These parts do not meet any of the DFA criteria, therefore they are theoretically unnecessary parts and those should be eliminated.
- **DFD Criteria and the Guidelines;**
  Based on DFD criteria these parts if necessary, therefore they should be incorporated into the base and their materials should be change to HIPS thermoplastics which is same as the base and recyclable. Those modifications and changes in materials therefore reduce the number of necessary parts and eliminate the combinations of the existing mixed materials and replace them with materials that are same as the base and recyclable. Those changes therefore not only reduce the disassembly time, but also abolish the disassembly efforts for separating and sorting materials out, (meets the DFD criteria requirements of number 3 and points 3.a, 4.a, 4.d, 4.e, 4.f and 4.g of the DFD Guidelines).

Parts number (1, 3, 8 and 10)

- **DFA Criteria**
  These parts are separate fasteners and do not meet any of the DFA criteria, therefore they should be eliminated.
- **DFD Criteria and Guidelines;**
  Based on DFD criteria, these parts if necessary to be retained, therefore they should be incorporated into design as integral part of the pieces, such as snap-fits for easy disassembly, (meets the DFD criteria number 2 and points 3a, 4a, 4e, 4f, 4g, 6.b, 6.c, 6.d and 6.i of the DFD Guidelines). This integration therefore not only reduces the number of parts, but also reduces the combinations of the mixed materials thereby reduces the disassembly times and eliminates the disassembly efforts for separating and sorting materials out, (meets the DFD criteria requirements of numbers 2 and 3 and points 3.a, 4.a, 4.d, 4.e, 4.f and 4.g of the DFD Guidelines).

4.3 The Redesign of the VCR

The design analysis of the Toshiba VCR system shows that if subassemblies are arranged and modified to snap into the base and covers are modified and redesigned to snap on and also parts 2, 6, 9 are incorporated into the base and screws are replaced by snap-fits, then only eight separate items would be necessary for the design of this VCR, instead of 39. These eight items therefore represent the theoretical minimum number of items that needed to satisfy the functional requirements of this VCR. The redesign of this VCR therefore satisfy the disassembly requirements, where unnecessary parts were eliminated or combined and fastening methods were simplified and replaced by snap-fits for rapid and non-destructive disassembly. In addition incompatible materials were eliminated and replaced with recyclable materials, such as High-Impact Polystyrene (HIPS) Thermoplastics, which has molecular stability and retains its property under extreme heat, which makes it an excellent recyclable material. In the following sections the figure 4.3, illustrates the exploded view of the redesign of this VCR and figure 4.4 shows the bottom of right-back view of the redesign, followed by the figures 4.5 and 4.6, which illustrate the modifications that has been incorporated into design for obtaining the redesign for this VCR system.

