LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
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POSSIBILITY TO UTILIZE MODULARITY FOR POWER ELECTRONIC CABINET ASSEMBLY

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Supervisors: D. Sc. (Tech.) Harri Eskelinen & D. Sc. (Tech.) Pertti Silventoinen

TIIVISTELMÄ

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LUT School of Energy Systems
LUT Kone

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Possibility to utilize modularity for power electronic cabinet assembly

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Tämän diplomityön tarkoitus on tutkia ja analysoida kahden olemassa olevan UPS laitteen koteloiden modulaarisuutta ja rakennetta valmistus- ja kokoonpanoystävällisen suunnittelun keinoin. Tutkittavat laitteet on valittu Eaton Power Quality Oy:n UPS laiteperheen kahdesta eri sarjasta. Laitteiden suunnittelufilosofiat ovat olleet hyvin erilaiset.

Teoriaosassa kerrotaan UPS laitteiden toiminta ja laitteille standardeissa asetetut vaatimukset. Kirjallisuudesta löytyviä valmistus- ja kokoonpanoystävällisen suunnittelun keinoja, modulaarisuuden määritelmiä ja tavoitteita sekä menetelmien haasteita käydään läpi.

Tutkimusosassa esitellään lukijalle tuotteiden nykyisistä rakenteista tehtyjä havaintoja, sekä vaihtoehtoisia ratkaisuja kotelon rakenteeseen ja geometrioihin. Laitteiden rakenteen huomattiin poikkeavan toisistaan huomattavasti. Teoriaosioon pohjautuvat parannusehdotukset esitetään tekstin, kuvien, taulukoiden ja piirustusten avulla.

Tutkimuksen pohjalta Eaton Power Quality Oy:llä on tulevaisuudessa mahdollisuus kehittää ja yhtenäistää laitekoteloiden suunnitteluperusteita ja rakenneratkaisuja. Esitellyillä keinoilla on mahdollista saavuttaa säästöjä laitteiden valmistuksen kokonaiskustannuksissa.

ABSTRACT

Lappeenranta University of Technology
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Possibility to utilize modularity for power electronic cabinet assembly

Master's thesis

2019

73 pages, 42 figures, 14 tables and 7 appendices

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Keywords: modularity, DFMA, standardization, cabinet, housing

The aim of this thesis is to study and analyze two existing cabinet assemblies of UPS devices in terms of modularity and design for manufacture and assembly aspects. Studied products were selected from two product lines of UPS devices offered by Eaton Power Quality Oy. The design philosophies of the two products are very different.

Requirements set in standards and the basic operation of UPS are explained in theory part of the thesis. Literature review explores design for manufacture and assembly aspects, definition and goals of modularity and challenges of these methods.

Research part introduces observations made about the construction of the studied devices and alternative designs for cabinets' structure and geometries. Construction of the devices was noted to differ significantly. Proposals for improving the design are given in form of text, figures, tables and drawings.

Based on the research Eaton Power Quality Oy has the possibility to develop and unify the design basis and construction of electronic cabinet assemblies in the future. It is possible to reduce overall production costs with means introduced.

ACKNOWLEDGEMENTS

This master’s thesis is done for Eaton Power Quality Oy. The goal of the work is to give ideas and ways to simplify power electronic devices mechanical frame design.

I would like to thank Lappeenranta technical university and Eaton Power Quality Oy for the opportunity to finalize my studies. I would also like to thank my supervisors Harri Eskelinen and Pertti Silventoinen, as well as Juha Kuuluvainen for providing expert guidance about Eaton UPS products.

Timo Hakuli

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TABLE OF CONTENTS

Appendix VIII: Part integration 93PS

LIST OF SYMBOLS AND ABBREVIATIONS

3D	Three-dimensional
AC	Alternating Current
CAD	Computer Aided Design
DC	Direct Current
DFA	Design for Assembly
DFM	Design for Manufacture
DFMA	Design for Manufacture and Assembly
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
LUT	Lappeenranta University of Technology
PDM	Product Data Management
PLM	Product Lifecycle Management
UPS	Uninterruptible Power Supply
VRLA	Valve-Regulated Lead-Acid

1 INTRODUCTION

The cabinet of a UPS device has multiple functions, for example it acts as frame where electrical components are attached, it filters electromagnetic interference (EMI), it is used to protect operator from touching hazardous components and it holds the products exterior feature. Despite of this the cabinet design can be seen to be regarded as an inferior task to electrical design, and thus have less resources available.

1.1 Background

This research is done for Eaton Power Quality Oy in collaboration with Lappeenranta University of Technology (LUT). The idea for the study came from observations done about the mechanical components of power electronic devices. Product development and design in power electronics can be seen to be driven by functionality and performance of electronic components rather than aspects of design for assembly (DFA).

1.2 Objective and scope

The objective of this thesis is to evaluate existing uninterruptible power supply (UPS) assembly variants in terms of modularity and product family thinking using DFA analysis. Ways to simplify actual assembly and assembly procedures, thus reducing manufacturing and assembly costs are sought out in this research. Simplified design should also make servicing the devices easier and cheaper. Other “design for”- philosophies include design for manufacture (DFM), design for manufacture and assembly (DFMA), combination of above mentioned, among others (Eastman, 1996, p.1-3).

Performance demands of electronics in UPS devices makes functional modularity possible. Customization of electronic features of the device by client is possible to certain preset options. This thesis focuses on modularity and DFA aspects of mechanical components of the UPS assembly variants. Modularity can be seen as repeating geometries/dimensions, functional modules or assembly or manufacturing procedures. All three of these modularity types are considered to be positive features. Based on the results of DFA analysis, proposals for solutions to increase the modularity will be given. The results can be utilized to improve the design of whole range of similar products in the future.

How modularity is present in such power electronic devices?
What kind of modular solutions can be integrated to assembly?
What kind of modular structures make assembly procedures easier and faster?
Ways to improve modularity in different product series?

1.3 Research methods

Base for the research will triangulation; DFMA-questionnaires help determine critical components and assemblies, standards (IEC 60529, IEC 62040-1, IEC 62040-2 IEC 62040-3 and IEC 62477-1) and literature will give boundary conditions for new design. Comprehensive information of the products provided by Eaton give the basis for analyzes. Comparing existing design and new design done using three-dimensional (3D) computer aided design (CAD) software will show improvements in design. Virtual modeling and study of existing 3D models is done with help of SolidWorks software. Illustration of triangulation used is shown in figure 1.

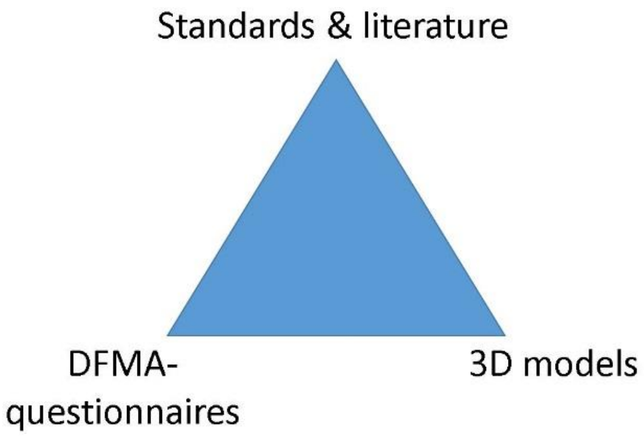


Figure 1. Triangulation between standards & literature, DFMA-questionnaires and 3D models.

2 UNINTERRUPTIBLE POWER SUPPLY DEVICES

Uninterruptible power supplies (UPS) are used to protect vital loads, such as medical equipment in hospitals, computer systems and telecommunications systems, by functioning as power supply in case of power outage. UPS devices also provide necessary power conditioning for sensitive equipment against disturbances in the power supply from the power grid. (Bekiarov & Emadi, 2002, p.597)

The power supply is connected to the input of the UPS system, a rectifier turns alternating current (AC) to direct current (DC), which is used to power the inverter and charge the batteries. Inverter turns the DC back to AC and feeds the load that is connected to output of the UPS. A bypass, also known as static switch can be used when quality of power feed from the grid is good enough so that the power conditioning is not needed. (Bekiarov & Emadi, 2002, p.598) Principal of UPS device is shown in block diagram in figure 2 below.

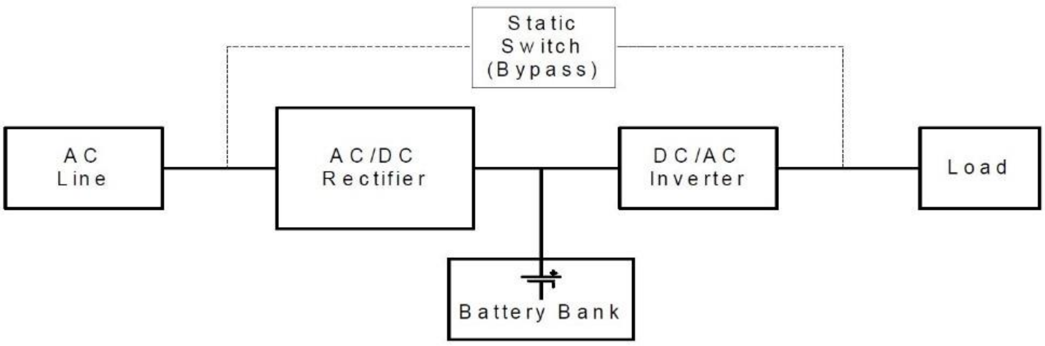


Figure 2. Typical UPS block diagram (Bekiarov & Emadi, 2002, p.598)

2.1 Requirements and constraints for UPS devices

There are number of different constrains and requirements set up for UPS devices by standards, for example set levels of allowed electromagnetic interference, cooling requirements, electrical safety requirements and mechanical requirements, which all have to be taken into account when considering design changes. On top of aforementioned, there may be additional regional requirements concerning UPS devices that also have to be met.

Standard IEC 62040-3 (2011, p.26) states normal operating conditions for UPS devices, temperature range is set from 0°C to 40°C and air humidity range is from 20% to 80%, condensation may not occur. Normal operating altitude is considered to be below 1000m above sea level. There are no requirements for splash proofing as the devices are designed to operate indoors, in a dry environment.

2.1.1 Electromagnetic compatibility requirements

Electromagnetic compatibility requirements of UPS devices are stated in standard IEC 62040-2, permitted levels of electromagnetic interference emitted by device, capability to stand external electromagnetic interference, testing methods and performance criteria are covered by the standard. In other words, the device must not electromagnetically disturb other equipment in its operating environment and device must endure electromagnetic interference occurring in its operating environment. Cabinet of the UPS device itself provides the barrier against EMI, the efficiency of this barrier is evaluated during testing. The electrical connections through the cabinet walls are pathways for interference to get in and out, which can be suppressed with filtering components integrated to electrical cables and in some cases to electrical connections. (IEC 62040-2, p.7-22)

2.1.2 Electrical safety requirements

Electrical safety requirements set to UPS devises are stated in standards IEC 62040-1 and IEC 62477-1. Standard IEC 62040-1 refers to safety requirements specified for UPS devices and IEC 62477-1 to general safety requirements power electronic converter systems and equipment.

There are limitations set about access to device internals when all access doors are sealed, the operator must be protected from hazardous parts of the machine. Testing is done by inserting test finger (shown in figure 3) through possible openings, contact between hazardous parts and test equipment is not allowed. (IEC 62477-1, p.59-60)

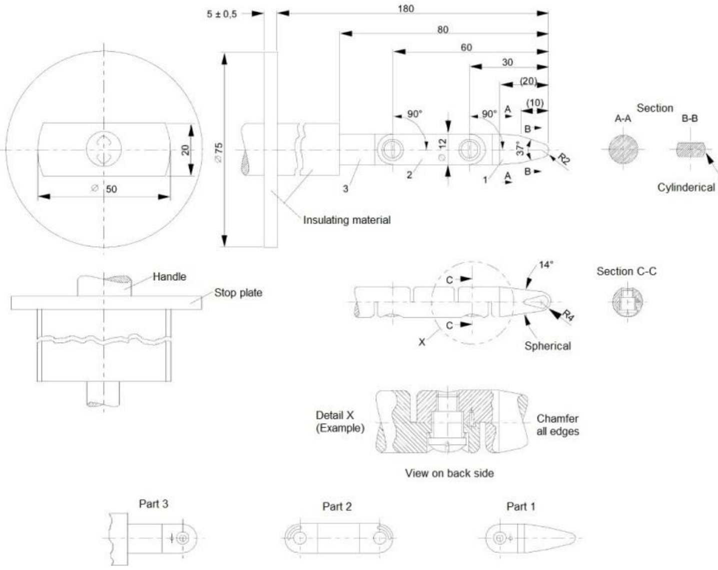


Figure 3. Test finger (adaption IEC 60529 p.33)

2.1.3 Cooling and venting of the device

Cooling solutions such as fans have been dimensioned according to operating environment temperatures. When making changes in the design of the UPS components and cabinet, sufficient air flow for cooling must be ensured. Cross sections of cooling air passages have to have certain area to provide enough air flow to cool components and not to be altered when making changes.

Standard IEC 62040-1 (2017, p.27) states requirements for ventilation of device with batteries inside. The battery compartment ventilation must be sufficient enough, so that risk of pressure or dangerous gas mixture buildup is reduced. Usually battery compartments are insulated from the rest of the device, as the battery compartment vents need to be at certain distance from any possibly arc-generating elements.

2.1.4 Mechanical requirements

According to IEC 62477-1 (2012, p.76) “Enclosures shall be suitable for use in their intended environments”. This leaves the responsibility of specifying the devices intended operating environment and designing the device accordingly to the manufacturer. Conditions during transportation are one aspect that has to be taken into account when designing the enclosure, the cabinet must be rigid enough to provide adequate protection for the electronics.

Under normal operating conditions the device must remain its physical stability and may not post any danger to operating or maintenance personnel by becoming physically unstable (IEC 62477-1, 2012, p.80).

The device may not fall over if tilted to 10 degrees from upright position. Device that is placed on floor may not fall over if a force of 20% of total weight of device, however not more than 250N, is applied on the device in any direction (except upwards) and below 2m of height. (IEC 62477-1, 2012, p. 87)

To prevent hazards to operating and maintenance personnel in normal operation, the structure of the cabinet must have sufficient mechanical rigidity. Standard IEC 62477-1 (2012, p.85-88) gives testing methods for mechanical rigidity:

1. Cabinet outer parts must endure force of constant force of 250N ±10N for 5second time. The force is applied by testing tool with a 30mm diameter contact area. For devices with mass of above 18kg, the force is applied from above and from each side.
2. Parts of cabinet that are accessible to operator but protected with a door or hatch, that fulfills requirements set above, must withstand 30N ±3N for time of 5seconds. The force is applied with test finger shown in figure 3.
3. Component and parts that are not considered part of the cabinet structure have to withstand constant force of 10N ±1N.
4. Cabinets external surfaces must pass impact test. A smooth solid steel ball with a diameter of 50mm and mass of 500g ±25g is dropped from height of 1,3m on horizontal surfaces. A pendulum impact test is done on vertical surfaces, same dimension steel ball is hung from a string and swung from 1,3m vertical height to vertical surfaces. See figure 4. The pendulum impact test can be replaced by drop impact test by turning the device 90degrees around horizontal axis.

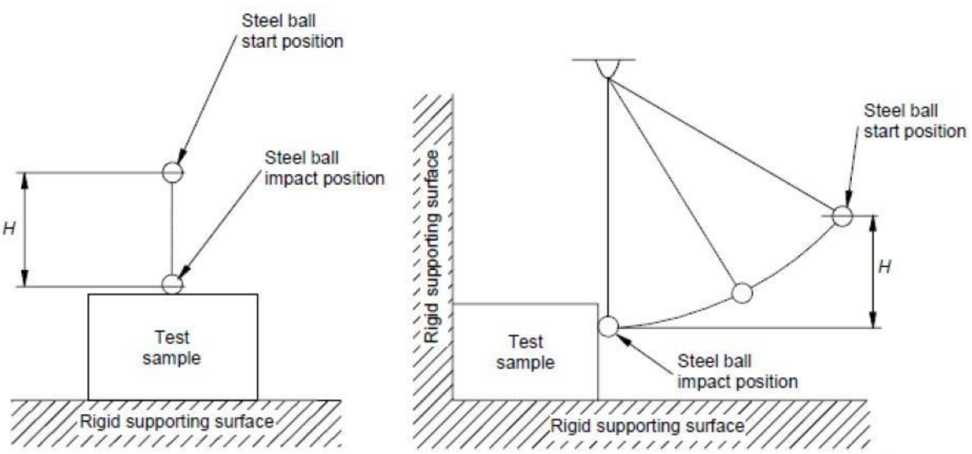


Figure 4. Impact test with a steel ball (adaption IEC 62477-1, p.86)

Handles and handgrips must be securely fastened and may not come loose in normal use. (IEC 62477-1, 2012, p.88)

2.1.5 Integration of mechanical and electrical requirements

Safety requirements for uninterruptible power systems are given in standards IEC 62477-1 and IEC 62040-1, as standard IEC 62040-2 states electromagnetic compatibility requirements for the devices. Some of the given mechanical design requirements are directly tied to electrical requirements and vice versa. Standard gives instructions and guides design work, for example minimum distances between energized parts and frame, size and type of electrical connections, protective earth specification and insulation of energized parts. Requirements that affect the design of the cabinets mechanical aspects are listed below.

To reduce the possibility of electrical wire mechanical damage, the paths of electrical wires must be smooth with no sharp edges. Hole edges on metal parts, where wires pass through, must be sufficiently rounded or equipped with bushing. Fixtures for adequate securing of wires must be provided. (IEC 62040-1 p.124)

Any of the devices parts that can be touched must not exceed set temperature limits, this may dictate placement of certain components. (IEC 62477-1 p.66-67)

Standards state requirements to cabinet design for containing possible leakages from batteries inside the device and coatings against leaked substances if valve-regulated lead-acid (VRLA) batteries are not used. (IEC 62040-1, p.27)

A fire enclosure is needed for example if any of the products circuits are connected directly to mains or at time of failure any components temperature rises to the point of inflammation. Requirements for fire enclosures, given in standard IEC 62477-1, state for example size and placement of openings, enclosure materials and material thicknesses. These restrictions opening sizes and placement on top and sides of the device must render unlikely for any object to fall through and coming in contact with hazardous elements and thus creating a fire hazard. In addition to leakages from batteries, the bottom part of the cabinet has to contain flaming or molten material in case of fire. As can be seen the requirements for fire enclosure affect for example the design of openings for cooling and ventilation. (IEC 62477-1, 2012, p.62-65)

Standards give the boundary conditions for improvement of product modularity, they dictate which changes are possible and which are not. Standards set the mechanical, electrical, cooling and safety conditions that device has to meet.

3 DFMA AND MODULARITY

In this chapter the main literature findings, the base for the research work is presented. The basics of DFA, DFM and DFMA, as well as modularity, are discussed. The challenges of implementing these methods are also considered.

Even though this thesis concentrates in DFA aspects of product design, it is essential also to consider DFM aspects in unison. A product can be designed to be easy to assemble, but parts for it can be difficult to manufacture, or vice versa. Therefore both DFM and DFA aspects are examined in this chapter.

3.1 Design for Manufacturing and Assembly

There are number of "design for"-philosophies, one of them being DFA, which means that the product is designed to be easy and cost-effective to assemble. DFM means designing is done with easy and cost-effective to manufacturing in mind. DFMA philosophy combines DFA philosophy with DFM. (Boothroyd, Dewhurst & Knight, 2002, p.1)

Basic principle of design for manufacturing and assembly is to make the manufacturing and assembly stages easier to carry out. Design decision which lead to expensive and hard to manufacture components and products can be avoided by introducing information about manufacturing and assembly processes available to design team. Some of the means for achieving these goals are virtual modeling and interdisciplinary product teams. (Eskelinen & Karsikas, 2013, p.7-8)

When applying "design for"-philosophies, for example selecting construction materials and designing geometries of parts, it is crucial to make sure that products functional requirements are fulfilled, see figure 5.

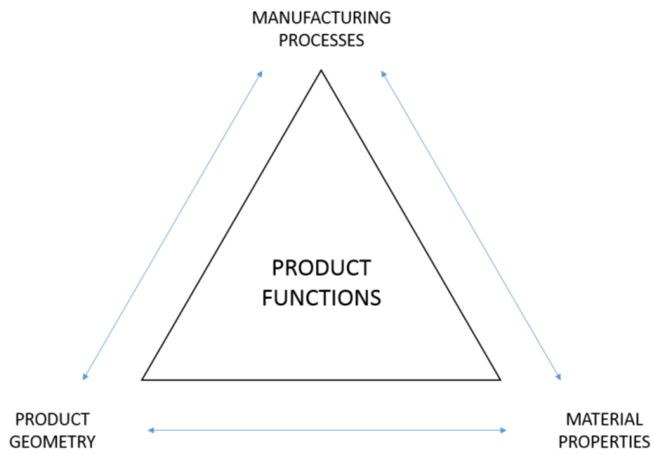


Figure 5. Products functional requirement (adaption Eskelinen & Karsikas, 2013, p.7)

Goals of DFMA are usually considered to be improving integration between design, manufacturing and also service, faster development time of product with lower cost, improvement of product quality and reliability, shorter lead time, increase in productivity, easier maintenance and quicker response to customer wishes and requirements. Consideration of DFMA aspects should be done during design phases of the product, not afterwards. According to DFMA guidelines, the designing stage could be considered to be the first manufacturing stage of product. One of the basic principles of DFMA is that designer has to ensure, not only the functionality of the product, but also the ease of manufacture and assembly with intended methods. (Eskelinen & Karsikas, 2013, p.9)

The separation of design and manufacturing stages can be seen to result from designer neglecting to notice manufacturing modules of construction when concentrating only on functional modules by utilizing standardization and modular constructions. Production equipment improvements usually lead to changes in product design; the manufacturing methods are often stated by production equipment capabilities, not by the demands of the product. Company organization rarely encourages towards cross-technical approach; teamwork between design, manufacturing and business departments from the beginning of the product development process should be promoted. It is possible that the organization is spread around the globe, so it is difficult to setup co-operation between design and manufacturing when they are done in different regions. Designers might have too little information about manufacturing methods and practices in the region of manufacturing. The designed product could be very expensive to manufacture, or might not be possible to manufacture at all. The finished product itself can be marketed and sold around the world. (Eskelinen & Karsikas, 2013 p.9-10).

Studies have proven that as high as 80% of final product costs are determined during design stage. The cost of making a change in design will increase in magnitude when progressing further from design stage. The cost of change after design stage is done, but manufacturing has not started, is 10 times greater than in design stage. When product has entered manufacturing stage, cost of design change is 100 times greater than during design stage. If design change has to be done after product launch has taken place and customers have purchased the product, the cost will be 1000 times greater than during design stage (Hidahl, 2002 p.69, Boothroyd et al., 2002 p.5).

3.2 Reduce costs applying DFMA/DFA guidelines

There are number of guidelines and rules to minimizing manufacturing and assembly costs. DFMA/DFA aspects relating to modularization and standardization will be presented in this section.

