LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
LUT School of Energy Systems
LUT Mechanical Engineering

Niko Matlouthi

APPLYING DFMA APPROACHES TO THE DESIGN OF FASTENING COMPONENTS AND METHODS FOR AN UNINTERRUPTIBLE POWER SUPPLY UNIT

Examiners: Professor Harri Eskelinen
Professor Pertti Silventoinen

ABSTRACT

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Applying DFMA approaches to the design of fastening components and methods for an uninterruptible power supply unit

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This research was a result of a collaboration between Eaton power quality Oy and the Lappeenranta University of Technology. The objective of this research was to analyze the joining methods from a DFMA perspective. DFMA analysis provides a systematic approach that results in a product designed with easy manufacturing and assembly stages. DFMA ultimately leads to reducing part count and overall costs. 93PS and 93E UPS models were analyzed and a DFMA analysis of the joining methods was performed and joining efficiency ratios were measured. The systematic DFMA analysis of the fastening methods resulted in recognizing areas for improvements within the mechanical and electrical requirements and limitations for the design of UPS units. The suggested improvements cover the decrease of used joining methods and joining components, the decrease of required special tools during assembly, and improvement the assemblability of a UPS unit. Moreover, a general guideline for implementing DFMA philosophy on the fastening solutions was generated to aid mechanical designers in future models.

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Niko Matlouthi

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LIST OF SYMBOLS AND ABBREVIATIONS

t_{ma}	Actual assembly time [min]
$N_{min}t_a$	Theoretical minimum assembly time [min]
E_{ma}	DFA index ratio
E_d	Design efficiency ratio
E	Assemblability value
N	Number of components
K	Cost saving ratio
I_h	Handling index
R_h	Total handling ratio
I_f	Fitting index
R_f	Total fitting ratio
n_A	Number of critical components
n_B	Number of non-critical components

AC	Alternating current
AEM	Assembly evaluation method
BOM	Bill of materials
DC	Direct current
DFA	Design for assembly
DFM	Design for manufacturing
DFMA	Design for manufacture and assembly
IEC	International electrotechnical commission
PES	Production evaluation system
PDM	Product data management
UPM	Uninterruptible power module
UPS	Uninterruptible power supply

1 INTRODUCTION

In a fast pacing world with new products coming to the market in unprecedented pace, companies are required to improve their product design philosophy for better manufacturability, assemblability, maintainability, and sustainability aspects (Ulrich & Eppinger 2011, pp. 1-6). In the western world, in order to be able to compete with low cost production countries, companies should pay more attention on the design of their products. Product design must be innovative and pay attention for the maintainability of their product, since maintenance is a big part of the business models for many companies (Parida & Kumar 2009, pp 17-18). A product that is easy to assemble, easy to manufacture and has been designed with maintenance as a main design requirement will bring big savings for the company. Design for manufacture and assembly philosophy can be a great tool for companies to achieve products with optimized low costs.

1.1 Research background, problem, questions and scope

This research was proposed by the target company with an aim to implement a design for manufacture and assembly (DFMA) approach on the joining methods of a specific uninterruptible power supply models to further enhance the cost-effectiveness of the assembly and find a modular solution for the joining methods that can be applied on a wide variety of products.

Currently the target company does not have an optimized design solution for the joining methods used in a specific uninterruptible power supply which leads to ineffective utilization of the company’s resources. Answering the following questions could lead to the improvement of the above-mentioned situation.

How does the implementation of a systematic DFMA analysis lead to an optimized solution for joining components for a cost-effective assembly work? How to identify the most critical elements of the joining components and their impact on the effectiveness of the assembly work? How is the effectiveness of joining efficiency defined?

1.2 Research objective and methods

The main objective of the thesis is to implement DFMA approaches to analyze and enhance the joining methods used in a specific uninterruptible power supply, in respect to the target company's wishes, the electrical and mechanical requirements and constraints, and safety regulations. These requirements and constraints are defined by international electrotechnical commission (IEC) standards IEC 62040-1 and IEC 60950-1. The research methods in this work consist of literature review on DFMA approaches and joining methods in sheet metal, comparison and reviewing of 3D models of the studied UPS models using Creo and SolidWorks software, and discussions with the research group members. A representation of the methods used are shown in the following figure 1.

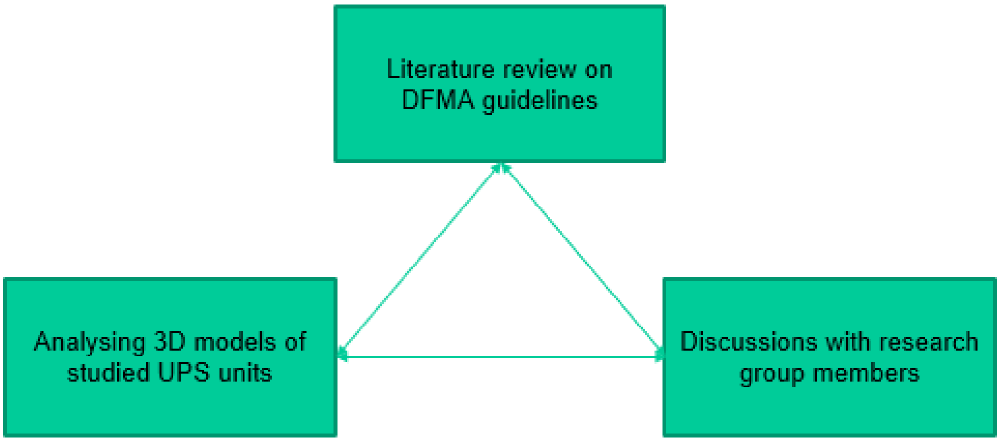

Figure 1. A representation of the triangulation of research methods used in this research

2 DESIGN FOR MANUFACTURE AND ASSEMBLY

According to Boothroyd et al. (2010) designing for manufacture and assembly can be defined as the link which connects the designing and the manufacturing departments within an organization. DFMA can be divided into two groups; Designing for assembly (DFA) and design for manufacturing (DFM).

DFA focuses mainly on optimizing the assembly stage of parts or whole system. There are many systematic methods that can be used in order to make the assembly faster, cheaper and performed more ergonomically if done manually. This can be achieved by designing parts that can be assembled from several directions, designing parts that have self-orienting mechanisms, combining parts and designing as little parts as possible.

On the other hand, DFM focuses on insuring that designers design parts that can be manufactured with the available manufacturing methods and tools. This will aid in less redesigning at later stages, that tends to increase overall costs. It is of most importance to take into consideration the manufacturing methods and materials in the earliest stages of designing.

DFMA can be supported by different approaches to achieve an optimized product. The utilization of modularization and standardization and platforms, using the most suitable manufacturing methods and materials, using feature-based systems such as computer aided software, control and management of design and assembly processes to reduce cost.

The main goals of DFMA are reducing overall costs, reducing lead time and increasing productivity. DFMA also brings together different departments in an organization which is the modern approach for product development. For insuring competitiveness in the market, DFMA must be included in the earliest stages of product development. (Boothroyd, Dewhurst & Knight 2010)

2.1 DFMA background and development

During the early 70’s, design for ease of manufacture was a common term used to describe the manufacturability of a certain part. Designers at this era payed attention of possible manufacturing errors that might accrue in later stages. It was of high importance that a designer is aware of different manufacturing processes and their capabilities and limitations. However, a quantitative measurement method for manufacturability did not exist, and the manufacturability was mainly a responsibility of the suppliers. (Boothroyd, Dewhurst & Knight 2010)

The earliest development of DFMA began with research on assembly automation. A handbook was published by the University of Massachusetts that cataloged feeding and orienting techniques for certain parts. This handbook made it possible to categorize and analyze different feeding and orientations of different parts and it also allowed to recognize what parts were easier to feed and orient, and which parts were harder. This gave the designers a tool to avoid shapes and geometries that are harder to feed and orient during the assembly. This lead to a research into studying design for manufacturability and initiating a methodology that can be implemented in other occasions. Based on the study on feeding and orienting, Boothroyd, Alan Redford and Ken Swift worked together on studying product design for automatic assembly. There were able to illustrate that reducing part number and making the assembly operation easier to perform lead to lower assembly time. Further researches on the topic of design of manufacturing and design for assembly led to the conclusion that reducing number of parts, not only does it reduce assembly costs, but it reduces the total part cost as well. (Boothroyd, Dewhurst & Knight 2010)

Several companies began implementing DFMA with their product design, in the believe that it would save them millions annually, as the manufacturing managers at Xerox believe (Boothroyd, Dewhurst & Knight 2010). Additionally, the Ford Motor company has announced in 1988 that the implementation of DFMA resulted in over one Billion US dollars in savings (Bogue 2012, pp. 112-118).

2.2 Successful examples of implementing DFMA

There are plenty of examples where DFMA analysis has resulted in a drastic savings in costs and assembly time. In this chapter few examples are highlighted to demonstrate the value added by applying different DFMA approaches.

2.2.1 Dell’s Optiframe computer family

Dell implemented DFMA on the design of the chassis of its computer product Optiframe. The successful implementation of DFMA resulted in decrease of assembly time by 32%, and the part count by 50%. Moreover, improvements in throughput in factory was improved by 78% and in direct labor efficiency by 84%. Dell estimated that the successful implementation of DFMA resulted in $15 million in savings. The following figure 2 demonstrates the different in part count between the original (top) and improved design (bottom) (Bogue 2012)

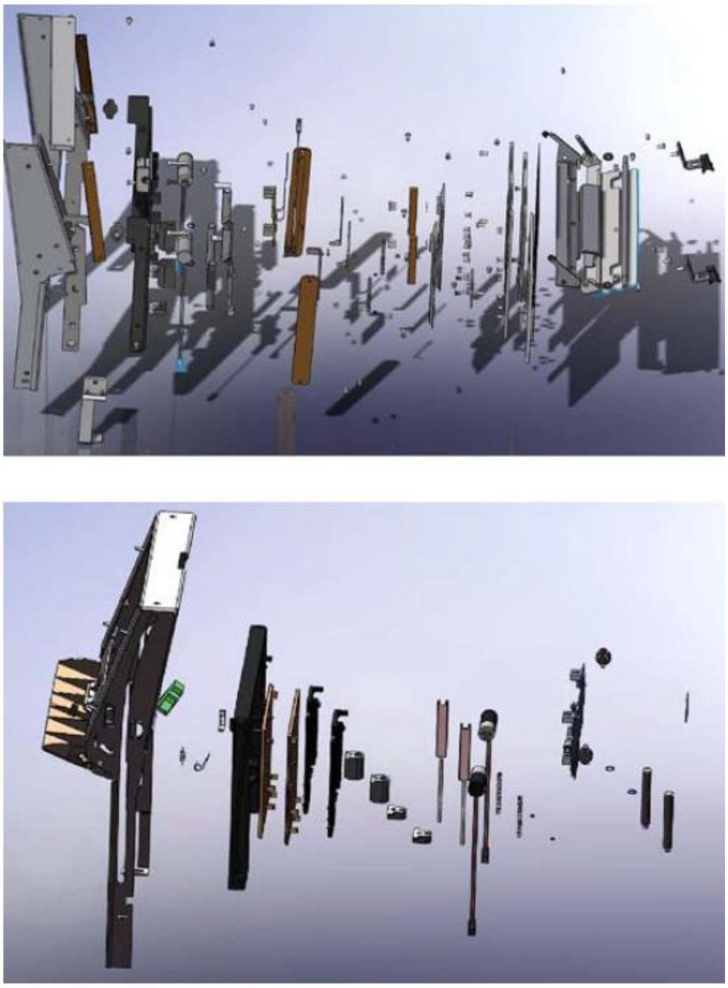

Figure 2. Original and improved design of Dell’s Optiframe computer (Bogue 2012)

2.2.2 QSTAR case

QSTAR manufactures spectrometer that are high-tech and massive instruments in low volume. The manufacturing department in this institution realized that the assembly time has a direct influence on the costs. The original design required days for assembly and testing. The engineers in QSTAR decided on using a DFA software to analyze the design and promote solutions to shorten the assembly time and ease the assemblability of the instrument. The main red flag that was noticed after the analysis was the number of fasteners used to connect several resistors and metal rings. Four screws were needed to fasten each of the 32 resistors. Using a connector that connects just by pressing into the base was suggested to reduce the number of screws. With other suggestions, the total number of components was reduced from 289 parts in the original design to 144 parts in the modified design with only three screws and nuts to hold all these parts together. QSTAR was able to reduce material costs by over $35,000 per unit and by reducing part count, the errors from design and manufacturing were reduced. (Boothroyd, Dewhurst & Knight 2010, pp. 21-22)

2.3 DFMA approaches and guidelines

DFMA provides a structured method to design a product that can be manufactured and assembled with ease. A design engineer mainly utilizes the manufacturing technologies and materials that are familiar to him/her, and this leads to products that are not optimized in terms of manufacturability and assemblability. Thus, a systematic DFMA analysis is an important and vital tool that can enhance the manufacturing and assembly characteristics of a product.

