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APPLYING DFMA FOR PRODUCT DEVELOPMENT PROCESS OF PANEL HANDLING MACHINERY

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TIIVISTELMÄ

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DFMA:n soveltaminen paneelinkäsittelykoneiden tuotekehitysprosessiin

Diplomityö

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82 sivua, 10 kuvaa, 6 taulukkoa ja 7 liitettä

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Tässä diplomityössä tarkastellaan kuinka DFMA:ta voidaan soveltaa tuotekehitysprosessiin Dieffenbacher Panelboard Finland:lle tyypillisissä tuotteissa. Työ on tehty lähtökohdasta, jossa ei ole omaa tuotantoa, aiheuttaen rajoituksia valmistus- ja tuotantodatan saatavuudelle. Kyseisille tuotteille on luontaista matalan tuotantovolyymi, joskin kohtalaisen korkean arvo, tyypillisesti valmiin kokoonpanon kokoluokan ollessa useita metrejä ja tuhansia kilogrammoja. Tuotantokustannukset ovat keskeinen ajuri tuotekehityksessä, joskin niiden arviointi on haastavaa, joten tämän diplomityön puitteissa on relevanttia tarkastella DFMA:n sovellettavuutta kyseisille tuotteille.

Työssä tarkastellaan kirjallisuutta liittyen DFMA:han ja erityisesti siihen, mitä ovat ajurit olemassa olevien metodien ja työkalujen takana. Erilaisten tuotteiden luonne valmistuksen ja kokoonpanon osalla vaihtelee suuresti teollisuudenalan mukaan, minkä vuoksi on olennaista ymmärtää, miksi DFMA pyrkii ohjaamaan suunnittelua johonkin suuntaan. Tämän diplomityön puitteessa myöhäisemmässä tuotekehityksen vaiheessa ollutta tuotetta käytettiin esimerkkinä, miten valmistettavuutta ja kokoonpantavuutta voitaisiin arvioida mahdollisimman objektiivisesti mahdollistaen kuitenkin vertailun eri varianttien välillä. Kyseistä esitystavasta muodostetaan erilaisia DFMA:n ideologian mukaisia mittareita tuotettavuuden arviointiin.

Kirjallisuuskatsauksen osalta voidaan todeta, että tunnetuimmat DFMA-työkalut eivät sovellu suoraan esimerkkituotteeseen. Tämä ei kuitenkaan tarkoita, etteikö DFMA:ta voisi soveltaa tuotekehityksessä, sillä tyypillisissä tuotteissa ilmenevät tuotantohaasteet ovat hyvin havaittavissa DFMA:n taustalla olevien ajureiden näkökulmasta. Visuaalinen esitys tuotteen rakenteesta ja tuotantoprosessista on esitetty työssä, josta edelleen voidaan muodostaa DFMA:n kannalta olennaisia mittareita ja kuvaajia. Jatkokehitystarpeita kuitenkin vielä esiintyy esimerkiksi analysointimittareiden realisoinnissa suhteelliselta asteikolta käytännöllisempiin arvoihin.

ABSTRACT

LUT University
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Applying DFMA for product development process of panel handling machinery

Master's thesis

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82 pages, 10 figures, 6 tables and 7 appendices

Examiners: Adjunct Professor Mika Lohtander
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Keywords: DFMA, product development, workshop

In this master's thesis is inspected how the DFMA could be applied to the product development process at typical products of the Dieffenbacher Panelboard Finland. This paper relies on the basis that there is no own production, hence causing limited access to the production data. A typical product in this paper has a low production volume but rather high value, usually product's main assembly's dimensions being in several meters and weight in thousands of kilograms. The production costs are vital, but difficult to estimate driver in the product development, thereby it is relevant to inspect the applicability of DFMA for this case.

The DFMA related literature is reviewed to understand what the drivers behind existing methods and tools are. The nature of production does differ notably as the field of industry varies, thereby it is important to understand why the DFMA tries to direct the product development to a direction or other. Within this master's thesis, a product in its later stages of development process was is used as an example How the manufacturability and assemblability could be estimated as objectively as possible, while still having an option for comparison between different variants. From said method different metrics is formed to analyse the drivers behind the DFMA.

According to the literature review, the most well-known DFMA methods and tools are not directly applicable to the products of this paper. This does not render the use of DFMA out since the typical production challenges can be notified to exist in the drivers of the DFMA. A visual representation of the product's structure and production processes is presented, which allows one to form metrics and graphics that analyse the issues according to the drivers of the DFMA. Further development aspects rose, for example on realising the analysis metrics in more practical values instead from the relative scale.

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This topic was much more in-depth than I did at first thought, hence the more interesting it was. Thereby I thank Dieffenbacher Panelboard Finland for the opportunity to do this master’s thesis. The guidance, feedback and discussion was also vital for the completion of this paper, thus I do thank adjunct professor Mika Lohtander and M.Sc. Kriste Niemelä for supervising this master’s thesis, as well as everyone else who did share a thought during the work.

Lauri Viitanen
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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

ρ	Density of the material [kg/m^3]
A	Number of essential parts
B	Number of non-essential parts
C_m	Machining cost [€]
C_{mat}	Material cost [€/kg]
Ed	Design efficiency [%]
f_i	Value of the i^{th} assigned similarity factor
Q	Batch size
R_m	Machining rate [€/h]
S_o	Overall weighted similarity
ta_i	Basic set-up time for i^{th} machine [s]
tb_{ij}	Set-up time for j^{th} tool, used for i^{th} machine [s]
t_{no}	Non-operation time [s]
t_o	Operation time [s]
T_{su}	Total set-up time [s]
V_w	Volume of the workpiece [m^3]
w_i	Weighting factor for i^{th} similarity factor

Usually processing rates for machines are presented in €/h, thereby the machining rate R_m is in hours in contradiction to the seconds of the SI-units.

Abbreviations

AEM	assemblability evaluation method, used only with Hitachi AEM
BOM	bill of material
CAD	computer aided design
CAM	computer aided manufacturing
CE	concurrent engineering
CNC	computer numerical control
DFA	design for assembling
DFC	design for cost
DFM	design for manufacturing
DFMA	design for manufacturing and assembling
DFP	design for production
DFX	design for X
KC	key characteristic
MAG	metal active gas
MIG	metal inert gas
MOST	Maynard operation sequence technique
MTM	methods time measurement
MS	Microsoft's software, such as MS Excel or MS Visio
NPD	new product development
NVA	non-value adding
PD	product development
VA	value adding

1 INTRODUCTION

This master's thesis explores how design for manufacturing and assembling (DFMA) could be applied into a new product development (NPD) process of panel handling machinery design industry with limited availability to production and manufacturing data. Known DFMA methods are investigated and inspected what are the drivers behind those and how the methods could be applied to reflect the nature of products on hand. This thesis is done during later design phases of an actual NPD process in collaboration with Dieffenbacher Panelboard Finland.

1.1 Motivation

The question of what the customer values in the industry of delivering entire factories and production lines may have rather many parameters and aspects to account in the product development (PD). The design process does have many stakeholders that affect to the direction of the development, arguably the most important ones being the external ones, such as the customer. One obvious parameter that is valued by the customer is the price of the product. How the price forms in the PD process is rather complex and wide question, but one major cost driver is certain from the point of the view of the internal stakeholders' of the PD; the cost of manufacturing and assembling of the product to be delivered at the end.

Vast quantity of academic world agrees that around 70% of the cost of manufacturing operations is formed at the earliest stages of the PD (Lempiäinen 2003, p. viii). The DFMA has been known for several decades, some forms existing already at the early 2000th century, while the abbreviation "DFMA" was presented at 1970s by Geoffrey Boothroyd and Peter Dewhurst. Many other DFMA -related methods have been presented over time, hence the general desire for better manufacturability and assemblability has and does exist strong. Over different industries, applying the DFMA has resulted part count reductions of 50%, which has realised as 45% cost savings at assembling processes and as 30% savings at the cost of entire product (Swift & Booker 2013, p. 3). For Finnish industry, small batch assemblies are typical, which require commonly a vast share of the entire production time and requires a lot of floor area from the production facilities (Ihalainen 2003, pp. 478–479). For assembling volumes less than hundreds of thousands the assembling almost always happens manually, only notable exception being electronic circuit boards (Ulrich & Eppinger 2012, p. 262).

The process of turning the drawings of the machinery and 3D-models into physical product is not always easy, simple, or straight forward, hence determining how the price tag forms for manufacturing and assembling is not simple either. In the limitations of this master's thesis, difficultness of that is aggravated having majority or all manufacturing and assembling to happen by sub-contractors, thus the possibility of inspecting own production performance and product design continuously, on first hand, is reduced. For these issues is presented the DFMA, which mean is to produce a product design that is easier to manufacture and easier to assemble. Even if we do not exactly know what happens at the workshop but knowing and proving that the product is easier to make, according to all stakeholders, should the cost of manufacturing and assembling shift for better direction. Excellent addition to this would be the possibility to prove the effects of the improvements when the cost of production is discussed with the sub-contractor.

The cost of the product is one of the most important aspects in the PD, yet as told by Niazi et al. (2006, pp. 569–570) also the quality of the product, cost, delivery time and flexibility are vital aspects for success. The desire by different stakeholders to have cost estimations is there even though the PD would be still be at the earlier stages, hence the possibility for cost estimation at early on is stressed. The estimations are obviously tied to parameters such as customisation level, nature of available data as well as on product complexity. Vague estimation techniques may be difficult and even cause unfavourable design choices to be made, hence understanding the estimation methods well is vital.

1.2 Research problem and questions

As described in the motivation, the DFMA offers intriguing opportunities, yet its application may not be that easy. To achieve objective and viable solution, should the background be well understood before applying any methods or tools directly on the PD issues on hand. For this master's thesis, can the research problem noted to be:

- Estimating the manufacturability and assemblability within the PD process would allow beneficial information but is difficult, since only limited access to production data is available.

Thereby, within this paper is the research problem inspected through literature review and how that can deliver insight to the issues of PD process of large physical size and weight assemblies. The research question of this master’s thesis is expressed as:

- How can the DFMA -synthesis applied at the PD with structural steel assemblies, which weight and physical size exceed well the limitations of what human can reach and handle without aiding machinery or tools?

The main research question is supported by following two sub-questions, which on the literature review seek to answer:

- What are the main drivers behind the most well-known DFMA methods and tools?
- Why does the existing DFMA tools operate as they do and in which context they are meant to perform?

1.3 Limitations

Due to the nature of production quantity of said machinery, a small volume production is relevant in the terms of this master’s thesis. For current stage, the processing methods such as material removing and forming are focused more, whereas processes related usually higher volumes, such as moulding and casting, are not considered as relevant in this master’s thesis. There are also several production methods that are not very suitable for mainly structural steel assemblies, thereby mainly operations that are realistic at the workshops are mostly inspected. The limitations of this master’s thesis can be expressed as:

- The literature review inspects the phenomena behind the DFMA, not how realised DFMA tools and methods can be applied to the products of this paper. The inspection of the phenomena behind the DFMA is not tied to the nature of the example product to not leave out possibly relevant issues.
- For analysing the example case, not all production processes in existence are relevant, since the products this master’s thesis realise mostly as structural steel assemblies produced at low volumes at sub-contracting workshops. Major production processes in the interest are machining, low volume forming processes, welding, and mechanical assembling.

- The access to the production data is limited, thereby the analysis focuses on inspecting how the PD issues can be inspected on relative scale, without the need to use in-detail production parameters.

1.4 Objective

The target of this master's thesis is to have a look into existing DFMA -methods as a part of a PD process and how those accommodate with the nature of the products of the collaborating company. Possibility of numerical and subjective comparison is a desirable method, thus finding parameters and values to be used that do not include the risk of getting contaminated by user's opinion and experience. Preferably, there is not either a need to make assumptions of the manufacturing and assembling possibilities. The goals under the set limitations can be expressed as:

- How do the drivers behind existing DFMA methods suit for the nature of the collaborating NPD process?
- What kind of estimators can be used to reliably and objectively, and how those could be presented within the environment of is related NPD process?
- What is required for enhancing the PD process to account better the manufacturability and assemblability?

2 THEORETICAL BACKGROUND

The well-known phenomena of “Lean” is focused on the value and performing actions which of the customer is willing to pay while simultaneously minimising everything that does not add value, known as waste. The value should be mostly defined by the most important stakeholders, realising as the customer and as the product user. When the discussion is on the DFMA, one benefit commonly noted is shorter PD times. This tends to be due spending more time on the concept development stages. This consequently allows one to spend less time on the development of initial design and reducing the time spent on the redesign phase. The bigger weight on the conceptual stage allows having beneficial effect to the total lead time of the PD process, which is illustrated on the **Figure *1***. According to Lempiäinen (2003, p. 49) during the PD phases 60 – 85% of the costs are tied, whereas actual production development can have only effect of 15 – 40%. This supports the idea of adding weight to the concept development of NPD and the desire for better cost analysis at earlier stages of the PD process.

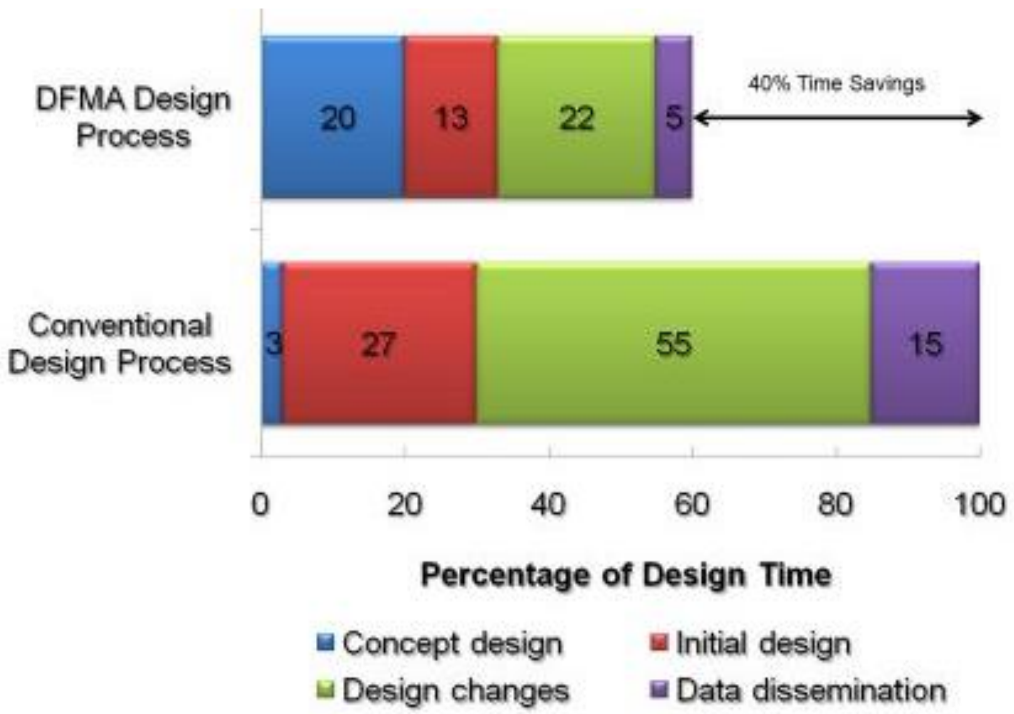

Figure 1. Higher investment into the concept design phase should yield shorter lead time for the entire development process (Boothroyd Dewhurst, Inc. 2020) DFMA.com webpage is commercial DFMA software provider.

2.1 Concept of value at the product development

When considering the word “value” in the PD or as expressed as “Value Engineering” (VE) by Pessôa & Trabasso (2017, p. 60) and the defining the value to be a rate of how much there is function to cost, can the value adding (VA) be considered to happen by improvement of the function or by reduction of the cost. Since the costs can be numerically measured, can it be quickly thought to be the main criteria for the VE. Though, according to Pessôa & Trabasso (2017 p. 60) and Mascitelli (2004, p. 16), the goal should not be only on the cost reduction but also including matters such as performance, reliability, quality, and safety. In value engineering approach should be through functions, which could be the product operating as it is meant to, the function being an element that sells the product or objective achieved by organizational units. The functions are performed for example by components, parts, products, equipment, services, and procedures. Even though cost reduction can usually be seen as the primary objective, according to the idea of VE, it should be on the value. This allows one to modify or remove elements that have the highest contribution to the overall cost without adding actual value to the functions. (Pessôa & Trabasso 2017, p. 60.)