3.2.1 Cost of parts

In most cases, the cost of procured parts will make up most substantial part of the total manufacturing cost of a highly engineered product. With the use of design rules to steer design process, the total cost of parts can be reduced. (Siva, 2017, p.1558-1559, Ulrich & Eppinger, 1995 p.191)

Cost of some parts can be high due to lack of knowledge about manufacturing process among designers, the capabilities and constrains are not known. For example, unreasonably tight tolerances may be assigned for dimensions, without realizing the difficulty of manufacturing with such accuracy. It is also possible that the features which increase the cost of part are not needed for the part to fulfill its function. The designer must be aware of difficult operations in production, and their cost drivers, to be able to avoid unnecessary costly manufacturing stages. Sometimes to help designers stay in the normal capability range of manufacturing process a set of constrains, also known as design rules, can be set. These constrains can be, for example allowable material types, preferred material thicknesses, minimum slot widths and maximum part dimensions. (Ulrich & Eppinger, 1995 p.191-192)

The unit cost of a part will decrease as production volume increases. Increase of production volume will also increase the quality and performance of the part in most cases, as manufacturer is able to improve the design and manufacturing process. The advantages of higher part volumes can be accomplished via the use of standard components. Standard components are parts that are used in various products throughout product series or product families. Standardization can be done in company or by external supplier that offers the part to several firms. (Ulrich & Eppinger, 1995 p.193-194, Bootroyd & at al., 2002 p.88)

Standardized and modular repeating geometric features such as dimensions of fillets and chamfers as well as hole diameters should be used as much as possible when designing product geometry, as this reduces the number of manufacturing tools needed. Selection of design features should be guided by standard tool geometries; standard tools cost less and are readily available. (Eskelinen & Karsikas, 2013 p.12-13)

3.2.2 Cost of assembly

Usually products assembly costs represent only a fraction of the total cost, still reducing costs in assembly stages produces substantial indirect advantages. Along with reduced part count and complexity, also support costs are reduced when applying DFA philosophy. (Ulrich & Eppinger, 1995 p.195, Lohtander & Varis, 2012, p.84)

According to Lohtander and Varis (2012, p.84-85), to keep manufacturing costs of a product as low as possible, companies operate in "global distributed manufacturing environment". This means that product development and design can be done one part of the globe, as manufacturing may happen across the world; a common mode of operation for Eaton Corporation. This leads to situation where it is possible that design team and manufacturing unit do not understand each other that well. Available materials, common manufacturing methods and standards may also vary depending on region.

Product construction simplifying is one of the main design concentrations emphasized by DFA. Simplifying can be done by minimizing part count, fastener count and number of reorientations. Use of multifunctional parts and modular assemblies can lead to desired simple constructions. There are three yes/no questions for recognizing critical parts from non-critical parts when conducting part elimination process for simplifying an assembly:

(1) Is the part required to move in relation to other parts?
(2) Is the part required to be manufactured of a different material or to be isolated from other parts in construction?
(3) Does the part enable assembly and disassembly procedures?

Function of examined part can be integrated to another existing part if answer to all three questions is no. Special care must be taken that new multifunctional parts created in the process are not too complex and thus expensive to manufacture. This is when DFM aspects have to be considered and DFA is expanded to DFMA. (Boothroyd, Dewhurst & Knight, 2002, p.1-4, Hidahl, 2002, p.71, Eskelinen & Karsikas 2013, p.85).

Parts produced by part integration may contain many of the geometric features of the parts combined and can generally be complex. This said, the increase of features on manufactured part usually increases manufacturing cost only slightly. In case of integrated part, the control of critical geometric features can be done in the manufacturing stage instead of assembly stage. There are cases where part integration is not advisable as it may bring about costly manufacturing stages for the component, for example machining of internals of hollow cast part. Thus part integration should be considered case by case. (Ulrich & Eppinger, 1995 p.196-197 & 253)

Reducing number of parts in construction leads to increased reliability, fewer defects, reduced cycle time and lower costs in configuration management, manufacturing, assembly and inventory. (Hidahl, 2002, p.71)

The ease of part insertion and attachment will make a great impact on assembly time; there can be large difference in time that takes assemble two similar products with same amount of parts. The geometry and required insertion path of a part will affect the time to grasp, orient and secure the part. (Ulrich & Eppinger, 1995 p.197-198)

Bootroyd, Dewhurst and Knight (2002, p.93-96) and Eskelinen and Karsikas (2013, p.87-92) give ways to ease assembly functions:

- Assembly order should be progressive and self-guiding when possible
- Favor self-aligning geometries. Insertion should be easy and have little or no resistance, chamfers to guide insertion preferred. Sufficient clearance should also be provided.
- Assembly in one main direction, gravity helps when parts or subassemblies are inserted form above.
- Avoid mid assembly reorientation of product in fixture.
- Minimize different tool count used in assembly.
- Use fasteners that need orientation as little as possible; avoid screw joining, favor snap fitting. Fastening procedures in order of increasing assembly cost:
    - Snap fitting
    - Bending
    - Riveting
    - Screw fastening.
- Part or subassembly insertion in single linear motion, avoid long insertion distances.
- Avoid geometries that can get tangled in storage.
- Part or subassembly should be possible to attach in one go and not need further adjusting, or other members of structure to secure it.
- Component or subassembly size and weight should be relatively small, so insertion by hand is possible and easy. The need to use of lifting devices should be avoided.

3.2.3 Cost of supporting functions

Striving to minimize part and assembly costs may also lead to reduction in production support functions costs. For example, the reduced total number of different parts reduces the workload in inventory management. Reduced amount of parts in product reduces the number of employees needed for production, this leads to reduction of the cost of supervision and human resource management. The need of engineering support and quality control is reduced by the use of standard components. (Ulrich & Eppinger, 1995 p.198-199)

One method of reducing the support function cost is to reduce the complexity of manufacturing system. Usually these systems include vast number of suppliers, different parts, people, and types of products and production processes, each increasing the complexity of system. In many cases, these variants are tracked, monitored, inspected, managed and recorded at great cost for the company. Manufacturing complexity can be demonstrated with a scorecard, shown in table 1, the impact of changes from initial design on complexity can be easily seen. (Ulrich & Eppinger, 1995 p.199)

Table 1 Manufacturing complexity scorecard (adapted from Ulrich & Eppinger, 1995 p.199)

Drivers of Complexity	Rev 1	Rev 2	Rev 3
Number of new parts introduced to the manufacturing system	6	5	4
Number of new vendors introduced to the manufacturing system	8	8	6
Number of custom parts introduced to the manufacturing system	2	2	3
Number of new ‘major tools’ introduced to the manufacturing system	4	3	2
Number of new production processes introduced to the manufacturing system	1	1	1
Total	21	19	16

One of important DFMA aspects is predicting the possibility and types of failure modes of the manufacturing and assembly process in early design stages, so design can be altered to prevent them from happening. This is called error proofing. One of the failure mode types is confusion between parts with marginally different geometry in assembly, for example, same diameter and pitch screws with slightly different length; M4x10 versus M4x20. In worst case the longer screw could come in contact with component behind mounting hole and cause damage if positioned in place of shorter one. These marginal differences can be either eliminated or overstated, so risk of confusion is minimized. (Ulrich & Eppinger, 1995 p.200)

3.2.4 Challenges in applying DFMA/DFA guidelines

The ease of assembly of the design cannot be evaluated quantitatively by these guidelines. In addition, there is no relative ranking system of the guidelines to illustrate which yield to most significant improvements in handling, insertion and fastening. The guidelines are simply a collection of rules that give experienced designer the means to design a product that is easier to assemble than a product that has been developed without using these guidelines. (Bootroyd & at al., 2002 p.92)

Some DFMA guidelines may have a strong influence on development time. Using these guidelines can lead to longer development times as more complex parts are designed. In some cases, the design and setting up the production of the complex part becomes the determining activity of complete development task. The impact of reducing manufacturing cost with DFMA decisions on development time should always be considered in unison. The development cost will also increase, if development time is lengthened. (Ulrich & Eppinger, 1995 p.201)

The influence of decreasing manufacturing costs is often seen to only have positive effects on product quality, as well as serviceability, ease of disassembly and recycling. However, reduced manufacturing costs can bring about problems with aspects of reliability and robustness. (Ulrich & Eppinger, 1995 p.202)

3.3 DFMA questionnaires

One way to ensure that DFMA aspects are considered during design phase of a part or a product is to adopt specially targeted DFMA questionnaires to design process. With questionnaires it is possible to evaluate analytically if DFMA aspects have been noted during design of part or assembly. Questionnaires apply different scoring tables or models to evaluate the design, or can simply be based on yes/no questions. Filled questionnaires are also a great asset when implementing quality control for the part or product. (Eskelinen & Karsikas, 2013, p.98)

There are number of readymade DFMA questionnaires to steer design work to follow DFMA guidelines during different stages of production process. Questionnaires can also be customized to better suit part or assembly in question. (Eskelinen & Karsikas, 2013, p.98)

Example of a questionnaire, for evaluation how well DFMA guidelines have been applied in practice, is shown in figure 6 (full-size version in appendix I). It is possible to compare different existing assemblies by calculating key figures using the questionnaire.

QUESTIONNAIRE 4 APPLYING DFMA GUIDELINES IN PRACTICE

Assembly name:__________ Page number ____/____ Date: __________
Document NO.:__________ Made by: __________ Appr by: __________

A. Overall assesment of assembly (Questions A 1...13)

Question	Answer	Score	Note!
1. How many parts in assembly?			>10= -1point ≤10= +1point
2. How many modular solutions in assembly?			>2= +1point ≤2= -1point
3. How many separate joining components in assembly?			>3= -1point ≤3= +1point
4. How many different kind of joining components or methods in assembly?			>3= -1point ≤3= +1point
5. How many assembly directions needed?			>1= -1point ≤1= +1point
6. How many different manufacturing methods for parts in assembly?			>2= -1point ≤2= +1point
7. How many different manufacturing and joining methods needed in assembly stage?			>1= -1point ≤1= +1point
8. How many standard components in assembly?			+ 1 point/std part
9. Is there enough space for tools, installation and robot grabbers in assembly stage?	Y/N		YES= +1point NO= -1point
10. Is there place for assembly errors to accumulate? Place:________	Y/N		YES= +1point NO= -1point
11. Has design utilized product family thinking?	Y/N		YES= +1point NO= -1point
12. Have the ergonomics of assembly work been checked?	Y/N		YES= +1point NO= -1point
13. Are individual part tolerance requirements in line with assemblys assembly tolerance requirements?	Y/N		YES= +1point NO= -1point
Assembly score:	Σ_1=		

Part name:__________ Page number ____/____ Date: __________
Document NO.:__________ Made by: __________ Appr by: __________

Part name:__________ Page number ____/____ Date: __________
Document NO.:__________ Made by: __________ Appr by: __________

B. Assesment of part (Questions B 1...17), repeat questions for each part in assembly)

Question	Answer	Score	Note!
1. How many functions for the part?			>2= +1point ≤2= -1point
2. How many manufacturing stages for the part?			>1= -1point ≤1= +1point
3. In how many different aligment can the part be inserted?			>2= +1point ≤2= -1point
4. How many preliminary processing stages manufacturing of the part requires?			>0= -1point 0= +1point
5. How many post processing stages manufacturing of the part requires?			>0= -1point 0= +1point
6. How many manufacturing procedures recur as "modular"?			>2= +1point ≤2= -1point
7. Have the guidelines for ease of manufacturing for manufacturing process been followed?	Y/N		YES= +1point NO= -1point
8. Is there enough space for tools, installation and robot grabbers in manufacturing stage?	Y/N		YES= +1point NO= -1point
9. Can the part be manufactured with standard tools?	Y/N		YES= +1point NO= -1point
10. Has the working allowance been assigned for part? How much:________	Y/N		YES= +1point NO= -1point
11. Is the chosen manufacturing method suitable for chosen material? Material:________ Manufacturing method:________	Y/N		YES= +1point NO= -1point
12. Is there overall tolerance been assigned for the part? Tolerance:________	Y/N		YES= +1point NO= -1point
13. Is there place for manufacturing errors to accumulate? Place:________	Y/N		YES= +1point NO= -1point
14. Can the part be tangled to other part in assembly or sorting phase?	Y/N		YES= +1point NO= -1point
15. Has parametric design been utilized in dimensionig of the part?	Y/N		YES= +1point NO= -1point
16. Have the ergonomics of manufacturing work been checked?	Y/N		YES= +1point NO= -1point
17. Are part tolerance requirements for surface quality, dimensions and geometric features in line with eachother?	Y/N		YES= +1point NO= -1point
Part score:	$\Sigma_{part\ 1}$=		
Part total score:	$\Sigma_{parts}=(\Sigma_{part\ 1}+..\Sigma_{part\ n})$=		
DFMA Total score (Assembly + parts):	$\Sigma_{assembly}=\Sigma_1+\Sigma_{parts}$=		

Figure 6. DFMA questionnaire example. (adaption Eskelinen & Karsikas, 2013, p.103-104)

3.4 Quantitative methods

Assemblability can be evaluated and improved with analytical methods, which evaluate the ease of fitting of different parts of assembly with numerical indicators. These indicators identify possible problem points of assembly with numerical values. (Eskelinen & Karsikas, 2013, p.81)

According to Eskelinen and Karsikas (2013, p.81) some traditional methods are:

- Boothroyd-Dewhurst DFA method
- Hitachi Assembly Evaluation method
- Lucas-DFA method
- DFA software

3.4.1 Boothroyd-Dewhurst DFA method

Method is suitable to analyze and develop an existing assembly to be easier to assemble and cannot be used to evaluate brand new design. (Eskelinen & Karsikas, 2013, p.81)

Different procedures are used for manual, robotized and automated assembly, as shown in figure 7.

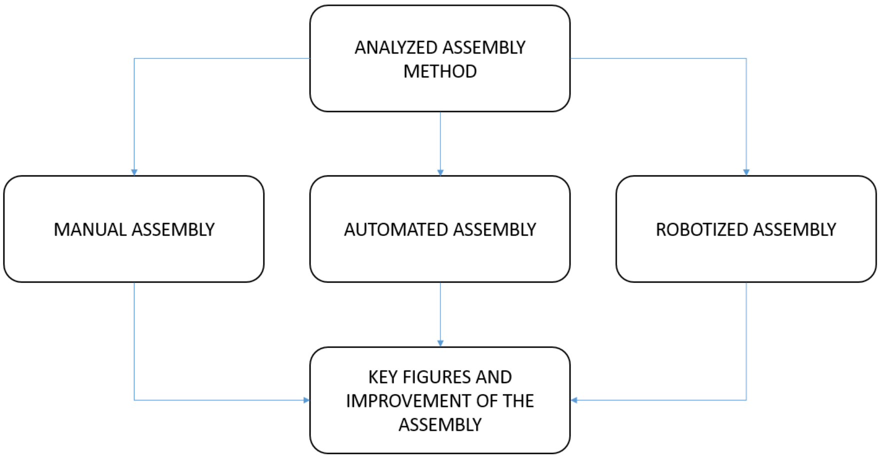


Figure 7. Boothroyd-Dewhurst DFA method has different procedures for manual, robotized and automated assembly (adaption Eskelinen & Karsikas, 2013, p.82)

First step of the method is to define assembly order for the parts and determine total installation time for each component. Total installation time includes handling and mounting times combined. As total installation times for each part are known, the overall assembly time and costs for the product can be calculated. Basis for the key figure describing assemblability is ratio between total number of parts and overall assembly time for product. In the second stage, the goal is to recognize critical parts for products functionality and merge non-critical parts to them, in order to reduce the total number of parts. Special attention should be given to sub-assemblies that have the longest overall assembly times. There is a possibility to create complex, hard and expensive to manufacture parts, when integrating non-critical parts to the critical ones. Assembly that is easier to put together might have higher total production cost. The method gives better indication of total improvement with addition of information about the cost of single part. (Eskelinen & Karsikas, 2013, p.81-83)

3.4.2 Hitachi Assembly Evaluation method

Method is developed for improving products assemblability for automated assembly line, and does not differentiate manual and automated assembly. Method uses two key figures. First figure describes parts installation processes difficulty and type, for example “from above”, “screw joint”, “welding” etc. Each process has a set penalty value that describes the difficulty of installation compared to the easiest “top down”-installation, which penalty value is zero. Combining each value gives the total penalty value for assembly, which describes the ease of assembly. Second figure accounts for assembly costs. Assembly time for the original assembly is measured and assembly cost calculated. New assembly versions with improved structures to reduce penalty values are compared to original assembly with the aid of ratio between assembly cost of new and original design. (Eskelinen & Karsikas, 2013, p.83)

3.4.3 Lucas DFA method

Method uses three key figures are, which describe installations relative degree of difficulty. The goal is to reduce the number of parts and evaluate the installation processes of them. (Eskelinen & Karsikas, 2013, p.83)

According to Eskelinen and Karsikas (2013, p.83), analysis of assemblability is divided into three stages, a key figure is calculated for each:

- Functional analysis, recognition of functional importance of parts
- Feeding analysis, handling of parts before assembly
- Fitting analysis, assembly procedure including grapping, positioning and mounting of the part.

In functional analysis, parts are divided to critical parts (A) and other parts (B). The functional efficiency of design, K, is calculated from the number of parts in each group:

$$K = \frac{100 \times A}{(A + B)}$$

Ratio can be improved by reducing the number in group B, the goal is to achieve ratio of 60% or above.

(Eskelinen & Karsikas, 2013, p.84)

Feeding analysis evaluates the effects of part or sub-assembly weight, size, shape, direction etc. to handling. Total feeding index is calculated by combining index values for each factor complicating handling. Feeding ratio is then calculated by dividing total feeding index with number of essential parts, value A taken from functional analysis. An ideal value for feeding ratio is considered to be 2,5. (Eskelinen & Karsikas, 2013, p.84)

Fitting analysis evaluates factors that complicate the actual assembly procedure, such as hindered visibility to installation spot. First total fitting index is calculated adding up index values of each factor complicating assembly procedure. Fitting ratio is then calculated as feeding ratio; dividing fitting index with total number of essential parts. 2,5 is also the ideal value for fitting ratio. (Eskelinen & Karsikas, 2013, p.84)

Lucas DFA method encourages to decrease part count in subassemblies by developing multifunctional parts. However, method has the same problem as Boothroyd-Dewhurst-DFA method, the individual part manufacturing cost is neglected. (Eskelinen & Karsikas, 2013, p.84)

3.4.4 DFA software

Software's for evaluating and improving assemblabilty are commercially available from several suppliers. DFA software utilizes information about assembly times and costs stored to product data management (PDM) or product lifecycle management (PLM) systems. Detailed data of assembly times and costs of parts are stored in the system and are available for analyzing the assembly, current or future design. Software calculates cost effectiveness of an assembly, but does not make design. (Eskelinen & Karsikas, 2013, p.84-85)

3.5 Modular product design

In modular design the goal is to design and produce complicated products with simple and similar parts and subassemblies, also known as modules. Modules must have interfaces so it is possible to connect them together to form a product. As each module performs a function or number of functions, and when coupled together the final assembly will produce an array of functions or a general function. (Kamrani & Salheih, 2002, p.45)

Bonvoisin, Halstenberg, Buchert and Stark (2016, p.489-490) state that designing a modular product can be thought of three ways;

- Designing a product with existing modules. For example, designing a personal computer using existing modules or building a structure by using Lego™ pieces.
- Identifying modules by analyzing relevance of component grouping on existing product by preset conditions and redesigning the modules. For example, clustering components needing frequent maintenance together and making them easy to remove.
- Designing of the modules and module interfaces by grouping functional elements into units.

According to DFMA principles a single manufacturing stage or action, for example welding a seam, attaching a rivet etc., can also be seen as a module. Production and setup times are reduced when a specific manufacturing action is repeated instead of using different actions. (Eskelinen & Karsikas, 2013, p.30)

3.5.1 Product modularity and modular product architecture

A product can be seen to have both functional and physical elements. The overall functions of the product are defined by combination of functional elements that produce the individual actions and transformations. Components, parts and sub-assemblies are the physical elements of a product, these elements carry out the functions of the product. The product architecture is the way physical elements are arranged to units and the way that the units interact. (Ulrich & Eppinger, 1995, p.180-181)

Modularity of a product means that the construction is divided to combination of independent units, modules, with predetermined interfaces or connections. One module should execute one or more functions independently; individual functions should not be divided to several modules. Similarity between physical and functional modules is the aim of product modularization, this keeps the module interfaces simple and also makes independent and parallel designing of modules feasible. (Österholm & Tuokko, 2001 p.8-9, Eskelinen & Karsikas, 2013, p.29)

Kamrani and Salhieh (2002, p.47) divide the modules into two categories: function and production modules. Products functions are executed by function modules, there are five classes; basic, auxiliary, special, adaptive and customer specific functions, analogy between functions and function modules is represented in figure 8. The production modules on the other hand are set up by requirements or wishes of production processes.

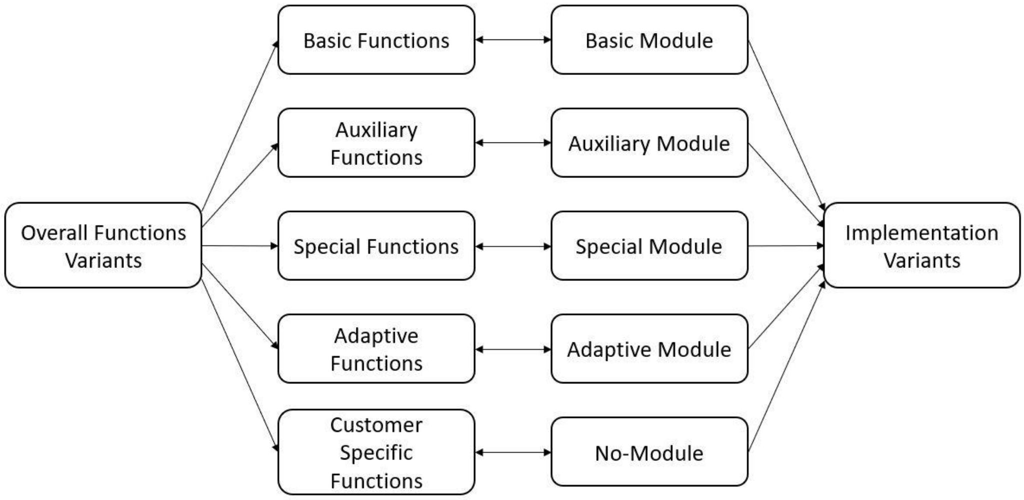


Figure 8. Analogy between function and module (adaption Kamrani & Salhieh, 2002, p.47)

As the complex structure is divided to smaller more manageable parts, it is easier to control the product and product development. “Good product architecture can be achieved with modularity.” (Ericsson & Erixon, 1999, p.17).

In an ideal modular product each function is executed by one individual module, with minimal and strictly defined interactions with other modules. When interactions and connections between modules are predetermined and kept standard, the individual modules can be changed or modified without making any changes to connecting modules and rest of the product. (Österholm & Tuokko, 2001, p.8-9, Eskelinen & Karsikas, 2013, p.29-30)

Decision to use subassemblies might be to overcome assembly difficulties in final assembly and is done in assembly planning stage of product development. High number of subassemblies might indicate poor design of the product, as assembly in one go is not possible. This means that subassembly might not be a module. Choice of using modules is a strategic decision. Because of the precisely defined interfaces of the module, it can be assembled elsewhere, which makes using subcontractors possible. (Ericsson & Erixon, 1999 p.19-20, Österholm & Tuokko, 2001, p.9)

3.5.2 Product architecture

Number of different product architecture possibilities might be considered when designing complex product, making the choice of product architecture a complicated but necessary task. Implementation of modularization can have an effect on product architecture, design goals guide designers in grouping components and functions to form modules. The challenge is in recognizing relevant criteria's from the design goals. (Bonvoisin, Halstenberg, Buchert & Stark, 2016, p.488-489)

One of the most important tasks in product development process is creating the product architecture, the basic core unit. Different modules are fitted into the core unit producing different variations of the product to satisfy customer need. The core unit should be able to house all expected different variants of the product offered. (Kamrani & Salheih, 2002, Ulrich & Eppinger, 1995, Eskelinen & Karsikas, 2013, p.30)

Product architecture can be managed on three levels: product range level (product family or product platform), product level and component level, shown in figure 9. Reducing complexity on component levels will result in exponential effects on higher levels (Ericsson & Erixon, 1999 p.17-18). In this Eaton case the proposed changes are done in component and product level.