According to Bogue (2012), there are three methods to apply DFMA. First, is following general set of rules and regulations to help designing parts with easier assembly and manufacturing characteristics. These rules aim to:

- Decrease the number of components, which will lead to reduced inventory and purchasing costs, simplified assembly, and improved reliability
- Using standard components and geometries, this improves reliability and reduces costs
- Minimizing the use of joining components and types, this leads to easier maintenance and reduces costs

- Material selection, selecting less dissimilar materials which require simplified fastening methods and manufacturing processes
- Not over-specifying tolerances and surface finish, which lead to easier manufacture and lower production costs
- Usage of modular design solutions, this simplifies the assembly and reduces costs
- Following poka-yoke designing method, which mean designing assemblies that cannot be assembled wrongly. This will reduce costs from re-work needed if assembled incorrectly.
- Designing for automated/robotic assembly

The second method is created by Boothroyd and Dewhurst, this method evaluates each component in an assembly by a value according to its assemblability. The sum of the values is then used as a comparing tool against the new design that followed the DFMA guideline. The new design is also focused on the components that are having a higher value.

The third method rely on the use of computer software to analyze the DFMA aspects of a certain design. This software can be automated to generate results based on given rules. BDI’s DFMA software is one of the most used software to evaluate and improve the design.

In addition to the Boothroyd and Dewhurst method, several methodologies covering DFMA has been developed world wide. Hitachi’s assembly evaluation method (AEM), Lucas DFA method and Fujitsu’s productivity evaluation system (PES). (Bogue 2012)

2.3.1 Boothroyd and Dewhurst evaluation method

The Boothroyd and Dewhurst evaluation method evaluates a design by analyzing each part and defining whether they are fundamental and critical part to the whole assembly. If not, then then next step is to try and eliminate that particular part. This ultimately results to a simplified assembly and assembly operations. Boothroyd (2011) has suggested that by asking the three-following question, it would be possible to determine the criticality of a certain part:

- During the normal operation mode of the product, does the part move relatively to all other parts that has been already assembled?

- Should the part be made from different material compared to other parts assembled, or does it require isolation (electrical, vibration isolation and damping)?
- Is the part separated from other assembled parts?

The DFA index ratio can be obtained for the main assembly

$$E_{ma} = \frac{N_{min} t_a}{t_{ma}} \tag{1}$$

In equation 1, The DFA index ratio E_{ma} can be calculated by dividing the theoretical minimum assembly time $N_{min} t_a$ by the actual assembly time t_{ma}

2.3.2 Hitachi evaluation method

The Hitachi's assembly evaluation method was founded in the late 60's in Japan by Hitachi Ltd. The aim of this method is to provide the design engineer with feedback from previous designs about the ease or the difficulty of a specific design. The Hitachi's AEM evaluates the ease of assembling a product by two ratios:

- The assemblability evaluation score E, which evaluates the design quality for assembly and the difficulty or ease of the assembly stage.
- The estimated assembly cost ratio K. This ratio is for estimating the improvements in assembly costs

The assembly evaluation is built mainly on the evaluation of assembly operations. Each assembly operation is connected to inserting and fixing processes. There is no direct connection to the feeding and orientation as in the Boothroyd and Dewhurst evaluation method. Therefore, the AEM is mainly focused on manual assembly than for automated assembly. (Leaney & Wittenberg 1992; Abdullah, Popplewell & Page 2003)

The evaluation process begins with defining the motions and operations required for inserting a part. A downward motion is considered to be the fastest and easiest assembly direction, both for human and machine. Therefore, negative points are given to any other motion or operation that is not a downward motion. The AEM also uses symbols to describe motions and operation and there are total of 20 symbol that can be used in the analysis.

The different assembly sequences are then gathered together in a table or a form and each sequence or part is then given a description, a symbol for the assembly direction, or assembly process. Each sequence is also given an assemblability value *Ei*. *Ei* is equal to 100 is the motion is downward motion. And the value E is changed according the direction of the assembly based on the Hitachi's scoring method. The total score of 100 would ultimately be the most ideal result for the assembly. However, a value of 80 and above is considered to be fit enough for automated assembly.

$$E = \frac{\sum E\mathrm{i}}{N} \tag{2}$$

In equation 2, The sum of *E*'s from every component is them gathered ad divided on the total number of components *N*. The *E* score can define the design for assembly efficiency, but it does not define the advantages of reducing the part count. The *K* ratio is used to define the cost savings gained from the new design.

$$K = \frac{Total\ assembly\ operation\ costs\ of\ the\ new\ design}{Total\ assembly\ operation\ costs\ of\ the\ previous\ design} \tag{3}$$

In equation 3. the ratio *K* can be only obtained by calculating previous assemblability value *E*. The method for estimating assembly costs rely on previous known actual costs.

2.3.3 Lucas DFA evaluation method

The Lucas method started with the cooperation between the Lucas organization and the University of Hull in the UK. The Lucas method does not focus on evaluating the assembly based on its cost effectiveness, but rather assess a design based on three ratios to describe its assemblability. This methodology evaluates a product design based on three factors: function analysis, handling/feeding analysis and fitting analysis as shown in the following figure 3

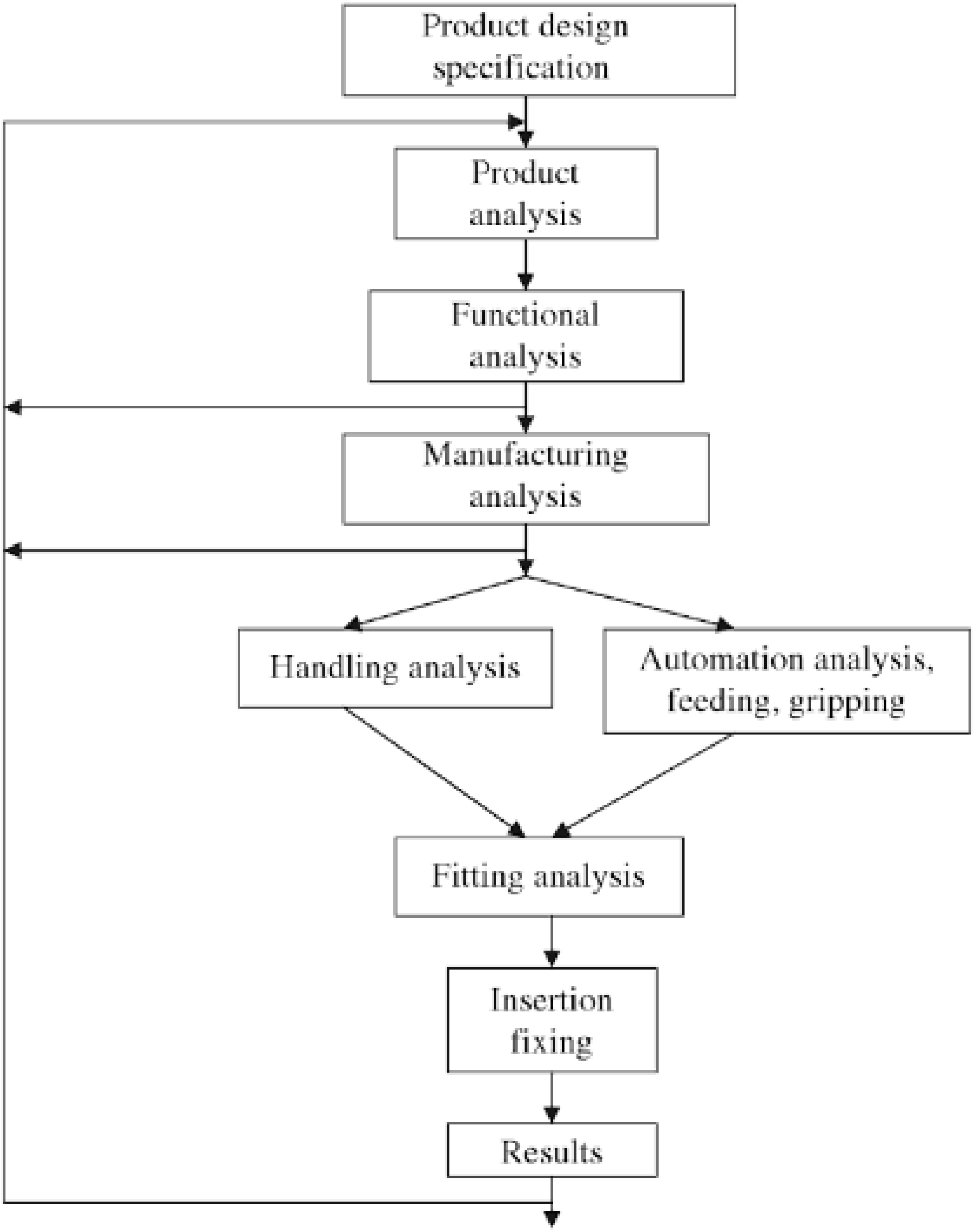

Figure 3. Assembly sequence flowchart for the Lucas DFA evaluation method (Mital et al. 2014, p.166)

The function analysis can be described as categorizing the assembly components into two categories; A parts and B parts, where A parts are parts required by the function and therefore are essential or critical to the functionality of the assembly. B parts in the other hand are not critical and their presence is mainly due to a design solution. The classification of the parts can also be achieved by the three general questions used in Boothroyd methodology to determine the criticality of a certain part.

$$E_d = \frac{100 \times n_A}{n_A + n_B} \tag{4}$$

In equation 4, The design efficiency ratio E_d can be calculated by dividing the sum of critical component n_A by the sum of all components n_A and n_B. The design efficiency ratio can be improved by decreasing the non-important part count B by eliminating or combining. A 60% ratio can be considered as a desirable target ratio.

Handling/feeding analysis helps rating the different components based on their size, weight, handling difficulties and handling orientation. Generally, handling is the term used when using manual assembly operations, while feeding is the term used for automated assembly operations. The analysis of part handling/feeding covers the nesting, getting tangled, rotational orientation, gripping difficulties and so on.

$$I_h = A + B + C + D \tag{5}$$

In equation 5, Handling index, I_h, obtained by analyzing each part of the assembly and assigning an index based on the previously mentioned criteria. The optimal index is equal to 1.5, this means that the part is easy to assemble, otherwise improvements to the design are suggested. The following table 1 presents the indices applied on weight, size, handling difficulties, orientation of assembled components and rotational orientation of components. The values of A, B, C and D are obtained from the following table as well.

Table 1. Lucas DFA method's manual handling and feeding indices mod. (Salustri & Chan 2003)

A- Size and weight (one of the following)	Convenient – Requires hands only	1.0
	Very small- Requires tools	1.5
	Large/Heavy- Requires more than one hand	1.5
	Large/Heavy requires crane of two people	3.0

Table 1 continues. Lucas DFA method's manual handling and feeding indices mod. (Salustri & Chan 2003)

B- Handling difficulties (All that apply)	No handling difficulties	0.0
	Gripping difficulties	0.2
	Sharp/abrasive	0.3
	Delicate	0.4
	Untouchable	0.5
	Sticky	0.5
	Flexible	0.6
	Severely nest	0.7
	Tangible	0.8
C- Orientation of part (one of the following)	Symmetrical -No reorientation needed	0.0
	End to end - Easy to see	0.1
	End to end – Not visible	0.5
D- Rotational orientation of part (one of the following)	Rotational symmetry	0.0
	Easy rotational orientation	0.2
	Hard rotational orientation	0.4

The handling index I_h will allow the measurement of total handling ratio R_h.

$$R_h = \frac{\sum I_h}{n_A} \tag{6}$$

In equation 6, the total handing ratio R_h is measured by dividing the total of handling indices, $\sum I_h$, by the total number of critical parts, n_A. An ideal handling/feeding ratio of 2.5 is considered an ideal ratio for an assembly.