The term “value” is also dependant of the perspective, whether it is the seller or buyer. This can be illustrated through equations as follows (Pessôa & Trabasso 2017, p. 60):

$$Value\ (for\ seller) = \frac{function}{cost} \tag{1}$$

$$Value\ (for\ buyer) = \frac{benefits}{price} \tag{2}$$

The value defined by the user and the customer, is the basis of lean thinking. If the development does not meet the expectations of the customer, no value is provided by the development process. At the PD process, identifying the value requires understanding the necessary characteristics and determining the value that the stakeholders expects to receive. This should emphasize the importance of the correct value identification at early stage since unnoticed problems will be very expensive to resolve, since they cause more waste and rework. Customer can be seen many times as the most important stakeholder and it certainly is in most of the cases, though it is noteworthy that there is also other stakeholders inside and outside of the company that have expectations of the product as well as may have influence to the development process. Failing to take in count all the stakeholders that affect the development with positive or negative impact or not having successful negotiation between them may lead to incorrect result that adds no value. There is also of the risk of incorporating needs by some stakeholders to be pushed into the product, which may very well be non-value adding (NVA). These ones could be such as (Pessôa & Trabasso 2017, pp. 61–62):

- Preconceived solutions, which are used since they have worked before.
- Personal interests to specific solutions.
- Underestimating the difficulty of new technology development. This may lead to exceeding the customer's budget and not answering to their needs.

Stakeholders are actively involved in the development process and their interests may be affected by the execution and completion. Identifying the stakeholders is important, since they are the ones who demand the value as well as may have influence (positive or negative) on the development process. (Pessôa & Trabasso 2017, p. 63.)

2.2 Lean in product development and production

Lean is a process that is about continuously learning and developing such a principles and methods that suits the nature of the organisation its applied. It is about achieving higher performance and being able to deliver better added value to the customer and society. The lean concludes from having uninterrupted flow, whether it is physical material, information, or products. Achievable with use matters such as standardised work, pull flow, clean environment, order, quality management et cetera. Concluding the lean also requires commitment from the management of the organisation, which is willing to invest into the employees and support the continuous improvement. There is wide variety of known lean tools available, but to be lean, one should not just mimic the methods, but understand the how to develop their own organisation as it is and uncompromisingly stay on the path of development. (Tuominen 2010, p. V.) The literate and commercial material about lean is commonly tied closely to the concepts of value and waste, consequently into VA processes and NVA processes. The best-known environment for lean seems to be on the factory floor management, though more academic content is available also, for instance of PD process.

The lean can realise in production at the factory floor through different yet evolving selection tools and techniques. In the manufacturing premises well known lean attributes are for instance as just-in-time inventory management and scheduling, pull systems, flowlines, workcells, and batch elimination. These attributes can be achieved for example by reducing the number of sub-assemblies and part count, assembling only on demand, using such a production processes that batch sizes can be minimised, move towards one-piece-flow, design the product for top-down assembling without orienting, design self-aligning assembling, designing for easier testing and inspection, supporting standardisation in part count and raw materials. (Mascitelli 2004, pp. 191–192.)

According to the basic principles of the lean, value can only be pulled through the value chain of the process. At the factory floor this can be seen as that latter step of the production pulls material and parts from earlier steps, or on other words nothing is manufactured to the storage that is not already requested from the next step. In the PD this does realise as only delivering that that the stakeholders consider important. This is not as easy to put in practise than it is to understand the statement, because (Pessôa & Trabasso 2017, p. 67):

- Too little time put into understanding what the internal and external stakeholders expects. Defining the value is partially result of wishful thinking and preconceived ideas.
- Understanding the stakeholders is not easy, their vision may be different to ours.
- What the value is, is hardly verbalised, thus it is more of a feeling.

2.3 Concurrent engineering

In modern PD environment team working in conjunction with concurrent engineering (CE) can even 80% of the late engineering changes be reduced by removing a lot of the re-doing of tasks caused by too late noted requirements. In the means of teamwork in PD, it does not mean just having one person from engineering department, but also from all other facilities and personnel of the company. (Mynott 2012, pp. 53, 204–205.) The team should act as a permanent core of the project, including one project manager that have authority over the team. The size of the team can vary depending on, if entirely new product is to be developed from a blank paper, or if the product is derivative from an existing one, or if it is just a minor change. The latter ones of the cases might need a smaller team yet allows more merging in the process phases of the development. In the NPD, bigger versatility in the members is recommended and even adding the strategical suppliers to the table of the project could be beneficial. This will bring in the abilities of the supplier and helps both sides mutually by developing the capabilities of both. Having team consisting also of other than initial engineering personnel reduces the formality of communication between departments by making it more natural and allow people to notice issues from different perspective more easily. (Mynott 2012, pp. 53–55.)

2.4 The Design for -methods

The design for X (DFX) -methods are simplifications of actor's interests that are focused on specific matter or subjects of a product in its lifecycle. At the design stage, the DFX methods wants designer to answer to the question of how to have the best fit of the product in its life activities and is defined according to Andreasen et al. (2015, p. 349) as "Design for X is a set of product synthesis methods and guidelines that serve to enhance the product life activities by addressing key issues related to the product and its activities.". The DFMA is one of the better known of these DFX synthesis methods, being divided into design for manufacturing (DFM) and design for assembling (DFA).

In addition to the most common DFM and DFA, several other orientations for designing exists, such as the design for disassembly, recyclability, environment, life-cycle, quality, maintainability and reliability. Said aspects can be subtracted under the abbreviation of DFX. These ones try to force the designer to think over longer timeframe at the entire life-cycle of the product. The timeframe of the design should not end at the moment when the use of the product stops, but the design should also note the recycling process. (Kuo, Huang, & Zhang 2001, pp. 246–254; Ulrich & Eppinger 2012, p. 255.)

The DFX methods should be used at the conceptual stage of the PD, which may be difficult since it is desirable to integrate several DFX-method simultaneously. The CE is a substantial methodology, when it comes to the time-rationalized PD, which allows better life-cycle oriented design by accounting several DFXs. The adoption at the early stage of PD process is not easy always, as said, and three approach classes can be presented, which into the attempts of applying several DFXs simultaneously may fall into (Andreasen & Mortensen 1997, p. 7):

- Co-ordination & timely: Which parameters of the design affects to which life phases of the product and affects to which life-phases’ performance of the system.
- “Look ahead”: Design characteristic decisions is followed up by product life investigation.
- Decision making: Product life consequences are examined with multi-criteria model to find the best design characteristics.

2.5 Design for Manufacturing

The DFM’s main goal is rather simple, help one to design products that are easier to manufacture. Obviously from DFM approach, the product should have better performance, reliability, appearance, maintainability and reduce the burden to the environment, though the main goal being in the reduction of costs. (Lempiäinen 2003, p. 13.) The DFM should be used in conjunction with DFA, since solely focusing on the ease of manufacture is not beneficial in the frame of entire DFMA. Hence, matters such as material and process selection are vital parts of the DFM, since those are affected and do affect to the aspects of DFA, which are discussed later this paper.

The manufacturing costs may be used as a measuring method for the manufacturability, but should not be used on its own, since focusing only on that may cause for example longer lead time or quality issues. In addition to the cost, the DFM analysis should include several aspects in conjunction, hence these can be presented with seven criteria (Lempiäinen 2003, pp. 19–21):

- Quality: Product’s ability to match the product description and specifications. Lack in quality will be seen on difficulties of quality management, quantity of rework and scrap and at warranty rework.
- Manufacturing costs: Fixed costs, variable costs and assemblability indexes.
- Flexibility: Capability to transfer desired changes to finished product.
- Risk: The effects of product structure to the manufacturing operations, quick increase of production volume (ramp-up).
- Lead time: ability to have low lead time, basic product, customer specific orders.
- Efficiency: Human and business resources.
- Environmental impact: Recyclability, manufacturing processes and dis-assemblability.

2.5.1 Material and process selection

In most of the cases, the selection of possible materials and processes that could be used for each component is wide and the best solution is not always that obvious. To produce a product from raw material is presented on simplified manner on the **Figure *2***, starting hierarchically from primary shaping and ending to assembling and testing. (Swift & Booker 2013, p. 10.) Part geometry design may cause difficulties and consequently higher manufacturing cost, if the capabilities, constraints, and cost drivers of the production processes are not known by the designer. One example of this is small internal corner radiuses for machining processes, as well as on setting too tight tolerances for manufacturing accuracy. One way to avoid such cases is to extend the designer's understanding into the production processes, realising as which kind of processes are difficult and which are the cost drivers of those. One approach could be to work closely with experts of production processes, that can deliver insight into the redesign to achieve easier operations. (Ulrich & Eppinger 2012, pp. 264–265.)

The material and process selection should be considered early at the PD process, and integrated element in the product structure before the decisions of structure and components are made. At the level of individual components, one should be aware of new and different manufacturing processes that might have become available after previous PD processes and make sure that also the suppliers are able to respond to the technology development in their own processes. This is also related to the ensuring the availability to selected components in the future. (Lempiäinen 2003, pp. 15–17.) At the choice of manufacturing process should the design be kept as free as possible, and not tie the choices to specific processes or technologies too soon (Andreasen et al. 2015, p. 357). This is related on how the DFMA should be applied into the PD and is related to the cost of manufacturing. The selection of manufacturing methods that are capable to achieve the desired geometry and requirements is wide, hence as described, require knowledge awareness from the designer. For a brief representation a manufacturing processing options, a tree adaptation of material removal and forming processes by Swift & Booker (2013, p. 11) is presented on the appendix I of this paper. This can be used for instance in the consideration of using sheet and plate metal forming processes instead the material removal processes, like machining to achieve the desired functions for the part. Hereby though, the design approach should be to first recognise and design the functions the part, and then decide the manufacturing method.

The processing method is not always tied to the production methods of the products, since for example according to Chang (2013, p. 40) computer numerical control (CNC) machining has lower setup cost in comparison to forming, moulding or casting. This allows for instance making physical prototypes, CNC machining being effective already at lower production volumes. The selection of suitable manufacturing method is closely tied also to the assemblability, and how easy it is for instance with assembling interfaces. That is furthermore related to the key characteristics (KC) of the product and discussed later in this paper.

As the Design for Cost (DFC) is discussed within the DFM, minimising the costs is a major goal, even though not the only one, as mentioned before. The DFM guides do offer a vast number of "how to" and "how not to", but to simplify the thought behind cost-wise thinking in the manufacturing operations presents a list of rules for minimising the costs (Pahl & Beitz 2007, pp. 561–562):

- Lower the complexity
- Lower the number of separate parts
- Fewer production processes
- Smaller overall dimensions, since material costs do increase disproportionately in comparison to the increasement of dimensions
- Larger volume and bigger batch sizes to reduce the effect of once-only costs (set-ups)
- Minimise precision requirements
- Note environmental viewpoints, for instance by aiming to save energy and material

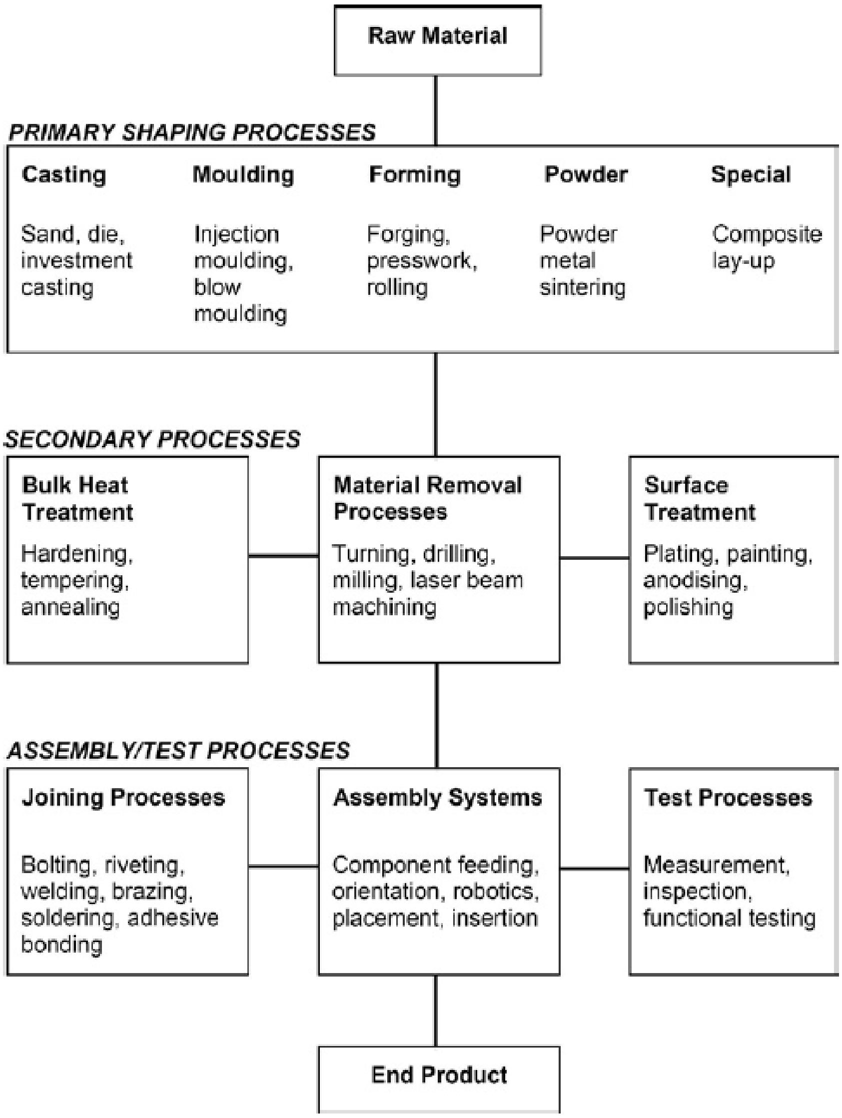

Figure 2. Hierarchy of manufacturing processes (Swift & Booker 2013, p. 10).

2.5.2 Virtual manufacturing

Virtual manufacturing allow designer to visualise and simulate the manufacturing operations in a computer environment. This does allow realising the potential issues in the manufacturing processes as well as estimate the manufacturing cost and time already at quite early steps of the PD process. For instance, for machining purposes a M-code and G-code can be generated by the designers with the use of virtual manufacturing, computer aided design (CAD) and computer aided manufacturing (CAM) being the most popular approaches. The use these requires input from the user in the form of, for example, the workcell, whether it is 3-axial milling machine or something else. (Chang 2013, pp. 40–51.)

Though, the virtual manufacturing may not always represent perfectly the practice, since there is also aspects such as clamping and collision avoiding in machining, reach of the tools limited by the geometry of the workpiece, feedrate and spindle speed suitability with different materials. (Chang 2013, p. 62.)

If the use of virtual manufacturing methods is not found suitable for the use, could the manufacturing complexity be estimated by having difficulty classes that are used to determine the manufacturability. Such a classification is presented on the appendix II by Swift & Booker (2013, pp. 361–362). In said classification, the shapes' have three main categories, a solid of revolution, a prismatic solid and flat or thin wall section. Each shape category is then divided into five complexity bands in increasing difficulty level. Note though that such a classification should be used only as an aid the selection of appropriate complexity level. (Swift & Booker 2013 pp. 361–363.)

2.6 Design for Assembling

The main goals of the DFA are matters such as minimising the numbers of physical elements in the assembly, going towards more ease of working and more fluent flow of actions (Kuo et al. 2001, pp. 244–245). General rule of thumb for better DFA can noted to be: Design for automation, whether it is viable in terms of volume or economical aspects. The simplification of the assembling for automation will also be beneficial at the manual operations. (Lempiäinen 2003, p. 155.)

Assembly's cost and quality are dependent on the type and number of operations that are needed to produce the combination of components and execute the auxiliary work to have a product as it is designed. The type and number of the assemblies are dependent on the layout design of the product, the form design of the components and whether the production is one-off or in batches. Since there is a vast quantity of ways of how the assembling can happen, can the design guidance be no more than lists of hints. Generally, the guide hints target to simplify, standardize, give opportunity for easier automation and have more certain quality of the product. (Pahl & Beitz 2007, pp. 375–376.)

The assembling should be as easy as possible to perform and there are quite many methods to go towards easier operations, such as (Ulrich & Eppinger 2012, pp. 269–270):

- Part insertion from top down, also known as z-axis assembly. This reduces part inverting, allows part stabilisation by gravity, and gives good visibility to the assembling.
- Self-aligning parts reduces the need for slow precision movements. Easy way to achieve with chamfering.
- No need to orient parts since it cumulates the assembling time. Worst case scenario is the need to orient in all three dimensions.
- One hand assembling is the fastest one, especially in comparison to the need of cranes and lifts. This is well related to the size of the part as well as on the need of manipulation.
- Reducing the need for tools at assembling, hence avoid the use of springs, cotter pins, snap rings et cetera.
- Assembling in single linear motion, hence the use of pin is better than screw.
- Securing part by insertion since unstable assembly requires more care, fixturing and generally slower operations.