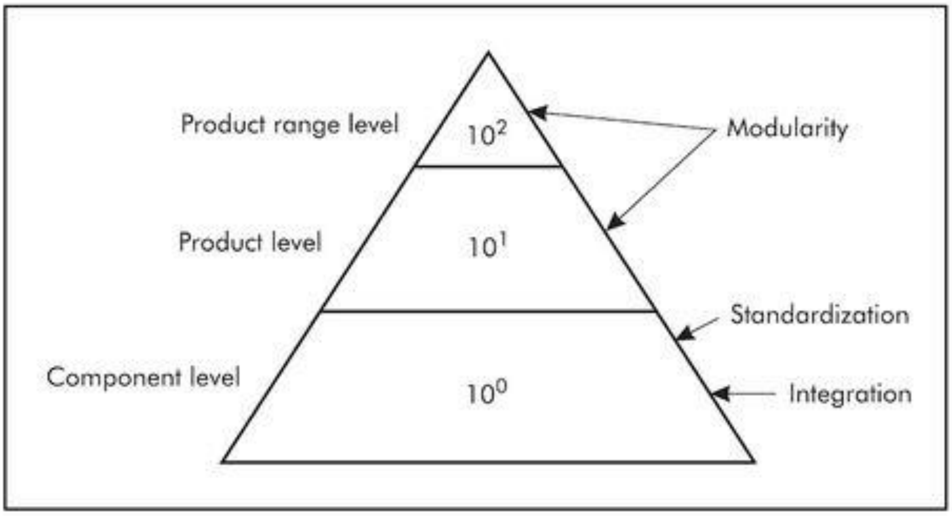


Figure 9. Levels for product architecture management (Ericsson & Erixon, 1999 p.18)

3.5.3 Module interfaces

Interfaces between modules can be evaluated with interface analysis; the modules are listed in a matrix in their assumed assembly order. Interfaces between modules are marked with letter codes, which specify the type of interface. Example types of interfaces and their codes are given in table 2. There are two ideal architectures according from assembly viewpoint, base unit- and hamburger assembly. In base unit assembly, the product is assembled around base module, while hamburger assembly is stacked from bottom to top, see figure 10. (Ericsson & Erixon, 1999, p.38-39, Österholm & Tuokko, 2001, p.30-32)

Table 2. Module interface types (adaption Ericsson & Erixon, 1999, p.38)

Interface	Example	Code
Solid	Rigid module connection, transmits forces etc.	G
Movement	Energy in form of rotation, alternating forces etc.	E
Media	Liquid, electricity etc.	E

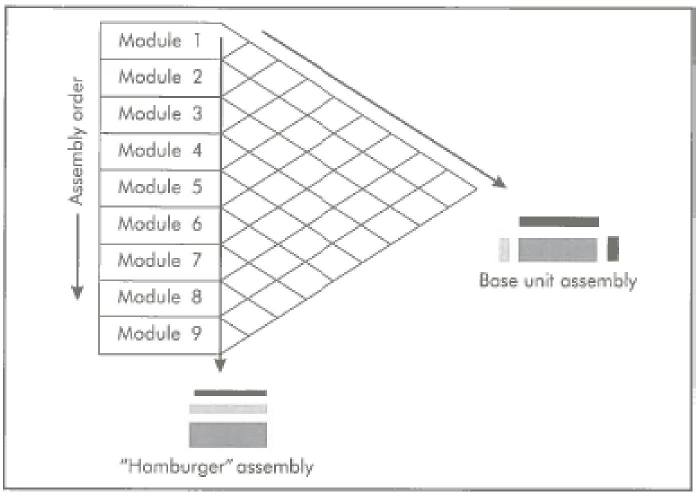


Figure 10. Module interfaces guide product structure. (Ericsson & Erixon, 1999, p39)

3.5.4 Standardization of modules

Standardization of modules and components and their interfaces enables the possibility to use same components and modules in several different products and product series. Standardization can be done if component or module carries out one or few common functions, which are generally used in different products. Standardization gives the possibility to manufacture the components or modules in larger volumes, which usually leads to lower manufacturing costs and improved quality. (Ulrich & Eppinger, 1995 p.135)

3.5.5 Modularization drivers

Ericsson & Erixon (1999, p.20-26) and Österholm & Tuokko (2001, P.14) list drivers steering modularization:

- Carryover – a module which is not likely to go through design changes during product platform existence, so it can be re-used from previous generation of product.
- Evolution of technology – a module which technology or customer demands can be expected to evolve or change in product life cycle time; for example new technology or new materials. (external).
- Planned design changes – changes or development to module and its technology is already known; strategic changes such as new product models, new features or production cost decrease. (internal)

- Technical specification – variation of module functions or performance in different products inside product family. Variations should be kept to as few modules as possible; for example different demands in different parts of world, such as devices operating voltage.
- Styling – variation of module appearance between products in product family; different appearance wanted in different product families.
- Common unit – a module used in whole product family; function that is needed in every product in product family. In ideal case common unit is combined with carryover.
- Process/organization – Parts needing special production methods are combined into one module.
- Separate testing – Possibility to do separate testing for modules before final assembly can improve quality and speed up identification of faulty production.
- Supplier available – Subcontractor supplied standard module. Subcontractor has responsibility of production, development and quality, design of module can be of own, subcontractor design or designed in co-operation.
- Service/maintenance –All parts requiring maintenance should be located in an easy to access service module. Module interfaces should be easy to disconnect and connect for quick replacing.
- Upgrading – A module which can be replaced with module with different functions, more functions or better performance.
- Recycling – Arranging modules by materials used, a module should contain as few different materials as possible. Recycling of a product is simplified when easy to recycle materials are kept separate from materials challenging to recycle.

3.5.1 Types of modularity

Types of module combinations can illustrate modularity of a product, as interactions between modules define type of modularity. Product modularity has few different definitions, which have similarities between them. Kamrani & Salhieh (2002 p.49-50) mention that there are four types of modularity; component swapping, component sharing, fabricate to fit and bus modularity. Shown in figure 11.

- Component swapping modularity (a): By coupling two or more different type of modules into one base module, product variants in same product family are created.
- Component sharing modularity (b): Same basic component is used in different the product variants, regardless of product family. Component swapping modularity is very similar to component sharing modularity.
- Fabricate to fit modularity (c): Number of basic components are connected to variable component, variable can be for example the length of a component.
- Bus modularity (d): A base module where any number of basic components can be connected in any location.

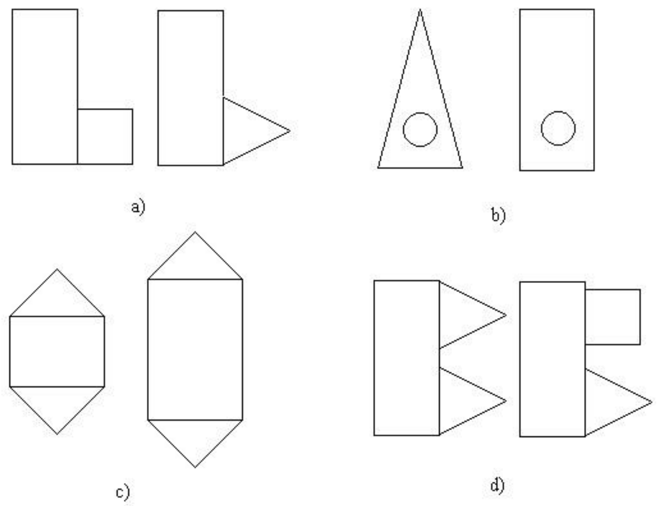


Figure 11. Types of modularity: a) Component swapping modularity b) Component sharing modularity c) Fabricate to fit modularity d) Bus modularity (adaption Kamrani & Salhieh, 2000, p.49-50)

Ulrich and Eppinger (2000 p. 184-185) divide modularity into three types; slot, bus and sectional modularity. Shown in figure 12.

- Slot-modular architecture: Each interface between modules is different, so module positions cannot be changed.
- Bus-modular architecture: Modules connect to common bus with same type of interface, module position does not matter.
- Sectional-modular architecture: All modules have the same type interface, but there is no main module where other modules connect.

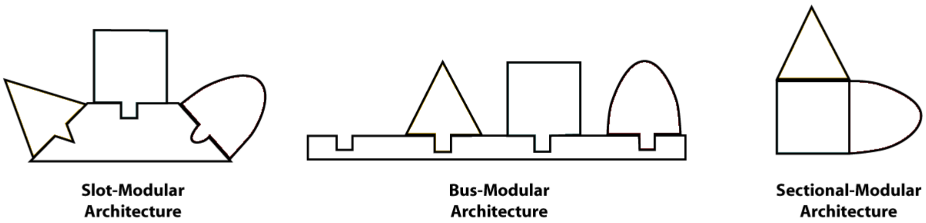


Figure 12. Modular architectures (adapted Ulrich & Eppinger, 2000, p.185)

Österholm and Tuokko (2001, p.10-11) divide modularity types similarly than Ulrich and Eppinger, but separate slot modularity tor four different types, see figure 13. Bus and sectional modularity are explained as by Ulrich and Eppinger. Four different slot modularity types are: component sharing modularity, component swapping modularity, parametric modularity and combination modularity. First three are defined same as Kamrani and Salhiehs corresponding modularity types, fourth is combination of the three.

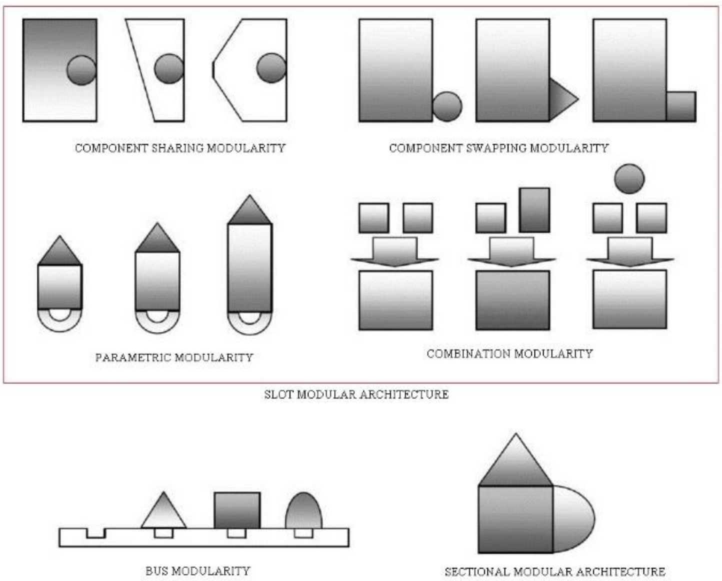


Figure 13. Modularity types (adaption Österholm & Tuokko, 2001, p.11)

3.6 Challenges in pursue of modularization

Vast number of benefits are claimed to be gained when utilizing modular product design by literature sources, for example reduced development costs, shorter development times and environmentally friendly end of life solutions. Yet the potential of modularization is left unclear due to poor explanation of the possible advantages and absence of acknowledged theoretical references. Large number of different methodological approaches and absence of general terminology complicates the use of modularization in product development and makes standardization of the procedures hard. (Bonvoisin et al. 2016, p.488)

Bonvoisin et al. (2016) list wide ranging instructions, in their comprehensive literature review, to fulfill goals set by modularization drivers while designing products. Concept maps with divers to reduce manufacturing costs and improve product modularity are presented in figures 14 and 15. Larger versions see appendices II and III.

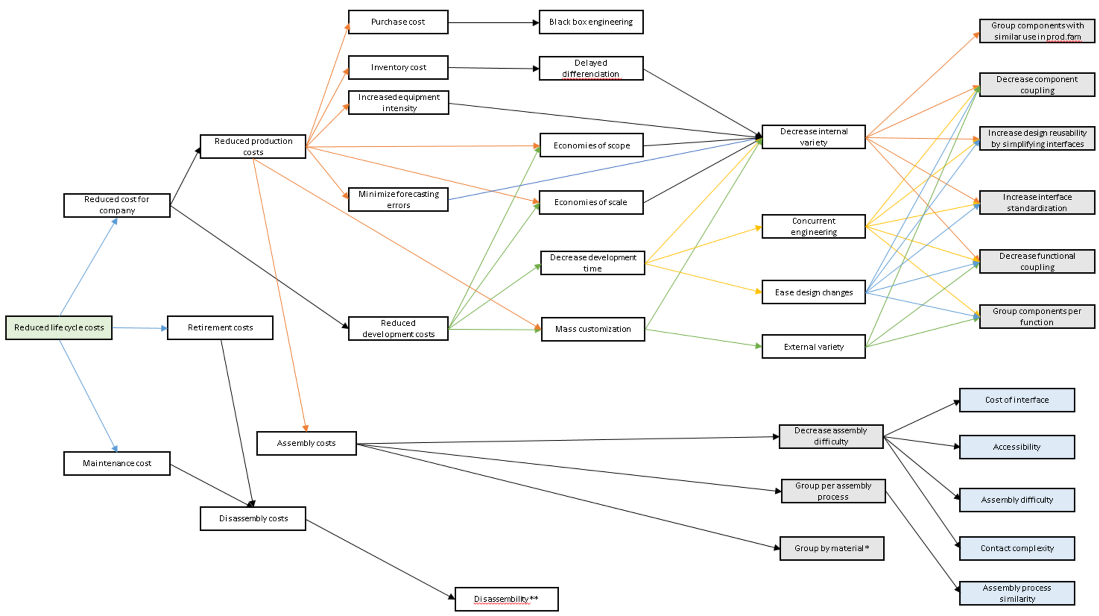


Figure 14. Concept map for reduced life cycle costs. * and ** see figure 13, (adaption Bonvoisin et al., 2016)

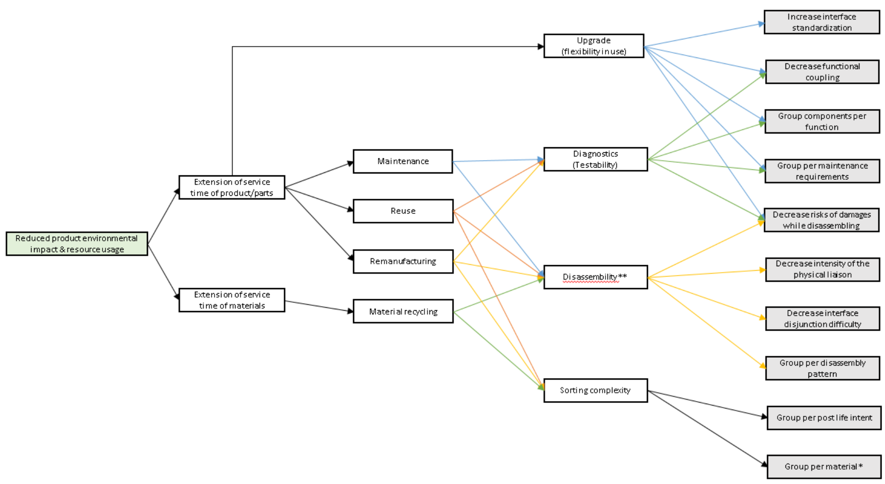


Figure 15. Concept map for reduced product environmental impact & resource usage. * and ** see figure 12, (adaption Bonvoisin et al., 2016)

Scientific means to improve the structure of an existing device design are presented in this chapter via literature review. The basic ways to simplify and modularize a product are discussed and they give foundation for the study. One of the most important means to reduce manufacturing costs of a product is to reduce part count by combining parts together, eliminating unnecessary components, reducing the number of fasteners and fastener types, this not only lowers the part costs but also decreases assembly costs. Modularization and using universal and common components is also a great way to degrease the manufacturing costs. This said there are not clear procedures to implement abovementioned actions given in literature; each case has to be evaluated individually. Usually the results can be evaluated only after the new and improved product is finished, by comparing it to previous version of the product.

4 STUDIED UNINTERRUPTIBLE POWER SUPPLY DEVICES

Eaton offers vast number of different products for UPS markets with different product lines. There are at least 27 different product series available depending on sales region, most of these product lines offer at least two optional sizes. Different product lines cover vast number of applications, from use at home to industry and from datacenters to marine use. UPS devices can be used as backup power source and surge protection for information technology and electrical infrastructures. (Eaton Corporation, 2018a)

In Eaton UPS product range there are variants with different power ratings assembled in same frame. The most powerful model assembled in product frame dictates the mechanical requirements, such as battery capacity, required space for electronics and cooling capacity.

The maintenance programs of UPS products are an important source of revenue for Eaton. Main maintenance items in UPS products are air filter elements, fans and batteries, some capacitors and PCBs need to be changed on occasion. There are number of different measurement and calibration tasks that need access to electronics inside the products housing. (Hakuli, 2017, Hakuli, 2018a)

4.1 Studied products

Three product series from Eaton’s datacenter product range were selected to be studied: 93E, 93PS and 9395P. A model from 93E and 93PS series each was selected for more detailed study; 20kVA-model from 93E series and 10kW-model from 93PS series. 9395P series was used to verify the findings. Sales figures for 93E 20kVA and 93PS 10kW models are between 2000 and 5000 units/year. Eaton supplied the two UPS devises to LUT electrical laboratory in Lappeenranta, where they were dismantled and studied. The assembly of the largest model Power Xpert 9395P was observed at assembly line in Eaton’s facilities in Espoo, Finland. Eaton provided 3D models, bill of materials, assembly instructions, datasheets and sales figures of the studied 93E and 93PS devices, along with sales figures and datasheets of the 9395P product series.

4.1.1 Eaton 93E

93E is marketed as value line of UPS devices for cost conscious customers, still having high efficiency. The product line is designed and produced in China for mainly Asian markets. Driving design philosophy has been cost-effectiveness, maintainability is not considered to be a key aspect when designing a product for Asian market as labor costs are negligible. (Hakuli, 2018a)

93E model series has two frame sizes, 20 and 30kVA versions fit in smaller frame, 40 and 60kVA versions in larger frame. Available 93E versions and sizes are presented in table 3. Image of 93E 20-30kVa version is shown in figure 16. (Eaton Corporation, 2018b)

Table 3. 93E models and sizes (Eaton Corporation, 2018b)

Series	Model [kVA]	Size (W x D x H) [mm]
93E	20, 30	530 x 800 x 1360
93E	40, 60	600 x 800 x 1880

Figure 16. Eaton 93E 20-30kVA model (Eaton Corporation, 2018b).

93E can switch between four different modes;

- Standard Normal mode, load is supplied by the inverter and/or batteries need charging
- High-Efficiency mode, load is supported by static switch with Standard Normal mode available on demand.
- Bypass mode, load is supported by grid
- Battery mode, battery supports load via the inverter (Eaton Corporation, 2018b)

The design of 93E 20-30kVA model represents hamburger assembly, where production modules are assembled from bottom up. From bottom up, there are two levels of batteries (four battery packs per level), breaker and connection level, power module level and control electronics and static switch level. The frame has 47 sheet metal parts, which are mainly fastened by screw joints. There are 198 screws; 8 different types, and 55 pop-rivets; 2 different types, used in frame assembly. Basic layout of 93E 20-30kVA model is presented in figure 17.

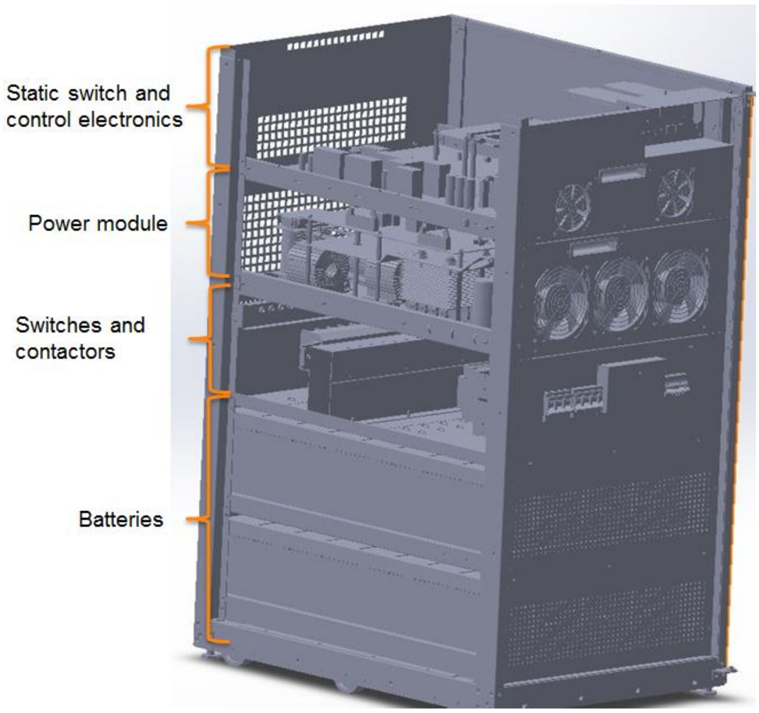


Figure 17. 93E 20-30kVa layout, left side panel, roof panel and front door removed

4.1.2 Eaton 93PS

Series 93PS UPS devices are designed to be more modular, scalable and efficient than 93E series. It is possible to add or change power modules even when device is running. There are also number of options available for 93PS line, for example the device can be equipped with external battery cabinet. The designing of 93PS line has been done in co-operation between China and Finland, production is also divided to China and Finland. Maintainability has been one of the main aspects steering the design of the product line. (Hakuli, 2018a)

There are two frame sizes offered (third one is being brought to market, but is excluded in this study). Small frame 93PS (8-20kW) has one 8, 10, 15 or 20kW power module. 20kW static switch is standard and 40kW one is offered as an option. Small frame 93PS has two strings of internal batteries. Large frame (20-40kW) 93PS has two power module slots, available module sizes are the same as small frame. Two power module slots make internal redundancy possible with 8+8, 10+10, 15+15 and 20+20kW modules. Static switch is 40kW and there are four strings of internal batteries. Available 93PS series models are shown in table 4, image of 8-20kW version is shown in figure 18. (Eaton Corporation, 2018c)

Table 4. 93PS models and sizes (Eaton Corporation, 2018c)

Series	Model [kW]	Size (W x D x H) [mm]
93PS	8, 10, 15, 20	335x750x1300
93PS	8, 10, 15, 20, 30, 40, 8+8, 10+10, 15+15, 20+20	480x750x1750

Figure 18. Eaton 93PS 8-20kW model (Eaton Corporation, 2018c)

93PS can switch between four different modes;

- Double conversion mode, load is supplied by the inverter and/or batteries need charging
- Energy Saver System-mode, load is supported by static switch with double conversion mode available on demand.
- Stored energy mode, energy is drawn from batteries via inverter
- Bypass mode, load is supported by static switch (Eaton Corporation, 2018c)

Small frame 93PS 10kW has characteristics of both hamburger and base unit assembly, lower battery compartment is hamburger design and top UPS cabinet is base unit assembly. There are four levels in the battery compartment, two battery packs in each. UPS cabinet is assembled around the power module. Power module is located on the left hand side of the cabinet, control and filtering electronics and connectors are located on the right hand side of the cabinet. Static switch is placed on top of the power module. It is possible to remove the power module by unscrewing four M5 screws, unlocking a latch and sliding the module out of the cabinet. The frame has 77 sheet metal parts which are largely fastened by rivet joints. There are 198 screws: 5 different types and 165 pop-rivets: 4 different types used in frame assembly.