The last part of the Lucas DFA method is performing fitting analysis of the assembled components. The fitting index can be measured as following

$$I_f = A + B + C + D + E + \mathrm{F} \tag{7}$$

In equation 7, similarly to handling indices, each component is given a fitting index, I_f, which is the sum of indices given to each part based on part placing and fastening, process/assembly direction, insertion (includes gripping, holding, moving), access/vision, alignment, and insertion force. The fitting indices for manual fitting are showing in the following table 2

Table 2. Lucas DFA method's manual fitting indices mod. (Salustri & Chan 2003)

A- Part placing and fastening (one of the following)	Self-holding orientation Self-securing Requires holding Bending Riveting Screwing	1.0 1.3 2.0 4.0 4.0 4.0
B- Process/assembly direction (one of the following)	Straight line from above Straight line from other direction Not a straight line	0.0 0.1 1.6
C- Insertion (one of the following)	Single Multiple Simultaneous multiple insertion	0.0 0.7 1.2
D- Access/Vision (one of the following)	Direct Restricted	0.0 1.5
E- Alignment (one of the following)	Easy Hard	0.0 0.7
F- Insertion force (one of the following)	No resistance resistance	0.0 0.7

The fitting index, I_f, is recommended to not exceed the value of 2.5. If it does exceed, then some changes are recommended.

$$R_f = \frac{I_f}{n_A} \qquad (8)$$

Lastly, in equation 8, a total fitting ratio, R_f, can be measured based on the sum of fitting indices from all the components, $\sum I_f$, divided by the total number of critical parts, n_A. The Lucas method, similarly as to the Hitachi method, evaluates the assembly based on summing penalty scores from the components based on these three evaluation criteria mentioned (Leaney & Wittenberg 1992). The three penalty scores can then be used to categorize the assembly and assign a design efficiency ratio, feeding/handling ratio, and fitting ratio. These ratios will express the difficulties in the assembly.

2.3.4 Fujitsu productivity evaluation system

The Fujitsu Productivity evaluation system (PES) is rather different than other DFA methods mentioned previously. The PES is more of a tool in a software package that aims to aid in designing parts with ease of manufacturing and assemble, it also focuses on cost effectiveness of designed parts. The Fujitsu PES depends heavily on previously collected data during production and it then uses them to analyze the assemblability and manufacturability of the new design. This is only possible if the designs are related and the previous parts can be reused in the new design. (Cho & Park 2014; Eskelinen & Karsikas 2013, pp.84-85)

The Fujitsu PES is based on four subsystems that aid in analyzing the new design, these four subsystems are: Assembly sequence specification subsystem, assemblability evaluation subsystem, manufacturability evaluation subsystem, and design idea and know-how reference subsystem. The following figure 4 demonstrate the relationship between these four subsystems.

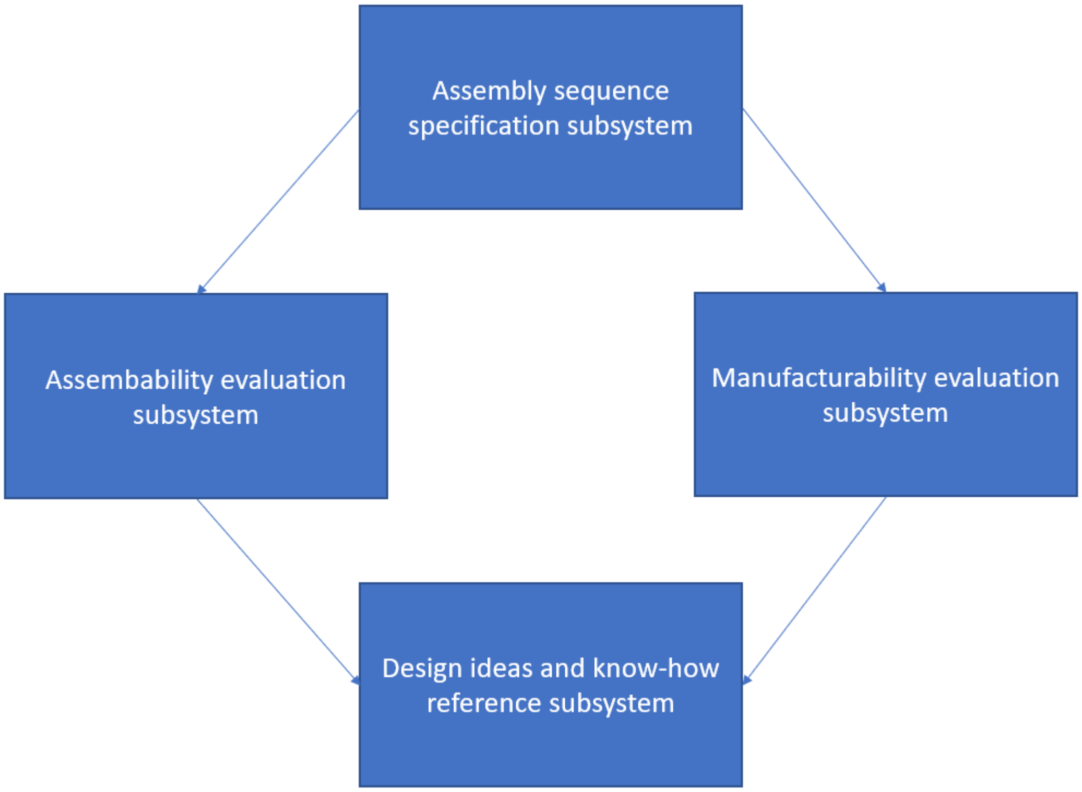

Figure 4. Fujitsu PES main principle

The assembly sequence specification subsystem utilizes previously obtained stored data and values for the assemblability and the manufacturability of certain parts. This will aid in estimating costs and assembly time. The designer is advised to use parts similar to parts from previous designs. The assemblability evaluation subsystem estimates the assembly time and easiness based on the data gathered from previous work. The handling and inserting of parts is included also in this evaluation. The designer can then identify high cost parts or processes in early stages with the aim to improve on these factors. The manufacturability evaluation subsystem is based on previous data as well, the data collected on part shape, size and different treatments can give a rough evaluation on costs. Obtaining a detailed manufacturability evaluation takes under consideration a larger number on input or data. The data used in this stage are usually different manufacturing stages, sheet metal type, tolerances, moulding, number of holes, post-processes and so on. (Bogue 2012)

The Fujitsu PES can be beneficial only if the required data from previous projects is available and well organized. The main disadvantage of this method is that it can only be implemented if the product under analysis is similar or identical to previous products of a company. This method also requires a continuous storing of data for future usage. (Bogue 2012)

2.4 Benefits of applying DFMA

DFM and DFA became popular with many companies during the 80’s (Ulrich & Eppinger 2011, p. 273) and this must be a sign that the benefits of implementing DFMA analysis in product development pay back and insure positive results. According to Eskilander (2001), there are two types of benefits from DFA; short term and long-term benefits. The short-term benefits are mainly specific product related. This include reducing part count, which will ultimately lead to many advantages. Some would say that best engineered part is no part at all, therefore, less parts means less documentation, less handling, less assembly time, less waste, and less storing (Eskilander 2001, p. 27). With fewer parts, the assembly time and lead-time would be decreased as a result. It is also good to mention that usually the manufacturing costs decreases and the quality of the product increases.

The long-term benefits gained from DFMA analyses are mainly to the organization and to the design engineers. The experience gained from systematic analysis of product will improve the know-how skills of the designers in the institution. This means that in future projects, DFMA philosophy will be implemented in early product development stages and assembly difficulties and quality problems are solved or avoided quickly. DFMA analysis also encourages cross team collaboration and helps build stronger product development teams. DFMA has proven to reduce product development time, and this allows companies to launch their new products and stay ahead of the curve. (Eskilander 2001, p. 29)

This theory part will be utilized in this research to identify a guideline for analyzing the DFMA aspects of the studied UPS units. The ratios mentioned would also be utilized to analyze and rate the UPS units. The ratios would aid evaluate the assemblability and efficiency of both assemblies.

3 FASTENING METHODS FROM DFMA PERSPECTIVE

Late design trends tend to focus on recyclable aspect of product. A design should allow disassembling and assembling of components. Selecting the right fastening methods can play a key role in achieving a higher design efficiency (Le Bacq et al. 2001). One of the most used processes in assembly is the mechanical fastening and joining processes (Shipulski 2010). It is a process where errors are easy to occur due to human error, and therefore a careful attention must be given to the design of fastening methods which could improve the assembly efficiency and time (Le Bacq et al. 2001).

Fasteners are used to connect different components together and fasteners can usually be screws, bolts, nails or rivets. In sheet metal, there are two types of joining methods; permanent and non-permanent. Under the permanent joining methods, welding and clinching are considered the most used methods in sheet metal. However, the non-permanent joining methods include all kind of mechanical fasteners for various purposes. It is important to take under consideration what are joined together, if the parts require maintenance or replacement, it is of the most importance to choose a joining method that can easily aid in assembling and disassembling of the parts. (Lempiäinen & Savolainen 2003, p. 180)

3.1 Joining methods in sheet metal

The studied assemblies in this research are mainly manufactured from sheet metal parts. This chapter will cover most common fastening methods used in sheet metal. There are two types of mechanical joining in sheet metal industry, mechanical joining without added fasteners and mechanical joining with some additional fasteners. The joining without additional fasteners relays on sheet metal forming. The joining of two or more sheet metals is achieved by deep drawing, self-piercing riveting, hemming, flanging, or clinching of the sheet metal material. These joining methods are useful in cases where thermal joining cannot be performed, these methods also have no damage to pre-coated material, and they are considered a perfect solution when working with materials hard to weld or joining different type of materials together. These methods also do no release heat nor consume high level of energy if compared to spot welding or other thermal joining method. (Timings 2008, pp. 386-390)

Hemming is the process of folding two sheet metal over each other to obtain a locked edge. The purpose of this is to reinforce the edge or to obtain a more appealing design. An example of hemming process is shown in the following figure 5

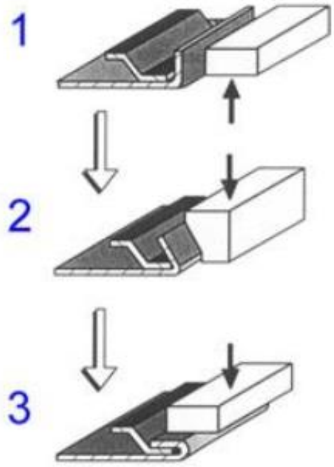

Figure 5. An example of hemming process (EAA 2015, p. 3)

Hemming is widely used joining methods in automotive industry, it can be fully automated, however, it is costly and is mainly used for large parts.

Clinching is also one of the most common joining mechanism in sheet metal industry, due to their outstanding properties. Clinching can join dissimilar material that are otherwise very hard to weld together. The joining strength of clinched joints are of characterized by good strength and vibration damping capabilities (Jagtap et al. 2017, pp. 8104-8105). The main principles in clinching is cold forming of sheet metal to obtain plastic deformation to create a joint without any external fastening elements or welds. A tool is required to perform a clinching process, the clinching tool is usually consisting of a die and a moving part to allow material flow. The clinching starts with the punch clamping the metals to be joined, then the punch draws the material into the die, and then, due to the plastic deformation of metal, the die part opens and allows the material flow and the two materials are interlocked and a joint is created. An example of clinching and clinching tool is shown in the following figure 6.