2.6.1 Assembling interfaces

Bigger products’, such as ships and automotive, can have quite complex body structures causing manufacturing to be expensive, especially if it is to be manufactured from one piece of raw material. The complex body structures usually are composition of several sub-parts, such as beams and panels to achieve more reasonable manufacturing cost. Manufacturing and assembling operations have variations, which do cause more difficulties with the dimensional integrity as the number of parts increases. Having tight tolerance requirement are not quite cost efficient, especially if there is manufacturing operations such as forging and bending, hence relative dimensions between parts can be specified, but the locations of the joints may not be. The contact areas between parts should be designed such a way that a small amount of relative motion between the parts to be joined is allowed. These areas are known as “slip planes” as expressed by Lee & Saitou (2003, pp. 464–465) and for instance, their orientation should be designed such a way that they provide adjustability at the critical dimension’s direction during the assembling stage. With a complex structure of the product, with several critical dimensions, can the figuring out every parts’ slip planes, datum definitions, tolerance planning and assigning them as well as planning the assembling operations be quite an exhaustive operation with several iterations. Optimally there should not be a force needed to be used in order to clamp two parts together, since that will cause, not only residual stresses to the welds and fasteners, but may also alter the shape and dimensions of the parts, depending on how flexible they are. (Lee & Saitou 2003, pp. 464–465.) To achieve the necessary dimensional integrity for the assembly, one needs to understand the joint configurations and assembly sequence to achieve an in-process adjustability for the assembling process. Studies by Lee & Saitou (2003) and Mantripragada & Whitney (1998) offers methods for this assembling accuracy related difficulties with physically bigger sized assemblies. The design process of assembling interfaces should also be noted, since more beneficial assembling actions are achieved as the interfaces are reduced, standardised, and simplified. This yields a reduction in the quantity of connecting elements, operations, and quality requirements between the interfaces to be assembled. (Pahl & Beitz 2007, p. 377.)

Having a "part-centric" approach on the use of CAD does not comprehend with the logic of an assembly at abstract level. To move towards "assembly-centric" design can concept known as datum flow chain be used. At the method, can one realise the assembly problems caused by ineffective datum logic or choice of assembling procedures that do not support the datum logic consistently. The datum flow chain is related directly to the KCs of the product and takes note on the assembling sequence and choices of mating features and allows one to perform tolerance analyses by providing the needed information. (Mantripragada & Whitney 1998, p. 150.)

The KC is a point or a function that is critical for the part or product to perform correctly. The KCs should be realised in the design process to be able to ensure the overall performance of the product as an assembly. Elements such as tolerancing will affect to the locations of parts and features of the part and assembly, thus having an effect to the performance of the KC. As In example shown on the Figure 3 from the research paper by Whitney (2006, p. 316), a principle of KC is expressed. The hammer of the stapler have to align with staple and staple has to align with crimper in order to the stapler to work. The design has two KCs, which should match and can be affected, for example, by tolerancing. (Whitney 2006, pp. 316–317) By identifying the chain that joins the parts to each other in the assembly to join one end of the KC to other and the chain between the interface datums of the parts can in the end use this method to guide the dimensioning and tolerancing of each part. (Whitney 2006, p. 318.) As considering the KCs during the design process should be noted in order (Whitney 2006, p. 316):

1. How to deliver the KCs to the right locations? Where parts should be assembled in respect to each other?
2. How make sure that KCs remains as designed, when considering variation by manufacturing and assembling? When variation occurs, how it affects and what can be done to it?

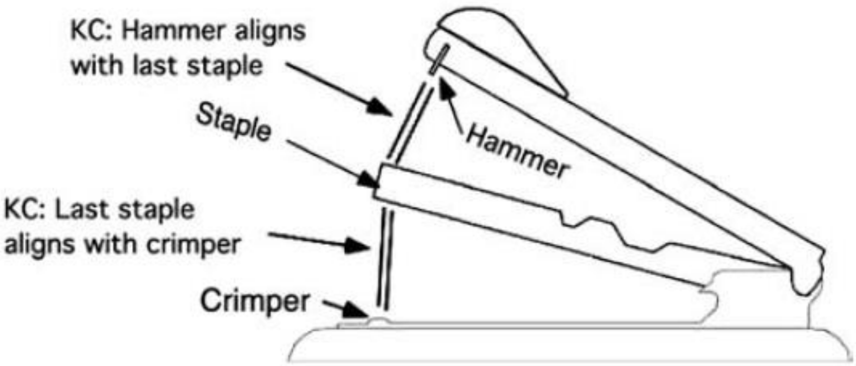

Figure 3. Stapler has two KCs (marked as double lines) that have to align in order to stapler perform as planned. The staple is connected to both, hammer and crimper, thus is affecting to two different KCs. (Whitney 2006, p. 316.)

2.6.2 Assembly sequence

Products can have quite big quantity of possible assembling sequences and the number of separate sequences, which increases rapidly as more parts are added, thus presenting each sequence option individually can be quite difficult in practice. To approach the issue of presenting and evaluating all available alternatives though a systematic and efficient way, two main ways can be used: ordered lists and graphical representations. Ordered list can contain listing of tasks, assembly states, subsets of connections and/or each assembly sequence can be represented by set of lists. The lists may be accurate of all features of the assembly, it is not always the most compact or useful. Graphical representation can be much more compact and useful, for instance by several sub-sequences sharing and assembling states existing in several assembling sequences. (Gottipolu & Ghosh 1997, p. 3448.) Having a method for assembly sequence evaluation would be beneficial to have and could consist for example of (Barnes et al. 1997, p. 3):

- Assembly time in relation to accepted standard
- Quantity of assembly operations in relation to the part count
- Quantity of non-assembly operations in relation to the part count
- Design efficiency
- Handling and fitting ratios
- Conformability analysis

Here is mentioned aspects such as handling and fitting ratios, which are inspected later on in this paper at the chapter 2.8.

There have been cases of developing mathematical models and tools to estimate what would be the most suitable assembling sequence, especially with more complicated assemblies (Kai-Fu, Li & Cheng 2008 pp. 348–349). As an example, a research by Kai-Fu et al. (2008, pp. 348–349) presents an algorithm to evaluate the assembly sequences and has tested it with a component of aircraft's wing. They use in the case five objectives for the evaluation: assembly performance, assemblability, assembly cost, assembly quality and assembly time. They started with four different assembly sequences and did found out by, which one of those was the most optimal. The analysis was done with use of their algorithm and aid of four experts of assembly design, assembly process and assembly operation. (Kai-Fu et al. 2008, pp. 351–354.)

2.6.3 Assembling sequence and tolerancing

As tolerancing and assembling clearances are discussed in relation to the assembling sequence, which can be seen also as a method to shorten the PD time and cost. According to Lu, Fuh & Wong (2006, pp. 5037–5038) an ideal assembly design, each parts' position and orientation can be inferred with a 4 x 4 homogeneous matrix transformation in the assembly, if tolerances is not accounted, which is not realistic in practise. There is deviation from the ideal condition, since manufacturing processes cannot deliver parts in nominal dimensions and geometric shape, and the assembling processes having clearances caused by mating features' geometric tolerances. The deviation of the manufacturing processes does cause the need to use dimensional, positional and form tolerances to the parts at the design stage. The clearances in assembling on the other hand will cause deviations in position and orientation between the mating features of the parts. The manufacturing and assembling related issues accompanied by the order which in the parts are assembled, may the accumulation of positional and orientational deviations cause interferences at the later stages. (Lu et al. 2006, pp. 5037–5038.)

2.7 Manufacture and Assembly together

The DFMA's main benefits are significant cost savings which, as noted before, are a result of systematic review of the functional requirements of the product and using alternative joining processes. These allows replacement of the part clusters by implementing an integrated part. These kinds of solution rely on adoption of more wide variety of used manufacturing processes and used materials. (Swift & Booker 2013, p. 3.) In the PD process is analysing the DFA and DFM simultaneously, the DFA focuses matters such as part count analysis, design for easier handling and insertion and assembly costing, whereas DFM on material and process selection, designing for processing and component costing. (Swift & Booker 2013, pp. 8–9.)

In the DFMA, the assemblability and manufacturability are a bit problematic with each other, since the DFA can be simplified to be reducing the part count and DFM to be reducing part complexity. The reduce of the quantity of parts can be achieved by joining several functions into one part do result more complex parts in term of DFM. Though since material forming has moved from manual processing to CNC in for instance in milling, the difficultness of material forming has come down for more complex solutions. Generally, the assemblability is considered to be more important than manufacturability, since assembling is more labour intensive than manufacturing. In addition, the DFA's desire to reduce the part count it also realises in the fixed costs production, since if a part is removed from assembly, there is no need (Lempiäinen 2003, pp. 69–71):

- To design and test the part
- To manufacture and test the prototype of it, and furthermore manufacture it
- To have a new part under management
- To have a storing facility for the part
- To have a quality assurance and waste in production for that part
- For recycling
- For buying and transporting

Reducing the sources of variability is the way, since as higher precision is desired and more accurate tolerances are set, manufacturing costs increases consequently. Even an exponential relationship may exist between the manufacturing cost and precision, without even including the need of new machinery. The higher precision requirement may not though realise as higher cost at the level of entire product. The benefits of availability of higher precision may realise by allowing new products and capabilities as well as on matter such as performance, reliability, repair, part count reduction and so forth, extending beyond of the delivery of finished product. On the behalf of the DFA, higher precision possibility reduces the selectivity of assembling processes, reducing the need for fitting, removing rework and allowing assembling automation. (Donmez & Soons 2009, pp. 119–120.) Hence, as noted, the precision is not always beneficial in the terms of DFM and is beneficial for DFA, should the matter be inspected on the level of the entire product.

2.7.1 How the DFMA should be applied

The DFMA is a method that can improve the entire PD process to finished, manufactured product. Instead of having separate process for designing the product and then considering manufacturing operations afterwards, the two should happen simultaneously. The CE reflects that that separate actions of entire development process should work hand in hand, in this case meaning manufacturing and assembling being essential elements from the very first steps of the PD (Eskelinen 2013, pp. 7–9; Mynott 2012, p. 219.)

According to Eskelinen (2013, pp. 7–9) the use of DFMA main goals generally can be noted to be:

- Better integration of design and manufacturing
- Saving time and money in the PD
- Improving the quality and reliability of the product
- Shortening the lead time
- Increasing the productivity
- Better capability to respond to the needs of the customers

Whereas the DFMA can be integrated tools such as (Eskelinen 2013, p. 12; Ulrich & Eppinger 2012, p. 255):

- Virtual modelling and manufacturing
- Integrated product teams and interdisciplinary development teams
- Reversed design
- Directed question lists
- Multi-layer optimization
- CE

Before the first implementations of the DFMA at 1970s-1980s, the manufacturing was considered in the design process with the rules of right and wrong. After more extended adoption of the DFMA from the field of DFX, the foundations of manufacturing and assembling rules allowed even 50% reduction of the parts in the automotive industry. The manufacturing and assembling rules do perform well with limited number of manufacturing methods, but phenomena of increasement in the diversity of production methods has been a thing since then. Even though the identifying process for a good solution is easy, the problem articulation and successful designer guiding is much more difficult. For instance, considering the assembling, the designer can be guided to the principles and solutions to design and manage the assembly according to the criteria of optimal assembly as well as the use of assembly friendly design according to the principles related to the structure and connection of the product and individual parts. Such a guide may be a help, but the effect is still dependent of that, is the designer able see the possibilities for better solution. (Andreasen et al. 2015, p. 354.) Since a vast quantity of designers may not have excessive experience of production processes in practise, the awareness of the capabilities and actual production processes may be limited. This may realise in mitigation of problems at the production through, for instance tolerance assignment and specifying the geometries and material, which both have far-reaching consequences. Hence, DFA and DFM are effective ways for product performance measurement and support the designer's experience. (Swift & Booker 2013, p. 4; Ulrich & Eppinger 2012, p. 264.)

For the DFA, a more structured approach would be with creation of an overview of the product's cost structure, challenging quality aspects, required functions and production processes (Andreasen et al. 2015, p. 354). In comparison to the DFA, individual production processes do not have DFM -methods structured. Within this case, the design should be such detailed that analytical approach can be used to fit the processes, equipment as well as tooling in respect to the requirements set by the design. These can be measured with substances such as cost, time, quality, and productivity. (Andreasen et al. 2015, pp. 356–357.) This realises as that one should not design in mind a specific manufacturing process, but more as of to deliver a well detailed production method neutral design and after that see what manufacturing processes could deliver that. Though, according to Andreasen et al. (2015, p. 357) a better way would be to approach would be with the ‘way of building’, which is measured by a cost, in relation to the synthesis design for cost (DFC).

2.7.2 Design for Cost

The value creation for the product and cost reduction are in high significance in competition. There is quite number of factors that affects to the VA and cost of the development, though three main elements is noted to be the manufacturing, fixed and product life costs. The manufacturing costs are variable in relation to the sale volume and do consist of the manufacturing processes, materials, and components. The designers influence is rather easy to follow, since the needed parts and processes that are necessary to create the product are the origin of the cost. The fixed costs are not as directly influenced by the product, consisting of the production means, staff, and organizational activities, being in relation operation and utilization of the equipment, routines, and practises. This realises in practice at matters such as purchase and spare part routines, modularisation, distribution equipment, quality tests, repair routines and so forth. Product life costs are carried by both, the buyer and producer, consisting of installation, application, maintenance, disposal et cetera. There is a decision to be made by the designer, whether the produces should invest more into parts that lasts longer or requiring the buyer handle the cost in the mean of carrying out maintenance on more regular schedule. (Andreasen et al. 2015, p. 357.)

The DFC do not have a define scope that is agreed everywhere, instead it can be seen for instance either to be a virtue or on the other hand as a method that sets a definitive cost goal for the development, which is defined by the markets. As an example, a distribution of costs to “function per organs” can be made, based on the importance to the customer. In such a way, the unbalanced organs that are too costly can be replaced with a cheaper option. In this context, the manufacturing and machining cost and wages gives the cost distribution, a way to perform redesign on the unbalanced manufacturing operations. With these issues, there is an obvious association to the cost drivers of the product, which focus on the higher cost areas. Those can be for instance: modes of action, functionality, and materials. (Andreasen et al. 2015, pp. 357–358.) In relation to the cost reduction, a value analysis is proposed by Pahl & Beitz (2007, p. 15). Existing design can be analysed in respect to the desired functions and costs, followed by solution ideas that are made to meet the new targets (Pahl & Beitz 2007, pp. 15–18).

2.7.3 Design for Production

The production as a term does refer to: producing components with processes, such as primary forming, secondary forming, material removing, finishing, joining, and assembly with transport of the components, quality control, logistics of the material and operation planning. design for production (DFP) subsequently does mean minimising the production costs and time, while achieving the required quality level. (Pahl & Beitz 2007, p. 355.)

From the function structure can an overall layout design made, which determines the product or product division into assemblies, components, identifies the source of the components (in-house, bought, standard part, repeat part), determines the production procedure (for example the possibility of parallel production), approximation of possible batch sizes, means of joining and assembly, establishes the dimensions, defines suitable fits and influences the quality control procedures. (Pahl & Beitz 2007, p. 356.)

A simplification of the production processes by reduction of the number of processing steps is a generally a method that also reduces the costs. A way for reducing excessive processing steps could be substituting entirely new process step. By Ulrich & Eppinger (2012, p. 265) is noted a “net-shape” fabrication, which is described as by producing the final shape in a single manufacturing step, by using for instance moulding, casting, forging or extrusion, which allow to produce almost entirely ready geometry that only needs minor additional processing. (Ulrich & Eppinger 2012, p. 265.)

2.8 Existing DFMA methods

The lightest method is check-in lists that evaluates that where one is going on in the PD process. The check-in lists can be modified and directed to reflect better the products on hand, hence can be better suited for specific company or product family. These could also be integrated into the company's own quality management system, for example as stamp on the design documents that the design is performed following the DFMA guidance and principles. (Lempiäinen 2003, pp. 154–155.) An example list of questions for electro-mechanical product could be as follows (Lempiäinen 2003, p. 155):

1. Can the quantity of the parts in the product be reduced?
2. Can parts be combined by use more advanced manufacturing processes?
3. Is the product divided into sub-assemblies?
    - On what justification?
    - Is there more than one assembling direction in the sub-assembly?
    - Is there lose parts in the sub-assembly?
4. Can all parts be assembled with straightforward movement?
5. Can all parts be assembled with straightforward movement from top down?
6. Are additional fixing parts needed?
    - How many?
    - Are they similar?
    - Can the quantity of those reduced?
    - Can those ones be switched to better performing ones in the automated assembling?
7. Can the quantity of the joining interfaces be reduced?
8. Is there obvious base-part in every sub-assembly?
9. Has to the product be tested after assembling?
    - How?
10. Are the parts dimensions such a way that the tolerances do not sum up?

Whereas by Mascitelli (2004, p. 274) DFMA checklist for mechanical assemblies should include aspects such as:

- Ensuring sufficient access for hand and tools
- Avoid multiple orientations and opt for top-down assembling
- Avoid dissimilar metal interfaces
- Avoid two-part fasteners and prefer captive fasteners and snap fits
- Design components having self-location and self-alignment
- Prefer raw materials in the available standard forms

- Minimum number of operations in machining, aim for single machine processing
- Prefer open slots over holes and closed slots
- Note fixing and holding in the design
- Prefer generous fillets and radiuses over sharp corners

The manufacturability and assemblability has been in the interest for a history of modern manufacturing, though DFMA as a concept was founded around 1970s, as mentioned before. Different methods for DFMA has been developed over the time, and a collection of those was presented on the master's thesis by Owensby (2012, p. 5) and is presented on the Table 1. Earliest presented methods for production estimation is from 1948, whereas latest ones are more targeted or computational implementations of the best-known ones, which are arguably the Boothroyd-Dewhurst, the Lucas DFA and Hitachi AEM. Over the time there has been also several methods that are closely tied to specific companies and their products and production as can be seen from the Table 1.