The UPS cabinet of 93PS, the top part of the assembly, is manufactured and assembled in China. Final assembly of the product is done in Espoo, Finland. This stage includes the joining of UPS cabinet part on top of battery compartment, manufactured by subcontractor in Finland. The door of the device and the outer panels are also fastened in final assembly stage. See figure 19. (Hakuli, 2017)

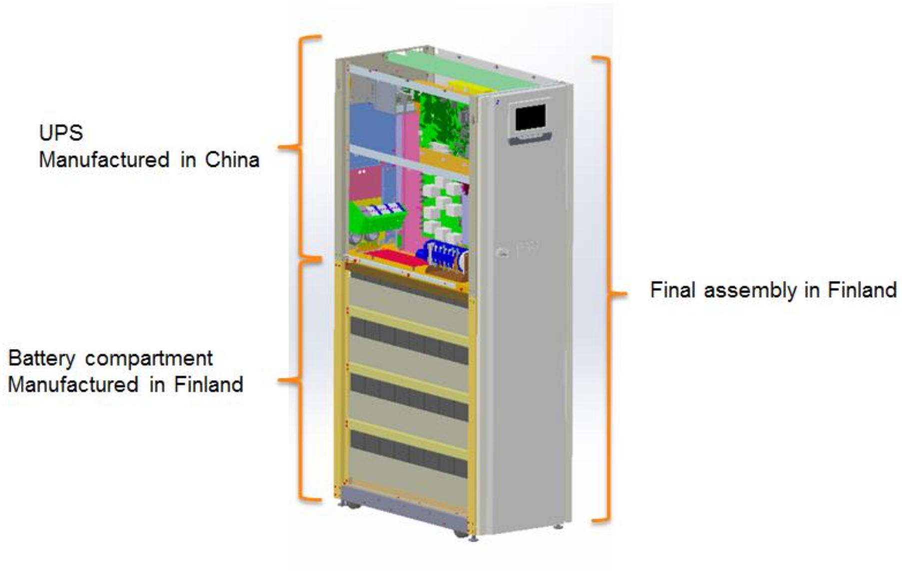


Figure 19. Layout and manufacturing regions of 93PS

4.1.3 Eaton Power Xpert 9395P

The Power Xpert 9395P UPS is intended to be used to ensure the operation of large data centers, large infrastructure projects, finance and banking critical infrastructure, large industrial complexes, healthcare, process control equipment and telecommunications installations. Images of two versions of 9395P (the 600kVA and the 1200kVA version) are shown in figure 20, the available models are presented in table 5.

Figure 20. Eaton 9395P: 600kVA model on left and 1200kVA model on right (Eaton Corporation, 2018d)

Table 5. 9395P models and sizes (Eaton Corporation, 2018d)

Series	Model [kVA]	Size (W x D x H) [mm]
9395P	250	1350x880x1880
9395P	300	1350x880x1880
9395P	500	1890x880x1880
9395P	600	1890x880x1880
9395P	750	3710x880x1880
9395P	900	3710x880x1880
9395P	1000	4450x880x1880
9395P	1200	4450x880x1880

The 9395P series is very scalable in terms of UPS capacity, static switch capacity and synchronizing with other UPS devices, see figure 21.

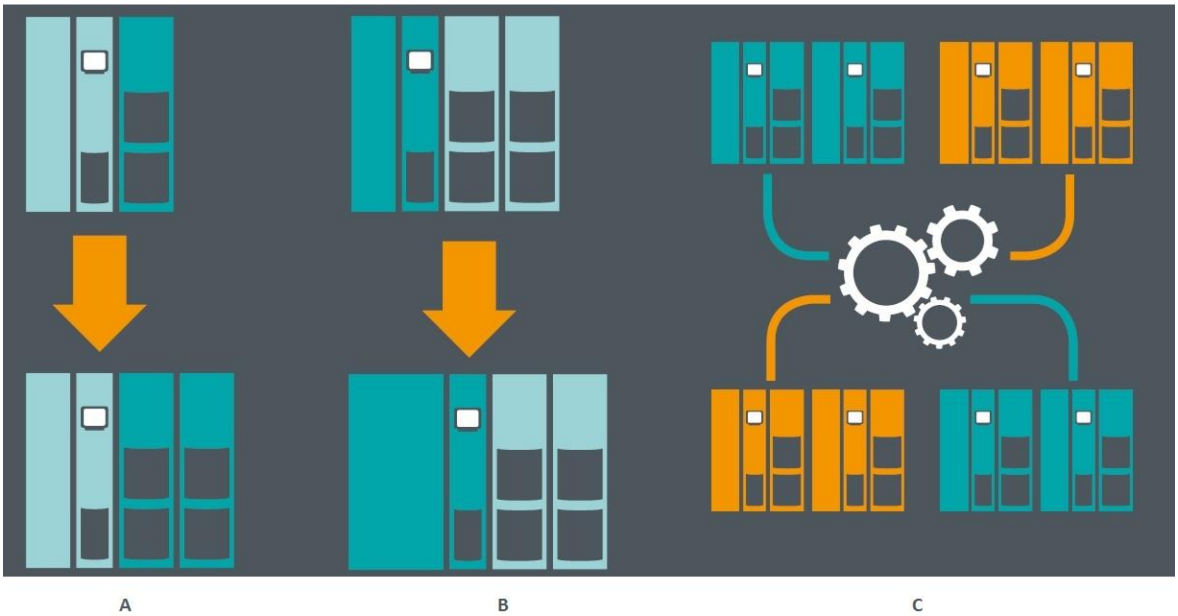


Figure 21. Power Xpert 9395P scalability, A) capacity, B) static switch size and C) synchronization. (Eaton Corporation, 2018d)

The assembly stages of 9395P were observed during two visits to Eaton Espoo facility.

4.2 Observations of cross disciplinary team

During the detail study of products-phase of the project, a cross disciplinary meeting for the research team and electrical engineers was held on seventh of March 2018. The agenda of the meeting was to make observations and discuss possible development areas for the electrical sections of the products. Ideas from both mechanical and electrical engineers were discussed and observations were thought to be interesting. A strong recommendation towards disciplinary team work was noted when designing a new or redesigning an old product. (Hakuli, 2018b)

One of the main observations and possible development area was integration and optimization of printed circuit boards (PCB). Number of connections and amount of electrical wires between different circuit boards could be reduced by integrating PCBs, decrease in amount and length of electrical wires usually leads to lower EMI levels emitted by the device. It was noted that component placement on the PCBs is relatively loose and by optimizing and compacting the component layout the size of PCBs could be reduced. (Hakuli, 2018b)

The amount of free space inside housings was noted. Eliminating free space along with reduced size and number of PCBs, the outside dimensions could be shrunk considerably. Although, ensuring the proper cooling of the device might require some of the free space left. (Hakuli, 2018b)

Concern about the access to fans on 93PS was stated, as they are one of the main maintenance items. The fans on 93E seemed to be more accessible. Also the fuses are positioned inside the housing on both devices and discussion about the possibility of placing them on the back wall arouse. (Hakuli, 2018b)

Discussion about dividing power module of 93PS to three separate modules was held, so that each phase would have its own module. (Hakuli, 2018b)

5 PROPOSALS FOR IMPROVING PRODUCT DESIGN

Proposals for improving cabinet design are presented in this chapter. Study was concentrated on standardization of geometric features and joining methods, and possibility of part integration, universal frame design, parametric modularity and improved maintainability.

5.1 Standardization

As standardization can be implemented in different ways, the following examples of geometries, joining methods and material thicknesses give possibilities for simplifying the design of cabinet components.

5.1.1 Geometries

93E and 93PS frame sheet metal parts have vast number of different geometries, for example different diameters of holes, fillet radiuses, square hole dimensions and chamfer dimensions. There are 23 different diameter holes on 93E and 18 on 93PS, used diameters of holes for example are 3.2, 3.3, 3.5, 4.0, 4.2, 4.5 etc. Square slot widths differ even on same sheet metal part, for example single front panel for 93PS (SLOT-CSB) has five different slot widths, shown in figure 22. By constraining available diameters of holes, slot widths, fillet radiuses etc. the number of different dimensions would be reduced, which would lead to fewer tools needed for manufacturing part. This would in turn reduce manufacturing costs of sheet metal parts.

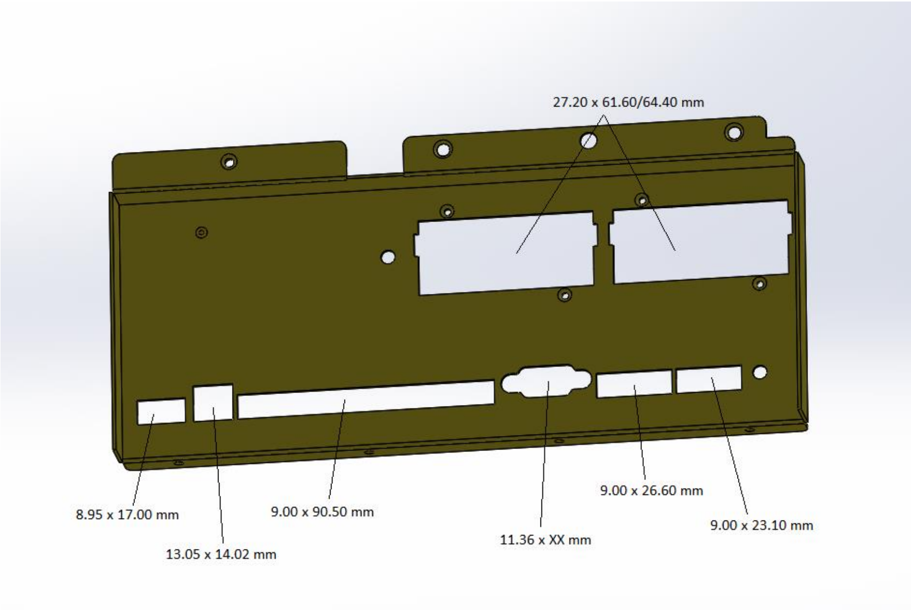


Figure 22. Square hole slot dimensions on single panel of 93PS

There are few recurring geometries, for example 10x10mm square holes intended for cooling airflow on both 93E and 93PS back walls, diameter 8.0mm hole for lightening the battery tray on 93PS and diameter 4.0mm hole for cooling airflow on 93E back wall, shown in figure 23.

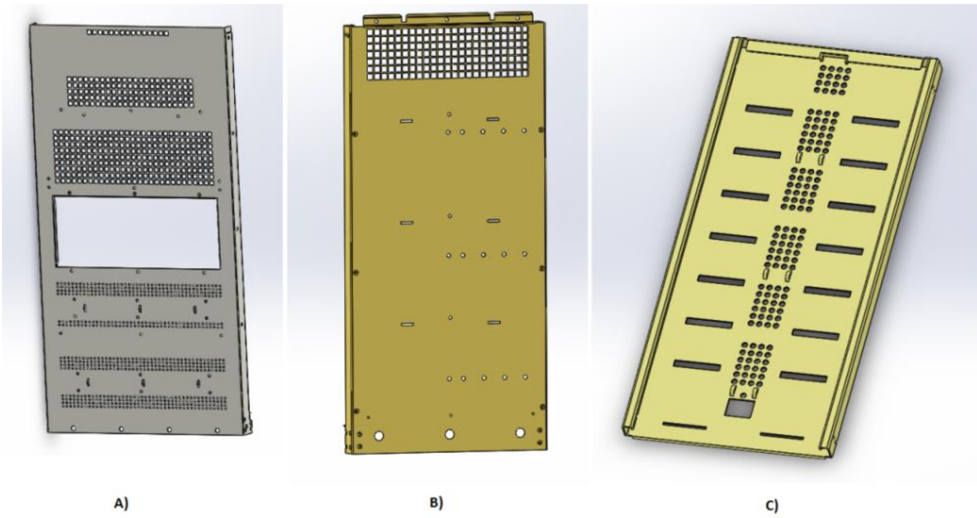
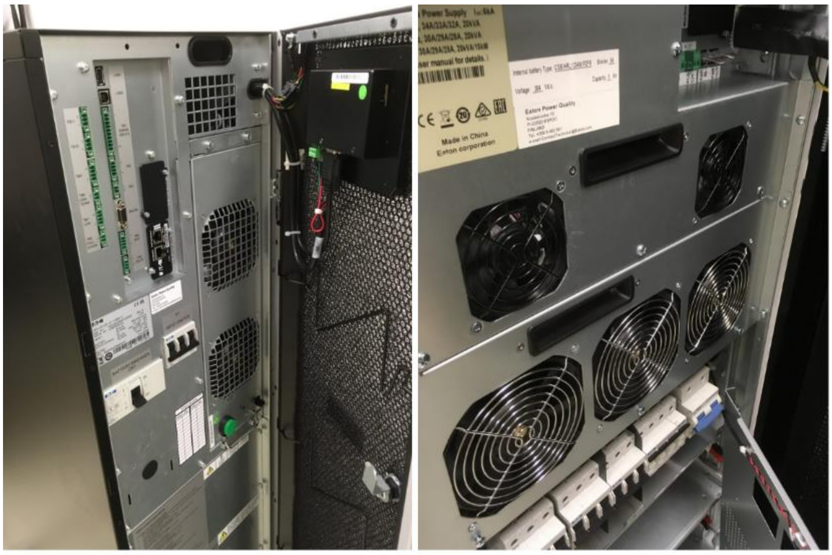


Figure 23. A)10x10mm (top) and diameter 4.0mm holes (bottom) in 93E back wall B) 10x10mm holes on 93PS back wall C) diameter 8.0mm holes on 93PS battery tray

The 93PS uses punched 10x10mm, alongside 5x7mm and 7x9.5mm square holes in front of fans, but on 93E there are separate fan grills. By using same punched square hole configuration also on 93E five parts could be eliminated and modularity would increase, see figure 24.



A) B)

Figure 24. Fan guards, A) 93PS fans are behind punched square holes, B) 93E has separate guards in front of fans.

5.1.2 Joining methods

There are vast numbers of different kind of attaching methods and fastener types in the studied products, some of the different types of fasteners were selected for closer inspection. From table 6 can be seen that for example in 93E there are 198 screws of eight different types. The number of fasteners per sheet metal part is 7.55 on 93PS and 7.06 on 93E. All collected data of 93E and 93PS geometries and fasteners can be found in appendices IV and V.

Table 6. Fastener variety on 93PS and 93E.

	sheet metal parts		nut insert	no of types		Stud	no of types		standoff	no of types		pop rivet	no of types		screws	no of types	total number of fasteners	fasteners per part
93PS	77		108	6		45	8		65	3		165	4		198	5	581	7,55
93E	47		17	4		41	6		21	2		55	2		198	8	332	7,06

In some parts of the devices the fastener variety comes very apparent, as can be seen in figure 25. Image represents joint between 93PS's UPS cabinet and battery compartment. There are five different types of fasteners shown in the image; M4 Philips head screw, M4 torx-head countersunk screw, 3.2mm rivet, 3.2mm countersunk rivet and 4.8mm rivet. The variety can be explained by manufacturing country, the upper UPS cabinet is manufactured and assembled in China and the lower battery compartment is manufactured in Finland, the joining of the two is done in Finland.

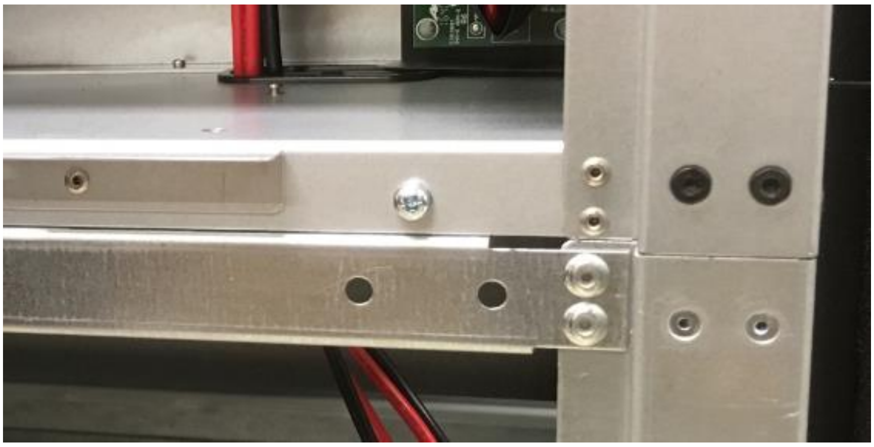


Figure 25. Example of fastener variety on small area on 93PS.

The joint between UPS cabinet and battery frame can be examined as an example where standardization of mounting hardware and methods of affixing could lead to noticeable benefits. Mounting of the UPS cabinet on top of the battery frame is done in Eaton Espoo facility; the UPS portion is lifted with special lifting jig and positioned on top of the lower frame. The two halves are secured with six M4 Philips head screws and 13 M4 torx-head countersunk screws. See figure 26.

The design could be revised so that only one type of screw would be used, for example M4 torx-head countersunk screw. Also the screw count, 19pcs, seems high for the application. Even switching only the head type from Philips head to same size torx-head as others, would simplify the assembly procedure as only one tool would be needed for joining. There is no need to dismantle this connection, so screw joint could be replaced with rivet joint, which is less expensive.

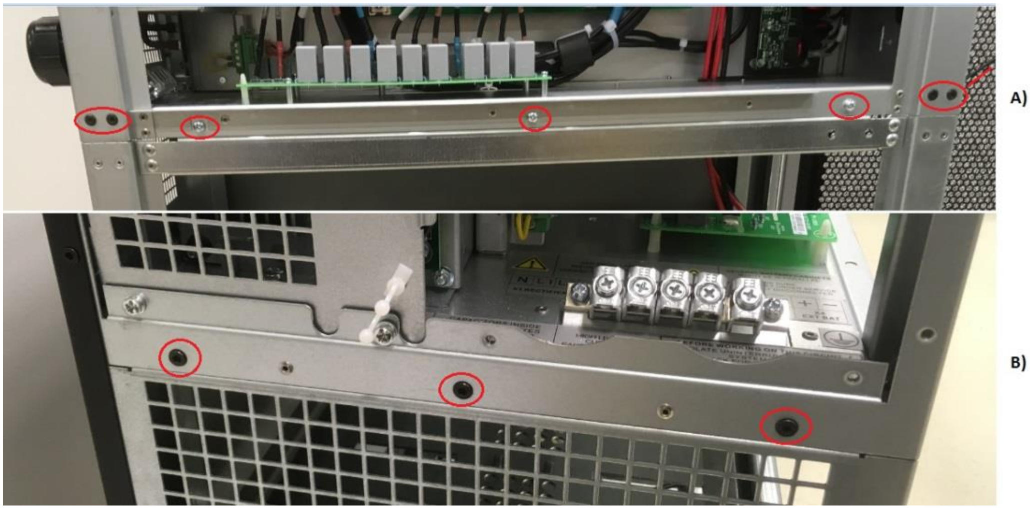


Figure 26. 93PS interface between UPS cabinet and battery frame: A) view from side B) back of the device.

There are different types of methods of affixing PCBs, for example metal standoff and screw or plastic stand. In some cases, different types are used for affixing single circuit board, as shown in figure 27. Filtering circuit board on 93PS is attached with metal standoffs and screws as well as plastic stands.

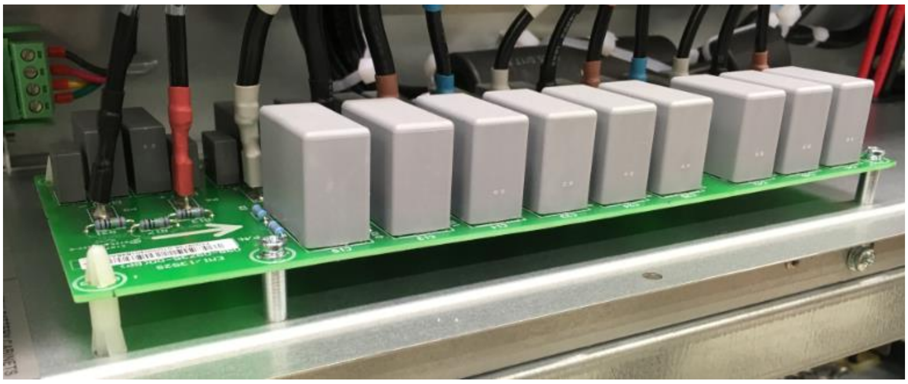


Figure 27. Two different types of mounting styles for single circuit board on 93PS

Reducing the number of different types of fasteners and methods of affixing can be done by standardizing and setting constraints on fasteners and methods of affixing. Decrease of number of fastener types lowers the inventory costs as number of recorded items is reduced. If assumed that the total number of fasteners is not reduced, the individual amount of remaining fasteners is increased. It can be assumed that as ordered lot sizes become larger, the purchase price per unit lowers. The module connections should be done with standardized and as few different type of fasteners as possible.

5.1.3 Material thicknesses

Seven different sheet thicknesses are used on both devices, as measured from 3D models they are 0.8, 1.0, 1.2, 1.25, 1.5, 2.0 and 2.5mm. By standardization of sheet thicknesses, the number of different thicknesses could be reduced to roughly half, for example the material thicknesses used could be limited to 1.0, 1.5, 2.0 and 2.5 mm. By reducing the thicknesses used, the stock/inventory could be reduced. The purchase quantities of selected sheet metal thicknesses would increase and thus reducing purchase costs per unit. Manufacturing time and costs would also be reduced when more parts could be manufactured from same thickness sheet metal in one go.

5.2 Universal frame design

Albeit, the product architecture and design strategy is very different between 93E and 93PS, the actual volume of electronics in both is nearly identical. Maximum battery capacity of the products is identical, eight battery packs. The volume of the batteries differs by small amount due to different style of packing of the battery cells. The battery dimensions and volumes are presented in table 7.

Table 7. Battery pack volumes 93PS and 93E

	W [mm]	L [mm]	H [mm]	Volume [mm^3]	pcs in product	Total volume [mm^3]	Total volume [m^3]
93PS	113	613	155	10736695	4	42946780	0,04294678
93E	104	615	155	9913800	4	39655200	0,0396552
difference				822895		3291580	0,00329158

Volume of main electronics was calculated from outline dimensions of electrical components and assemblies. PCBs, fuses breakers, terminals and fans were included to electrical components. Estimates of PCB dimensions had to be used in few cases, as some components were not included in model. 93PS has got 25 main electrical components as 93E has 24, the total volumes of electrical components with battery pack volumes added, are presented in table 8. Component individual volumes for 93PS and 93E are presented in appendices VI and VII.

Table 8. Main electrical component volumes 93PS and 93E

	Main electrical components volume [mm^3]	Main electrical components volume [m^3]		Battery pack total volume [m^3]	Total volume [m3]
93PS	44572112	0,044572112		0,04294678	0,087519
93E	45162526	0,045162526		0,0396552	0,084818
difference	-590414	-0,000590414		0,00329158	0,002701

Even though 93E electrical component volume is slightly less than 93PS's, the housing internal volume is much greater on 93E, shown in table 9. By this comparison, the 93E electrical components would fit inside smaller housing of 93PS.