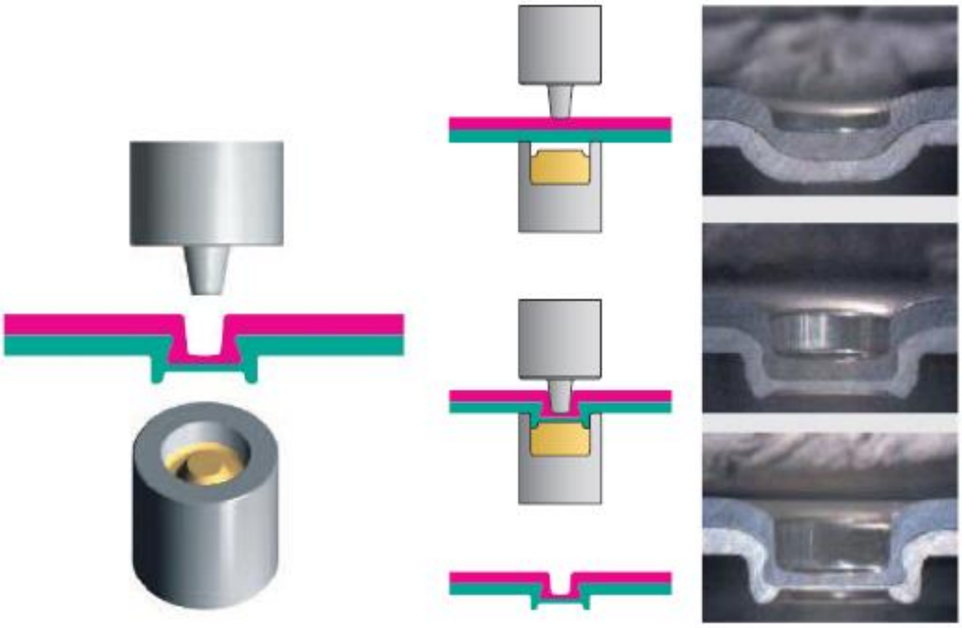

Figure 6. Clinching process and clinching tool parts (EAA 2015, p. 11)

The most common methods of mechanical joining with some additional elements in sheet metal are rivets and threaded fasteners (EAA 2015, p. 20). Riveting is mainly used when there is no need for disassemble or maintenance in later stages. Rivets provide great joining capabilities and are not affected by vibrations as badly as other threaded fasteners such as screw-nut combination, riveting force is hard to measure and is estimated to be between 650 N and 850N (Proso, Slavic & Boltezar 2015, p. 75). Rivets are also a great solution when accessibility is limited, rivets can be installed from one side only. This allows greater freedom in product design since there will be no need for space for tools and clearance. Rivets also provide higher design strength, since sheet metal are usually thin, the hole diameter used to insert rivet or screw affects the strength characteristics of the design. Rivets require a smaller hole than screw and nut combination. Blind rivets are also the fastest joining method available and can be highly automated, an automatic riveting machine can deliver up to 50 rivets per minute (Doppke 2007, p. 34). Tooling costs are also lower for rivets, since there would not be need to expensive threading tool to create the hole/thread, and inserting a rivet can be done manually or with a cheap electric or hydraulic tool. Riveting allows also the joining of dissimilar material with different mechanical properties. Rivet expand when are inserted which make them an effective repelling of water, dust, and fumes. This expansion makes them also resistant for vibration compared to screw-nut combination.

Some type of rivets can be used also with mismatched hole sizes and badly aligned holes, it is also considerably easy to insert a rivet comparing to other threader fasteners, screws must be torqued properly whereas rivets are set or not set, only a visual inspection is enough to determine whether the rivet is properly inserted or not. There are however disadvantages in using rivets as well, rivet material can be considerably weaker that the material of designed part and the strength load requirement will not be satisfactory for the rivet material, rivets are particularly weak against tension forces (Skorupa et al. 2015, p. 417). Rivets also require proper hole sizes and surface quality to perform effectively, too small hole and the inserting of rivet might be difficult, too big of a hole and the required clamping characteristics are not achieved. Also, the presence of burrs around the hole edge can cause unperfect installation, any vibration can weaken and wear the burr which will contribute to weakening the rivet joint. An example of inserting a rivet is shown in the following figure 7

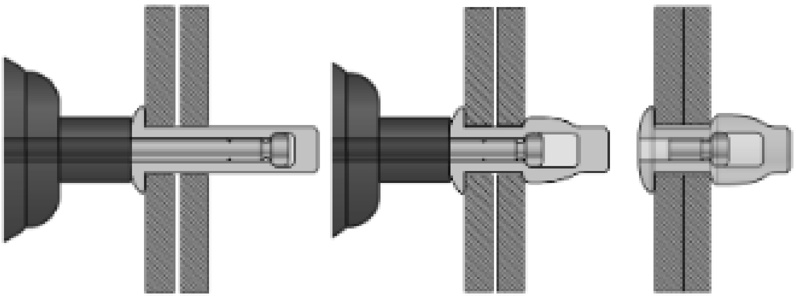

Figure 7. Installation of blind rivet (EAA 2015, p. 46)

Other joining methods with additional fasteners include screws and bolts. Screw and bolt-nut fasteners are widely used due to their large clamping force and availability worldwide (Bhattacharya, Sen & Das 2010, p. 1215). Bolted connection can be achieved by either using bolt-nut combination or by using bolts and studs connected to the sheet metal. Threaded stud are commonly used with aluminum sheet where disassembly is frequent, multiple screwing and screwing of aluminum can cause wear of the threads and ultimately failure.

The main difference between screws and bolt are that using screws is only possible when the hole is threaded whereas bolts are used mainly with nuts and studs. The following figure 8 demonstrates the difference between bolts and screws.

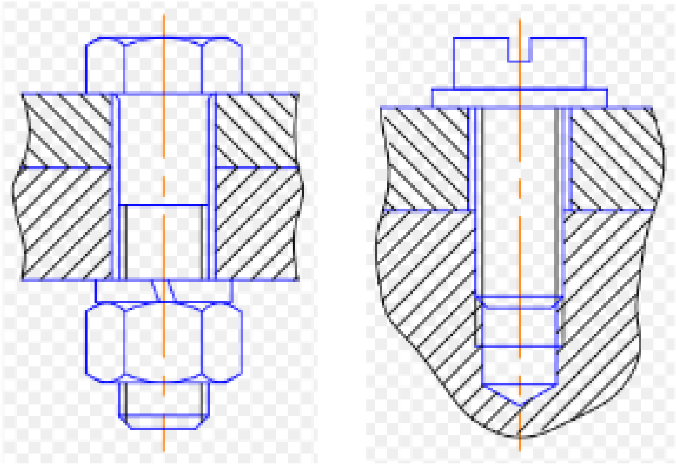

Figure 8. Difference between bolted joint (left) and screwed joint (right) (EAA 2015, p. 20)

There are however several types of screws for different application. Self-tapping screw are the type of screws that form the thread in a hole while it is screwed into it. These types of screws are only driven into pre-drilled holes and the thread is then formed without any special tool. This method is mainly used with aluminum sheet due to the softness of the material. (EAA 2015, pp. 23-25)

Studs are used particularly with thin sheets, and when a thread pitch of tapping screw is smaller than the thickness of that specific material. Studs are usually threaded, and they are either functioning as a nut or a bolt. Studs are used when high torque is required or when continuous assembling and disassembling are required. There are numerous types of studs used in the sheet metal industry. However, the main types of studs are three; press-in studs that uses pre-drilled hole, studs attached by riveting to pre-drilled holes, and self-piercing studs.

Press-in nut and bolt-inserts are pressed into pre-drilled holes by applying downwards force. The press force will deform the workpiece (sheet metal) and allow the material to flow around the grooves on an insert stud to form a strong connection and lock it. The following figure 9 demonstrates the principle for nut and bolt inserts.

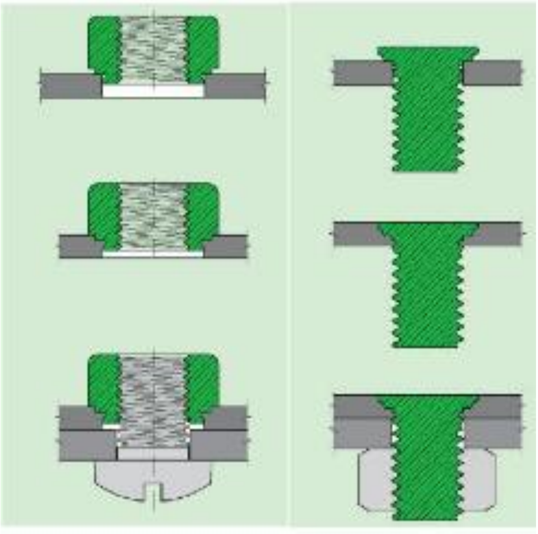

Figure 9. Press-in nut (left) and bolt (right) (EAA 2015, p. 27)

On the other hand, studs attached by riveting to pre-drilled holes can withstand loads from both sides. The deformation happens within the stud and it forms a lock around the sheet material. This type of inserts can be used with sheet thicknesses of 0.5 to 5 mm.

Self-piercing inserts are capable of piercing their own hole into the sheet metal material. This might lead to extra savings when pre-drilled holes are not required. Self-piercing inserts are first clamped into a punch and the sheet metal is placed on the die. The punch then moves down and the groves on the insert create a hole on the sheet metal, the sheet material is then deformed around the insert and creating a locked joint. The following figure 10 demonstrate the working principles of self-piercing inserts. Self-piercing insert are usually rectangle shaped because it allows more torque to be applied. (EAA 2015, p. 34)

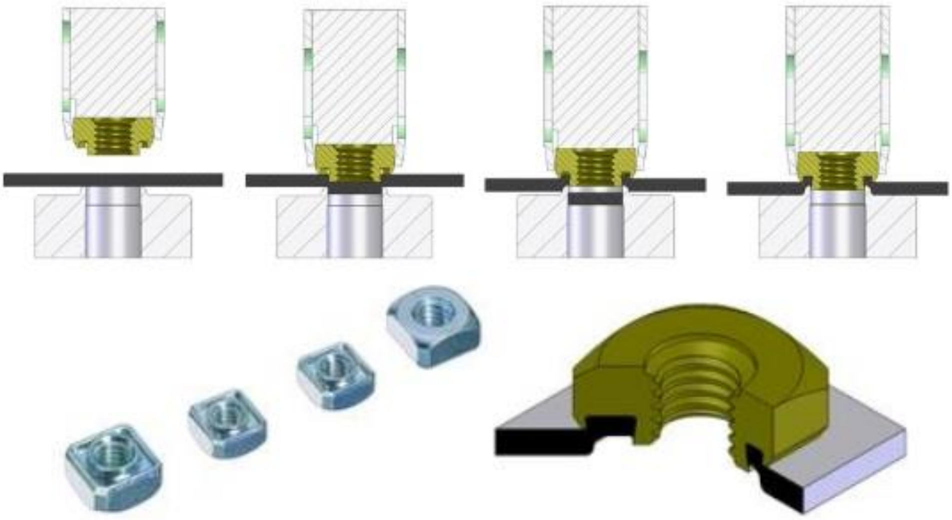

Figure 10. Installation of self-piercing insert (EAA 2015, p. 33)

Last type of inserts are blind rivet nut and bold insert. They are considered the most adaptable solution when working with thin sheet and threading is not possible due to the limited thickness. This type of inserts is also commonly used when sheet material is soft, and disassembly is required often. The use of this solution will save the sheet material from wearing. The working principle of blind rivet inserts is simple. Similarly to other type of inserts, a pre-drilled is required where the blind rivet insert will then be inserted from one side only. A pressing tool is then required to properly finish the installation. The insert is threaded onto the tool, then it is inserted to the pre-drilled hole. It is then pulled back which will deform the insert and make the strong link between the sheet and the insert, this is followed by unthreading the insert and moving the tool away from the sheet metal. The following figure 11 demonstrates the installation of a blind rivet nut and bolt inserts. The material of these inserts can be aluminum, stainless steel and steel. The material is selected according the required strength and corrosion resistance of the design. There is also different type with different features, some type split under the sheet metal and creates extra surface for achieving higher pull-out forces compared to previously mentioned blind rivet insert. Other type has better features for damping vibrations or noise. (EAA 2015, pp. 35-38)

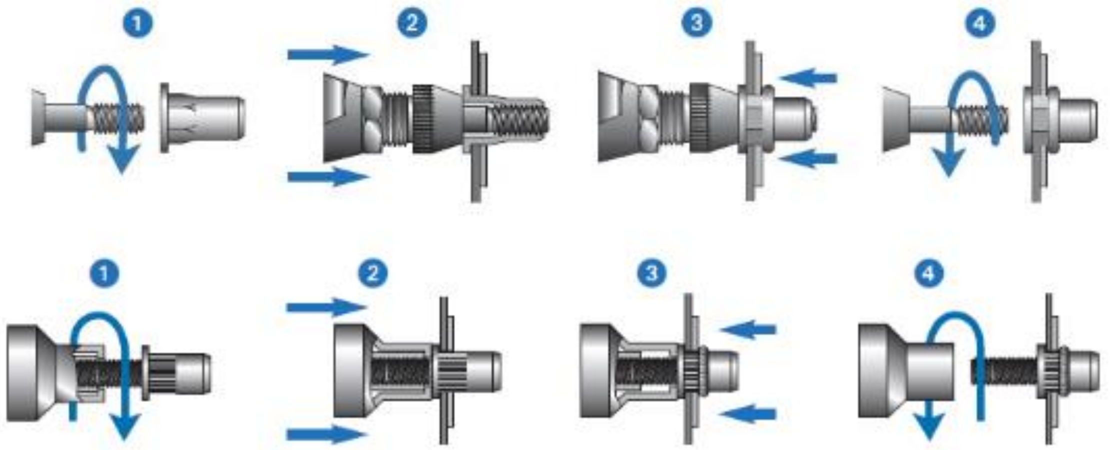

Figure 11. Installation of blind rivet insert nut (top) and bolt (down) (EAA 2015, p. 37)

Choosing the correct joining methods for a specific design depends on many factors. Each of the mentioned joining methods have specific advantages and disadvantages. The designer should recognize and select the most suitable joining methods for specific role. The joining methods mentioned in this chapter are used in the studied assemblies and are commonly used in the sheet metal industry. Thus, the recommendations at the end of the research will consider only these joining methods for easier implementation of recommended changes.