Table 1. Collection of DFA methods according to the literature review of a master's thesis from Clemson University (Mod. Owensby 2012, p. 5).

DFA method	**Description**	**Developer**	**Date**
Methods-Time Measurement (MTM)	Assign operations with pre defined assembly times to parts	Harold Maynard	1948
Manufacturing Producibility Handbook	Reference manual of manufacturing and assembly guidelines	Corporation (GE)	1960
Boothroyd and Dewhurst method	DFA based on minimum part criteria and handling and insertion difficulties	Academic & Consulting (Boothroyd and Dewhurst)	1977
Assembly Evaluation method (AEM)	DFA based on one motion for one part	Corporation (Hitachi)	1980

Table 2 continues. Collection of DFA methods according to the literature review of a master's thesis from Clemson University (Mod. Owensby 2012, p. 5).

DFA method	**Description**	**Developer**	**Date**
Design for Assembly and Cost Effectiveness (DAC)	Uses 30 key words to evaluate design	Corporation (Sony)	1988
Assembly Oriented Product Design	Accesses a parts functional value	Warnecke & Bassler	1988
Lucas DFA Method	Set of questions to determine assembly time	Academic & Consulting (Miles & Swift)	~1986
MOSIM	Focus of implementing DFA through CAD software	Corporation (Angermuller & Moritzen of Siemens)	1990
DFA Sandpit	Proactive DFA software based on original Lucas method	Academic (Swift & Jared)	2000

As noted, the most common methods for DFMA-analysis that have also appeared as software are the Hitachi AEM, Lucas DFA and Boothroyd-Dewhurst. These methods allow designer to analyse the costs of the assembling actions at an earlier stage of the PD, by using of databases to evaluate numerically the designs. (Lempiäinen 2003, pp. 155–156.) Of these three the Boothroyd -method distinguishes accurately between the manual assembling and different levels of automated assembling. The Lucas -method distinguishes between manual and automation but does not separate the different types of automation in the assembling processes. the Hitachi AEM does not give an explicit consideration to the automation. (Leaney & Wittenberg 1992, pp. 4, 7.)

Important is to note that these methods of Boothroyd-Dewhurst, Lucas and Hitachi, on base level are made to cover up chiefly mechanism-based assemblies that can be assembled on top of the desk in terms of convenient size. For instance, a product in a size and weight of a car, the worker is required to walk, hence DFA methods' synthetic data is not applicable. Maynard operation sequence technique (MOST) or integrated business control, which are high-level methods time measurement (MTM) -based techniques could allow better approach. (Leaney & Wittenberg 1992, p. 9.) To understand and have a general understanding of how DFMA structure appears, in following chapters the Boothroyd, Lucas and Hitachi -methods are explained, even though none of those can be directly used in the case of this master's thesis.

For clarity and numerical presentation, can the basic force values by human for manual assembling actions be defined as (Lempiäinen 2003, pp. 71–72):

- Assembling from seated position by desk
    - assembling force from top-down 20 N
    - active work area 200 mm x 300 mm
    - parts to be assembled from area of 400 mm x 600 mm
- Assembling from standing position
    - manual handling up to 100 N
    - top-down force 50 N
    - natural working area around the workstation is theoretically unlimited, though this causes inclusion of the walking into the processing time

The Hitachi assemblability evaluation method (AEM) analyses the movements and required actions in order to be able to fit, attach and secure the parts on the assembly. Simple and downwards move in assembly is assumed to be the easiest and fastest, thus punishing points in the analysis is given from actions that differs from the described ideal one. In the model of Hitachi, the assembling process is designed to be compared to the best possible one and to give punishment from fabricated assembly data. (Lempiäinen 2003, p. 156.)

In the Hitachi's model, the analysis is performed through assemblability points and assembly's cost ratio. The first one evaluates the difficultness of actions without accounting the efficiency resulted by the quantity of separate parts, whereas the latter one compares how much the costs decreases to the earlier variations of the product. The construction is inspected through part by part, marking up all required assembling actions for specific part. If all actions are ideal, or in other words performed downwards is maximum points of 100 achieved for the part. All diverting actions from the ideal one reduces points off from the 100. Assemblability value for the entire assembly is achieved by having a mean of the all the parts' points. If above 80 is achieved as a mean, the assembly is considered to be good on its assemblability and expected to have low assembling costs. This step though does not take note on the quantity of parts in assembly. In the next step, the assembling time of entire construction, consequently the cost of assembling is compared to previous variation. If the assembling is with 30% less cost, the new variation is considered successful. (Lempiäinen 2003, pp. 156–157.)

In Boothroyd-Dewhurst method, the DFMA is based on timing of the handling and insertion actions, hence might require accurate numbers that are compiled from the floor of specific factory. The Boothroyd -method by Boothroyd and Dewhurst has commercially available software as well as handbook which of both have received updates and newer editions by time the time. The first step is to establish whether the production is performed by high speed automation, robotics or manually, obviously the choice being determined by the desired production volume. Whichever the production method is, improving the assembly starts from the reduction of the number of the parts, by examining each part of the assembly in turn. One should find out if the part exists for fundamental reasons and if not, the part should be eliminated for the sake of simplifying the assembly and assembling operations. If the separate existence of the part cannot be justified, it is considered to have theoretical minimum part value of 0 and if it exists with fundamental reason, it has theoretical minimum part value of 1. In the Boothroyd-Dewhurst method three fundamental reasons for part's existence are (Leaney & Wittenberg 1992, pp. 4–5; Ulrich & Eppinger 2012, p. 268):

- Part does move relative to the other parts assembled
- Part is made of different material in relation to the other ones assembled
- Part is separate allowing assembling or disassembling of the parts already assembled

Whether any of the DFA evaluation techniques chosen by the production volume, a worksheet is filled, every individual part being handled on each one's own row. The handling and inserting actions are accounted progressively, giving operational cost per part. All evaluated parts can then be represented as the total assembling cost and if re-designs are done total results compared. The Boothroyd-Dewhurst method results monetary value for the design, which is further on affected by for instance shop floor wages, automaton equipment cost, payback period and forecast of production volume. (Leaney & Wittenberg

1992, p. 5.) Notable though, that there might be a need to calibrate the constants of the calculation in order to get up to date values. The design efficiency in the Boothroyd-Dewhurst method is the ideal assembling time divided by the estimated assembling time, hence production time estimation is necessary.

The Lucas DFA method is based on point scale, depending on the difficulty of the assembly, thus giving relative measurements instead of absolute values. In the said method, a penalty factors are set to the parts, thus the evaluation of the DFA is not based on the monetary values, like it is based on the Boothroyd-Dewhurst and Hitachi methods. These are associated with the potential problems of the design, including the feeding and inserting the parts during the assembling operations. The Lucas method have three scores of design efficiency, feeding ratio and fitting ratio. (Leaney & Wittenberg 1992, p. 7; Lempiäinen 2003, pp. 157–158.)

During the PD at the functional analysis the parts are divided into two groups, allowing consequently to calculate the design efficiency *Ed* as follows (Leaney & Wittenberg 1992, p. 7):

$$Ed = \frac{A}{A+B} * 100\% \tag{3}$$

In the equation 3, the *A* is number of essential parts and *B* number of non-essential parts in the assembly. This can be used to pre-estimate the design before more effort is put into it, unlike with Boothroyd-Dewhurst method, which assumes that the design exists already. This should reduce the part count of the product and design efficiency should be targeted to be 60% or higher. (Leaney & Wittenberg 1992, p. 7; Lempiäinen 2003 p. 158.) In the Lucas method the feeding and fitting ratios are compared against a database or tables, which from the feeding or fitting indexes are drawn from. For instance, with tolerancing, these tables or database can have the corresponding tolerancing classes to the values that can be used in the comparison process later in the PD process. (Lempiäinen 2003 pp. 158–159.)

Like at the Boothroyd-Dewhurst method, at the feeding analysis of the Lucas method the handling and insertion times are inspected. The problems associated with the handling actions of the parts are scored with the use of appropriate table, thus resulting individual feeding index. The target index value is 1.5 and it should not be exceeded, since then re-design is to be considered. Furthermore, the feeding and fitting ratios of a part of a product can be calculated followingly, the feeding one having optimal value of 1.5 and fitting 2.5 (Lempiäinen 2003, p. 158):

$$Feeding\ ratio\ = \frac{Total\ Feeding\ index}{Number\ of\ essential\ components} \tag{4}$$

$$Fitting\ ratio\ = \frac{total\ fitting\ index}{Number\ of\ essential\ components} \tag{5}$$

If automated assembling is in the mind as designing a product, the Lucas DFA’s evaluation mainly affects to the feeding analysis and questions for it are much more extensive compared to the ones for manual assembly, which ones are also rather different. When comparing to the Boothroyd-Dewhurst -method, the questions are quite a similar, though not as in depth. In the Lucas DFA, fitting analysis question are more similar for manual and automated assembling, differences being on how the penalty indices are allocated. (Leaney & Wittenberg 1992, p. 7.)

In the MTM technique the motion that production requires is predetermined, resulting a set goal time, which represents how long defined operation should take. The set time is found out by analysis, which determines the ideal time that the task requires. Furthermore, the collected data of expected time can be used at for example in production planning. In the building process of MTM, every motion should be segregated into individual motions, which makes the result of the method effective, yet founding the system is very labour intensive. (Dochibhatla, Bhattacharya & Morkos 2017, p. 3.)

Whereas MTM can be used to find the standard times for production, which is rather tedious work with huge quantity of data, the MOST sequence model is a predetermined standard time system for industrial work measurement. In the MOST, in comparison to MTM, there is already set collection of consistently repeating motion patterns that have identifiable sequences, which all are measured in time measurement units, which furthermore can be used for instance at scheduling. (Karim, Tuan & Emrul Kays 2016, p. 979.)

2.9 Estimating the production

The estimation of the cost of the product is beneficial to be able to be done as accurately as possible and as early as possible during the NPD process. Majority of the costs will be committed at the principle solution selection stage of the PD, whereas during the production and assembling opportunities to reduce the costs are quite short. Starting the cost optimisation as early stage as possible will be beneficial, even though that would prolong the design process, since design changes at the production phase will be very expensive. (Pahl & Beitz 2007, p. 535.) Of the production time assembling can account even over 50% and realise as 20% of the total production cost, the rest being on the material and other production actions. Of the assembling operation time only half is actual mating and joining of parts (Samy & Elmaraghy 2010, pp. 1015–1016).

As the cost of the product is tried to be estimated during the PD processes, different methods can be used depending on the stage of the PD process, which are well described on the corresponding literature. Though according to Żywicki & Osiński (2019, p. 117) implementing standard methods from the literature may be rather difficult task with a quite a workload. That may very well be also aggravated with aspects such as insufficient experience and knowledge and the quality of available data being poor. By Hooshmand et al. (2016, p. 24) is noted that top-down methods for cost estimation are more suitable for the earlier phases of the PD process, since detailed information is not yet available, whereas more accurate bottom-up methods goes well at the later stages, when starting estimation from component and detail level is possible. The top-down methods are held on quite high level resulting rather inaccurate outcome. The bottom-up are more data intensive and complex but will yield more reliable estimation. Work breakdown structure may be used to dismantle the project into its components for the bottom-up estimation.

As the DFMA method should produce ability to design more manufacturing and assembling friendly products, should there be a numerical method to compare different solutions to each other, high desire being that that numerical value is in monetary units. In the following chapters is inspected possibilities to estimate the cost of the production with the benefits and drawbacks of different approaches. Major concern in the cost estimation will be the reliability of the results and possibility of wide deviation in the estimated values. The costs of the production can be divided into indirect (overhead) and direct costs, which of the former one in many times is simplified by the use of multiplication factor to the direct cost. From the designer's perspective though, calculating the variable direct costs may very well be sufficient limitation to be able to compare different solution variants. (Pahl & Beitz 2007, pp. 535, 537.)

2.10 Production cost forming

As the sale price of a manufactured good is inspected, the price does form from many other elements other than just the actual material forming and joining actions, such as machining and welding, as can be seen from the **Figure *4***. Other than the primary costs of production, there is quite amount of indirect costs, such as maintenance, supplies, utilities and so forth. Capital investments are also substantial in the field of manufacturing, including matters such as equipment, building and land. Working capital is in addition to the fixed capital (equipment, facility, building) is also necessary, consisting of raw material on hand, purchased parts and hardware from the vendors, and semifinished and finished product in the manufacturing process accounts receivable and day-to-day operations cash. (Chang 2013, pp. 243–244.) As inspecting the Figure 4 **Error! Reference source not found.**and the s cope of this master's thesis, the focus on this paper is on the manufacturing costs and how to estimate those.

The variable costs and fixed costs are implemented differently from a company to company. A common way is that the variable overhead costs are integrated to the direct costs using multiplication factors, such as (Pahl & Beitz 2007, p. 537):

- 1.05 to 1.3 for indirect material cost
- 1.5 to 10+ for indirect production labour cost
- Addition(s) in relation to the machine use

The choice of multiplier depends on the production process and used machine tools, thus it would be beneficial to consider possibility of different production process allowing one to achieve reduce in costs. Modifying the product or production structure may lead to the need to modify also the factory planning. (Pahl & Beitz 2007, pp. 535–537.)

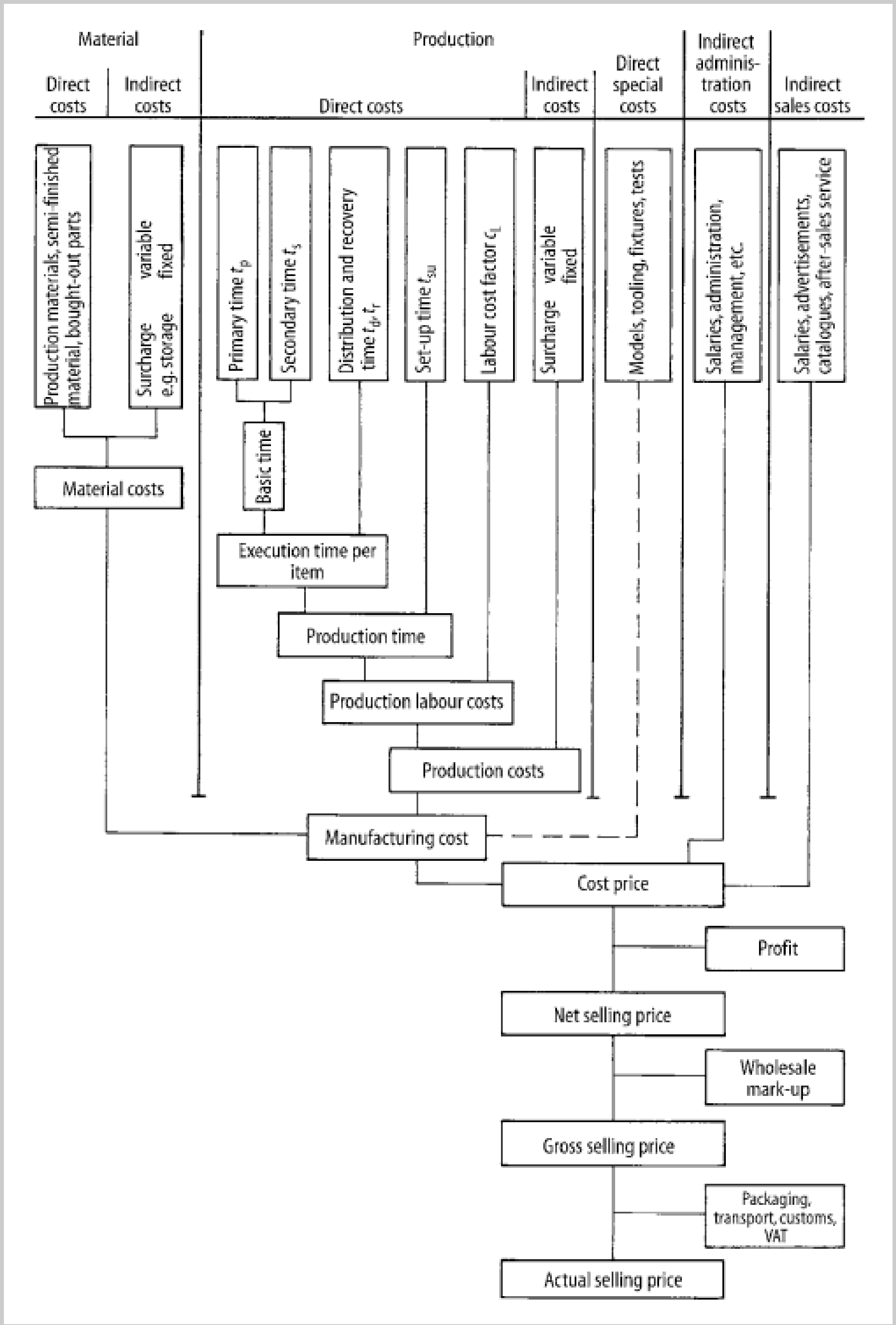

Figure 4. The manufacturing cost forms of many different aspects as is presented by (Pahl & Beitz 2007, p. 536).