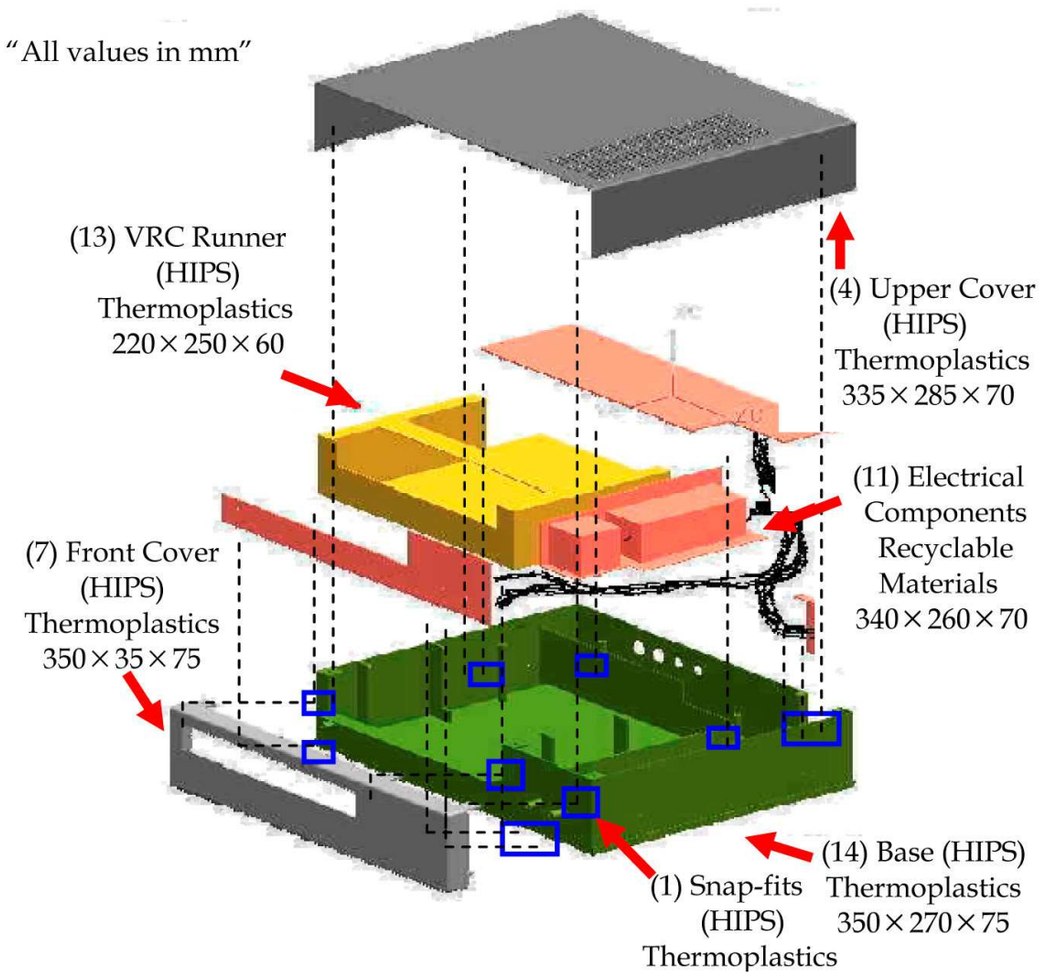


Fig. 4.3. Exploded View of Re-Design of the VCR

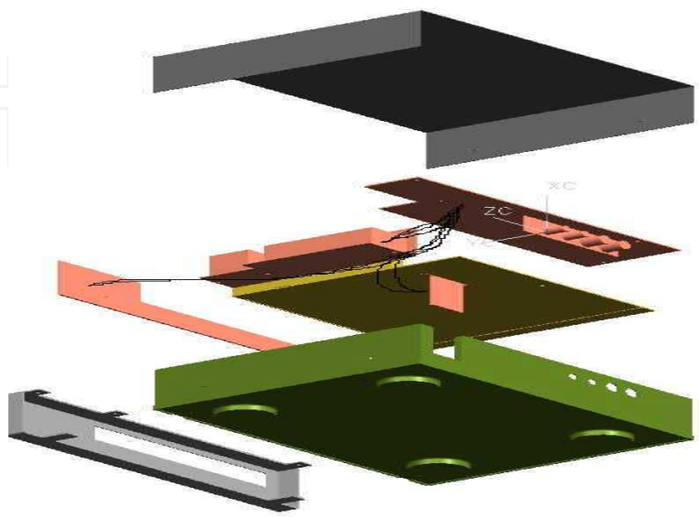


Fig. 4.4. the bottom of right-back view of the redesign

The figure 4.5 illustrates the redesign and modification of the base and also the integration of components and snap-fits onto the base. The figure 4.6 illustrates the redesign of the snap-fits for the Upper cover to the base and on the bottom part of the base for front cover of this VCR system.