3.2 DFMA guidelines for fastening solutions

DFMA guidelines for fixing and joining can be extracted from the main guidelines for DFMA. It is advised that fasteners should be eliminated or minimized with the design solution that support this approach. The following guidelines according to Moultrie (2012) and Boothroyd (2012, p. 74) can be followed when designing joining solution according to DFMA approaches;

- The minimizing of fasteners can be achieved by choosing same type of fasteners with similar drives.
- Use standard fastening elements, this includes parts, processes and methods.
- Designing joining solution that can be inserted from only one linear direction as show in figure 12.
- Fasteners must be also away from obstructions and a clearance for tools must be considered.
- It is preferred that fasteners used only on flat surfaces

- An appropriate spacing between fasteners must be designed and not cramped in one place
- Design self-fastening features
- Design that allows one handed assembly
- Parts are supported or secured during insertion
- Minimize assembly tools
- Design chamfers to allow the ease and guided insertion of screws

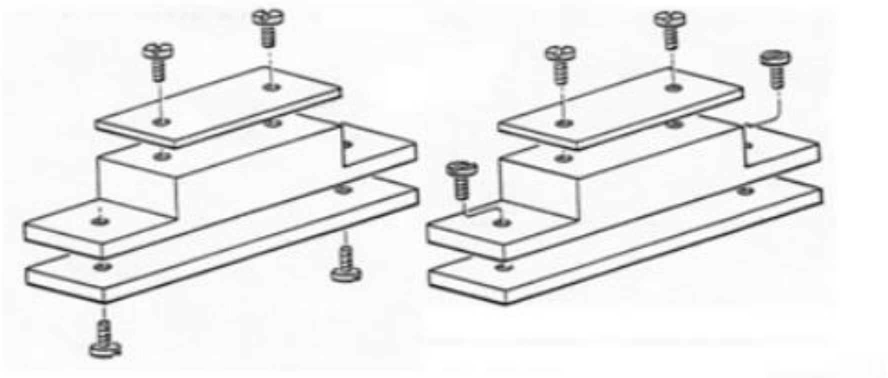

Figure 12. Example of optimized singular fastening direction (Moultrie 2012)

The drive type of screw and the number of threads have an importance in optimizing the assembly time. There is a direct connection between operation time and the type of the slot used and the number of threads in the fastener used. Boothroyd et al. (2010, p. 99) has demonstrated that Allen screw type can be inserted faster than Philips-type screws and slot-type screws. as shown in the following figure 13

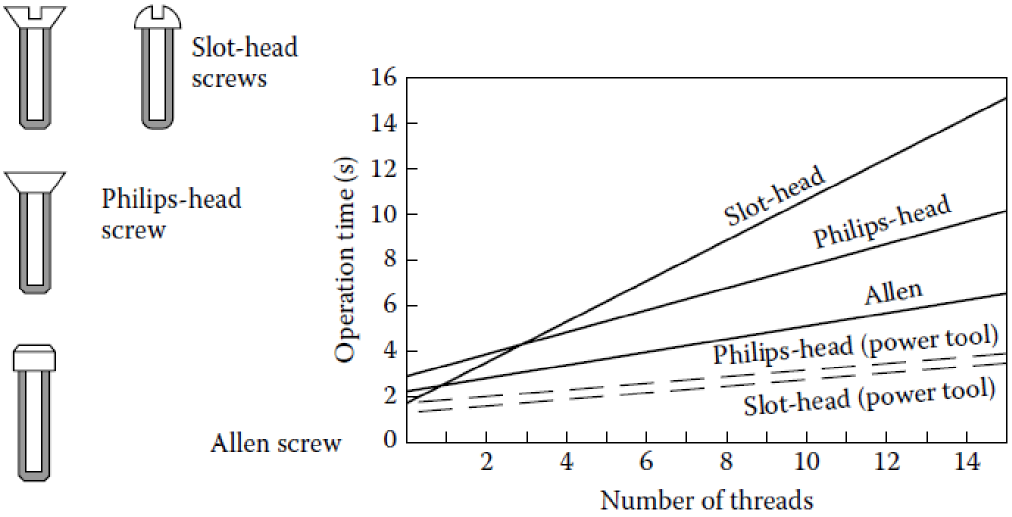

Figure 13. Effect of number of threads and screw type on assembly duration (Boothroyd et al. 2010, p. 99)

4 MECHANICAL DESIGN FEATURES OF UPS UNITS

In this thesis, two UPS units were investigated and analyzed. The units are model 93E 15-20 kVA and 93PS 8-20kW standard frame as shown in the following figure 13

Figure 14. 93PS 15-20kW (Left) 93E 15-20kVA(right)

4.1 Uninterruptible power supply

Uninterruptible power supply systems are a solution for providing continuous, clean and monitored electrical power to any sensitive output that requires continuous electrical input, such as medical support system, communication system, data storing systems, or any application deemed important. In this chapter, different UPS operation modes, the typical structure of an UPS, and the mechanical and electrical design requirement are introduced.

4.1.1 Functionality of a UPS

One of the main reasons of using UPS is protecting a sensitive device. A UPS removes surges, spikes, and other harms that can damage the output device. Also, during electrical blackouts and power interruptions, the batteries in a UPS will function as a temporary emergency power supply. According to Aamir et al. (2016) the main characteristics of UPS systems that considered when purchasing or comparing UPS systems are the following:

- Regulated output sinusoidal with low total harmonic distortion

- Irrespective in the input voltage and changes in the output
- Low response time from online mode to battery powered mode
- Low cost, small size, high efficiency and reliability

Typically, there are four operation modes available for EATON’s UPS systems. First is called double conversion mode. In this mode, the highest level of protection can be achieved since the output is isolated from the main input. The system converts electrical power from AC to DC and then back to AC, hence the name double-conversion, as shown in the following figure 14. The batteries are also in charging mode at this stage.

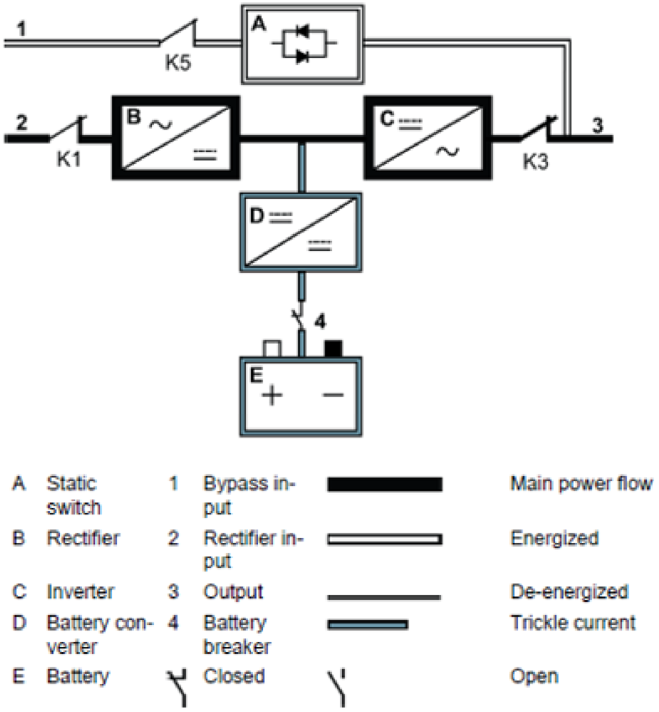

Figure 15. Double conversion mode for UPS systems (Eaton 2016, p. 20)

Second mode is called energy saver system (ESS). The UPS provides main current directly to output load through the static bypass if input current is within safe levels. The system switches to double conversion mode within 2ms if any interruptions are detected. The following figure 16 demonstrate the current path in ESS mode.

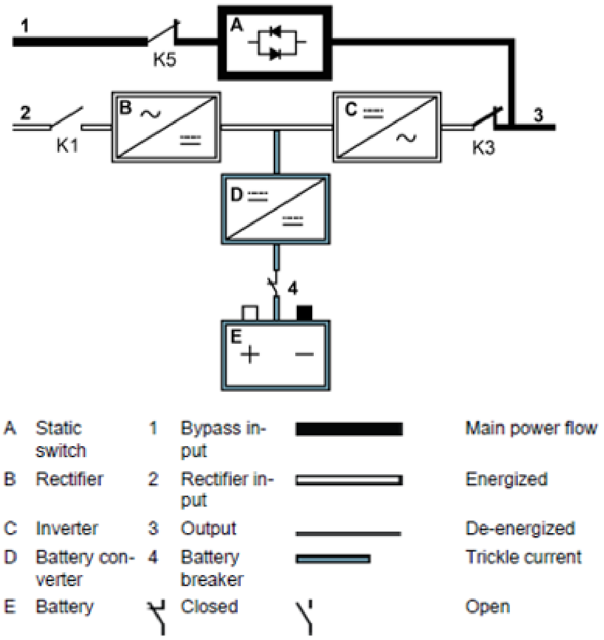

Figure 16. Current path in ESS mode (Eaton 2016, p. 22)

Third operation mode is called stored energy mode or battery mode. The UPS will run on stored energy mode if any utility power outage has occurred. In this mode, the UPS batteries are providing emergency DC current which is converted to AC by an inverter. The following figure 17 represents the current path during battery mode

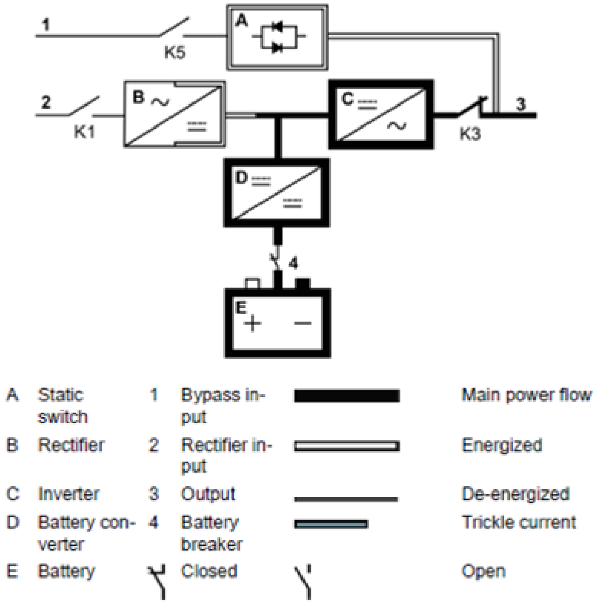

Figure 17. Current path in battery mode (Eaton 2016, p. 24)

The fourth and last operation mode is called bypass mode. This operation mode is activated if internal failure, overload, or load fault are detected. The UPS can also be maintained during this operation mode without interrupting the power supply to output load. The current is delivered directly from the input source to the output load. The following figure 18 demonstrates the current path during bypass operation mode.