The cost structure of semi-similar products' does change in relation to the overall dimensions and batch size. For instance, with bigger batch size the one-off costs like set-ups do get reduced, whereas the share of material cost does increase as the larger dimensions are present. (Pahl & Beitz 2007, pp. 558–560.) Noteworthy addition to the discussion of batch size, is the approach of lean manufacturing at the factory floor. As mentioned by Mascitelli (2004, p. 193) the elimination of batch process in lean manufacturing is hard concept to grasp due to the intuition telling bigger batches being better. Big batches in the production yields long cycle-times and causing product mix to be incremented to the batch sizes, which is furthermore difficult in terms of scheduling. Batches causes higher inventory costs with decreased customer responsiveness of the manufacturing premises as well as cause difficulties on the moving of large-batch equipment and increase maintaining costs and reduce general flexibility.

For the cost estimation of standard components, can the estimation be made by either comparing to similar parts that are already in use or by price quotation from vendor. On the quotation the quantity is rather significant factor. For very high production volumes, such as 100 000 a year, a custom component from the vendor can be economical option which allows having components to be very specified. Noteworthy though is that in the bigger picture, including matter such as field operations, production system, an introduction of new parts does increase the complexity and support costs. (Ulrich & Eppinger 2012, p. 261.)

2.11 Cost estimating methods for product development

Different methods for the cost estimation exist, main methods presented on Table 3 according to Martin, Dantan & Siadat (2007, p. 246). Analogical and parametric methods are the best ones to apply at the conceptual stage of the PD, though the lack of information of the product is problematic, hence yield too rough estimation to allow validify the design choices. (Martin et al. 2007, pp. 245–246; Niazi et al. 2006, p. 570.)

The cost estimation techniques presented on the Table 3 can be divided into qualitative (intuitive and analogical) and quantitative (parametric, analytical) techniques, which of both have their advantages and limitation as presented on

Table 4. Qualitative methods base on comparing to previous experience and use of similarities. Use of the history cost data of previous product present useful here. Regression analysis and neural networks being good examples of methods that can achieve decent accuracy if said history data is available. Quantitative methods are focused on more detailed approach, though are primarily left for later stage use since accurate product data is needed. (Niazi et al. 2006, pp. 563–564.)

Table 3. Accuracy of cost estimation techniques at different stages of the PD (Mod. Martin et al. 2007, p. 246).

	Description	**Best applicable for**	**Accuracy**
Intuition method	Evaluation of cost regarding personal knowledge and intuition.	Preliminary stage	from -30% to 50%
Comparison	Evaluation using similar parts	Preliminary stage	from -30% to 50%
Analogical method	Case-based evaluation, definition of main parameters for comparison with previous cases	Conceptual design	from -14% to 30%
Parametric method	One or several parameters are chosen to be critical. They are used along with coefficients to evaluate the cost	Conceptual design	from -14% to 30%
Analytical method	Direct and indirect costs are considered. Each cost is calculated and then they are all summed to get the product cost	Detailed design	from -5% to 15%

Table 4. Cost estimation methods, their advantages, and limitations. Adapted according to the literature research of (Mod. Niazi et al. 2006, p. 570).

Cost estimation techniques				Key Advantages	Limitations
Qualitative Techniques	Intuitive Techniques	Case-Based Techniques		Innovative design approach	Dependence on past cases
		Decision Support Techniques	Rule-Based Systems	Can provide optimized results	Time-consuming
			Fuzzy Logic Systems	Handles uncertainty, Reliable results	Estimating complex feature costs is tedious
			Expert Systems	Quicker, more consistent & more accurate results	Complex development & programming necessary
	Analogical Techniques	Regression Analysis Model		Simpler method	Data intensive, High dependency on data quality, Linearity issues
		Back Propagation Neural Network Model		Deal with uncertain & non-linear problems	Completely data-dependent, Higher establishment cost
Quantitative Techniques	Parametric Techniques			Utilize cost drivers effectively	Ineffective when cost drivers cannot be identified, Complex development
	Analytical Techniques	Operation-Based Cost Models		Alternative process plans can be evaluated to get optimized results	Time-consuming, Require detailed design & process planning data
		Break-Down Cost Models		Easier methods	Detailed cost information required about the resources consumed
		Cost Tolerance Models		Cost effective design tolerances can be identified	Require detailed design information
		Feature-Based Cost Models		Features with higher costs can be identified	Difficult to idnetify costs for small & complex features
		Activity-Based Cost Models		Easy & effective method using unit activity cost	Require lead-time in the early design stages

If the cost estimation is tied to the matters of DFMA, obviously one should achieve lower costs by applying the said methods, but the accuracy changes as well as applicability of DFMA during different stages of the PD process. The cost is one decisive criterion at the conceptual stage, even though it is highly subjective approximation. With availability of more accurate specifications, trade-offs are made causing for instance worse manufacturability, hence causing higher cost for the product. At the phase when breaking the product into individual components, can be established manufacturability complexity estimations. For accurate cost analysis, the detail level phase of the development is to be reached. (Ulrich & Eppinger 2012, pp. 255–256.)

2.11.1 Common qualitative cost estimating methods

Case-based reasoning at the cost estimation bases on the previously manufactured products, which costs are known. A new product is compared to the earlier ones to know the similarities. The earlier product is set as a basis and new product's price is estimated by making adjustments from the known manufacturing cost. Identifying the similarities allows one to incorporate the previous data at early stage to the NPD allowing one to reduce the need to obtain cost estimations from a scratch. The cost estimation can be performed at the level of entire product or even at the level of individual component or solid feature, obviously if respective data is available. (Chang 2013, p. 249.)

In an analogical technique, the similarities between the new and existing products are identified and quantified. The existing product cost data is used then as a base for the new product with the use of overall weighted similarity, expecting that the product is already on the more detailed level of the development process. (Chang 2013, pp. 249–251; Pahl & Beitz 2007, pp. 539, 547–548.) The cost estimation through weighted similarity S_o can be presented as (Chang 2013, p. 249):

$$S_o = \frac{\sum_i (w_i f_i)}{\sum_i w_i} \tag{6}$$

In equation 6, the f_i is value of the i^{th} similarity factor assigned and w_i is weighting factor of the i^{th} similarity factor.

A regression analysis is a common method of analogical techniques, when it comes to the estimation of the cost based on historical data. If a linear relation can be expected in the cost relation to characteristic parameters, such as weight, diameter, shaft height et cetera, can equation $y = a + bx$ be formed. With relationship like this established, can the cost easily and quickly, within certain limits, be estimated at early step of the design process. Noteworthy though is that that the estimation is not exactly certain. (Chang 2013, p. 249; Pahl & Beitz 2007, p. 545.) The equation is set up graphically and usually requires computer support and may require considerable effort. The regression equation should be built to allow change the parameters to allow easier updating. Simplifications and similarity considerations can be used to the regression analysis to have more easily maintainable cost functions. (Pahl & Beitz 2007, pp. 545–546.)

2.11.2 Common quantitative cost estimating methods

Quantitative techniques are based on analysing the product design in detail, including the features and respective manufacturing processes for those. The cost is calculated by analytical function or by summing together elementary units that represents the resources consumed in the production cycle. These methods are usually usable only at the later phases of the PD due the need for having a detailed product design, including bill of materials (BOM), but gives more accurate result in comparison to qualitative methods. By having a complete product information with required materials and manufacturing and assembling processes for each part, can the product be decomposed to represent the different resources consumed at the production. The analytical techniques as such do provide generally accurate results, if there is available cost data and effort is put into the cost calculations. (Chang 2013, pp. 251–252.)

As an example of the quantitative cost estimation, for instance machining cost C_m can be calculated followingly (Jung 2002, p. 229):

$$C_m = R_m \left(\frac{T_{su}}{Q} + t_o + t_{no} \right) \tag{7}$$

In equation 7, the R_m is machining rate, T_{su} is set-up time, t_o is operation time, t_{no} is non-operation time and Q is batch size. As can be seen, this is rather detailed estimation method requiring, not only detail product information, but also production data, such as dividing between operational time and non-operational time, on other words as VA and NVA times.

In addition to this equation, there is material cost and factory expenses to be added on top of the machining cost. The machining time is composed of set-up time, operation time and non-operation time, as can be seen from the equation 7. The operation and non-operation time are proportional to the quantity how many units is manufactured, whereas the set-up time is proportional to the quantity of how many settings there is in a batch. (Jung 2002, p. 229.)

2.11.3 Estimation of highly customised products

If the estimation is focused on the production time in highly customised products production, three common methods do exist, which are knowledge based, predictive and statistical estimations. In the case of customized products, the production time determining is usually difficult and the methods used at mass production usually become with rather limited usability as the number of product variants increase. (Żywicki & Osiński 2019, p. 118.) There is several methods available in the field of mass-production, such as MTM mentioned earlier in this paper, but the presented three more suitable for customised products can be summarised as (Żywicki & Osiński 2019, p. 119):

- Knowledge-based: employee determines how long it takes finish the production task. Estimation bases on the experience and knowledge of the specific employee
- Statistical: history data of similar or analogical products
- Predictive: history data of similar operations accounting how characteristics of the product, such as dimensions, weight and area, has affected to the duration of inspected operation

In the research paper by Żywicki & Osiński (2019) a simulated manual production process was done to compare the three methods of estimating the production time on five variants of the simulated product, which all had same four processing steps. One of research's results is presented on the Figure 5 as how well the calculated production times reflect the actual measured time. According to the simulated production, in the research is noted that the experience-based estimation is the least accurate, whereas statistical methods is the most accurate, though it needs reliable and large source of good data. Other notable observation in the research (not visible from the Figure 5) was that on the simpler operations results tend to be overestimated, whereas for more complex operations times were underestimated. (Żywicki & Osiński 2019, pp. 120–126.)

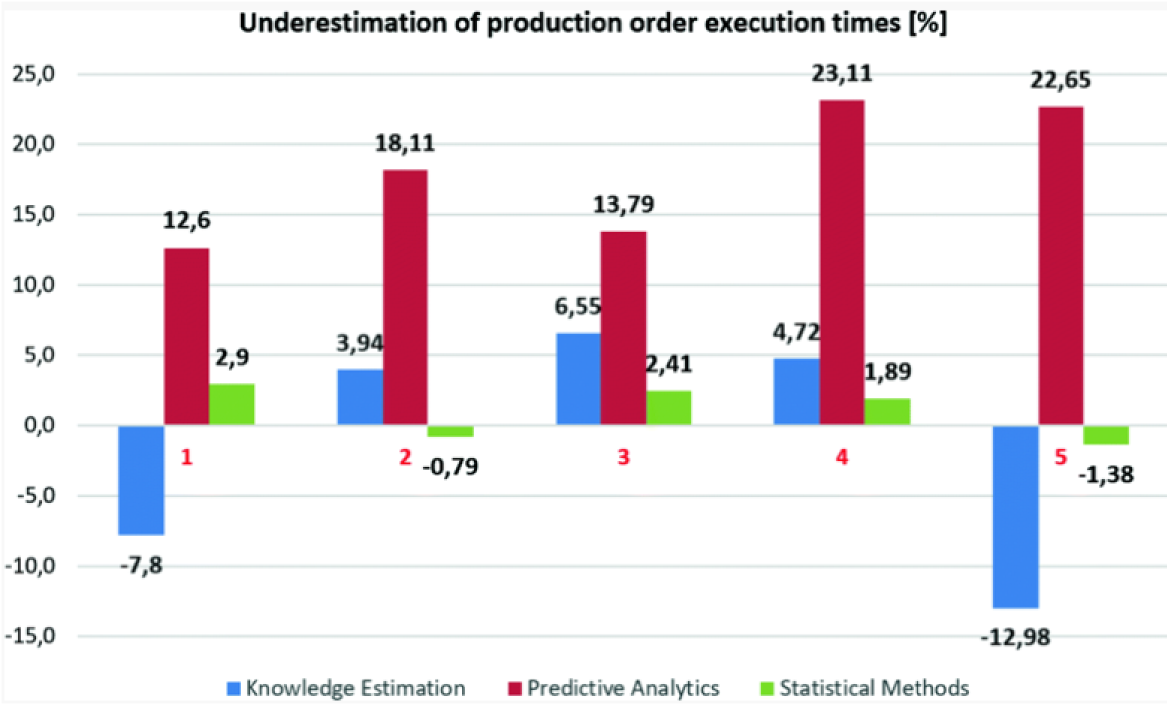

Figure 5. How much the different production time estimation methods differ from the measured time in the research paper of Żywicki & Osiński (2019, p. 125). Values represent how well the evaluation methods reflect to the measured time on five different simulated product variants. Below zero values means underestimating the production time.

2.11.4 Estimating machining cost

Since machining processes produce chips that have no other uses than ones after recycling, the material costs does not include the use of scrap as cost reducing element, but only being the volume of the original workpiece, which of the desired shape is subtracted from. The material cost C_{mat} in subtractive manufacturing operations can be calculated as (Chang 2013, p. 260):

$$C_{mat} = V_w * \rho * C_{mat} \quad (8)$$

In equation 8, the V_w is the volume of the workpiece, ρ density of the material and C_{mat} the cost of the material by weight. As the material cost is expressed on the equation 8, for a machining processes this is quite significant one, often being over 50% of the total cost of a part (Chang 2013, p. 260).

The non-operational time can be divided into the workpiece handling time and tool engaging time, total time being sum of the two. The handling time does consist of, for instance, part handling, loading and unloading at the processing machinery, thus subsequently also of clamping and unclamping. There are also other aspects such as chip cleaning that counts to this time. The tool engaging time consists of matters such as positioning, and feed and speed adjusting. (Chang 2013, p. 259.)

As an example, in the machining, mounting of the stock material to the workbench or feed table is a very critical and time consuming operation, and one should notice for instance the toolpaths and avoid the risk of the workpiece loosening and subsequently moving during processing. Common mounting methods are vises and chucks, though for odd-shaped pieces specialised jigs may be necessary. (Chang 2013, p. 63.)

Whereas the equation 7 presents the machining cost, the machining time itself forms as a sum of set-up time and operation and non-operation times. The set-up time forms from the setup of machine and set-up tools. The set-up time T_{su} can be expressed as follows (Jung 2002, p. 231):

$$T_{su} = \frac{\sum_i ta_i + \sum_i \sum_j tb_{ij}}{Q} \tag{9}$$

In equation 9, the ta_i is basic set up time for i^{th} machine, tb_{ij} set-up for j^{th} tool used for the i^{th} machine and Q batch size.

2.12 Welding production and weldability

As the requirements of the welding process is inspected in conjunction with the quality management system of the sub-contracting workshop, one should pay attention specifically to the welding requirements at the phase of the contract and design review, necessary requirement of welding proficiency of the welding and inspection staff, handling and storing of the material and additives as well as the requirement those set to the welding, used machinery, welding related actions, such as sub-contracting, aftertreatment and aftertreatment temperatures and inspection and testing of the welds accompanied by traceability, rework actions and quality certifications. In addition to these, at the design review attention should be paid on (Lepola 2016, p. 408):

- Weld locations, welding sequence, performing the welding reliably
- Weld shape and surface requirements
- Base material separation and requirements to the welded joint
- Dimensions of the groove, preparation methods and root support
- Workshop welds in comparison to on site welds
- Welding process inspection, its timing and possibility
- Other special requirements (heat treatment, environment et cetera)

In addition to the ever so common metal inert/active-gas (MIG/MAG) welding, there is a variety of other processes available, some to name tungsten insert gas, manual metal arc, spot welding, laser welding, friction welding and so forth, the list being a long one today. Many of the welding processes may be case specific, yet in terms of productivity and DFMA, considering the use other method may yield better outcome. The choosing of the most suitable welding method is not always an easy feat since it is affected simultaneously by several aspects such as (Lepola 2016, p. 208):

- Base material and its weldability
- Heat input limitations
- Material thickness
- Groove preparation
- Available machinery
- Availability and price of welding consumables
- Quality requirements
- Proficiency of the welder
- Assembling accuracy
- Working environment
- Welding positions
- Mechanisation of the welding

If the different welding processes are inspected with the heat input can the common arc welding processes noted to be the middle ground as can be seen from the Figure 6 by Nee (2014, p. 595). As if different manufacturing processes are inspected from the perspective of DFMA, this may be noteworthy, when it comes to assembling accuracy and assembling tolerances, since heat input may cause distortions at the assembling interfaces.