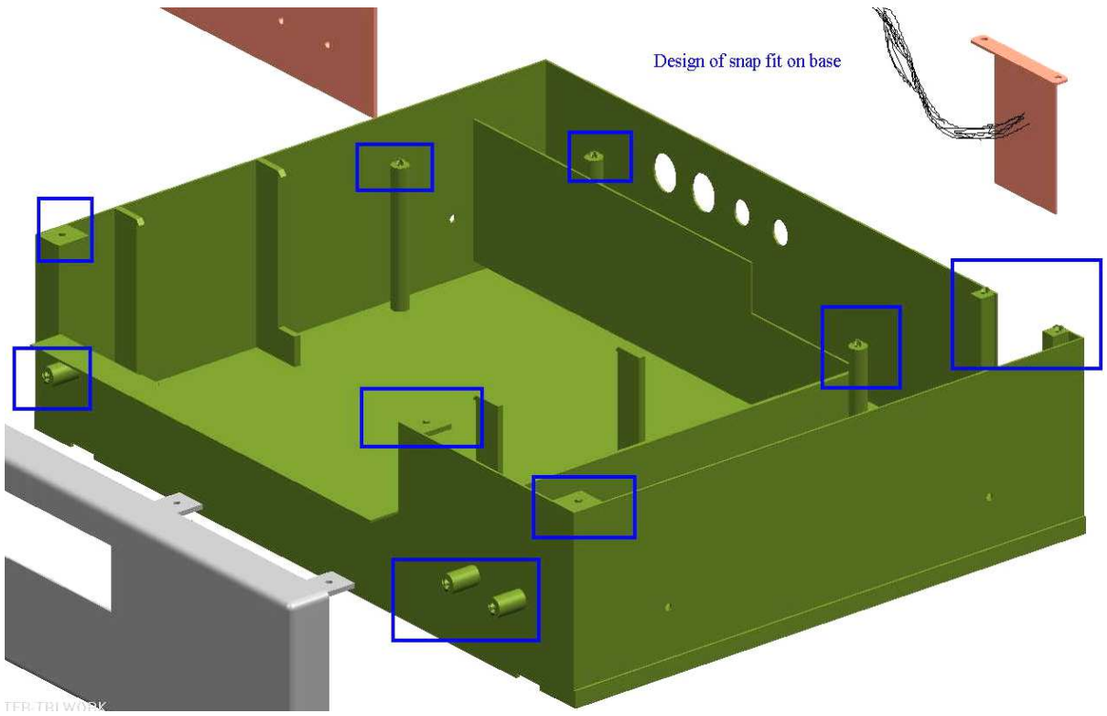


Fig. 4.5. The Redesign view of the Snap-fit and other integrated components

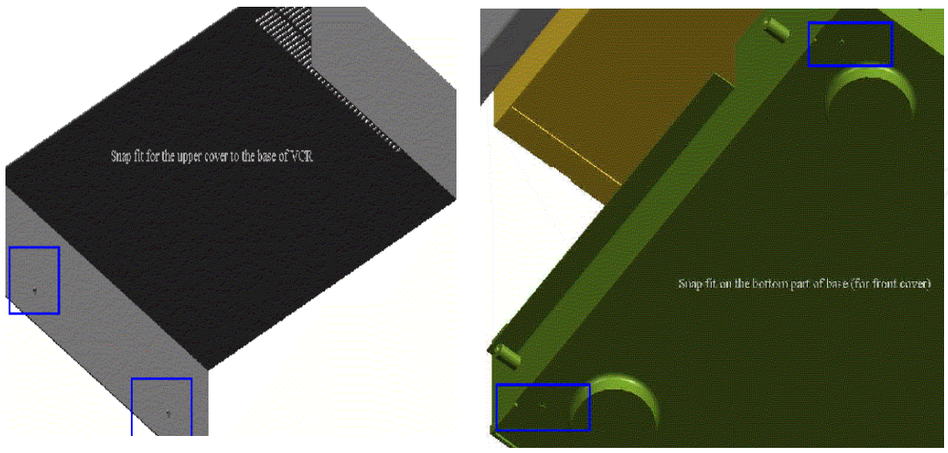


Fig. 4.6. the redesign of snap-fits for the Upper cover and on the base for front cover