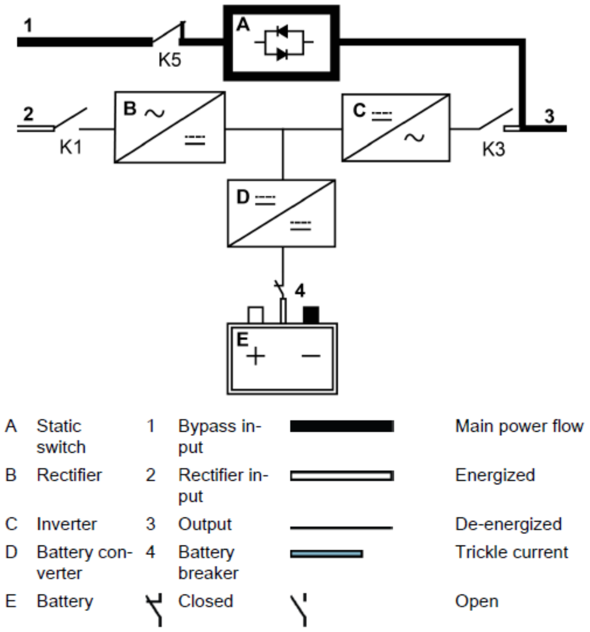

Figure 18. Current path during bypass mode (Eaton 2016, p. 26)

4.1.2 Structure of a UPS

A UPS unit is usually built from a single standing cabinet. The cabinet is shielded to prevent dangerous level of voltage outside of the enclosure. Inside the cabinet is a centralized static bypass, it is chosen according to the desired performance level of the UPS. In the 93PS and 93E models, the available static bypass ratings are 20 kW and 40 kW.

The output power of Eaton’s UPS units is determined by the uninterruptible power module (UPM). The UPS for 93PS are ranging from 8 kW to 40 kW. A UPM contains an inverter, a rectifier, battery converter, and independent control. Additionally, a UPS consists of a body frame and internal batteries. The frame of 93PS and 93E are made from galvanized steel sheet metal. The following figures 19 and 20 show the location of battery housing compartment and the UPM compartment module in 93PS model and in 93E model respectively.

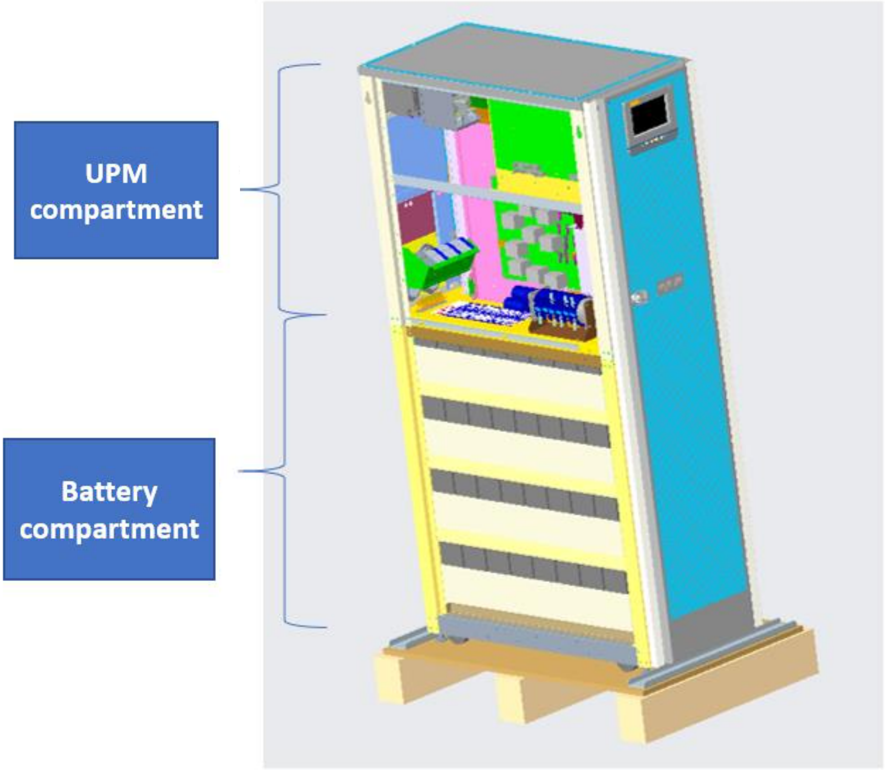

Figure 19. The location of UPM and battery compartment in the 93PS model

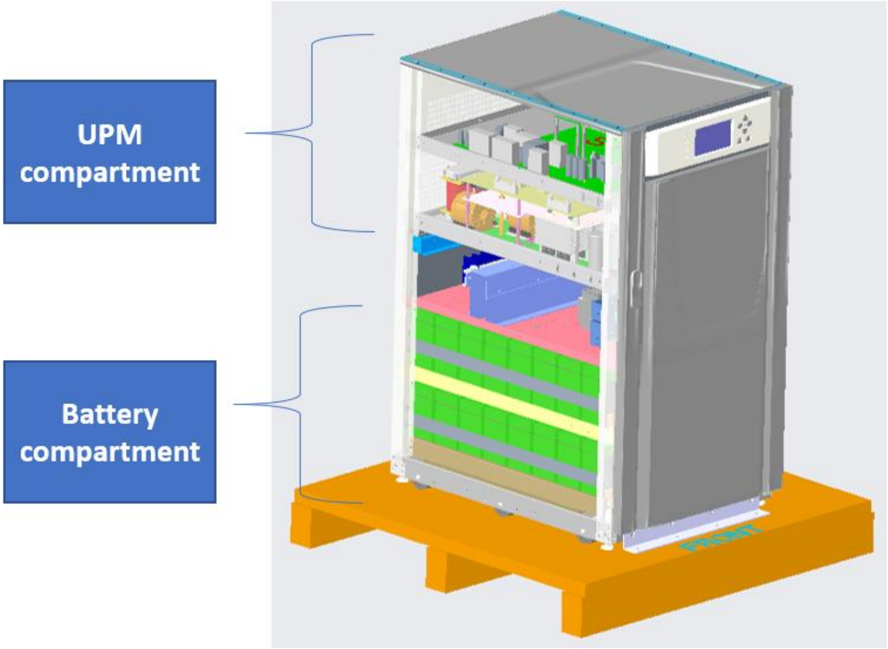

Figure 20. The location of UPM and battery compartment in the 93E model

The 93PS and 93E models were disassembled at the laboratory of power electronics in order to gain a better understanding on the structure and components of both UPS models. A team of experts from the applied electronics department of the Lappeenranta university of technology were guiding, consulting and explaining in a detailed manner about the power electronics components used in the two UPS models. Furthermore, the 3D models of both models were studied to determine the count and type of different fastening components used. The following tables 3 and 4 list the number and type of fasteners used in both models.

Table 3. Fastening components used in 93E 20-40kw

Name	Types	Quantity
Bolt part	4	50
Nut part	5	69
Screw part	22	434
Spacer	6	30
washer	6	95
Rivet	1	15

Table 4. Fastening components used in 93PS 20-40kw

Name	Types	Quantity
Bolt part	0	0
Nut part	6	61
Screw part	35	625
Spacer	4	18
washer	9	52
Rivet	6	116

UPS goes under a maintenance program, and according the interviews with representatives from the company, several parts are changed according to a periodic maintenance schedule. The changed parts are air filters, air fans, and batteries when they have reached their end of usable life.

4.1.3 Manufacturing and assembly stages

Both models are manufactured and assembled by Eaton. However, the model 93E is manufactured, assembled, tested and packaged completely in China and sold particularly to the South-east Asian market. It has however found its way to other markets due to its lower cost compared to the 93PS model.

The 93PS is assembled tested and packaged in Finland. However, the UPM unit is assembled and manufactured in China and is then connected to the battery housing compartment in Finland.

4.2 Integration of mechanical and electrical requirements

The design of a UPS unit is regulated by the following IEC standards: IEC 60950-1 and IEC 62040-1. These standards contain electrical and mechanical requirements that must be followed in the design stage of UPS units.

4.2.1 Electrical requirements

A UPS unit construction should be designed in a matter that eliminates the risk of having a contact of bare parts at hazardous voltages and that an adequate isolation is provided for parts and wiring in operator access areas. Test finger, test pin and test prob are used to inspect that no bare parts can be accessed from openings in the enclosure after the removal of parts that can be removed by the operator. The battery compartment requires a door that can be opened with use of tool. Bare parts at hazardous voltage must be guarded and isolated to prevent unintentional contact during service operation. The wiring must be designed in a way that eliminate sharp edges to reduce the risk of failure. Holes must be smooth edged in order to protect wires from getting damaged. Wires must also be fastened securely, and the risk of disconnected wires must be eliminated. Screws used to fasten parts that require electrical pressure must engage at least two complete threads (IEC 60950-1 2005, pp. 65-148)

4.2.2 Mechanical requirements

A UPS unit must cover both the stability and the mechanical strength requirements listed in the standards. A UPS unit must stay physically stable to allow an operator to work safely, it must not fall over when angled to a 10° angle from its upright position. It also should withstand a force of 250 N applied from any direction to the unit at a maximum height of 2m without falling. It is required that a UPS's mechanical strength endures handling in normal use and it must not create hazardous situations for the operator. All components and parts, except the enclosure parts, must endure a force of 10 N. Parts protected by a door or a cover must withstand a steady force of 30 N. External enclosures must resist a force up to 250 N for five seconds on the sides and top of the enclosure. The force is applied with a suitable test tool that has a circular plane with a diameter of 30 mm. (IEC 60950-1 2005, p. 170)

An impact test is performed on the external surface of a UPS unit. A steel ball with a diameter of 50 mm and a mass of 500 g is dropped from a height of 1.3 m to the horizontal and side surfaces of the external enclose as shown in the figure 21.

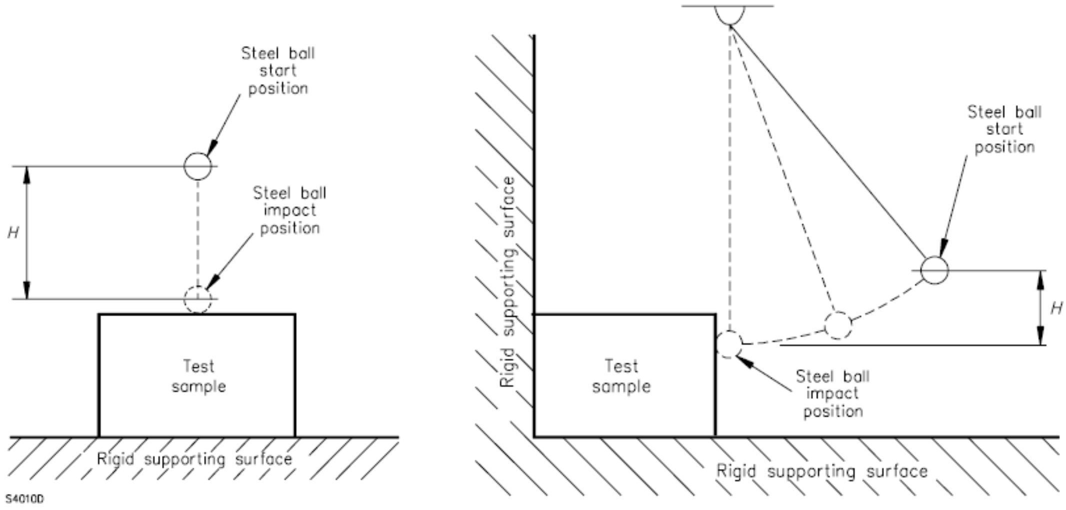

Figure 21. Impact test with a steel ball (IEC 60950-1 2005, p. 172)

The design of a UPS unit must not contain sharp edges and corners. It is required that they are rounded or smoothed to eliminate the risk of cutting of operator's hand. Fastening components must withstand normal use and not get loose that would create a hazard. Openings in the enclosure of a UPS unit should be designed in a way that prevents the fall of foreign parts inside the UPS. Openings also should not exceed 5mm in any dimension. (IEC 60950-1 2005, p. 194)

In this chapter, mechanical design features of the studied UPS units are mentioned, and they are considered in the analysis of mechanical joining methods from DFMA perspectives. The suitability of the suggested improvements is covered under these mechanical and electrical design rules and requirements.

5 DFMA ANALYSIS OF FASTENING SOLUTIONS

The Lucas methodology was chosen as the main DFMA guideline in this research. The Boothroyd method requires assembly time for each component, and this information is unavailable since the assembly is performed in multiple places. Some sub-assemblies come ready assembled from subcontractors, the UPM for the 93PS model comes assembled from China and the total assembly time given by the company consists of assembly time as labor, testing, and packaging time. Therefore, a concreate outcomes cannot be obtained with this data. However, the Lucas method will allow a systematic analysis of each part which will lead to calculating four key ratios to determine the efficiency evaluation of the joining process.