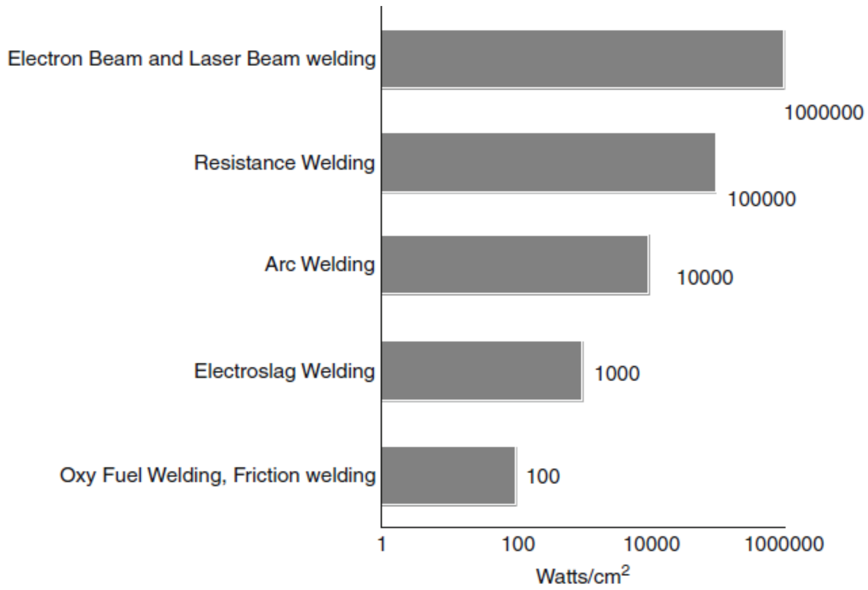

Figure 6. The heat input intensity of different welding processes (Nee 2014, p. 595).

Material-wise, the weldability consideration is affected by matter such as hardening, hydrogen cracking, hydrogen content, pre-heating, hot cracking, cooling rate, heat input and heat input limitations. All these matters are relevant for all structural steel grades, though there is obviously grade specific properties and nature that effects on how the weldability realises. (Lukkari 2019, p. 98.)

The welding position is the position of the workpiece as it is welded and is a part in the welder qualification standard. To determine the welding position, has to the welding direction be determined, including the information is the welding proceeding upwards or downwards. In addition to the position, one should also consider the joint type in the production welding, even though that does not affect to the welding position. (Lepola 2016, pp. 22, 249.) The welding positions for production purposes can be seen for instance from the standards ISO 6947:2019, ASME section IX and AWS A3.0M/A3.0. The former one (ISO) use different labels to the latter two, but all have same definitions for welding positions.

2.12.1 Estimating the welding

A research by Troha, Kern & Roblek (2019) inspects different approaches of calculating found from field of science by other authors. The paper included case study of 1 to 2-unit series production with repeating orders, product weight being 2000 – 18 000 kgs with 10 – 100 fillet and butt welds. Material is regular structural and fine-grain steel and welding happens with manual MAG process. In the case study a intuition pre-calculation for the welding times were comparable on the average accuracy of -30% to +50% and analytical estimation -5% to +15% (Troha et al. 2019, pp. 391–394), which is in line with other sources, such as Martin et al. (2007, p. 246) on the Table 3. As the results of the study of Troha et al. (2019) is discussed, in addition to the obvious welding process parameters, several aspects were noted to affect the welding time, such as (Troha et al. 2019, p. 394):

- Size and form of the joint
- Requirement to weld through the root
    - Non-destructive testing
- Thickness and type of the material
    - Preheating
    - Interpass temperature
- Complexity of the product
    - Multiple turns of the product for more suitable welding position
- Size of the product
    - A need to use scaffolding
    - A need to move the welding machine (for example to the scaffolding)

These though may be case and product specific as well as depending on the machinery of the workshop, like availability and capability of cranes for rotating heavier pieces. Though, if simplified, according to the Ulrich & Eppinger (2012, pp. 264–265), the welding cost forms of two attributes of the total length of weld created as well as of the number of welds. Hence, if the welding time and thereby welding cost is estimated, in addition to the welded length one should also include the information of the number of individual welds, but to be more accurate there is also quite many other parameters affecting. If the welding is considered through the concepts of VA and NVA times, if only the arc time (assuming arc welding) is considered VA, the total share of NVA time is rather big of the entire welding time.

3 METHOD FOR STUDYING THE DFMA APPLICABILITY

This master's thesis was done in collaboration with Dieffenbacher Panelboard in Finland. The products are related in mechanical handling of panel board products, realising at the scale of entire production lines after the panel forming processes. In this paper as an example product is used a panel transportation wagon, that is used in the storage to move panel stacks with weight up to 60 000 kg. The transportation wagon was during the time this master's thesis at the later phases of NPD process, thus quite detailed 3D-CAD models did exist.

A method for analysing the DFMA aspects of the product should be at first as objective as possible. This is due, as described at the literature review, the experience-based approach is easy and quick, it lies with the risk of subjectivity and on basis is affected by the experience and opinion of one. Hence, steps are taken to minimise inputs that are user dependent. Secondly the method is not tuned to be used just once, but also to allow automation of working procedures for better efficiency and easier iterations. The automation also supports the reliability between iterations by reducing the risk of errors caused by manual use, as well as unifying how the process happens with different users and iterations.

3.1 Current state

Currently there are no DFMA-methods applied, though the basic principles of manufacturability and assemblability are known and applied to the part level design. All manufacturing and assembling are outsourced since there is no in-house production facilities or equipment available. During the product design, the cost estimation is done with the qualitative analysis, basing on previously known history data from earlier similar projects. At the time of this master's thesis, the cost distribution does exist only on the scale of entire product, hence there is no available production data that could be used to assign typical values that reflect specific structures.

The products realise mostly as parametric 3D-CAD models, since similar machines are delivered according to the customer specifications and necessary customisation. This would allow the use of regression analysis to be a method to estimate the price within an individual product family. Regression analysis can be formed to estimate the cost of that individual family, expecting that there is enough data to have reliable estimation. For the NPD, the use of regression analysis relying to the history data is not the optimal approach currently, though approach through similarity factors could be suitable, such as the one expressed on the equation 6.

3.2 Methods

In this paper, a top-down, qualitative approach for the DFMA analysis is constructed by representing the product's structure through the parts and connections between those is made. This representation is developed further by attaching detailed product and assembling process data to parts themselves as well as on the connections between the parts. This does yield objective product structure and production representation that cannot be affected by the user. The product structure representations can be then used to form data graphics and numerical values that represent how the DFMA driver appear at the example product.

In practise, an example product that is in later stage of the PD process, hence has 3D-CAD models, is chosen to represent the products on hand in this paper. At the first step the product data, in form of BOM, is exported from 3D-CAD software to spreadsheet program, which is in this paper Microsoft (MS) Excel. The product structure is then expressed at a diagram drawing software, in this paper with MS Visio, as an exploded view, and the parts are connected to each other with corresponding production related information according to the 3D-CAD model and drawings of the product. The product structure accompanied with production related data is then exported to the spreadsheet, where numerically DFMA related issues can be presented, according to what is relevant by the literature review.

The product structure representation process in this paper is described more detailed at the chapter 3.2.1, which results the product structure with the part-to-part connection accompanied with relevant connection information generated into spreadsheet file. This allows collection of the product structure and production information to same database, which allows one to calculate relevant values for decision making. The results of the example product is then analysed at the chapter 4.2 to estimate the DFMA issues of the example product as well as estimate the usability of presented DFMA metrics.

3.2.1 Process steps for the product structure representation

The BOM of the entire product is generated and exported from the 3D-CAD software into the spreadsheet file, which includes initial product data, such as dimensions and weight. From that data input can the weight distribution of sub-assemblies inspected, as presented on the Table 5. On said table, the sub-assemblies' weight do include the weights of lower level sub-assemblies, hence the lower level assemblies are included multiple times. This is due weight being notable factor in the handling of assemblies during production processes, thus inspecting how easy the part is to handle, practical weight is to be used. From the Table 5 can be noted that over third of the sub-assemblies do have a weight equal or over 100 kg.

Table 5. How example product's assemblies weight distributes. The assemblies accounted include both, assembly's own parts weight and the weight of the child sub-assemblies. Majority of smaller sub-assemblies are present at the below 20 kg, and majority of bigger assemblies at the area of 100 – 200 kg.

Weight of the assembly [kg]	**Quantity of assemblies**	**% of all assemblies**
<10	7	18 %
10…19	12	32 %
20…29	2	5 %
30…49	2	5 %
50…99	1	3 %
100…199	8	21 %
200…499	3	8 %
500…999	2	5 %
>1000	1	3 %
Total	**38**	**100 %**

The exported data includes information which assembly or sub-assembly every individual part belongs to, but there is not part-to-part relationship available. To understand better the structure of the product assembly for the standpoint of DFMA, as well as allowing one to form part-to-part linking for numerical use, exploded view of the product is formed at the diagramming tool, which is in this master's thesis MS Visio Professional 2016. The use of "professional" -version of MS Visio is not obligatory, but necessary in terms of working method automation and error-proofing by allowing one to automated the data linking between the spreadsheet program (in this master's thesis MS Excel) and the MS Visio, thus reducing significantly manual data handling. For the context, approximately 200 separate component identification numbers were to be handled at this stage with the example product.

In the diagramming software, a blank flowchart page is used, with a pre-defined stencil to represent and automate the dividing process of shapes to different purposes and to include necessary information. In this paper two example assemblies generated on the diagramming software are presented; on the Figure 7 is a simple bearing support structure that is welded from steel plates and on the Figure 8 is a motor support structure that is assembled with mechanical joining using bolts, screws and washer as well as with fits, that could be putting part on with or without force. There are four shapes used to represent the product structure: a part (rectangular), a weld joint (diamond), a mechanical joint (hexagon) and a fit joint (circle). Mentioned pre-defined stencil includes said four shape types. All physical parts are marked with rectangle, which is blue for custom parts or green for bought or standard parts. Parts are linked to each other by using the three other shapes (diamond, hexagon, and circle) that represent the used assembling methods in the product on hand. Welds are marked as they are in the assembling drawings. Mechanical joint includes assembling two or more parts with use of fasteners such as bolts, nuts and screws. Fit joins are either assembling that have no special requirements, hence just laying the part there or joining the parts with the interference fit.

In addition to connecting parts diagramming software with assembling actions, data is tied to every shape. The parts contain general information originating already from the BOM of the product. The weld, mechanical and fit shapes require additional information regarding the assembling event itself. On the appendix III is presented what information is added to each type of assembling shape. In this paper the data added to these are from the 3D-CAD models and the manufacturing and assembling drawings of the product.

To unify how the assembling direction and welding position is perceived, the main assembly's orientation is fixed, and all assembling direction happens in relation to that. The welding position is determined assuming that the parts and weld seam is to be in the orientation that they are in the main assembly. These directions are presented on appendix IV. The assembling and welding may not happen in these orientations and directions in practise, hence this is made only to ensure personal experience and opinion may not affect how the assembling is documented at the diagramming software. These assembling direction realises at the Figure 7 and Figure 8 as a coloured arrow or as a white box next to the shape. When the assembling direction is not unambiguous, such as with the drive chain with "Fit 2", "Fit 3", and "Fit 4" at the Figure 8 the white box is used instead of the arrow. There are also few other limitations on how the product structure is built on the diagramming software to reduce or remove the effect of personal experience and opinion, more accurately presented on appendix V. For the purpose of the DFMA analysis, the fixed coordinate and assembling direction can be handled at the spreadsheet to respect the practise better, but for diagram software presentation this is obligatory to have unambiguous data entry.

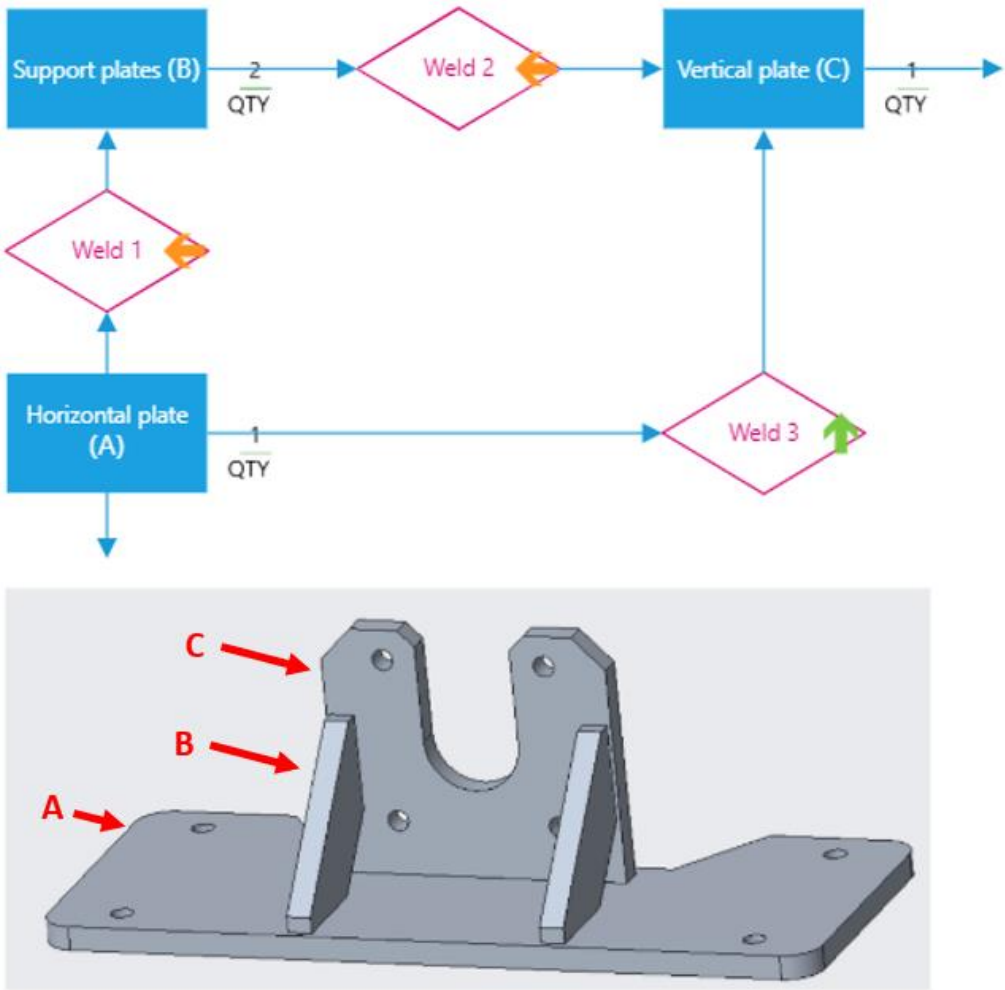

Figure 7. A welded assembly presented on diagramming software. The welded structure joins forward to other parts from Horizontal plate (A) and from Vertical plate (C). The Vertical plate can also be seen as the base part of this sub-assembly, thereby other parts (A & B) of the sub-assembly assembles towards it.

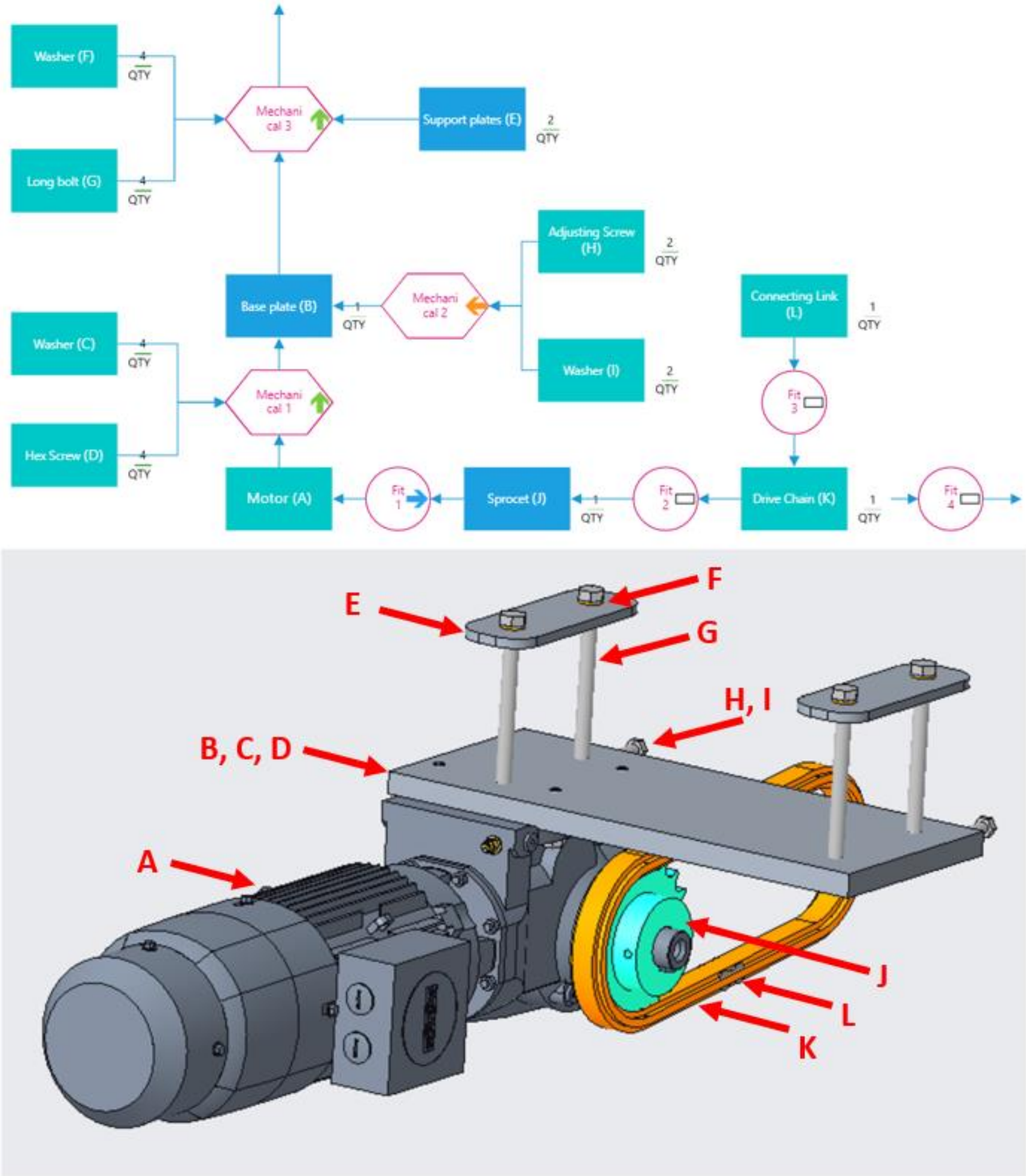

Figure 8. A motor assembly presented on the diagramming software containing mechanical joints and fit joints. The assembly assembles forward to other assemblies from Drive Chain (K) with Fit 4 and from Base plate (B) with Mechanical 3. The Base plate can also be seen as the base part of this sub-assembly, since other parts joins to it, and sub-assembly itself is joined to the main assembly through it.