4.4 Discussions

The Toshiba VCR system was analysed in an integrated form for both its original and redesign. The design analysis clearly reveals that one of the changes that need to be made to a design is material selection, since the optimum return from disassembly is affected by the material used in the product, i.e. the mix of materials, the compatibility of materials, and recyclability of materials and so on. That is because if the number of different types of materials are minimised and common recyclable materials are utilised then the time of disassembly operations will be reduced and additional costs of separating and sorting materials out will be eliminated. In addition the potential risk of contaminations will be reduced and the purity of materials will be maintained for reprocessing.

Furthermore, the other important changes which need be made to a design is joining techniques and fastening methods. As discussed earlier that fasteners are critical factors in disassembly operations and have a direct impact on disassembly time and ultimately on disassembly costs. That is because; the reduced number of fasteners translates to reduce number of disassembly operations that in turns reduces the disassembly time and thereby reduces the disassembly operation costs. Another important change that needs to be made to a design is the accessibility to components in a product, which is a critical factor in disassembly operation and has a direct impact on disassembly costs. If the potential accessibility of disassembly is large, then the cost of disassembly will be reduced, because that makes it easier to use the required tools in order to perform the disassembly operations and remove the desired components.

The design analysis of this VCR system therefore clearly showed that the integration of design for ease of disassembly into product design and development phase offers significant opportunities to ease the problems associated with disassembly and thereby obtain an efficient design to reduce the disassembly operations time and costs. The design for ease of disassembly guidelines with those of DFD criteria therefore provide a structured approach to seeking design for ease of disassembly in an integrated form at the early stage of product design and development phase. That is because most of the product attributes are mainly fixed at the design stage and therefore most of the problems associated with disassembly should be tackled and dealt with at the design phase through the use and application of the DFD criteria and the guidelines.

The main aim of this study therefore is to communicate disassembly improvement priorities to product design and development team and provide the information, knowledge, and the necessary tools to designers in order to assess and evaluate their design decisions. To identify the design changes and make the right choice, by deciding about the structure of a product, its components constructions, materials, joining techniques, accessibility to parts etc. to make the necessary design changes at the early stage of the product design and development phase to ease the problems associated with disassembly. An informed decision at the design phase can and will result in better product specifications to attain a design that eases the disassembly problems and reduces the potential negative environmental impacts, thereby guarantees an efficient disassembly operations during and/or at the end of the product life cycle.

5. Conclusion

This study provided the methodology and the way in which DFD should be integrated into early stage of product design and development phase. It is in the design stage that product attributes are mainly fixed and therefore most of the problems associated with disassembly should be tackled and dealt with. In this study, a framework for integration of the ease of disassembly into product design and development phase were established and 3 criteria for assessing DFD were identified and a set of DFD guidelines for the ease of disassembly were provided. For validation the DFD criteria and the provided guidelines, an industrial size product- A Toshiba VCR was analysed as a case study for its design. The results of this analysis clearly demonstrated the applicability and effectiveness of the purposed methodology and the DFD guidelines, where joining elements were redesigned for the purpose of rapid and non-destructive disassembly and the numbers of parts were reduced from 39 to 8 parts. In addition the numbers of material types were reduced from 5 to 2, which are recyclable. Through the minimisation of parts and reduction in materials varieties, the complexity of the product and its weights were reduced, thereby the accessibility was enhanced and the overall structure of the product were consequently simplified towards ease of disassembly.

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This book pilots the reader into the future. The first three chapters introduce new materials and material processing methods. Then five chapters present innovative new design directions and solutions. The main section of the book contains ten chapters organized around problems and methods of manufacturing and technology, from cutting process optimisation through maintenance and control to the Digital Factory. The last two chapters deal with information and energy, as the foundations of a prospering economy.

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