5.1 DFMA analysis for the 93PS model

It was observed that the design of 93PS is much more efficient compared to the design of the model 93E. The model 93PS had less dissimilar sheet metal parts, fewer joining components compared to the 93E model. However, it was noticed that there are numerous unnecessary joining methods and components used throughout the unit, which could be decreased in order to achieve higher assembly efficiency, the assembly efficiency is then compared using the key ratios used in the next chapters. To simplify the analysis of joining components, the UPS will be divided in four areas of focus; main frame, door, UPM, and outer covers.

5.1.1 Main frame of 93PS model

The main frame of the 93PS model as, shown in the following figure is housing the batteries and is attached to the UPM module, the door and the outer covers.

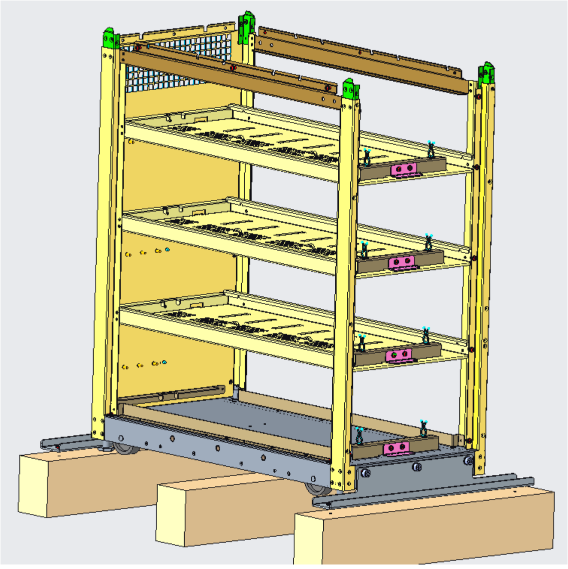

Figure 22. Battery housing frame of the 93PS model

The criticality of components and joining methods are demonstrated in the following table 5. The criticality of components as described in chapter 2.3.1 and a component can be identified as a critical component if the mentioned requirements are met.

Table 5. critical and joining components used in battery frame of 93PS model

Part name	Quantity	Criticality	Joining methods	Joining components
Left front pillar	1	A	5 methods (3 types of rivets and 2 types of screws	27
Right front pillar	1	A	5 methods (3 types of rivets and 2 types of screws	29
Plate 93pm 10-20kw battery module top beam	2	A	3 methods (1 type of rivet, 1 type of screw, and 1 type of insert nut	10
Battery shelf	3	A	1 type of rivet	9

Table 5 continues. critical and joining components used in battery frame of 93PS model

Part name	Quantity	Criticality	Joining methods	Joining components
Pillar end	4	B	2 (1 type of rivet and 1 type of screw	2 pcs with 5 components 2 pcs with 4 components
Plate 93ps-20 bm rear	1	A	6 (3 types of rivets, 2 type of screws, 1 type of insert nut)	45
Battery side support	2	B	1 type of rivet	6
Plate 93ps-20 bm bottom	1	A	3 types (2 types of nut insert and 1 type pf rivets)	36
Plate 93pm 10-20kw bottom battery fastening	1	B	1 type of rivets	3
Plate 93ps-20 battery fastening	4	B	1 type of screw	2
Plate 93pm 10-20 kw battery fastening bracket	4	B	1 type of screw	2
Plate 93ps-20 base wheel frame	2	A	1 type of rivet	8
Plate 93pm 10-20kw transport support	2	A	2 (1 type of washer and 1 type of bolt)	18

The total number of different joining methods are seven and they are shown in the following table 6

Table 6. List of joining methods used in battery compartment

Joining technology/method	Name	Tools required
Rivet	RIVET CONTRSUNK HEAD d3.2 THK 1.6-3.2	Rivet gun
Rivet	RIVET CUP HEAD d4.8/D10.1 THK 1.6-6.8 Fe Cr	Rivet gun
Rivet	RIVET CUP HEAD d3.2/D6.4 THK 1.6-3.2	Rivet gun
Cross-head screw (Pozidriv)	M8 X 18 SCKT HD CAP SCR	Cross drive
Torx-head screw	SCREW FLA-TX M4x10 DIN965 8.8 BLACK	Torx-drive
Hex-head bolt	M8 X 18 SCKT HD CAP SCR (HEX)	Hex-drive
Washer	WASHE SPRING M8 Fe DIN127B R1	Hand insertion

The design efficiency, E_d, can be measure using equation and the value for E_d in the main frame can be measured as 46%

5.1.2 93PS door

The following table 7 lists the number of components used in the door sub-assembly of the 93PS model

Table 7. List of components used in the sub-assembly of the door

Part name	Quantity	Criticality	Joining methods	Joining components
Plate 93ps-20 door	1	A	2 (1 type pf screw and 1 type of rivet	20
Plate 93ps-20 door side r	1	A	1 type of screw	6
Plate 93ps-20 door side l	1	A	1 type of screw	6
Plate 93ps-20 filter retainer	2	A	1 type of screw	2
Plate 93ps door hinge	2	B	1 type of screw	2

Table 7 continues. List of components used in the sub-assembly of the door

Part name	Quantity	Criticality	Joining methods	Joining components
Display screen	1	A	1 type of Philips screw	4
Filter 93ps-20 door	1	A	1 type of clip retainer	4
Door hinge fixing	1	B	1 type of screw	2

There are four different joining methods used in door assembly. A list of the methods is shown in the following table

Table 8. Joining methods used in door sub-assembly

Joining technology/method	Name	Tools required
Torx-head screw	SCREW FLA-Tx M4x10 BLACK DIN7500-M	Torx-drive
Rivet	RIVET CUP HEAD d3.2/D6.4 THK 1.6-3.2	Rivet gun
Philip-head screw		Philips drive
Clip retainer	WIRE FORM 93PM 10-20KW DOOR FILTER RETAINER	Hand insertion

5.1.3 UPM of 93PS model

A bill of material for the UPM was not available for analysis. However, from the 3D models the fastening types was possible to be listed. The following table 9 lists the main joining components and methods used in the UPM

Table 9. Joining methods used in the UPM

Joining technology/method	Name	Tools required
Rivet	Rivet-32-flat	Rivet gun
Rivet	Rivet-32-2	Rivet gun

Table 9 continues. Joining methods used in the UPM

Joining technology/method	Name	Tools required
Screw	SCREW & WASHER M4*10 TRUSS CROSS ZN	Philips-drive
Insert nut	Nut-040-138	Insert tool
Insert nut	Nut-050-138	Insert tool
Nut	NUT M4 HEXAGON(HEX)TEETH	Wrench/socket
Insert nut	NUT-040-077	Insert tool
Insert bolt	STUD-KOALA-M4-6	Insert tool
Insert bolt	STUD-050-120	Insert tool
Insert nut	130105159-004	Insert tool
Insert nut	130105159-014	Insert tool
Insert stud	STUD-040-100	Insert tool
Standoff	040-712-180	Insert tool
Screw	SCREW WASHER+SPRING WASHER M3*8 HEX ZN	Philips drive
Insert stud	STUD-040-080	Insert tool
Standoff	Standoff-for-receptacle-board	Insert tool

5.1.4 Outer covers of 93PS model

The following table 10 lists the parts used in joining the outer covers to the main frame.

Table 2. joining components used for the outer covers of the 93PS model

Part name	Quantity	Criticality	Joining methods	Joining components
Battery module dead front	1	A	1 type of screw	10
Side cover plate	2	A	3 types of screw	19
Top cover plate	1	A	1 type pf screw	12

Three joining methods are used in the outer cover sub-assembly and they are listed in the following table 11.

Table 11. Joining methods used for the outer cover of 93PS

Joining technology/method	Name	Tools required
Torx-head screw	SCREW FLA-TX M4x10 DIN965 8.8 BLACK	Torx-drive
Philips-head screw	SCREW & WASHER M4*10 TRUSS CROSS ZN	Philips-drive
Nut-insert	NUT CAPTIVE PRESS-IN M4	

5.2 DFMA analysis for the 93E model

Similarly to the 93PS model, the 93E was analyzed based on four categories; main frame, door, UPM, and outer covers

5.2.1 Main frame of 93E

The frame of the 93E model is analyzed and design efficiency is measured based on design ratio equation. The following figure 23 presents the frame used for this model.

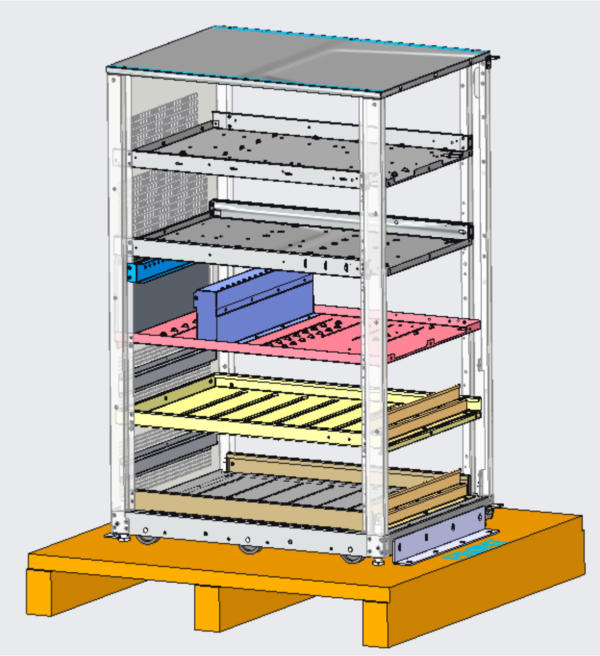

Figure 23. Main frame of the 93E model

The following table 12 lists the parts and their criticality, joining methods used for each part, and joining components used in the assembly of the main frame.

Table 12. List of parts used for the main frame of 93E model

Part name	Quantity	Criticality	Joining methods	Joining components
Support plate (emea-l 20k) 1352l Eaton	1	A	2	6
Support plate (emea-r 20k) 1352l Eaton	1	A	2	8
Support plate (sts 20k) 1352l Eaton	1	A	3	16
Slide (emea 20-40k) 1352l Eaton	2	B	2	5
Support plate	1	A	1	14
Support plate. (for batt,20-40k new) 1352s etn	1	A	1	15

Table 12 continues. List of parts used for the main frame of 93E model

Part name	Quantity	Criticality	Joining methods	Joining components
Bracket (bat 20-40k) 1352l eaton	2	B	1	8
Rear cover (emea 20k) 1342 etn	1	A	3	15
Bracket (ground 20-40k) 1342 etn	1	A	3	12
Support plate (emea base) 1352l eaton	1	A	6	50
Rear panel (emea 20k) 1352l eaton	1	B	1	6
Bracket (tb 20-40k) 1342 etn	1	B	3	12
Bracket (tb 20-40k) 1342 etn	1	B	2	8
Bracket (switch 20k) 1352l eaton	1	A	1	6
Not listed (battery back support)	2	B	1	6
Battery.keep plate(front) 1352s etn	2	B	1	3
Support plate (upm emea) 1352l eaton	1	A	2	6
Front panel (bat 20k) 1342 etn	1	A	1	14

5.2.2 Door of 93E model

The following table 13 lists the components used in the sub-assembly of the door.

Table 13. list of components and joining methods used in door sub-assembly of the 93E model

Part name	Quantity	Criticality	Joining methods	Joining components
Front panel 1	1	A	4	6
Front panel 2	1	B	4	18

5.2.3 UPM of 93E model

The main joining components and methods used in the UPM are listed in the following table 14.

Table 14. Joining methods used in the UPM

Joining technology/method	Name	Tools required
screw	Screw & washer M4*10 Truss cross ZN	Philips-drive
Nut	Nut M5 hex blue ZN conical spring washer	Wrench
Nut	Nut M4 hex ZN conical spring washer	Wrench
Snap-fit	Plastic snap-fit insert	Insert tool
Rivet	Rivet	Rivet gun
screw	Screw M3*6 flat NI	Philips-drive

5.2.4 Outer cover of 93E model

The outer covers are attached to the frame by 32 bolts and the joining type and tool required are listed in the following table

Table 15. Joining methods and tool required for attaching the outer covers for the 93E model

Joining technology/method	Name	Tools required
Bolt	Bolt 8*12 M5*0.8	Wrench/socket

All required information to further analyze the studied units are listed in these tables in this chapter. Firstly, it is important to recognize critical and non-critical components since this can aid in decreasing the total number of components used in both assemblies. Non- critical components can be designed to be integrated or eliminated completely if possible. Secondly, different fastening methods and components were listed which can aid in identifying similar type of fastening components that can be replaced or decreased in order to achieve the desired results. The results from these tables are also used in identifying the key ratio that would allow us to compare and rate different assemblies based on their joining efficiency.