The entire product’s chart can be delivered back to the spreadsheet within this paper through MS Visio’s built in “Shape Report” -tool, which uses specified report generation rules that responds to the needs of the DFMA-analysis. These generation rules do not alter the data or its relations, only exports the data in specified order to the columns of the spreadsheet for easier and repeatedly similar referencing over different iterations or changes into the product structure. This is to automate further the DFMA analysis by allowing to quickly test different iterations of the product structure with the use of same pre-built and tuned spreadsheet file without a need to alter again cell references or other setting at every new run. At this point the 200-part assembly with production processes added, realises as spreadsheet with over 500 rows and 27 columns, hence manual handling is not relevant option. The increase comes from the added assembling event -shapes and connectors at the visualisation of the product structure at the diagramming software, which of all add new row to the spreadsheet.

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4 RESULTS AND THE DFMA ANALYSIS

In the following chapters is inspected how does the DFMA issues realise in the example product and couple of analysis metrics derived from it. As expressed in the methods of this master's thesis, the example product's structure is represented with a diagramming software, and as a result it is exported to the spreadsheet, where the DFMA aspects can be analysed. The literature review was directed with few questions, as described in the introduction of this paper, hence the findings of the theoretical part is then applied to the resulted construction of the example product. This allows analysing the relevant DFMA aspects from it according to the areas of interests noted from the literature.

4.1 Key findings

On the behalf of the literature review can be noted that the presented more common and well known DFMA methods suite well for, for instance electronics industry or industries of smaller products, which unfortunately do not reflect well the nature of products of this master's thesis. Even though the existing methods and software, as they are, do not to work directly with the products in this case, there is a lot to notify that are common matters in all of the methods and are also applicable to the product of this paper. The DFMA methods are founded on the issues of assemblability and manufacturability, hence inspecting how those issues are present in the product of this paper can the estimation on the product level presented. This can furthermore be used to enhance the manufacturability and assemblability aspects, as well as take notes for the future use. The applicability of the DFMA according to the literature review is presented more in-detail in the chapter 4.1.1.

As the example product is represented, can the DFMA analysis conducted using suitable metrics. As the methods for analysis cannot be derived directly from the production, should consideration be given how to represent the DFMA issues to allow comparison between iterations on usable yet beneficial manner. Product and production structure can be expressed for instance using diagram presentation, which allows visual inspection. If the representation is built to respond data export and handling can more numerical approach be conducted. Initial results for the case of this master's thesis' example product is presented on the chapter 4.1.2 and furthermore analysed on the chapter 4.2.

4.1.1 DFMA applicability according to the literature

Quite many DFMA textbooks and guides do present vast quantities of “do this way instead of that way” tips and tricks for designer to follow during the product design processes. For DFA aspects, these can be for instance self-aligning holes and part placement, untangleable part geometry, symmetrical parts, direct visual access to the assembly, self-fastening joints and so forth (Pahl & Beitz 2007, pp. 378-382,384). For DFM purposes, common presented aspects could be for example on hole placement on bended sheet and plate metal parts, distance and change of direction between bends, tolerance requirements on bended parts, through part threaded holes instead of a bottomed ones, using self-tapping screws, several machinability aiding geometry issues, and so forth (Pahl & Beitz 2007, pp. 364–371). Many part level solutions may also receive different reception at the workshop that is to manufacture it. These aspects could be for instance part requiring machining before welding and additional machining after the welding. For the welding operations, design rules are also available, such as at Pahl & Beitz (2007, p. 372). Noteworthy of these lists of guides is that they may get excessively long and, in the end, not deliver the designer the context. This may yield into neglection of other important considerations, which can realise in unfavourably manner at the later stages of the PD. (Mascitelli 2004, p. 276.)

As expressed in the literature review of this paper, the DFMA is at its strength at the conceptual phase of the PD, where it could affect to the entire structure of the product. The effects on that level could realise not only in better reliability on the performance of the product, but also on the reliability of manufacturing and assembling to happen as it is thought. Inspection of the product structure could yield reduced number of parts, which realise directly in shorter lead times and more simple and obvious operations. Indirectly this is to affect also to logistics, error proofing, assembling accuracy and repeatability. Hence, for these reasons, the DFMA analysis that starts from the structural level of the product and flows towards individual parts is favoured when inspecting suitable metrics for DFMA drivers. For current stage, this is also more secure approach since detailed production data is not available.

The DFMA as a sub-category of DFX, is well known and does give notable benefits according to the literature but should not be considered as a standalone. In the topic of DFX is noted that several DFXs should be used simultaneously, which is not necessarily easy, but there are methods such as CE to aid said approach. Thereby, this applies to the DFMA as well, as it should be an integrated element of the PD process used in conjunction of different stakeholders and different areas of the PD organisation. To achieve beneficial application of the DFMA, should the principles of "why" understood well and used in the correct context of the PD. One of the targets of the literature review was to inspect the drivers behind the DFMA applications, methods, and tools. Such approaches are presented on the theoretical part of this master's thesis and after considering how those operate, the phenomena behind the practise is then applied to the example product in the form of DFMA analysis.

4.1.2 The example product

From the exported data of the product structure visualisation at the diagramming software, can be drawn a simple pie chart (Figure 9), which shows that for the example product's majority of assembling actions are welding with share of 41%, whereas mechanical joints being the second most common with 25%. This pie chart does not comment how big share of the assembling cost is by different types of assembling methods, only presents how many of each type of assembling shape there is of all assembling shapes. Hence, as the product structure is constructed at the diagramming software according the set rules, this pie chart does represent how many individual assembling events there is and furthermore how many set-ups appear at minimum during the assembling. Theoretically, already from this representation assembling cost could be calculated if average multiplication factors in monetary units for each type of events is established, but in my opinion that may be still a bit questionable approach to represent the practise.

All added assembling shapes can be attached directly to other part shape or to other assembling shape. In case of only one assembling shape between parts, the assembling can be achieved with one setup. If there are several assembling shapes between parts, or on other words assembling shapes join to other assembling shapes, there is several setups required to complete the assembling event. This realises especially with welds, as can be seen from the Table 6, since if the welder has to change position, welding has to end and start again, a new setup is considered to happen. For this product, multi-setup assembling events appear only on welded joints. Majority of the "Fit" assembling events were rather simple and "Mechanical" events were included as one even though some joints went through several parts and sub-assemblies. For representing complexity of mechanical joints is presented a pie chart on the Figure 10 on how many additional elements is needed in addition to the two parts to be joined. The additional elements may be bolts, screws, nuts, washers et cetera, but also custom parts or sub-assemblies if they are used to fasten the two main parts together. If there is zero additional parts in the joining event, it means that one or other of the parts is fastener itself.

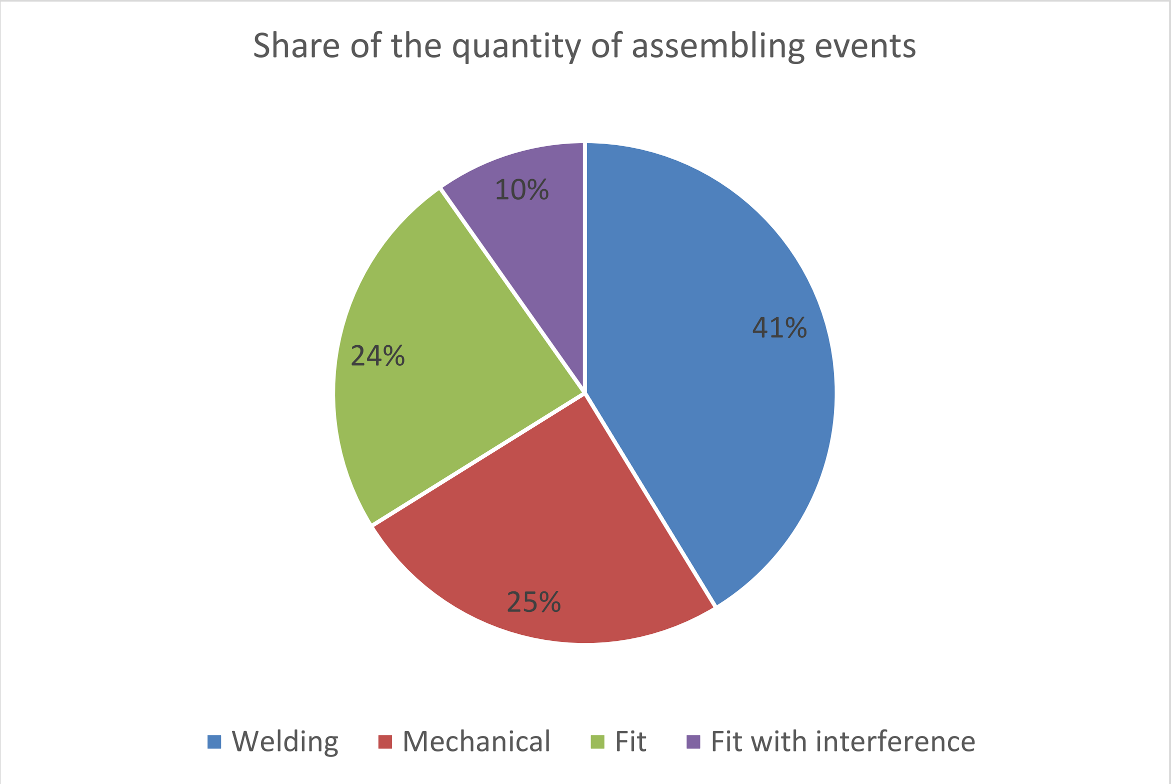

Figure 9. How different joining methods share at the example product. Total of 378 separate assembling events is included in the assembly.

Table 6. Complexity of assembling events presented, whether specific event leads to a part shape or to another assembling event.

	To part event	To new set-up event	Total events
Welding	95	61	156
Mechanical	94	0	94
Fit	91	0	91
Fit /w interference	37	0	37
Total	317	61	378

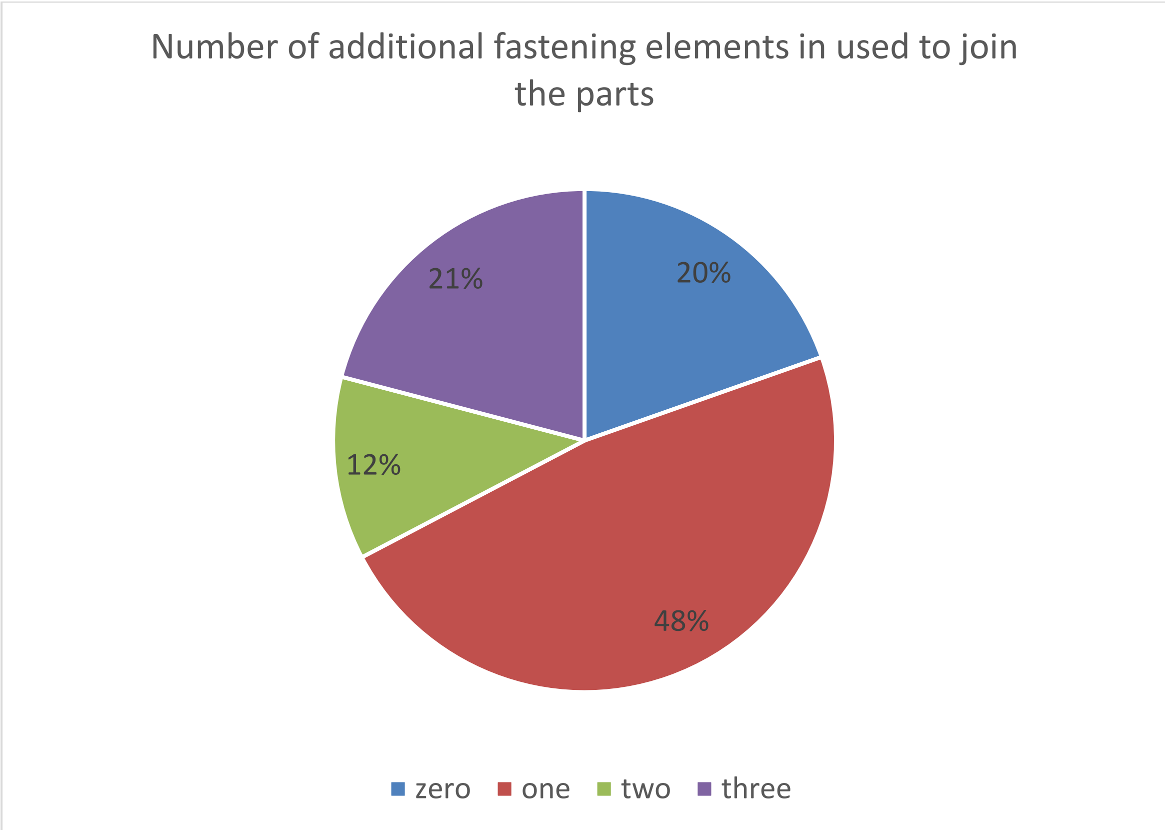

Figure 10. How many additional fastening elements is required to join two main parts together. With the case of "zero", other of the two parts is the fastening element itself, for example lifting loop or plain bolt alone on threaded hole. Fastening element may be either bolt, screw, washer et cetera miscellaneous component or other custom part or even sub-assembly.

4.2 Analysing metrics for the example product

Due to the difficulties related to the typical products, as described before, measurement tools to evaluate the DFMA aspects of the product is to be found. Absolute in-practise numbers are quite difficult or even impossible to calculate, since the generation of accurate estimation of "how" the production happens at the subcontracting workshop is rather unreliable. For sure, closer inspection can be performed with collaborating workshop through the means of CE, though a question rises if those results are usable in case of other workshop or even the same workshop, when machinery, workers and job queue vary. And as the DFMA is a method for PD to be used from the earliest stages of the development process, such accurate estimation is not necessary, since the goal should be in the optimisation for the product structure. After the structure is optimised can the analysis flow down to more in-detail aspects on part level. This in well tied to the cost analysis moving from qualitative techniques to the quantitative as the PD process proceeds and more detailed information becomes available.

Assembling directions

The difficultness of assembling and the quantity of NVA time in the assembling process can be estimated though how many different directions the assembling actions must happen from. If there is several different required directions, may difficult to reach or blocked paths exists, the assembling happen at the workshop though difficult working orientation, may the assembly be needed to be rotated to allow easier access, more walking around and approaching be required, and so forth. Rotating the parts and walking around are NVA time, which is not desirable, especially in the case when the parts do weight several hundred kilograms and physical size is measured in meters. Whether the assembling happens in a way or other, can a note be made that reducing the assembling directions is beneficial in the terms of DFA, which is strongly supported by literature, researches and case studies inspected.

On the Appendix VI is presented the product’s sub-assemblies with weight and assembling direction distribution. Different assembling directions are marked with different coloured bars, the height of the bar representing how many actions is required for this sub-assembly. The quantity of assembling actions is presented on the left vertical axis. On the right vertical axis is the weight in kilograms and the red horizontal lines shows the weight of each sub-assembly. From this graph can be investigated which sub-assemblies have complex assembling to do, which most likely realise in high NVA time. One should not use this graph to inspect how many assembling events there are but more of on how many different assembling directions the assembling has divided into. If the sub-assembly has many bars on equal height it is more difficult to assemble than if it had one to a few bars only. This inspection can be then tied to the weight of the sub-assemblies, since higher weight realises in the use of cranes and lifts as well as probably on bigger physical size, which realises for instance in more walking. The weight value presentation allows one to optimise which sub-assemblies are more critical to be developed from the perspective of DFMA. From the principle standpoint, a goal should be to have only one bar, and any additions to that is not favourable, similarly as at the Hitachi AEM -method. This obviously does not yield accurate monetary values for difficultness of the operations, but more of relative comparison between the product's sub-assemblies.