Table 9. Housing internal volumes of 93PS and 93E

Series	Model [kW]	Size (W x D x H) [mm]	Volume [mm^3]	Volume [m^3]
93PS	8, 10, 15, 20	335x750x1300	326625000	0,326625
93E	20 & 30	530 x 800 x 1360	576640000	0,57664
difference			-250015000	-0,250015

Universal frame design could be achieved if PCB dimensions and mounting point locations would be predetermined and standardized. Circuit board modules would have certain possible dimensions, for example two or three possibilities. These sizes would have certain standardized mounting point locations. By knowing each PCBs size and mounting point locations, the frame could be designed to accept each combination required to form different products.

The universal frame could be considered a common unit and also carry over for future devices. The electronics would have technical specification and planned design as module drivers. As it is important to differentiate the looks, or styling, of the different series products, the door and outer panels would be treated as modules driven by styling. When using universal frame for multiple product series, the differentiation could be done with different style of front door and LCD-interface. With current design of 93E and 93PS have different frames, batteries, electronics and doors, as well as esthetics. In figure 28 the devices are characterized with four main components each.

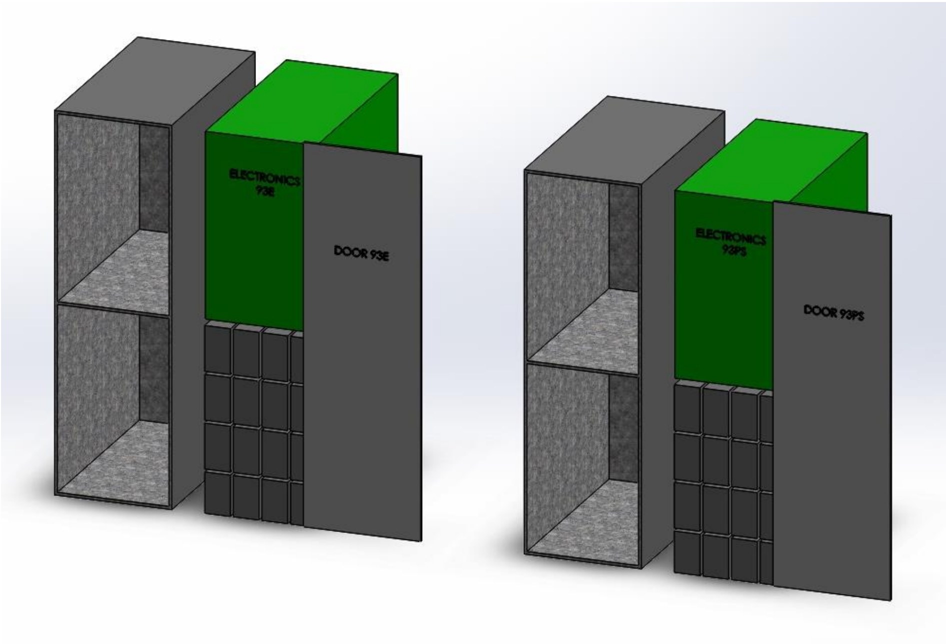


Figure 28. Basic main components of 93E and 93PS with current design

With the implementation of universal frame design different series or even different products could share components or entire frames. For example 93E and 93PS could share frame and battery components, only electronics and door would be different between the different models, shown in figure 29.

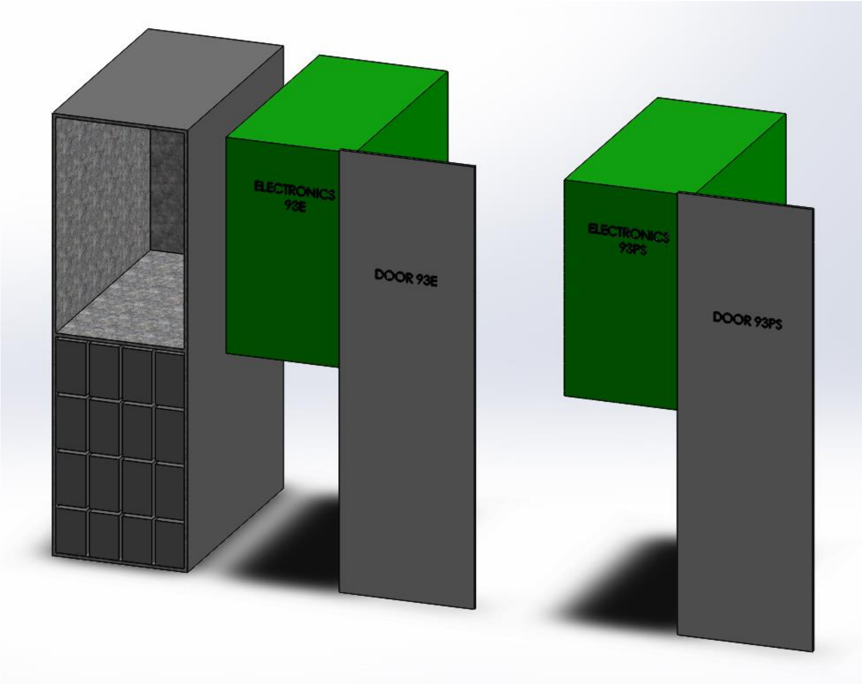


Figure 29. Possibility of universal frame design for 93E and 93PS.

5.3 Parametric dimensioning

With current frame design two of the outside dimensions, width and height, change when frame size changes in both studied product series. Outside dimensions of 93E and 93PS are shown in table 10.

Table 10. Eaton 93E- and 93PS-serie outside dimensions (Eaton Corporation, 2018b, Eaton Corporation 2018c)

Series	Model	Size (W x D x H)
93E	20-30kVA	530 x 800 x 1360
93E	40-60kVA	600 x 800 x 1880
93PS	8-20kW	335x750x1300mm
93PS	20-40kW	480x750x1750mm

In next example the frame is characterized with nine basic components; bottom plate, middle plate, back wall, two front posts, two sides, top and a door. When two outside dimensions are changed when stepping up in frame size means that every main component in frame is different, see figure 30. Yellow color on the large frame means that one of the parts dimensions changes compared to small frame size, red color means that two of the parts dimensions changes.

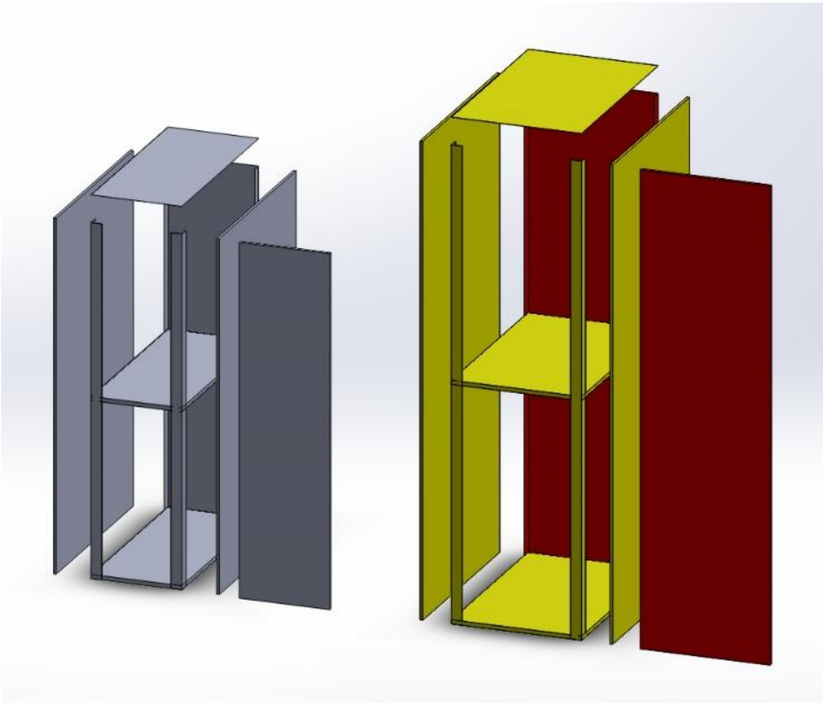


Figure 30. Characterization of current design between small frame (left) and large frame (right).

Similar characterization of small and large frame parts when only width is changed as stepping up in frame size is shown in figure 31. Yellow color on large frame part indicates that one dimension of the part changes, gray color on the large frame part indicates that the same part from small frame can be used.

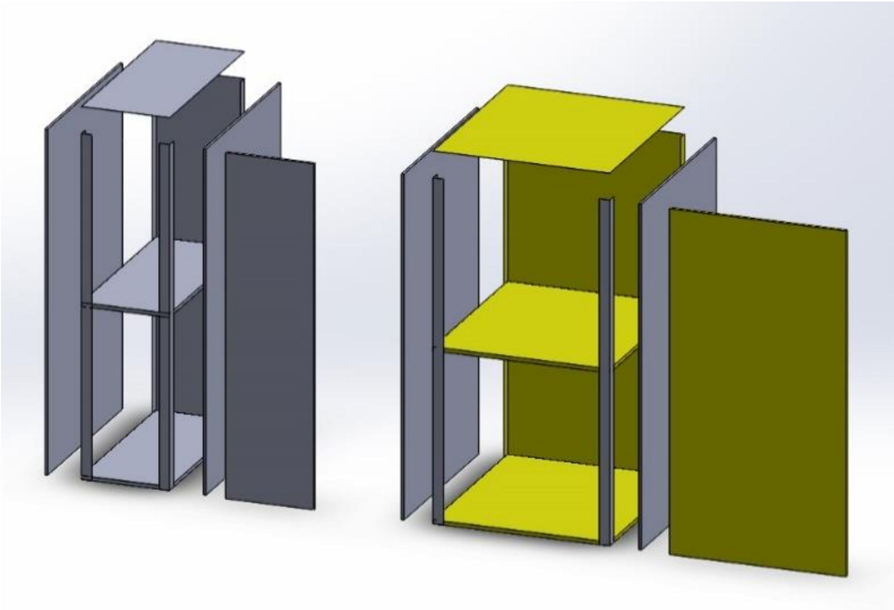


Figure 31. Characterization of design where parametric dimension is applied between small frame (left) and large frame (right).

With parametric dimensioning overall part count of product series could be reduced as same parts could be used in small and large frames. Parametric dimensioning could also simplify and reduce the cost of part manufacturing, as parts would be parametric modular.

5.4 Common parts

Possibility to use same parts in multiple products should be encouraged, for example studied products 93E and 93PS are attached to shipping pallets by L-profiles shown in figure 32. Both profiles are manufactured out of 3mm thick mild steel, but have slightly different geometries.

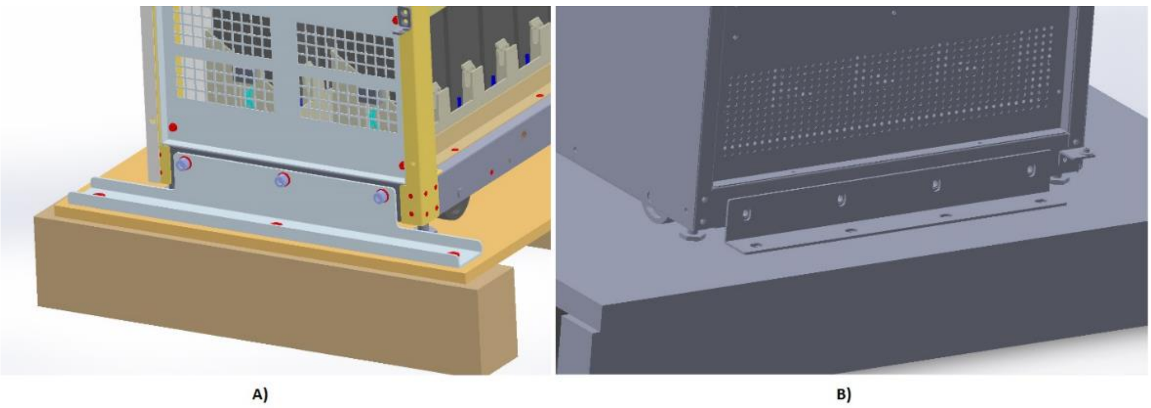


Figure 32. Mounting L-profiles; A) 93PS B) 93E.

With reducing number of mounting bolts to three and modifying the location of nut inserts on 93E, the L-profile from 93PS could be used on both. This profile could also be simplified by removing one bend. Simplified profile shown in figure 33, and profile in use in figure 34.

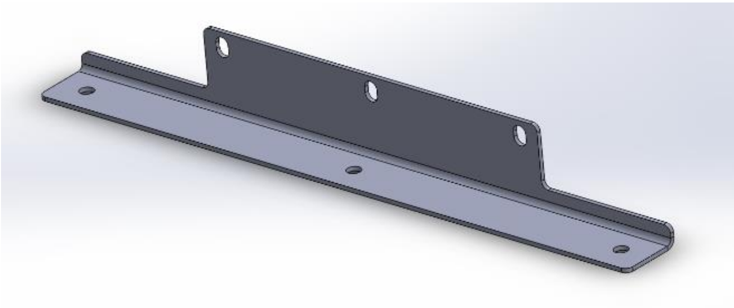


Figure 33. Simplified mounting L-profile

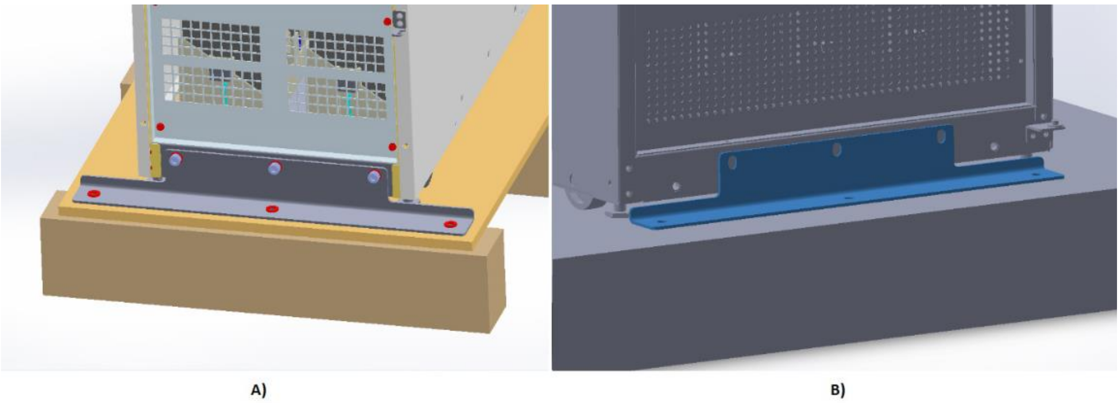


Figure 34. Simplified L-profile in place, A) 93PS B) 93E (some mounting hardware missing)

5.5 Part integration

Two candidates for part integration can be found inside 93PS power module. Located on sidewall there is an L-profile bracket and an air guide underneath it, shown in figure 35 and 36. Both parts are made out of sheet metal by cutting and bending. The bracket is fastened to the sidewall by three M4 Philips head countersunk screws with nut inserts mounted on the bracket. The air guide is fastened with two M4 Philips head countersunk screws with nut inserts mounted on the guide and one M4 flange nut. Similar design is found also on the left hand side of the power module.

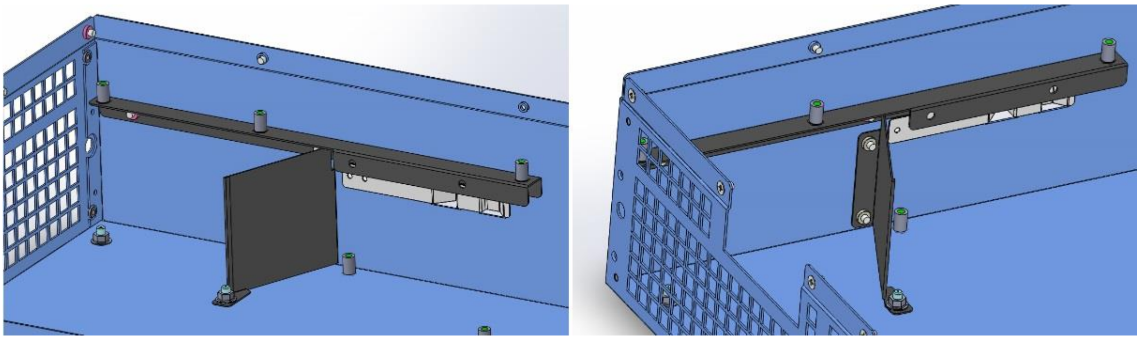


Figure 35. L-profile bracket and air guide inside 93PS power module, all electronics removed from 3D model for better view.

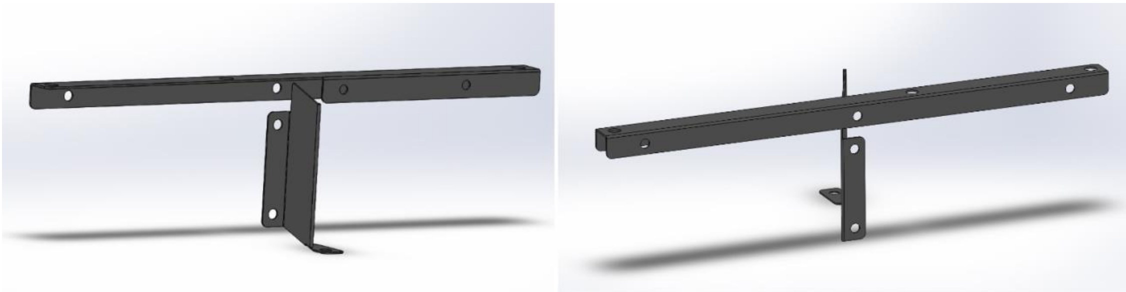


Figure 36. Sheet metal parts only, nut inserts and standoffs removed.

By integrating the two sheet metal parts all the functional geometries are kept plus one M4 Philips head countersunk screw along with nut insert can be removed. Integrated design is shown in figure 37. Three parts can be eliminated by single integration of two sheet metal parts, shown in table 12.

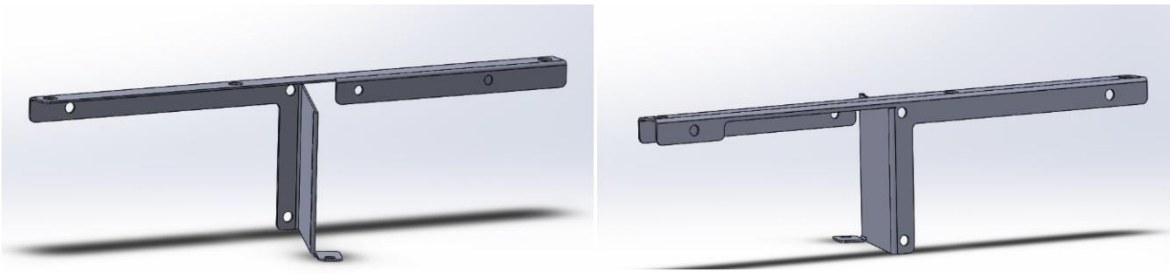


Figure 37. Integrated part.

Table 11. Part count comparison of single integration of two sheet metal parts on 93PS power module

Part	original	integrated
Sheet metal	2	1
Nut insert	5	4
M4 screw	5	4
Flange nut	1	1
Total	13	10

SolidWorks drawing of integrated bracket shown in figure 38, for full-size version see appendix VIII.

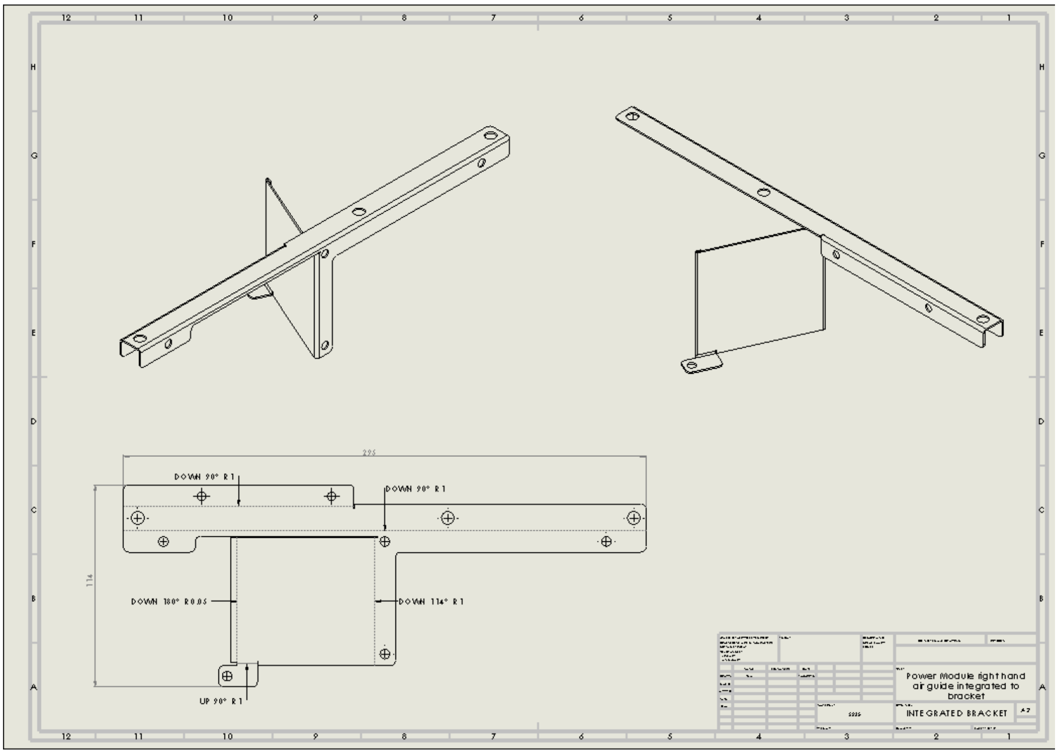


Figure 38. SolidWorks drawing of integrated part.

5.6 Improving maintainability

Concerns about maintainability aspects of 93PS arouse during cross disciplinary meeting. Fans were stated to be among the main maintenance items in the products. The static switch fan on 93PS is located next to the heat sink inside the device, fan location shown in figure 39. There are two air tunnels, one made out of plastic sheet and one out of sheet metal, between the front panel and the fan. Dismantling the fan requires the removal of outer the shell sheet metal from top and right side of the device, wire routing profile and air tunnels have to be removed also. The fan itself is attached to the metal air tunnel by four M4 Philips head countersunk screws. Total of 49 parts was counted to be dismantled to extract the fan, see table 13.

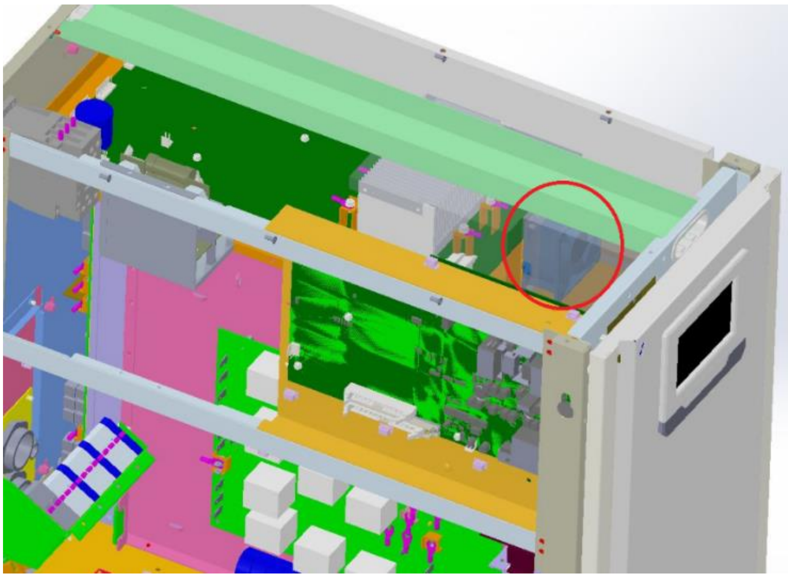


Figure 39. 93PS static switch fan location. Side and top panels removed plus plastic and metal air tunnels hidden in image

Table 12. Parts needed to be removed to change static switch fan on 93PS.