6 RESULTS

Based on the previous analysis of the assemblies, an evaluation for the joining efficiency will be measured based on these three key ratios. The total number of components is considering only the sheet metal parts and not any electrical parts.

$$A1 = \frac{Number\ of\ different\ kind\ of\ joining\ components}{Total\ number\ of\ compoents}$$

$$B1 = \frac{Number\ of\ different\ kind\ of\ joining\ compoennts}{number\ of\ different\ joining\ technologies\ or\ methods}$$

$$C1 = \frac{Number\ of\ special\ tools}{Total\ number\ of\ components}$$

It was noticed that the assembly of the 93PS model requires seven different tools, consists of 77 sheet metal part, 693 joining component, and 44 different type of joining method. The 93E model requires six different tools, consists of 47 sheet metal part, 872 joining components, and 60 different type of joining methods. The following table 16 lists the joining efficiency ratios of both 93Ps and 93E models.

Table 16. Joining efficiency ratios

	A1 (lower the better)	B1 (higher the better)	C1 (lower the better)
93PS	693/77= 9	693/44 = 15.75	7/77 = 0.09
93E	872/47= 18.55	872/60 = 14.53	6/47= 0.12

6.1 DFMA observations of joining components.

The high number of different joining components and methods used in the design of both UPS units is an indication that there is an area of improvement. The main observation considering the 93PS model was on the number of used fasteners to connect the battery compartment with the UPM. Two types of screws are needed to connect the UPM and the battery compartment. The number of different joining methods is also apparent in the following figure 24 where five different joining methods are used in a small area.

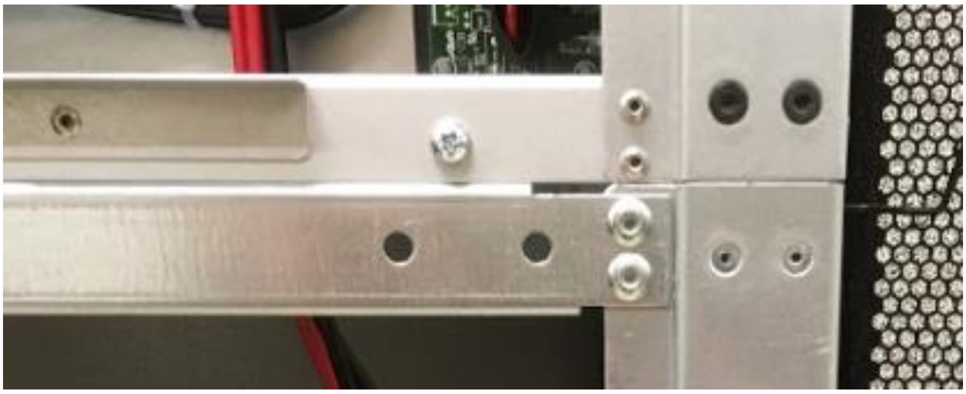

Figure 24. Four different joining methods used to connect UPM and battery compartment in 93PS model

The inserting direction of screws in the 93PS model is made convenient and easy for the assembly worker, no big differences in insertion direction was noted. In the UPM sub-assembly, some parts were assembled with uneasy direction of screw insertion, the direction was from inside to outside, which is not an ergonomic position for the assembly worker.

The 93E model had much more areas that can be improved. Most of the sheet metal plates used to house the power electronics were mounted on top of screws. Some plates were connected to the main frame with three different types of screws in a very small area as shown in the following figure 25.

Figure 25. Three type of screws and multiple insertion direction of screws used in 93E model

It was also noticed that the plates did not contain any self-aligning features for easier assembly. Plates did not have any mounting features that aid in supporting the plates on the frame parts while the assembly worker is inserting the fasteners. The direction of screw insertion was varying a lot as shown in the previous figure 25.

6.2 Improvement suggestions

Based on the DFMA analysis for the joining methods of both models. The following improvements are suggested. A detailed list of suggestions is included as appendix 1.

6.2.1 Suggestion for the 93E

The improvement suggestions for the 93E are listen in the following table with rating according to easy-hard to apply and low-high impact on improvement the efficiency of joining methods

Table 17. General suggestion for 93E model

93E	Easy to apply	Difficult to apply
Low impact	• Replace all type of screws with Torx screws for best efficiency • Replace bolt and nuts used for attaching air flow flaps with snap-fit fasteners	• Optimize the positioning of electrical components to improve wiring
High impact	• Use rivets to affix frame parts • Use rivets for joining parts that are not meant for disassembly and maintenance.	• Design changes to the support plates used for housing the electrical components with self-supporting features (slot that can be inserted to the rear cover) • Design the supporting pillars with feature to hold the plate while assembling

6.2.2 Suggestion for 93PS

The improvement suggestions for the 93PS are listen in the following table with rating according to easy-hard to apply and low-high impact on improvement the efficiency of joining methods

Table 18. General suggestion for 93PS model

93PS	Easy to apply	Difficult to apply
Low impact	• Replace all type of screws with Torx screws for best efficiency	• Optimize the positioning of electrical components to improve wiring
High impact	• Replace threaded fasteners with rivets in the UPM unit for parts that are not needed maintenance • The insertion direction of several fasteners used in the UPM can be improved for better accessibility	• Replace fastening methods used for PCBs with snap-fit fasteners if possible

6.3 New joining efficiency ratio based on the suggestion

The fastening efficiency ratio should be improved by implementing the suggestions for the fastening methods and components. It is advised that the value A1 and C1 are minimized and the ratio B1 is maximized. It is also important to improve the design efficiency, and this can be achieved by eliminating the non-critical parts B by means of combining and merging. This will ultimately decrease the number of fasteners required even more. An accurate estimation of fastening efficiency ratio cannot be obtained due to the number of factors affecting the type and number of fasteners used.

7 DISCUSSION

The DFMA analysis of joining components of both models allowed the recognition of possible improvements in future models. By recognizing the criticality of assembly components and analyzing used fastening solutions, a list of suggestions was generated to be used when designing future models. Additionally, the key ratio to measure the efficiency of joining solutions can be used as a tool to evaluate different models.

7.1 Comparison and connection to former research

There are plenty of researches on the topic of DFMA from a general perspective. Most of the researches aim to provide general guidelines on implementing DFMA philosophy in product design. This research however aimed to provide guideline for only the fastening components and methods used in a product design.

7.2 Reliability and validity analysis

The observations and notes were made in collaboration with other research group members. This insures that results are considered from different viewpoints. The part considered in this research are mechanical parts used in both models. This does not include the electrical components that come pre-assembled like the display screen or the power electronics components. The design changes might not reduce the costs of single parts, but it would improve the assembly and disassembly of the products which will lead ultimately to improved maintenance capabilities.

7.3 Sensitivity analysis

Due to the large number of fasteners used in both models, the expected results from the suggested changes are towards minimizing assembly time and costs. The fastening efficiency ratio can also be utilized on other UPS models to evaluate them against each other.

7.4 Key findings

The key findings in this research are recognizing the possible areas where improvements can be achieved in order to improve the fastening efficiency of the assemblies. Key ratios will aid in evaluating different fastening solutions and evaluate fastening efficiency between different models. Moreover, the guidelines will give a direction to be followed when designing future products.

7.5 Novelty values, Generalization and utilization of the results

This research provides the target company with specific and general guidelines that could be utilized to improve the design of the studied models, or as guidelines to be used in designing a new product in the future. The guidelines mentioned in this research will aid the designers to focus on making a product that follows DFMA methodology which will ultimately lead a product that is easy to assemble, manufacture, and perform maintenance on. These guidelines are focused on improving and optimizing the fastening solution.

7.6 Recommendations for further studies

Further studies should be conducted on the UPM unit. This includes optimization of PCB positioning and wiring used within a UPS unit. It was mentioned during meetings with Eaton’s representatives that wiring takes a large part of assembly time. It was also noticed during the analysis of the two models that improvements on the maintenance of the devices can be achieved. The static switch fan for the 93PS model requires 49 parts to be disassembled in order to get access to the fan. More recommended research includes improvements on product data management (PDM) system, it was noticed that many parts were missing in the bill of materials (BOM) and some identical screws used in both models had different part name/number.

8 SUMMERY

This thesis was part of research project for Eaton with collaboration with Lappeenranta University of Technology. The research was divided on studying the modularity, sheet metal design from a DFMA prospective, and fastening method design from DFMA perspective. The two models studied in this research were Eaton’s 93PS and 93E UPS units.

A systematic DFMA analysis of a product design can shed the light on improvement opportunities. In this research, the DFMA analysis of the joining methods used in the two studied models proved that there is an opportunity of improvements to achieve better assemblability of the UPS units. With a systematic DFMA analysis, the areas of improvements can be recognized, and this provided a clear idea of what must be changed. In this research multiple suggestions were given to improve the DFMA aspects of both models. The DFMA analysis also allowed the recognition of critical key ratios that allow the comparison and evaluation of old and new designs. The key ratios mentioned in this thesis can indicate a direction of possible improvements that need to be implemented in order to increase the assemblability of the devices. The efficiency of joining was measured by the key ratios mentioned in the discussion chapter and the main key aspects of these ratios include the number of special tools, number of different joining methods, and total number of joining components.

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APPENDIX I.1

Suggestion for 93E

- Usage of rivets to affix the frame parts. There is no need to disassemble the frame parts in normal usage or for maintenance and therefore using rivets (blind rivets) for joining these parts can be the most reasonable solution to decrease assembly time.
- Using rivets can also be a modular solution for affixing the frame parts throughout different UPS models
- The support plates and 373-55875 are mounted on top of screws or studs to aid the assembly worker while attaching these plates to the correspondent support frame. This can be improved by designing these mentioned support plates with geometries that can be inserted into slots on the rear cover 373-55871.
- The usage of rivets will replace 11 pcs M5 holes with 11 pcs 5mm holes for support plate 373-56210
- The sliding rack 373-45197 can be eliminated from the assembly as it does not appear to have a reasonable function in the assembly.
- Support frame 373-56202 will be attached directly to the frame, this requires adding 12 pcs 5mm holes.
- Replacing 7 pcs M5 holes with 7 pcs 5mm holes for the support plate 373-55875
- Replacing 11 pcs M5 holes with 11 pcs 5mm holes for the support plate 373-56300. Also adding a bend at the back side near the rear cover to function as a support plate for the battery sub-assembly. This results in eliminating part 373-55362 (battery support plate) and 6 pcs 3.3 mm flush rivets
- For the support plates 373-56206 and 373-56207, replacing 6 pcs M5 threaded holes with 6*5mm holes for connecting the 4 support plates with blind rivets. Removal of self-clinching nut M6 used in connecting parts 373-56197 and 373-56210. Removal of M4 Pin that holds the upper support plate 373-56210
- For the rear cover 373-55871, Removal of 2 pcs 5.5 threaded holes. Removal of 2 pcs 5 mm threaded holes. Replacing 4 pcs M5 holes with 4 pcs 5mm holes.
- For the two brackets 373-56213, replacing 4 pcs M5 threaded holes with 4 pcs 5mm holes and use blind rivets instead of M5 screws for attaching these 2 brackets with the rear cover and the 2 support plates 373-56206 and 373-56207 in each bracket.

APPENDIX I.2

- Using rivets for joining components that are not meant to be disassembled in later stages, such as bracket 373-55876, bracket 373-56189, and bracket 373-55874. This will improve the direction of assembly and access for the assembly worker. This will lead to replacing 8 pcs M5 threaded holes with 8 pcs 5mm holes used for riveting.
- Optimize the positioning of electrical components and their wiring. Excessive use of zip ties was observed in this model.
- Modularize the fixation method of PCBs on the supporting plates. Using snap-fit fasteners for assembling PCBs.
- Replace all type of screws with Torx screws for better efficiency
- Replace nuts and bolts with snap-fit fasteners for attaching air flow flaps.

Suggestions for 93PS

- The battery housing frame appear to be optimized since it has undergone a previous DFMA analysis.
- The components used to hold the battery rack can be replaced. The sub-assembly of part P-157001549 and P-157001438
- The assembly direction of the screws used for the attaching the terminal support 373-G14083 to the frame of the electronic module can be changed or replaced by rivets.
- Replacing threaded fasteners with riveting in the UPM for parts that do not require later changing or maintenance
- Use snap-fit fasteners for fastening PCBs
- Replace all Philips with Torx headed screws for better efficiency