93PS				
Part/action	pcs	fasteners	pcs	Total parts to dismantle
top	1	M4 screw torx head, countersunk	12	
side panel	1	M4 screw torx head, countersunk	14	
wire conduit	1	M4 screw Philips head, countersunk	2	
"		M4 hex nut	2	
plastic air tunnel	1	M4 hex nut	2	
"		plastic rivet	4	
metal air tunnel	1	M4 hex nut	2	
		cable tie	2	
detaching fan		M4 screw Philips head, countersunk	4	
	5		44	**49**

On the 93E model the static switch fan is attached directly to front panel by two M4 screws, the air tunnel is behind the fan. Fan location shown in figure 40. The front panel is attached to frame with 10 M4 screws, bringing the total number of parts needed to remove to 13. See table 14. The static switch fan is considerably easier and faster to replace on 93E than on 93PS.

Figure 40. 93E static switch fan visible when front door opened.

Table 13. Parts needed to be removed to change static switch fan on 93E.

93E				
Part/action	pcs	fasteners	pcs	Total parts to dismantle
Front panel	1	M4 screw Philips head	10	
detaching fan		M4 screw Philips head, countersunk	2	
	1		12	**13**

Power module fans or capacitors on the 93PS cannot be changed onsite, as the module itself is in closed housing and would need special premises for the work. The module is exchanged and maintenance work is to be done elsewhere. 93E power module fans are attached straight on detachable front panel with total of 6 M4 screws, similarly as static switch fan. The front panel itself is attached to frame with seven M4 screws. Fans are secured to the panel by two M4 screws each. The power module fans on the 93E are easily replaced, changing of the power module capacitors on other hand needs substantially more disassembly, but can be done onsite.

A four field analysis of the proposed changes to the product design is presented in figure 41, where the difficulty of action is presented in horizontal rows and impact on DFA in vertical columns. As can be seen some easy to apply actions result in high impact on DFA, for example common parts and components.

	LOW IMPACT ON DFA	HIGH IMPACT ON DFA
EASY TO APPLY	-Standardization of material thicknesses -Standardization of hole geometries	-Common parts/components -Standardization of fastener types and methods of affixing
DIFFICULT TO APPLY		-Universal frame design -Parametric modularity -Improving maintainability

Figure 41. Four-field analysis of proposed design changes.

6 DISCUSSION

DFMA analysis has been used to improve electronic devices for decades. For example, Dell corporation designed their Optiframe® computer chassis utilizing DFMA method. They achieved 32 percent reduction in assembly time, 50 percent reduction in purchased part count, 67 percent reduction in screw types and 44 percent reduction in average service time. (DFMA, 2018a) Whirlpool reached a 29 percent reduction of part count and 26 percent reduction in assembly time by following DFA guidelines when redesigning their microwave oven. (DFMA, 2018b).

6.1 Objectivity and reliability of results

Standards concerning UPS-devices give goals for design work by setting certain requirements for the products, but seldom give concrete means to achieve them. Set limits are given, but means to reach them are not stated. This makes design of new UPS products a guessing game in some extent. For example, the EMI levels are set by standards, but the way to achieve acceptable levels are left to manufacturer. Typically EMI levels of the device are found out in the testing phase of the prototype.

The main literary sources used can be considered to be the corner stones of DFMA literature and they are frequently cited in studies and scientific papers. The literature supports the findings and observations of this study.

Initial intention was to use DFMA-questionnaires to evaluate modularity, but the unsuitability of these questionnaires for the task came apparent as the work progressed. The sheer workload to modify the questionnaires to suit evaluation of modularity would have been overwhelming, as clear methods for analyzing modularity are lacking. The existing DFMA-questionnaires suit improving DFM and DFA aspects of a product, but when applying those to large assemblies like studied products the task easily becomes very large even if only cabinet frame parts would be examined.

Some difficulties were encountered accessing the product 3D models, the original models are designed with PTC’s Creo-software and converted to SolidWorks form. Opening of the models took considerably long time, especially models of the 93E. Some of the mounting hardware in the models had been lost during conversion, some of the part orientations were also wrong. There are some obscurities between part and assembly names in models and bill of materials.

Evaluation of the effect of proposals compared to previous solutions is difficult before prototype of the improved product is manufactured and measurements of, for example, assembly time for both versions have been done and compared. However it can be assumed that simpler product with fewer parts is faster to assemble bringing the manufacturing cost down. Simpler parts are easier and faster to manufacture, thus they can assumed to be cheaper to purchase. Utilizing universal parts and components across product series and families degreases number of different items in storage and also increases the lot sizes ordered, which both can be assumed to lower price per item.

6.2 Key findings

One of the main objectives for the research was set to assess the modularity and product family thinking of different product variants and resulting product families of uninterruptible power supplies. There were indications of product family thinking inside product series, but not between different product series. Modular features could be recognized especially in 93PS series, for example detachable power module and scalable battery capacity. It is possible to increase the modularity in UPS product families by using common components and parametric modularity when designing the future products and product families. To succeed in the task requires tight collaboration between different design departments, financial department and subcontractors not only locally, but across the globe.

Even without clear methods for analyzing the grade of modularity of different designs, the literature gives ways to improve cost-effectiveness of a product. Simplifying design, using standardized fasteners, using same parts in different products, using standardized geometries et cetera can be used to reduce manufacturing costs. Relation between theory and practice is presented in figure 42.

Literature	Practice
Simplify design	• Part integration -> reduced part count • Eliminate unnecessary features • Standardize/constrain fastener type variety • Standardize/constrain methods of affixing
Modular geometries	• Standardize/constrain hole diameters, fillet radiuses, slot widths etc. • Standardize/constrain sheet metal thicknesses • Similar solutions in different product lines
Modular components	• Universal parts for different product lines • Universal frame design for multiple products • Standardize/constrain available PCB dimensions and mounting point locations
Assembly/Disassembly -> Maintainability	• Make main maintenance items easy to access • Standardize/constrain fastener type variety and methods of affixing ->Less tools & different actions

Figure 42. Relation between theory, presented in literature, and practice

6.3 Novelty value, and generalization and utilization of the results

As different product series are designed and manufactured in different regions of the globe, the idea of single frame for multiple product series can be challenging to implement. The strategy for design is completely different in Espoo than it is in China, labor and other costs are significantly different in these places. However, in the future the single frame design could be viable option as costs continue rising in Asia and margins will shrink.

The future development of competitor devices must be also taken into account. There will be pressure to cut manufacturing costs, as the quality and features of products of low-cost production countries are catching up to western made products.

Solar electric power plants becoming more common will demand more energy storage capacity that could be met by utilizing UPS-systems. This means growing markets and the demand of systems, which in turn mean the need to produce devices in shorter lead-time.

6.4 Topics for future research

As was noted in the cross disciplinary teams meeting, the layout of the PCB's could be optimized to produce more compact circuit board designs. There is a possibility to integration some of the PCB's. The idea of same PCB's used in multiple products was also thought of.

When studying the material provided by Eaton a notion of possibility to improve utilization of PDM-system in the company was raised. The system could steer design, material selection etc. by setting constrains and design rules inside the system. Well organized PDM-system could ensure utilization of existing parts and part designs from all Eaton offices and design teams in designing of new products. Dividing design tasks between offices would also be easier with PDM-system.

7 SUMMARY

By setting up design rules and constraints, the design and construction of power electronic devices cabinets could be kept uniform. If existing design could be used for new product, there is no sense in designing a new one. Uniformity in designs requires knowledge about work done in design teams in all company locations, this can be achieved with global wide utilization of PDM system. PDM system can also reduce the amount of unnecessary work, as all already designed parts and components are available for every designer to use.

It is shown that the design of the cabinet frame of UPS device can be simplified, component count can be reduced and production costs lowered by following guidelines presented in thesis. Examples of ways to improve design were given in forms of tables, images and text. The results might seem like insignificant first, but as only two products were studied and very different design solutions were found, it can be supposed that the variety of different solutions is much greater in whole product range. By harmonizing designs between different products the developing, production, inventory, maintenance and supporting cost can be brought down significantly.

The task of redesigning of the current cabinets following guidelines given in the thesis was realized to be overwhelming and somewhat useless, as there was no possibility to test requirements for the devices set in the standards. It was also stated that making major changes to the construction of the current products before end of design life is highly unlikely. Nevertheless, given instructions can be applied when designing a new cabinet or improving the design of existing cabinet on any similar power electronics devices in the future.

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QUESTIONNAIRE 4 APPLYING DFMA GUIDELINES IN PRACTICE

Assembly name:____________________ Page number ____/____ Date: _______________
Document NO.:____________________ Made by: ____________ Appr by: ____________

A. Overall assesment of assembly (Questions A 1...13)

Question	Answer	Score	Note!
1. How many parts in assembly?			>10= -1point ≤10= +1point
2. How many modular solutions in assembly?			>2= +1point ≤2= -1point
3. How many separate joining components in assembly?			>3= -1point ≤3= +1point
4. How many different kind of joining components or methods in assembly?			>3= -1point ≤3= +1point
5. How many assembly directions needed?			>1= -1point ≤1= +1point
6. How many different manufacturing methods for parts in assembly?			>2= -1point ≤2= +1point
7. How many different manufacturing and joining methods needed in assembly stage?			>1= -1point ≤1= +1point
8. How many standard components in assembly?			+ 1 point/std part
9. Is there enough space for tools, installation and robot grabbers in assembly stage?	Y/N		YES= +1point NO= -1point
10. Is there place for assembly errors to accumulate? Place:_______________	Y/N		YES= +1point NO= -1point
11. Has design utilized product family thinking?	Y/N		YES= +1point NO= -1point
12. Have the ergonomics of assembly work been checked?	Y/N		YES= +1point NO= -1point
13. Are individual part tolerance requirements in line with assemblys assembly tolerance requirements?	Y/N		YES= +1point NO= -1point
Assembly score:	Σ_1=		

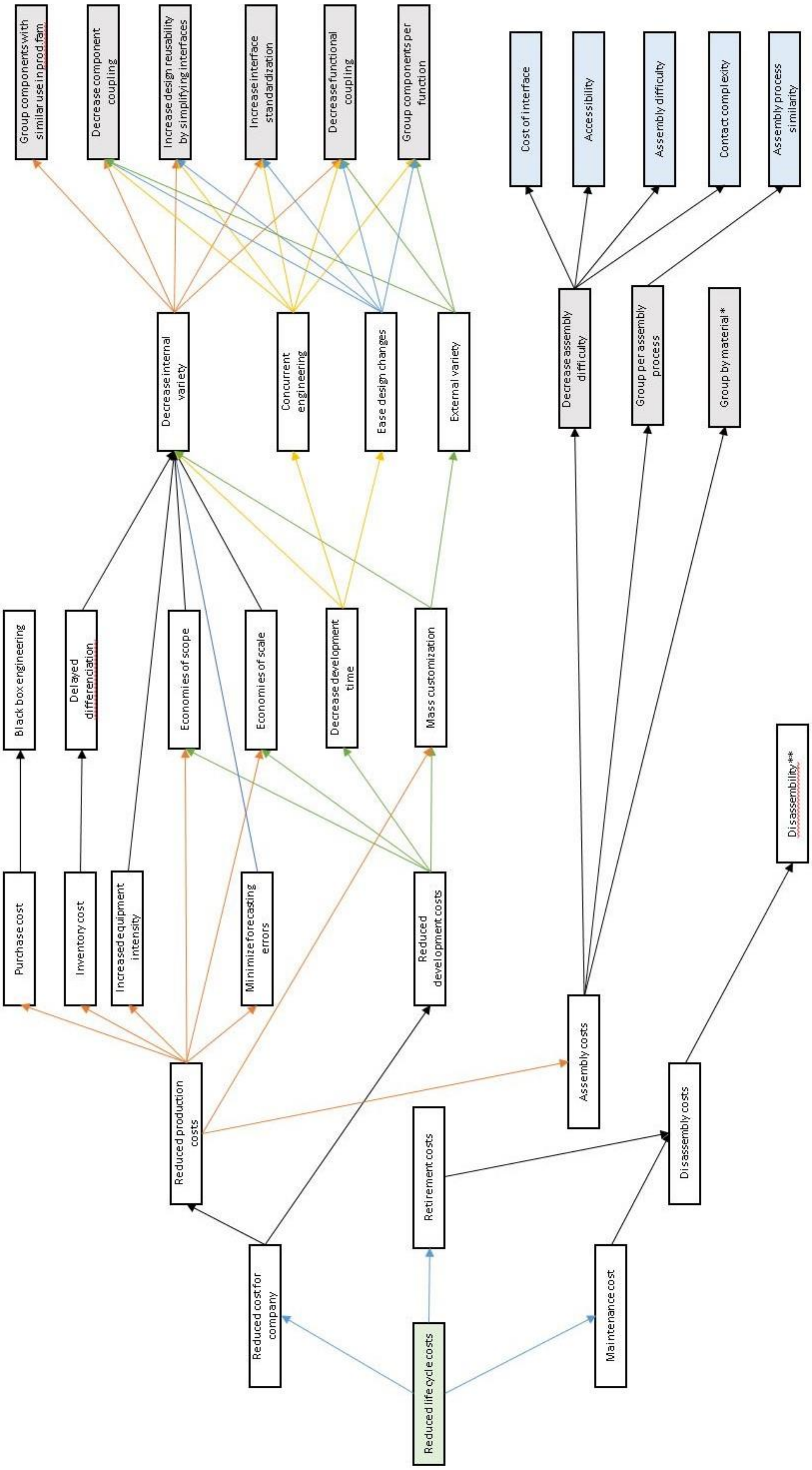
Part name:____________________ Page number ____/____ Date: _______________
Document NO.:____________________ Made by: ____________ Appr by: ____________

B. Assesment of part (Questions B 1...17), repeat questions for each part in assembly)

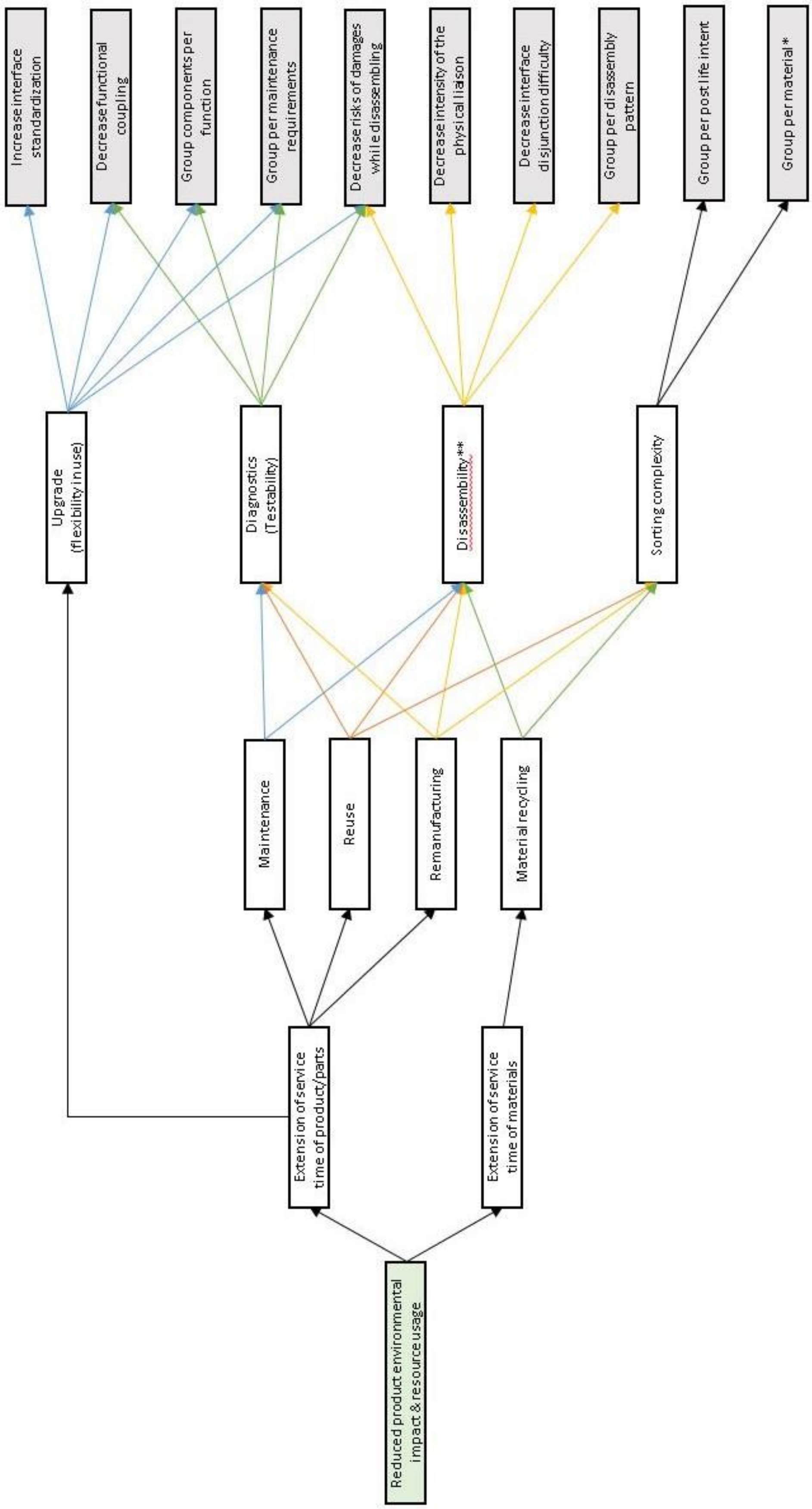
Question	Answer	Score	Note!
1. How many functions for the part?			>2= +1point ≤2= -1point
2. How many manufacturing stages for the part?			>1= -1point ≤1= +1point
3. In how many different aligment can the part be inserted?			>2= +1point ≤2= -1point

4. How many preliminary processing stages manufacturing of the part requires?			>0= -1point 0= +1point
5. How many post processing stages manufacturing of the part requires?			>0= -1point 0= +1point
6. How many manufacturing procedures recur as "modular"?			>2= +1point ≤2= -1point
7. Have the guidelines for ease of manufacturing for manufacturing process been followed?	Y/N		YES= +1point NO= -1point
8. Is there enough space for tools, installation and robot grabbers in manufacturing stage?	Y/N		YES= +1point NO= -1point
9. Can the part be manufactured with standard tools?	Y/N		YES= +1point NO= -1point
10. Has the working allowance been assigned for part? How much:____________________	Y/N		YES= +1point NO= -1point
11. Is the chosen manufacturing method suitable for chosen material? Material:___________________ Manufacturing method:_____________________	Y/N		YES= +1point NO= -1point
12. Is there overall tolerance been assigned for the part? Tolerance:______________________	Y/N		YES= +1point NO= -1point
13. Is there place for manufacturing errors to accumulate? Place:__________________	Y/N		YES= +1point NO= -1point
14. Can the part be tangled to other part in assembly or sorting phase?	Y/N		YES= +1point NO= -1point
15. Has parametric design been utilized in dimensionig of the part?	Y/N		YES= +1point NO= -1point
16. Have the ergonomics of manufacturing work been checked?	Y/N		YES= +1point NO= -1point
17. Are part tolerance requirements for surface quality, dimensions and geometric features in line with eachother?	Y/N		YES= +1point NO= -1point
Part score:	$\Sigma_{part\ 1}=$		
Part total score:	$\Sigma_{parts}=(\Sigma_{part\ 1}+..\Sigma_{part\ n})=$		
DFMA Total score (Assembly + parts):	$\Sigma_{assembly}=\Sigma_1+\Sigma_{parts}=$		

APPENDIX II, 1, Reduced life cycle costs



APPENDIX III, Reduced product environmental impact & resource usage



APPENDIX IV, 1, 93E Fastener variety and geometries

Assembly	Part	pcs in assembly	special fasteners	no of types	note	nut insert	no of types	new types	acc	Stud/pin	no of types	new types	acc	standoff	no of types	new types	acc	pop rivet	no of types	new types	acc	screws	no of types	new types	acc	Washers	no of types	new types	acc	Nut	no of types	new types	acc
Main assemnly									0				0				0				0				0				0				0
									0				0				0				0				0				0				0
Bottom assembly									0				0				0				0				0				0				0
	Main plate	1	4	1	weld nut for stand	8	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0
	Wheel side	2				0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0
	Stiffener plate	1				0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0
Assembly			10	2	Wheels and stands				1				0				0	28	1	1	1				0				0				0
Front posts									1				0				0				1				0				0				0
	Left post	1				1	1	1	2	1	1	1	1	0	0	0	0	0	0	0	1	7	2	2	2	0	0	0	0				0
	Right post	1				1	1	0	2	1	1	0	1	0	0	0	0	0	0	0	1	6	2	0	2	0	0	0	0				0
Assembly									2				1				0				1				2				0				0
Back wall									2				1				0				1				2				0				0
	Main plate	1				0	0	0	2	3	1	1	2	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0				0
	Box	2				0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0				0
Assembly									2				2				0	12	1	0	1	10	2		2				0				0
Powermodule slide rails									2				2				0				1				2				0				0
	Rail	2				0	0	0	2	4	1	0	2	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0				0
Assembly									2				2				0				1	16	2	1	3				0				0
Hinges									2				2				0				1				3				0				0
	Top hinge	1				0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	3	0	0	0	0				0
	Bottom hinge	1	1	1	Hinge stud, 7.12mm	0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	3	0	0	0	0				0
Assembly									2				2				0				1	4	1	0	3				0				0
Side guides, bottom									2				2				0				1				3				0				0
	Guide	2				0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	3	0	0	0	0				0
Assembly									2				2				0				1	16	1	0	3				0				0
Battery tray									2				2				0				1				3				0				0
	Battery tray	1				0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	3	0	0	0	0				0
	Battery holder	2				0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	3	0	0	0	0				0
Assembly									2				2				0				1	15	1	0	3				0				0
Mid tray									2				2				0				1				3				0				0
	Main plate	1				0	0	0	2	14	2	2	4	0	0	0	0	0	0	0	1	0	0	0	3	0	0	0	0				0
	Connector holder, pt1	1				0	0	0	2	0	0	0	4	0	0	0	0	0	0	0	1	0	0	0	3	0	0	0	0				0
	Connector holder, pt2	1				0	0	0	2	0	0	0	4	0	0	0	0	4	1	0	1	0	0	0	3	0	0	0	0				0
Assembly									2				4				0				1	8	1	0	3				0				0
Breaker assembly									2				4				0				1				3				0				0
	Mounting plate	1				0	0	0	2	4	1	0	4	5	1	1	1	0	0	0	1	0	0	0	3	0	0	0	0				0
	Stand for switch	1				0	0	0	2	3	1	1	5	0	0	0	1	0	0	0	1	0	0	0	3	0	0	0	0				0
Assembly									2				5				1				1	4	1	0	3				0				0
Earthing rail									2				5				1				1				3				0				0
	Sheet metal part	1				0	0	0	2	0	0	0	5	0	0	0	1	0	0	0	1	0	0	0	3	0	0	0	0				0
Assembly									2				5				1				1	4	1	1	4				0				0
Power module									2				5				1				1				4				0				0
	Main plate	1				0	0	0	2	10	2	1	6	0	0	0	1	2	1	1	2	0	0	0	4	0	0	0	0				0
	Upper plate	1				0	0	0	2	0	0	0	6	7	1	0	1	0	0	0	2	0	0	0	4	0	0	0	0				0
Assembly									2				6				1				2	2	1	1	5				0				0
Static switch module									2				6				1				2				5				0				0
	Main plate	1				0	0	0	2	0	0	0	6	0	0	0	1	2	1	0	2	0	0	0	5	0	0	0	0				0
Assembly									2				6				1				2	15	1	0	5				0				0
Power module fan									2				6				1				2				5				0				0
	Sheet metal part 1	1				0	0	0	2	0	0	0	6	0	0	0	1	0	0	0	2	0	0	0	5	0	0	0	0				0
	Sheet metal part 2	1				0	0	0	2	0	0	0	6	0	0	0	1	0	0	0	2	0	0	0	5	0	0	0	0				0
Assembly									2				6				1	2	1	0	2	7	1	0	5				0				0
Static switch fan									2				6				1				2				5				0				0
	Sheet metal part 1	1				0	0	0	2	0	0	0	6	0	0	0	1	0	0	0	2	0	0	0	5	0	0	0	0				0
	Sheet metal part 2	1				0	0	0	2	0	0	0	6	0	0	0	1	0	0	0	2	0	0	0	5	0	0	0	0				0
Assembly									2				6				1	2	1	0	2	6	1	0	5				0				0
Xslot									2				6				1				2				5				0				0
	Panel	1				0	0	0	2	1	1	0	6	4	1	0	1	0	0	0	2	0	0	0	5	0	0	0	0				0
Assembly									2				6				1				2	6	1	0	5				0				0
Connector plate									2				6				1				2				5				0				0
	Plate	1				0	0	0	2	0	0	0	6	0	0	0	1	0	0	0	2	0	0	0	5	0	0	0	0				0
Assembly									2				6				1				2	6	1	0	5				0				0
Door									2				6				1				2				5				0				0
	sheet metal, bottom	1				0	0	0	2	0	0	0	6	0	0	0	1	0	0	0	2	0	0	0	5	0	0	0	0				0
	sheet metal, top	1	1	1	hinge stud, 5.40mm	0	0	0	2	0	0	0	6	0	0	0	1	0	0	0	2	0	0	0	5	0	0	0	0				0
	stiffener	1				0	0	0	2	0	0	0	6	0	0	0	1	0	0	0	2	0	0	0	5	0	0	0	0				0
Sheet metal assembly									2				6				1	3	1	0	2	9	1	1	6	0	0	0	0				0
	U-rail	2				0	0	0	2	0	0	0	6	2	1	1	2	0	0	0	2	0	0	0	6	0	0	0	0				0
	lock latch	1				0	0	0	2	0	0	0	6	0	0	0	2	0	0	0	2	0	0	0	6	0	0	0	0				0
	display back cover	1				0	0	0	2	0	0	0	6	0	0	0	2	0	0	0	2	0	0	0	6	0	0	0	0				0
Assembly									2				6				2				2	1	1	0	6				0				0
Plastic shields									2				6				2				2				6				0				0
	plastic shield	2				0	0	0	2	0	0	0	6	0	0	0	2	0	0	0	2	0	0	0	6	0	0	0	0				0
Assembly									2				6				2				2				6				0	16	1	1	1
Battery front panel									2				6				2				2				6				0				1
	Plate	1				0	0	0	2	0	0	0	6	3	2	0	2	0	0	0	2	0	0	0	6	0	0	0	0				1
Assembly									2				6				2				2	22	3	1	7				0				1
Breaker shield									2				6				2				2				7				0				1
	Sheet metal part	1				1	1	1	3	0	0	0	6	0	0	0	2	0	0	0	2	0	0	0	7	0	0	0	0				1
Assembly									3				6				2				2	1	1	0	7				0				1
Panels									3				6				2				2				7				0				1
	Side	2				3	1	1	4	0	0	0	6	0	0	0	2	0	0	0	2	0	0	0	7	0	0	0	0				1
	Roof	1				3	0	0	4	0	0	0	6	0	0	0	2	0	0	0	2	0	0	0	7	0	0	0	0				1
Assembly									4				6				2				2	33	2	1	8				0				1
		47				17			4	41			6	21			2	55			2	198			8	0			0	16			1

APPENDIX IV, 2, 93E Fastener variety and geometries

Assembly	Part	pcs in assembly	note	thickness	new dims	acc	Outline dimensions	Round holes	no of dims	new dims	acc	Round holes countersunk	no of dims	new types	acc	Threaded holes	no of types	new types	acc	Square holes	no of dims	recurring dims	note	Oval holes	no of dims	recurring dims	note	bend operations	no of bend angles	new angles	acc	Fillets	no of dims	new dims	acc	chamfers	no of dims	new dims	acc	cable tie holder	"dimple" hole
Main assembly						0					0				0				0												0				0				0		
						0					0				0				0												0				0				0		
Bottom assembly						0					0				0				0												0				0				0		
	main plate	1		2,00	1	1	47.3 x 495.6 x 664.6	302	2	2	2	34	1	1	1	37	2	2	2	0	0			0	0	0		8	1	1	1	0	0	0	0	0	0	0	0	0	0
	Wheel side	2		2,00	0	1	45.3 x 48.0 x 655.7	15	4	3	5	0	0	0	1	0	0	0	2	0	0			0	0	0		3	1	0	1	2	1	1	1	0	0	0	0	0	0
	Stiffener plate	1		2,00	0	1	45.0 x 390.0 x 536.0	344	2	0	5	0	0	0	1	0	0	0	2	0	0			0	0	0		4	1	0	1	0	0	0	1	0	0	0	0	0	0
						1					5				1				2												1				1				0		
						1					5				1				2												1				1				0		
Front posts						1					5				1				2												1				1				0		
	Post left	1		1,50	1	2	31.4 x 63.1 x 938.4	25	5	3	8	6	1	1	2	14	2	0	2	1	1		9x40	0	0	0		8	1	0	1	16	1	0	1	0	0	0	0	0	0
	Post right	1		1,50	0	2	31.4 x 63.1 x 938.4	26	5	0	8	5	1	0	2	18	2	0	2	0	0			1	1	0		8	1	0	1	17	1	0	1	0	0	0	0	0	0
						2					8				2				2												1				1				0		
Back wall						2					8				2				2												1				1				0		
	Main plate	1		1,50		2	53.0 x 498.6 x 938.4	652	5	4	12	20	2	0	2	19	2	1	3	392	2	1	10x10	0	0	0		15	1	0	1	20	1	0	1	0	0	0	0	6	0
	Box	2		1,20	1	3	16.68 x 49.0 x 417.0	6	1	0	12	0	0	0	2	0	0	0	3	0	0	0		0	0	0		6	1	0	1	4	1	0	1	0	0	0	0	0	0
						3					12				2				3												1				1				0		
Powermodule slide rail						3					12				2				3												1				1				0		
	Rail	2		1,50	0	3	35.5 x 38.1 x 623.5	1	1	0	12	4	1	1	3	4	1	0	3	0	0	0		0	0	0		4	1	0	1	8	1	0	1	0	0	0	0	3	0
						3					12				3				3												1				1				0		
Hinges						3					12				3				3												1				1				0		
	Top hinge	1		2,50	1	4	18 x 25 x 25	0	0	0	12	3	2	1	4	0	0	0	3	0	0	0		0	0	0		1	1	0	1	4	1	0	1	2	1	1	1	0	0
	Bottom hinge	1		2,50	0	4	30 x 18.5 x 27.5	2	1	0	12	0	0	0	4	0	0	0	3	0	0	0		0	0	0		1	1	0	1	4	1	0	1	0	0	0	1	0	0
						4					12				4				3												1				1				1		
Side guides, bottom						4					12				4				3												1				1				1		
	Guide	2		1,50	0	4	40.1 x 40.5 x 590	4	1	0	12	0	0	0	4	4	1	0	3	0	0	0		0	0	0		5	1	0	1	6	1	0	1	0	0	0	1	0	0
						4					12				4				3												1				1				1		
Battery tray						4					12				4				3												1				1				1		
	Battery tray	1		2,00	0	4	41.9 x 457.6 x 649.3	6	2	0	12	0	0	0	4	17	2	0	3	0	0	0		168	1	1	D4x11	10	2	1	2	8	1	0	1	0	0	0	1	0	0
	Battery holder	2		2,00	0	4	38.0 x 55.3 x 413.7	5	1	0	12	0	0	0	4	0	0	0	3	0	0	0		3	1	1	D5.5x11	4	2	0	2	2	1	0	1	0	0	0	1	0	0
						4					12				4				3												2				1				1		
Mid tray						4					12				4				3												2				1				1		
	Main plate	1		1,20	0	4	32.8 X 457.0 X 649.3	239	3	0	12	0	0	0	4	10	2	0	3	1	1	0	20x28	0	0	0		4	1	0	2	12	1	0	1	4	1	1	2	28	0
	Connector holder, pt1	1		1,50	0	4	70.5 x 117.0 x 466	19	1	1	13	4	1	1	5	2	1	0	3	0	0	0		0	0	0		3	1	0	2	6	1	0	1	0	0	0	2	0	0
	Connector holder, pt2	1		1,50	0	4	23.7 x 80.5 x 440	8	2	0	13	0	0	0	5	0	0	0	3	0	0	0		0	0	0		3	1		2	2	1	0	1	0	0	0	2	0	0
Assembly						4					13				5				3												2				1				2		
Breaker assembly						4					13				5				3												2				1				2		
	Mounting plate	1		1,25	1	5	50.0 x 100.0 x 457.2	32	3	0	13	0	0	0	5	4	1	0	3	2	1	1	4.5x (8.5x)	2	1	1	D4.5x	4	1	0	2	10	2	1	2	4	1	0	2	0	0
	Stand for switch	1		1,00	1	6	35.0 x 35.0 x 302.0	4	1	0	13	0	0	0	5	0	0	0	3	0	0	0		0	0	0		6	1	0	2	8	1	0	2	0	0	0	2	0	0
						6					13				5				3												2				2				2		
Earthing rail						6					13				5				3												2				2				2		
	Sheet metal part	1		1,50	0	6	37.8 x 40.0 x 465.0	10	2	0	13	0	0	0	5	4	1	0	3	0	0	0		0	0	0		4	1	0	2	8	1	0	2	0	0	0	2	0	0
						6					13				5				3												2				2				2		
Power module						6					13				5				3												2				2				2		
	Main plate	1		1,50	0	6	34.5 x 454.0 x 647.8	50	6	3	16	0	0	0	5	3	1	0	3	6	1	1	1.5x3.5	2	1	1	D7.5x15.6	9	1	0	2	12	2	1	3	2	1	1	3	3	0
	Upper plate	1		1,20	0	6	31.4 x 236.7 x 452.0	27	7	3	19	0	0	0	5	0	0	0	3	1	1	1	20x28	1	1	0		3	2	0	2	8	2	1	4	0	0	0	3	0	10
						6					19				5				3												2				4				3		
Static switch module						6					19				5				3												2				4				3		
	Main plate	1		1,20	0	6	34.5 x 491.6 x 649.3	54	5	0	19	0	0	0	5	14	2	0	3	4	3	1	4x4	0	0	0		10	1	0	2	20	2	0	4	0	0	0	3	25	0
						6					19				5				3												2				4				3		
Power module fan						6					19				5				3												2				4				3		
	Sheet metal part 1	1		1,20	0	6	43.8 x 179.8 x 458.3	7	1	0	19	8	2	0	5	0	0	0	3	3	2	2		0	0	0		4	1	0	2	8	1	0	4	2	1	1	4	0	0
	Sheet metal part 2	1		1,00	0	6	21.0 x 20.0 x 125.0	2	1	0	19	0	0	0	5	0	0	0	3	0	0	0		0	0	0		4	1	0	2	4	1	0	4	0	0	0	4	0	0
						6					19				5				3												2				4				4		
Static switch fan						6					19				5				3												2				4				4		
	Sheet metal part 1	1		1,20	0	6	81.3 x 191.4 x 458.3	12	2	0	19	6	2	0	5	0	0	0	3	3	2	1	75x75	0	0	0		6	1	0	2	10	1	0	4	0	0	0	4	0	0
	Sheet metal part 2	1		1,00	0	6	21.0 x 30.0 x 125.0	2	1	0	19	0	0	0	5	0	0	0	3	0	0	0		0	0	0		4	1	0	2	4	1	0	4	0	0	0	4	0	0
						6					19				5				3												2				4				4		
						6					19				5				3												2				4				4		
Xslot						6					19				5				3												2				4				4		
	Panel	1		1,20	0	6	79.3 x 162.5 x 202.4	16	6	1	20	0	0	0	5	7	2	1	4	8	6	4		1	1	0		10	2	0	2	14	1	0	4	1	1	1	5	0	0
						6					20				5				4												2				4				5		
Connector plate						6					20				5				4												2				4				5		
	Plate	1		1,20	0	6	1.2 x 195.0 x 448.0	176	3	0	20	0	0	0	5	0	0	0	4	0	0	0		0	0	0		0	0	0	2	4	1	1	5	0	0	0	5	0	0
						6					20				5				4												2				5				5		
Door						6					20				5				4												2				5				5		
	sheet metal, bottom	1		1,00	0	6	33.7 x 500.0 x 910.9	2500	5	0	20	0	0	0	5	2	1	0	4	2	2	0		2	1	1	D6.5x8.4	13	3	2	4	8	1	0	5	3	2	2	7	0	0
	sheet metal, top	1		1,00	0	6	26.0 x 135.2 x 500.0	10	3	1	21	3	1	1	6	8	1	0	4	1	1	0		0	0	0		7	2	0	4	17	1	0	5	0	0	0	7	0	0
	stiffener	1		2,00	0	6	2.0 x 20.0 x 20.0	1	1	0	21	0	0	0	6	0	0	0	4	0	0	0		0	0	0		0	0	0	4	0	0	0	5	1	1	1	8	0	0
Sheet metal assembly			Spot welding			6					21				6				4												4				5				8		
	U-rail, bottom	2		1,00	0	6	9.0 x 29.8 x 330.0	2	1	0	21	0	0	0	6	0	0	0	4	0	0	0		0	0	0		3	2	0	4	8	1	0	5	0	0	0	8	0	0
	lock latch	1		2,50	0	6	15.0 x 17.9 x 25.5	1	1	0	21	0	0	0	6	0	0	0	4	1	1	0	8.4x8.4	0	0	0		2	1	0	4	4	1	0	5	0	0	0	8	0	0
	display back cover	1		0,80	1	7	27.4 x 107.4 x 375.5	11	2	0	21	0	0	0	6	0	0	0	4	1	1	0	22x74.8	1	1	0		7	2	0	4	16	1	0	5	0	0	0	8	0	0
Assembly						7					21				6				4												4				5				8		
Plastic sheets						7					21				6				4												4				5				8		
	Sheet	2				7					21				6				4												4				5				8		
						7					21				6				4												4				5				8		
Battery front panel						7					21				6				4												4				5				8		
	Plate	1		1,20	0	7	15.0 x 458.3 x 508.4	1070	3	0	21	0	0	0	6	0	0	0	4	4	4	1	46.6 x	0	0	0		4	1	0	4	8	1	0	5	0	0	0	8	1	0
						7					21				6				4												4				5				8		
Breaker shield						7					21				6				4												4				5				8		
	Sheet metal part	1		1,00	0	7	41.5 x 73.0 x 124.0	0	0	0	21	0	0	0	6	0	0	0	4	0	0	0		0	0	0		6	1	0	4	13	1	0	5	2	1	0	8	0	0
						7					21				6				4												4				5				8		
Panels						7					21				6				4												4				5				8		
	Side	2		0,80	0	7	21.2 x 665.8 x 938.7	15	2	1	22	0	0	0	6	0	0	0	4	0	0	0		1	1	0		4	2	1	5	4	1	0	5	0	0	0	8	0	0
	Roof	1		0,80	0	7		9	2	1	23	0	0	0	6	0	0	0	4	0	0	0		0	0	0		5	1	0	5	10	1	0	5	0	0	0	8	0	0
						7					23				6				4												5				5				8		
						7		5665			23	93			6	167			4	430				182				202			5	309			5	21			8	66	10

APPENDIX V, 1, 93PS Fastener variety and geometries

Assembly	Part	pcs in assembly	note	special fasteners	no of types	note	nut insert	no of types	new types	acc	Stud	no of types	new types	acc	standoff	no of types	new types	acc	pop rivet	no of types	new types	acc		screws	no of types	new types	acc		Washers	no of types	new types	acc
Top frame																																
	Bottom plate	1		0			10	2	2	2	2	1	1	1	5	1	1	1	2	1	1	1		0	0	0	0					
	EMC plate	1		0			0	0	0	2	0	0	0	1	0	0	0	1	0	0	0	1				0	0					
										2				1				1				1					0					
	Back plate	1		0			2	1	0	2	2	1	1	2	0	0	0	1	0	0	0	1		0	0	0	0					
										2				2				1				1					0					
	Front post left	1		0			0	0	0	2	0	0	0	2	0	0	0	1	0	0	0	1		0	0	0	0					
	Front post right	1		0			0	0	0	2	0	0	0	2	0	0	0	1	0	0	0	1		0	0	0	0					
		1		0						2				2				1				1					0					
	Vertical plate mid	1		0			0	0	0	2	0	0	0	2	6	1	1	2	0	0	0	1		0	0	0	0					
										2				2				2				1					0					
	Top plate	1		0			5	2	0	2	5	1	1	3	11	1	0	2	0	0	0	1		0	0	0	0					
										2				3				2				1					0					
	Right side fixed plate	1		0			0	0	0	2	0	0	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
	Left side fixed plate	1		0			0	0	0	2	0	0	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
										2				3				2				1					0					
	Side rail	2		0			1	1	0	2	0	0	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
										2				3				2				1					0					
	Wire route	1		0			0	0	0	2	0	0	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
										2				3				2				1					0					
	Hinge	1		0			0	0	0	2	0	0	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
										2				3				2				1					0					
	Breaker cover	1		0			0	0	0	2	0	0	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
										2				3				2				1					0					
	Switch cover	1		0			0	0	0	2	0	0	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
										2				3				2				1					0					
	Fan router	1		0			2	1	0	2	0	0	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
										2				3				2				1					0					
	DC-breaker support	1					7	2	0	2	0	0	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
										2				3				2				1					0					
	MCU plate	1		0			2	1	0	2	0	0	0	3	12	2	0	2	0	0	0	1		0	0	0	0					
	Slot CSB	1		1	1	cable tie holder	0	0	0	2	1	1	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
										2				3				2				1					0					
	Terminal support	1		0			0	0	0	2	0	0	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
	Terminal plate	1		0			0	0	0	2	0	0	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
										2				3				2				1					0					
	Input breaker plate	1		0			0	0	0	2	0	0	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
										2				3				2				1					0					
	back plate	1		0			0	0	0	2	0	0	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
										2				3				2				1					0					
	Cable through plate	1		0			0	0	0	2	0	0	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
	Cable access plate	1		0			0	0	0	2	0	0	0	3	0	0	0	2	0	0	0	1		0	0	0	0					
										2				3				2				1					0					
	PM connector plate	1		0			0	0	0	2	7	3	2	5	9	1	1	3	0	0	0	1		0	0	0	0					
										2				5				3				1					0					
	Contactor for relay	1		0			0	0	0	2	0	0	0	5	0	0	0	3	0	0	0	1		0	0	0	0					
										2				5				3				1					0					
	Fuse fix	1		0			0	0	0	2	6	1	0	5	0	0	0	3	0	0	0	1		0	0	0	0					
										2				5				3				1					0					
Assembly										2				5				3	43	2	1	2		49	4	4	4					
Battery compartment										2				5				3				2					4					
	Base	1		4	1	wheel axle with pin	24	3	3	5	4	1	1	6	0	0	0	3	24	1	1	3		0	0	0	4					
	Wheel side panel	2		0			0	0	0	5	0	0	0	6	0	0	0	3	0	0	0	3		0	0	0	4					
										5				6				3				3					4					
	Back plate	1		0			3	1	0	5	0	0	0	6	0	0	0	3	0	0	0	3		0	0	0	4					
										5				6				3				3					4					
	Front post left	1		0			0	0	0	5	0	0	0	6	0	0	0	3	0	0	0	3		0	0	0	4					
	Front post right	1		0			0	0	0	5	0	0	0	6	0	0	0	3	0	0	0	3		0	0	0	4					
										5				6				3				3					4					
	Side guides	2		0			0	0	0	5	0	0	0	6	0	0	0	3	0	0	0	3		0	0	0	4					
										5				6				3				3					4					
	Battery tray	3		0			0	0	0	5	0	0	0	6	0	0	0	3	0	0	0	3		0	0	0	4					
										5				6				3				3					4					
	Battery guide back wall	1		0			0	0	0	5	0	0	0	6	0	0	0	3	0	0	0	3		0	0	0	4					
										5				6				3				3					4					
	Top edge sides	2		0			6	1	0	5	0	0	0	6	0	0	0	3	0	0	0	3		0	0	0	4					
										5				6				3				3					4					
	Connecting piece	4		0			0	0	0	5	0	0	0	6	0	0	0	3	0	0	0	3		0	0	0	4					
										5				6				3				3					4					
Assembly										5				6				3	84	3	0	3	<---N	4	1	0	4	<---NOTE!!				
Door										5				6				3				3					4					
	Frame	1		0			0	0	0	5	0	0	0	6	0	0	0	3	4	1	0	3		0	0	0	4					
										5				6				3				3					4					
	U-profile	1		0			0	0	0	5	0	0	0	6	0	0	0	3	0	0	0	3		0	0	0	4					
										5				6				3				3					4					
	Hinge (stud side)	2		1	1	stud	0	0	0	5	0	0	0	6	0	0	0	3	0	0	0	3		0	0	0	4					
										5				6				3				3					4					
	side bar, hinge side	1		0			0	0	0	5	0	0	0	6	0	0	0	3	0	0	0	3		0	0	0	4					
	side bar, lock side	1		0			0	0	0	5	0	0	0	6	0	0	0	3	0	0	0	3		0	0	0	4					
										5				6				3				3					4					
Assembly				0			0	0	0	5	0	0	0	6	0	0	0	3	4	1	1	4		20	1	1	5		4	1	1	
Joining top to bottom	including battery mounting									5				6				3				4					5					
										5				6				3				4					5					
	battery holder main plate	4		0			0	0	0	5	0	0	0	6	0	0	0	3	0	0	0	4		8	1	0	5		0	0		
	battery holder lock plate	4		0			0	0	0	5	0	0	0	6	0	0	0	3	0	0	0	4		0	0	0	5		0	0		
										5				6				3				4					5					
	battery front cover	1		0			0	0	0	5	0	0	0	6	0	0	0	3	0	0	0	4		10	1	0	5		0	0		
										5				6				3				4					5					
Assembly				0			0	0	0	5	0	0	0	6	0	0	0	3	0	0	0	4		19	2	0	5		0	0		
POWER MODULE										5				6				3				4					5					
	Housing, bottom	1		0			10	2	1	6	12	3	1	7	11	1	0	3	0	0	0	4		0	0	0	5		0	0		
	Spring clip	1		0			0	0	0	6	0	0	0	7	0	0	0	3	0	0	0	4		0	0	0	5		0	0		
	L-hanger, left	1		0			3	1	0	6	0	0	0	7	3	1	0	3	0	0	0	4		0	0	0	5		0	0		
	L-hanger, right	1		0			3	1	0	6	0	0	0	7	3	1	0	3	0	0	0	4		0	0	0	5		0	0		
	Top plate	1		0			0	0	0	6	5	1	0	7	0	0	0	3	0	0	0	4		0	0	0	5		0	0		
	Side bracket	2		0			4	1	0	6	0	0	0	7	0	0	0	3	0	0	0	4		0	0	0	5		0	0		
	Air guide, right	1		0			2	1	0	6	0	0	0	7	0	0	0	3	0	0	0	4		0	0	0	5		0	0		
	Air guide, left	1		0			2	1	0	6	0	0	0	7	0	0	0	3	0	0	0	4		0	0	0	5		0	0		
Assembly				2	1	M4 nut, flange	0	0	0	6	0	0	0	7	0	0	0	3	4	1	0	4		44	1	0	5		0	0		
										6				7				3				4					5					
Fan assembly										6				7				3				4					5					
	Main piece	1		0			12	1	0	6	1	1	1	8	5	1	0	3	0	0	0	4		0	0	0	5		0	0		
	Side piece	2		0			4	1	0	6	0	0	0	8	0	0	0	3	0	0	0	4		0	0	0	5		0	0		
Assembly							0	0	0	6	0	0	0	8	0	0	0	3	0	0	0	4		4	1	0	5					
Sheet metal										6				8				3				4					5					
	Side	2		0			6	1	0	6	0	0	0	8	0	0	0	3	0	0	0	4		0	0	0	5		0	0		
	Roof	1		0			0	0	0	6	0	0	0	8	0	0	0	3	0	0	0	4		0	0	0	5		0	0		
										6				8				3				4					5					
Assembly				0			0	0	0	6	0	0	0	8	0	0	0	3	0	0	0	4		40	1	0	5		0	0		
		77		8			108			6	45			8	65			3	165			4		198			5		4			

APPENDIX V, 2, 93PS Fastener variety and geometries

Assembly	Part	pcs in assembly	note	thickness	new dims	acc	Outline dimensions	Round holes	no of dims	new dims	acc	Round holes countersunk	no of dims	new types	acc	Threaded holes	no of types	new types	acc
Top frame																			
	Bottom plate	1		1,50	1	1	297.5 x 649.7 x 21.5	41	4	4	4	0	0	0	0	0	0	0	0
	EMC plate	1		1,20	1	2	27 x 115	2	1	0	4	0	0	0	0	0	0	0	0
						2					4				0				0
	Back plate	1		1,25	1	3	332 x 584.35 x 50.75	19	3	1	5	8	2	2	2	20	1	1	1
						3					5				2				1
	Front post left	1		1,25	0	3	50.75 x 28.75 x 584.35	4	1	0	5	7	2	0	2	10	1	0	1
	Front post right	1		1,25	0	3	50.75 x 32.75 x 584.35	5	2	0	5	3	1	0	2	8	1	0	1
						3					5				2				1
	vertical plate mid	1		1,50	0	3	440 x 554.50 x 31.50	15	2	0	5	2	1	0	2	8	2	1	2
						3					5				2				2
	Top plate	1		1,50	0	3	201.50 x 649.70 x 33.50	29	3	0	5	0	0	0	2	0	0	0	2
						3					5				2				2
	Right side fixed plate	1		1,20	0	3	18x 31.20 x 592	6	1	0	5	0	0	0	2	0	0	0	2
	Left side fixed plate	1		0,80	1	4	14 x 15 x 517	7	2	0	5	0	0	0	2	0	0	0	2
						4					5				2				2
	Side rail	2		1,20	0	4	24 x 26 x 618.20	26	2	0	5	0	0	0	2	4	1	1	3
						4					5				2				3
	Wire route	1		0,80	0	4	28.80 x 88 x 640	2	1	0	5	2	1	0	2	0	0	0	3
						4					5				2				3
	Hinge	1		2,50	1	5	13 x 20 x 25	1	1	0	5	2	1	0	2	0	0	0	3
						5					5				2				3
	Breaker cover	1		1,50	0	5	26.50 x 297.40 x 581	14	2	0	5	0	0	0	2	4	1	0	3
						5					5				2				3
	Switch cover	1		1,00	1	6	26 x 74 x 86	1	1	0	5	0	0	0	2	0	0	0	3
						6					5				2				3
	Fan router	1		0,80	0	6	105 x 90.50 x 150.50	3	2	0	5	4	1	1	3	0	0	0	3
						6					5				3				3
	DC-breaker support	1		1,20	0	6	63 x 147.40 x 167.40	6	2	0	5	0	0	0	3	0	0	0	3
						6					5				3				3
	MCU plate	1		1,20	0	6	52.10 x 247 x 339.20	19	2	0	5	0	0	0	3	0	0	0	3
	Slot CSB	1		1,20	0	6	25 x 107.9 x 242.40	3	3	1	6	2	1	1	4	5	2	0	3
						6					6				4				3
	Terminal support	1		1,20	0	6	93 x 109.50 x 163.20	8	3	0	6	0	0	0	4	2	1	0	3
	Terminal plate	1		1,00	0	6	7.50 x 35 x 149	1	1	0	6	0	0	0	4	0	0	0	3
						6					6				4				3
	Input breaker plate	1		1,00	0	6	22.43 x 55.50 x 105	2	1	0	6	0	0	0	4	0	0	0	3
						6					6				4				3
	Back plate	1		1,20	0	6	10.50 x 324.20 x 433.10	11	2	0	6	0	0	0	4	3	1	0	3
						6					6				4				3
	Cable through plate	1		1,20	0	6	10 x 165 x 122.80	7	2	1	7	0	0	0	4	2	1	0	3
	Cable access plate	1		1,20	0	6	10 x 176.60 x 137.75	5	2	1	8	0	0	0	4	0	0	0	3
						6					8				4				3
	PM connector plate	1		1,50	0	6	22.5 x 103 x 439	23	4	3	11	0	0	0	4	0	0	0	3
						6					11				4				3
	Contactor for relay	1		1,00	0	6	7.50 x 35 x 80	2	1	0	11	0	0	0	4	0	0	0	3
						6					11				4				3
	Fuse fix	1		1,20	0	6	88.50 x 102.40 x 112.50	10	2	0	11	0	0	0	4	0	0	0	3
						6					11				4				3
Assembly						6					11				4				3
battery compartment						6					11				4				3
	Base	1		1,50	0	6	43.50 x 329.50 x 663.50	32	1	1	12	24	1	1	5	0	0	0	3
	Wheel side panel	2		1,50	0	6	41.50 x 43.50 x 652.50	32	3	1	13	0	0	0	5	0	0	0	3
						6					13				5				3
	Back plate	1		1,25	0	6	50.75 x 332 x 710.63	44	6	1	14	16	1	0	5	6	1	0	3
						6					14				5				3
	Front post left	1		1,25	0	6	28.75 x 50.75 x 694	10	3	0	14	9	2	1	6	8	1	0	3
	Front post right	1		1,25	0	6	32.75 x 50.75 x 694	10	3	0	14	9	2	0	6	10	1	0	3
						6					14				6				3
	Side guides	2		1,50	0	6	15 x 21.75 x 595	18	2	1	15	0	0	0	6	0	0	0	3
						6					15				6				3
	Battery tray	3		2,00	1	7	30 x 297.50 x 644	450	3	0	15	0	0	0	6	0	0	0	3
						7					15				6				3
	Battery guide back wall	1		1,50	0	7	15 x 22 x 290	3	1	0	15	0	0	0	6	0	0	0	3
						7					15				6				3
	Top edge sides	2		1,50	0	7	15 x 45 x 539.90	12	2	0	15	0	0	0	6	0	0	0	3
						7					15				6				3
	Connecting piece	4		1,50	0	7	11.50 x 31.70 x 60	16	1	0	15	0	0	0	6	16	1	0	3
						7					15				6				3
Assembly						7					15				6				3
Door						7					15				6				3
	Frame	1		1,00	0	7	28 x 329 x 1276	6	2	0	15	0	0	0	6	23	1	0	3
						7					15				6				3
	U-profile	2		1,00	0	7	12 x 26 x 220	0	0	0	15	4	1	0	6	0	0	0	3
						7					15				6				3
	Hinge (stud side)	2		2,00	0	7	12.70 x 16 x 41	0	0	0	15	4	1	0	6	0	0	0	3
						7					15				6				3
	side bar, hinge side	1		1,25	0	7	17.35 x 24.50 x 1276	0	0	0	15	6	1	0	6	0	0	0	3
	side bar, lock side	1		1,25	0	7	17.35 x 24.50 x 1276	0	0	0	15	6	1	0	6	0	0	0	3
						7					15				6				3
Assembly						7					15				6				3
Joining top to bottom	including battery mounting					7					15				6				3
						7					15				6				3
	battery holder main plate	4		1,50	0	7	22.5 x 32.2 x 200	8	1	0	15	0	0	0	6	8	1	0	3
	battery holder lock plate	4		1,50	0	7	20 x 20 x 60	8	1	0	15	0	0	0	6	0	0	0	3
						7					15				6				3
	battery front cover	1		1,00	0	7	13 x 297.4 x 652.5	10	1	0	15	0	0	0	6	0	0	0	3
						7					15				6				3
Assembly						7					15				6				3
POWER MODULE						7					15				6				3
	Housing, bottom	1		1,20	0	7	129.1 x 439 x 579.2	8	3	1	16	36	3	1	7	4	1	0	3
	Spring clip	1		0,80	0	7	15 x 111.7 x 10.8	2	1	0	16	0	0	0	7	0	0	0	3
	L-hanger, left	1		1,00	0	7	15 x 13 x 295	0	0	0	16	0	0	0	7	0	0	0	3
	L-hanger, right	1		1,00	0	7	16 x 13 x 295	2	1	0	16	0	0	0	7	0	0	0	3
	Top plate	1		0,80	0	7	14.5 x 439 x 579	0	0	0	16	15	1	0	7	0	0	0	3
	Side bracket	2		1,50	0	7	15 x 16.5 x 60	0	0	0	16	0	0	0	7	0	0	0	3
	Air guide, right	1		0,80	0	7	34.2 x 88.5 x 73	1	1	0	16	0	0	0	7	0	0	0	3
	Air guide, left	1		0,80	0	7	36 x 65 x 75	1	1	0	16	0	0	0	7	0	0	0	3
Assembly						7					16				7				3
						7					16				7				3
Fan assembly						7					16				7				3
	Main piece	1		1,20	0	7	34.8 x 130 x 436	6	3	1	17	12	1	0	7	0	0	0	3
	Side piece	2		1,50	0	7	21.5 x 29.5 x 129	0	0	0	17	4	1	0	7	0	0	0	3
Assembly						7					17				7				3
Sheet metal						7					17				7				3
	Side	2		1,00	0	7	13.7 x 668.5 x 1279.5	16	3	1	18	28	1	0	7	0	0	0	3
	Roof	1		1,00	0	7	20.5 x 335 x 668.5	0	0	0	18	12	1	0	7	0	0	0	3
						7					18				7				3
Assembly						7					18				7				3
		77				7		967			18	215			7	141			3

Assembly	Part	Square holes	no of dims	recurring dim	note	Oval holes	no of types	new types	acc	bend operations	no of bend angles	new angles	acc	Fillets	no of dims	new dims	acc	chamfers	no of dims	new dims	acc	cable tie holder	"dimple" hole
Top frame																							
	Bottom plate	2	2	0		1	1	1	1	6	2	2	2	0	0	0	0	0	0	0	0	0	0
	EMC plate	0	0	0		0	0	0	1	0	0	0	2	3	1	1	1	0	0	0	0	0	0
									1				2				1				0		
	Back plate	8	1	1	10x10	3	2	1	2	13	1	0	2	8	1	0	1	0	0	0	0	0	0
									2				2				1				0		
	Front post left	1	1	0		1	1	0	2	6	1	0	2	0	0	0	1	0	0	0	0	0	0
	Front post right	0	0	0		1	1	0	2	6	1	0	2	6	1	0	1	0	0	0	0	0	0
									2				2				1				0		
	vertical plate mid	0	0	0		0	0	0	2	8	1	0	2	13	1	0	1	0	0	0	0	21	8
									2				2				1				0		
	Top plate	3	2	2	6x	0	0	0	2	8	1	0	2	10	1	0	1	0	0	0	0	0	0
									2				2				1				0		
	Right side fixed plate	3	1	0		0	0	0	2	1	1	0	2	6	1	0	1	0	0	0	0	0	0
	Left side fixed plate	2	1	0		0	0	0	2	1	1	0	2	5	1	0	1	0	0	0	0	0	0
									2				2				1				0		
	Side rail	0	0	0		0	0	0	2	8	1	0	2	10	1	0	1	2	1	1	1	0	0
									2				2				1				1		
	Wire route	0	0	0		0	0	0	2	4	1	0	2	6	1	0	1	2	1	1	2	0	0
									2				2				1				2		
	Hinge	0	0	0		0	0	0	2	1	1	0	2	1	1	1	2	2	1	1	3	0	0
									2				2				2				3		
	Breaker cover	43	7	3	6x19, 8x , 10x10	2	2	1	3	5	1	0	2	12	1	0	2	0	0	0	3	0	0
									3				2				2				3		
	Switch cover	0	0	0		1	1	1	4	4	1	0	2	2	1	0	2	6	1	1	4	0	0
									4				2				2				4		
	Fan router	0	0	0		3	2	1	5	6	1	0	2	13	1	0	2	4	1	1	5	0	0
									5				2				2				5		
	DC-breaker support	0	0	0		2	1	1	6	8	2	1	3	5	1	0	2	2	1	1	6	3	0
									6				3				2				6		
	MCU plate	0	0	0		0	0	0	6	13	2	0	3	7	1	0	2	0	0	0	6	0	0
	Slot CSB	7	6	1	9x	1	1	1	7	5	1	0	3	7	1	0	2	0	0	0	6	0	0
									7				3				2				6		
	Terminal support	0	0	0		0	0	0	7	6	2	0	3	5	1	0	2	0	0	0	6	0	0
	Terminal plate	0	0	0		0	0	0	7	4	1	0	3	4	1	0	2	0	0	0	6	0	0
									7				3				2				6		
	Input breaker plate	0	0	0		0	0	0	7	4	1	0	3	13	1	0	2	0	0	0	6	0	0
									7				3				2				6		
	Back plate	224	1	1	10x10	0	0	0	7	13	2	0	3	22	1	0	2	0	0	0	6	0	0
									7				3				2				6		
	Cable through plate	0	0	0		1	1	1	8	5	1	0	3	11	1	0	2	2	1	0	6	0	0
	Cable access plate	0	0	0		2	1	0	8	1	1	0	3	5	1	0	2	0	0	0	6	0	0
									8				3				2				6		
	PM connector plate	32	2	2	10x10, 26.94x	0	0	0	8	7	1	0	3	8	1	0	2	0	0	0	6	0	0
									8				3				2				6		
	Contactor for relay	0	0	0		0	0	0	8	4	1	0	3	4	1	0	2	0	0	0	6	0	0
									8				3				2				6		
	Fuse fix	0	0	0		0	0	0	8	8	2	0	3	4	1	0	2	0	0	0	6	0	0
									8				3				2				6		
Assembly									8				3				2				6		
battery compartment									8				3				2				6		
	Base	2	1	1	4x62	0	0	0	8	6	1	0	3	0	0		2	0	0	0	6	0	0
	Wheel side panel	0	0	0		4	1	1	9	6	1	0	3	12	1	0	2	0	0	0	6	0	0
									9				3				2				6		
	Back plate	167	2	2	6x20, 10x10	0	0	0	9	8	2	1	4	0	0	0	2	6	1	0	6	0	0
									9				4				2				6		
	Front post left	0	0	0		0	0	0	9	6	1	0	4	7	1	0	2	0	0	0	6	0	0
	Front post right	0	0	0		0	0	0	9	6	1	0	4	7	1	0	2	0	0	0	6	0	0
									9				4				2				6		
	Side guides	0	0	0		0	0	0	9	10	1	0	4	12	1	0	2	0	0	0	6	0	0
									9				4				2				6		
	Battery tray	57	4	3	4x62, 10x66, 7.8x30	0	0	0	9	33	2	0	4	24	1	0	2	12	1	1	7	18	0
									9				4				2				7		
	Battery guide back wall	0	0	0		0	0	0	9	3	1	0	4	10	1	0	2	0	0	0	7	0	0
									9				4				2				7		
	Top edge sides	10	1	1	6x9	0	0	0	9	8	2	1	5	0	0	0	2	8	1	0	7	0	0
									9				5				2				7		
	Connecting piece	0	0	0		0	0	0	9	12	2	0	5	0	0	0	2	8	1	1	8	0	0
									9				5				2				8		
Assembly									9				5				2				8		
Door									9				5				2				8		
	Frame	4	2	2	10x22, 16x14	0	0	0	9	12	2	1	6	8	2	2	4	4	1	1	9	0	0
									9				6				4				9		
	U-profile	0	0	0		0	0	0	9	4	1	0	6	0	0	0	4	8	1	1	10	0	0
									9				6				4				10		
	Hinge (stud side)	0	0	0		0	0	0	9	2	1	0	6	8	1	0	4	0	0	0	10	0	0
									9				6				4				10		
	side bar, hinge side	0	0	0		0	0	0	9	2	1	0	6	16	1	1	5	4	2	2	12	0	0
	side bar, lock side	0	0	0		0	0	0	9	2	1	0	6	8	1	0	5	4	2	0	12	0	0
									9				6				5				12		
Assembly									9				6				5				12		
Joining top to bottom	including battery mounting								9				6				5				12		
									9				6				5				12		
	battery holder main plate	0	0	0		0	0	0	9	12	1	0	6	32	1	0	5	0	0	0	12	0	0
	battery holder lock plate	0	0	0		0	0	0	9	4	1	0	6	0	0	0	5	16	1	0	12	0	0
									9				6				5				12		
	battery front cover	160	1	1	10x10	0	0	0	9	4	1	0	6	8	1	0	5	0	0	0	12	0	0
									9				6				5				12		
Assembly									9				6				5				12		
POWER MODULE									9				6				5				12		
	Housing, bottom	214	1	1	10x10	0	0	0	9	11	1	0	6	14	1	0	5	0	0	0	12	0	0
	Spring clip	0	0	0		0	0	0	9	8	2	1	7	4	1	0	5	0	0	0	12	0	0
	L-hanger, left	0	0	0		0	0	0	9	1	1	0	7	8	1	0	5	0	0	0	12	0	0
	L-hanger, right	0	0	0		0	0	0	9	2	1	0	7	5	1	0	5	0	0	0	12	0	0
	Top plate	14	1	1	10x10	0	0	0	9	3	1	0	7	10	1	0	5	0	0	0	12	0	0
	Side bracket	2	1	0		0	0	0	9	8	2	0	7	0	0	0	5	4	1	1	13	0	0
	Air guide, right	0	0	0		0	0	0	9	3	3	1	8	6	1	0	5	0	0	0	13	0	0
	Air guide, left	0	0	0		0	0	0	9	2	2	1	9	6	1	0	5	0	0	0	13	0	0
Assembly									9				9				5				13		
									9				9				5				13		
Fan assembly									9				9				5				13		
	Main piece	313	4	3	5x7, 7x9.5, 10x10	0	0	0	9	8	1	0	9	14	2	1	6	0	0	0	13	0	0
	Side piece	2	1			4	1	1	10	6	1	0	9	12	1	0	6	0	0	0	13	0	0
Assembly									10				9				6				13		
Sheet metal									10				9				6				13		
	Side	0	0	0		0	0	0	10	14	2	0	9	16	1	0	6	0	0	0	13	0	0
	Roof	0	0	0		0	0	0	10	5	2	0	9	4	1	0	6	0	0	0	13	0	0
									10				9				6				13		
Assembly									10				9				6				13		
		1270				26			10	366			9	441			6	94			13	42	8

APPENDIX VI, Electronic component volumes of 93PS

	Electric components						
93PS							
no	desc	note	W	L	H		volume [mm^3]
1	TERMINALS		56	149	55		458920
2	710-FIRST-EMI		87	236	30	*	615960
3	MBS-ASM		85	332	87		2455140
4	710-SURGE-BOARD		50	130	35		227500
5	092-NZMN1-A100		90	145	73		952650
6	INPUT-BREAKER		53	80	67		284080
7	277-019		45	85	98		374850
8	710-09184	communications	176	230	31		1254880
9	710-MCU		163	321,5	30		1572135
10	9P-SSM-HPO-3		175	440	78	with heatsink	6006000
11	STS-FAN		80	80	38		243200
12	710-CT-BOARD		230	305	37		2595550
13	CB-TRIP-TERMINAL		17	45	20		15300
14	G-TERMINAL		17	87	25		36975
15	373-STS-FUSES		75	110	100		825000
1	POWER-DRIVE-BOARD		325	430	85	including all	11878750
2	IO-EMI-BODY		300	430	37		4773000
3	DC-BATTERY ASM		98	350	79		2709700
4	DC-ASSEMBLY		52	730	97		3682120
5	710-INTERFACE-BOARD		200	280	15		840000
6	710-09182	control	75	212	15		238500
7	FANS		120	369	38		1682640
8	FAN PCB		40	55	15		33000
9	PM-TERMINAL-ASSEMBLY		54	356	38		730512
10	098-BAT-EMI		35	70	35	*	85750
						total volume [mm^3]	44572112
						total volume [m^3]	0,044572112

APPENDIX VII Electronic component volumes of 93E

93E							
no	desc	note	W	L	H		volume [mm^3]
1	110-31824	connector	62	387	48		1151712
2	314-02075	connector	30	52	35		54600
3	314-02075	connector	30	52	35		54600
4	gl-emea-20k-switch		235	80	75		1410000
5	710-09794	First EMI	100	260	32		832000
6	nbd6z-125a		54	92	78		387504
7	dlim17		45	85	98		374850
8	9e-200kva-communiate		70	142	17		168980
9	STS-FAN	no 1	80	80	25		160000
10	STS-FAN	no 2	80	80	25		160000
11	PM FAN	no 1	120	120	38		547200
12	PM FAN	no 2	120	120	38		547200
13	PM FAN	no 3	120	120	38		547200
14	710-09790	PM pcb no 1	345	440	35		5313000
15	710-09792	PM pcb no 2	205	246	80		4034400
	710-09793	PM pcb no 3	205	187	80		3066800
	710-09787	PM pcb no 4	262	440	109	including heatsink	12565520
	710-09876	PM pcb no 5	60	165	10		99000
	082-11592	PM transformer 1	73	130	112		1062880
	082-11592	PM transformer 2	73	130	112		1062880
	710-09834	STS pcb no 1	129	460	55		3263700
	712-02893	STS	246	384	75	including heatsink	7084800
	712-02895	cntl interface pcb no 1	75	212	15		238500
	710-09789	cntl interface pcb no 2	230	212	20		975200
						total volume [mm^3]	45162526
						total volume [m^3]	0,045162526

APPENDIX VIII Part integration 93PS