Standardisation and use of bought parts

The DFA does support of the use of standardized parts over parts manufactured for the specific purpose, and part should not be made if it can be bought. If the product's production cost is estimated by weight, including all parts of the product without separating how the "make or buy" -question is answered on the level of individual sub-assemblies, may the benefit of the use of catalogue parts go hidden. The designer may do a beneficial decision according to the principles DFMA, but those may be lost, if the inspection of how high share of the sub-assembly is constructed from bought parts and how big from made parts. Following equation may be used:

$$Custom\ parts = \frac{weight\ of\ custom\ parts\ in\ the\ sub-assembly}{weight\ of\ entire\ sub-assembly}\ 100\% \qquad (10)$$

Having a high percentage value means that the sub-assembly do have more parts that require processing, thus higher €/kg rate can be seen acceptable. If the percentage is noticeably lower, there is much less need for manufacturing actions. This realises at that the €/kg rate should be lower for that sub-assembly, obviously assuming that the bought parts have lower price per weight to manufactured parts do. This could be used for proofing that the product should include less work at the production but also on the decision-making process whether the component should be made or bought. The price of the component can be compared to the €/kg rate of the sub-assembly to see which approach should be more beneficial. This obviously assumes that respective €/kg rates are available for different shares of custom parts per sub-assembly.

Multi-phase assembling actions

According to the DFA and DFP, the assembling actions should be as simple as possible and the quantity of actions per part should be minimised. In the Lempiäinen (2003, pp. 81–82) is an order to try reduce the number of components, joining, joining elements, fitting and handling in manual assembling operations. For instance, the use of self-aligning and self-fastening parts do support this phenomenon. As the assembling actions are marked on the visual presentation of the product structure, can the quantity of necessary actions per part and per assembly be inspected visually and numerically. If one welding action is defined to include weld seam weldable from one orientation, yet part is joined by welding from several faces, or from both sides, does this require more “weld” shapes at the product structure visualisation -file. For numerical analysis, this could be used to estimated that does adding more complex and multi-stage welding events is worth in comparison to the achieved better performance or other benefits of the allowed by the more complex welded assembly.

Welding position and assembling direction

As noted, the welding position do affect to the welding cost in addition to the welding distance and number of individual welds. Hence for simple cost analysis, results can be achieved with the use of the number of individual welding events accompanied with the welded distance, assuming obviously that reliable source for forming the welding cost rate is available. For assemblability, including weldability, the consideration of welding position is suggested. Even though the welding position may not be considered at the cost estimation, it does have an effect on the NVA time of welding setup and preparation times through, for example, more clamping and attaching, securing and aligning parts is more difficult, safety issues, walking and moving around. This is also well related to the DFA’s concept of unifying the assembling direction, opting for top-down assembling direction, and using the gravity as a benefit.

On the Table 7 is presented the assembling directions of welding events accompanied with the welding positions according to ISO 6947:2019 (pipe and tube welding positions excluded for this example) in numerical values of total weld length in set combination of direction and position. Here is to be noted that the positions and directions are added in respect to the fixed coordinate system, thus many of the more difficult combinations does not realise in practise due part and assembly rotating. If the combination of difficult assembling direction and difficult welding position is desired to be derived into easier assembling action through rotating, should the weight and physical size of the assembly be referenced, since that does have an effect to the NVA time added. For cost estimation as an analysing method, could corresponding table be formed through empirical study, which has multiplication factors for each assembling direction and welding position combinations, thereby allowing one to calculate monetary units for this DFMA approach.

Table 7. The assembling direction accompanied with welding positions (ISO 6947:2019) measured by welded length in millimetres of the example product. The welding positions are assigned according to fixed axis defined by the orientation of the main assembly, which in all the parts (and weld seams) are located.

	PA	**PB**	**PC**	**PD**	**PE**	**PF**	**PG**	**PH**	**PJ0**
Z+		1652		240	720	1440	1440		
Z-	15600	360		360	15600			250	
Y+		2900		3600		5816	5816		
Y-		2720		3600		6056	6056		
X+		360							
X-		360							

Part manufacturing complexity

For part level manufacturing and production, cost estimation based analysis could be a difficult task, if information of available machinery and production control practises is not known at the phase of PD when the part geometry is chosen and the design is leaned towards DFA or DFM. Swift & Booker (2013, pp. 361–363) presents dividing parts into three categories, which was mentioned earlier at the literature review in this paper, of A (solid of revolution), B (prismatic solid) and C (flat or thin wall section). Each of these has five sub-categories from 1-5 (for example: A1, A2 … A5), where “1” is simplest and “5” the most complex. A more defined figure of the categorisation is available on the appendix I of this paper. This obviously does not deliver definitely accurate cost estimation in monetary units, but in the case when more accurate production environment features are still unknown, this could allow one to estimate and manoeuvre within the “how complex is optimal?” question set between the DFA and DFM. This could be also used inside the DFM itself, as different manufacturing and material options that could deliver the functions are compared.

Combination of DFA and DFM

Since the cause of the pursue for better DFM will hindrance the DFA and vice versa, should the optimal compromise be found from the middle ground. The tough matter is at the finding of comparable units that allows the optimisation process that have acceptable reliability at evaluating the manufacturability and assemblability. For instance, a machined part's processing time can be estimated with the use of virtual manufacturing, for example CAM, and as if the machine rate is known, can a quite accurate estimation the cost of manufacturing a part be made. Estimating accurately the assembling on the level of individual part can be achieved with for instance with production process engineering and the use of MTM or MOST. Though, for the case of entirely outsourced production accompanied with low volume – high value nature of the products that do not have fixed production environment, is the standard time -based methods out of bounds. At the design process with assembling estimation, for instance the lack of knowledge of working habits, available machinery, and production load from a sub-contractor to sub-contractor is problematic. Optimally the monetary units would be the absolute way to compare the manufacturability and assemblability to find the optimised solution, but the risk of bias and variation of one's experience and opinion in the forming of values relies there.

If the adoption of virtual manufacturing options may not seem suitable in long terms, can manufacturing difficultness categorisation used for the DFM half of the DFMA, whereas the DFA sides do require more production and history data. The presented diagram visualisation implementation and its data export for spreadsheet analysis could allow one to inspect the DFA issues, for instance "welding setups per sub-assembly" and "number of fastening elements in mechanical joining", which ones yield numerical values to use to be used in comparing the DFA to the DFM. In the "how complex is optimal" analysis, both DFM and DFA numerical values can be normalised to same scale for the comparison, but during the time of this master's thesis, the context of DFA values is impossible to form due the lack of production and history data. For future development the collection of production data is necessary to be able to understand how, for instance "Five fixing element per mechanical joining with average weight of component being 70 kg" compares with "machining time increased 30% due higher manufacturing complexity".

The difficultness of assembling can be estimated through the assembling direction distribution (Appendix VI), hence the difficultness variable could be formed from that for the comparison use with the manufacturability classes of the Swift & Booker (2013, pp. 361–363) described previously. Further study of actual production values in relation to these assemblability values should be made to be able to find suitable scale for comparison.

Product structure analysis

As mentioned earlier, on part level design there is well available guidance from the literature for better manufacturability and assemblability, but on the level of entire product's structure application of DFMA is not as easy. The approach of using diagramming software to present firstly the exploded view of the product through use of colour coded shapes and joining them with assembling events could be used further for structure analysis. In comparison to the 3D exploded view of the product that could be generated at the 3D-CAD software, the visual approach is not quite pleasant in the two-dimensional diagram presentation, but on assembling direction analysis the method is much less prone for user's personal opinion, experience and observation.

As the diagram presentation of the product is built by adding the joining shapes, the designer is forced to realise how many processing steps there will be. This could realise for instance at the welding markings, since a seam that is to weld around complex shape can be signed with a one marking at the drawings requires in practise several starts and stops to be completed. At assembling actions, one fastener can be used to join several parts and sub-assemblies at once, whereas in practise there may be present a lot of aligning, rotating and lifting, especially in the case of physically bigger and heavier parts and sub-assemblies.

As the manufacturing and assembling accuracy deviations are included in the tolerancing, a worthwhile subject to analyse is the cumulative effects of those at the level of entire product. This realises as manufacturing inaccuracies, assembling, and welding errors and distortions do cause intended assembling interfaces to not meet physically, which cause furthermore rework or excessive actions to be taken to succeed in the assembling. This issue is also presented on the literature review when inspecting the assembling sequences, interfaces and tolerancing. The cumulation of processing inaccuracies may also realise in the product structure levels on the subjects such as reliability, performance, visual appeality. Said diagram presentation of the product structure does have processing actions added between the physical elements of the assembly for the DFMA analysis purposes, hence this could be also used as a platform to integrate the tolerancing analysis of the product structure. By adding parameters, such as manufacturing deviation and assembling process accuracy deviation to the shapes, could cumulative deviation be calculated through determined path.

The drawing of critical paths of the product structure is also tied to the concept of KCs and optimising the path between functions that are critical for the performance of the product. This is also well related on the DFMA's idea of reducing the part count. This realises at the Boothroyd-Dewhurst's and Lucas DFA's methods through the concepts of the theoretical minimum part and essential and non-essential parts, which of both desires to have only the parts that deliver functions and remove everything else. If the product structure is drawn on the diagramming software starting from the functions and KC delivering parts, is it visually easier to optimise the paths between the essential ones.

The current construct at the MS Visio and the restrictions on how the representation is built allows the use the same data export to easier numerical approach for the handling for constructing the statistical models that represent the product's structure and critical-to-performance and critical-for-assemblability paths inside the product's assembly. In the context of PD process and time management, this would point out the areas, where the deviation of reliability success is much less favourable, hence allowing optimise into more in-depth and targeted DFMA analysis and improvement process into the dedicated areas.

5 DISCUSSION

During this master’s thesis it became more prevalent that access for more accurate and reliable production data is vital when it comes to evaluate the production processes numerically and objectively. Several DFMA methods presented do favour the access to the production data, though relative approaches are also possible, which route was taken in this paper.

5.1 Results and analysis

Through the presented approach and representation by numerically and visually at the diagramming software and numerically at the spreadsheet, can the assemblability and manufacturability be inspected. More weight sat on the product structure evaluation for better assemblability as in favour of the DFA. As said in most of the DFMA related literature, the DFMA is at its best when implemented at the earliest stages of NPD. The top-down methods and qualitative estimation techniques allows one to estimate the product at earlier stages, though the estimates being quite vague. The bottom-up methods and quantitative techniques at the later stages with more detailed information allows one to pursue for better accuracy but for the time of this master’s thesis this was hard to accomplish due the lack of access to define and consistent production engineering databases and production cost distributions. Numerical outcome in monetary units can be estimated, but personally I would not recommend it, since the deviation in the result is unknown due lack of detailed data, hence may yield to incorrect or unfavourable conclusions.

As the results and analysis stands in this paper, the outcome is still a bit abstract. This is due the lack of possibility to compute numerical results for majority of traditionally considered essential aspects, such as machining time and welding cost in absolute monetary units. As this paper topic is on the “DFMA” and not on the define cost estimation models, hence the consideration of having accurate numbers for cost estimating is irrelevant. Instead is presented a possible path of making the manufacturing and assembling easier in the context of the drivers behind the DFMA. Even though for now this paper does not realise the user the absolute monetary units, cost savings are achievable by the use of the DFMA, as has shown in numerous researches over the latest decades.

The results and analysis do not represent what happens at the production facility's floor in detail, and I think that is impossible if objective approach and the ease of iterations through work method automation is desired. Some of the analysing results can be presented to the sub-contracting workshop to prove that "our new design is easier for you" in the negotiation phase, but not all. Main goal in the analysis is after all, as described in the literature, to be used already at the conceptual stage of the development.

5.2 Presented DFMA approach in comparison to the existing ones

The suggested approach for analysing the DFMA aspects in this master's thesis is a new solution as it stands but bases on analysis methods studied in the field of corresponding science. Similarities to the visual diagram presentation can be found for instance from the assembling sequence related studies. Taking a visual approach itself for the product structure representation itself is not necessarily a new idea, since graphical representations are recommended approach to the lists at the subject of assembling sequences as mentioned in the literature review. Founding the connections between the parts and their main functions are also under inspection in the papers related to the KCs of the product and capability to deliver those. Use of spreadsheets and tables is not either a new thing, and some of the commercial DFMA software even relies on those, though the product and production structure data input is not similar to the one presented in this paper.

The approach stands in-between the lightest and the most data intensive methods. The checklists are possibly the lightest DFMA approach and can be very well tied to the quality management system of the PD organisation, but do not necessarily point out areas of possible issues continuously at the different stages of the PD process or suggest the direction the development should be directed. The existing DFMA software, such as Boothroyd-Dewhurst, can deliver quite in-depth analysis, but are quite demanding when it comes to starting the use with limited availability to the production data. Several studies on product structure representations that use diagrams, such as flowcharts, trees and breakdown structures are quite dedicated to analysing in-depth dedicated aspect are not directly usable in more vague and general approach. The suggested approach in this paper indeed stays on more general level, when it comes to analysing individual aspects, but should include more areas of interest that can be inspected in simultaneously.

The representation of the product's structure is much lighter and accessible through the visual means yet the accuracy and means of the analysis metrics can be enhance for the best possible correspondence as the PD process proceeds. The parallel use of the visual diagram representation with the calculation spreadsheet should be able to deliver option for simultaneously visually inspect the product's structure and draw numerical estimations of how dedicated areas of the product or the entire product realises. Thereby, a graphical presentation and a database based approach can be used not only in parallel, but also in conjunction to reflect as comprehensively the entire product. Obviously in the current installation there is still need for further development to enhance the accuracy of the analysis and usability of the results, more in-detail discussed in the following chapter.

5.3 For the future development

After this master's thesis there is still studying to do on tying the results and analysis better to in-practise values. The current DFMA approach is on relative scale and do not need the production data for the reasons mentioned. If more detailed information is collected and put on database for reference. This can be used to enhance results in detailed cases, but also in comparative analysis of different variation or iterations of same existing product. This should be started with measurement values that have as little as variables, which could be achieved for example by restricting the study on sub-assemblies of individual product. This could allow one to realise the scale of analysis values better, but one should also define the parameters to study with a care.

Within the limits of this master's thesis, the usability and efficiency on producing using results were not conducted, hence a work method study should be done on the use of the presented DFMA method. This could realise either as studying existing product variants or within an NPD process. The former may for the first steps easier to perform, since there the changes and improvements are already recognised, thereby a comparative reference material is available for tuning of the DFMA analysis process. A flowchart representation for this is presented on the appendix VII of this paper. The process in said flowchart, the DFMA process is considered to be tested with an existing product that has gone through improvement process. Hence there is old variant and new enhanced variant available with knowledge on the improved aspects and realisation of those.

The visual informativity at the diagramming tool representation could be significantly developed further to achieve better usability and possibly allow new use instances. Within the limits of this master’s thesis, the diagram visualisation was used merely to construct the product structure with the production events, but if for example capability do deliver more information in easily understandable form should be enhanced. The assembling direction is an important aspect in the DFMA discussion, which is thereafter implemented into the visual diagram representation. For current state how in practise the assembling direction realises is not easily or quickly readable on the level of entire sub-assembly or main assembly. More study and development should be done on how the assembling direction in 3D space can be represented, while remaining objective on the data input.

Since for the DFMA analysis purposes the product’s structure with assembling elements is constructed of same database, could new analyses besides the initial DFMA conducted from the same foundation. Production process and material related deviation data is available, could reliability analysis be done focusing on the most critical paths in the product’s structure, example topic being for instance at the tolerance stack up.

If the DFMA is one of the synthesis of the DFX and to be used simultaneously with the others and finding the suitable tools and methods for that is not clear currently. Different DFXs desire to dedicate on different aspects and focusing on singular DFX may have negative effect on the others, hence consideration on one alone is not preferable, which was also mentioned at the literature review of this master’s thesis. Few studies are on the topic of applying different DFXs, but there is still plenty of room to inspect on how several relevant DFXs to specific PD process could applied simultaneously through practical and usable tools or methods. CE is for sure one well known approach for the PD, but interesting topic would be the in-practise realisation that would give comparable units for the PD and how to ensure the optimal compromise in midst of many synthesis.

6 CONCLUSIONS

In this master's thesis, a top-down approach of evaluating manufacturability and assemblability is presented, in the environment where detailed production data is not currently available. The BOM of an example product of panel stack transporting wagon is imported into the diagramming software and presented with a two-dimensional exploded view, which in the components of the assembly are connected to each other. Direct connections on part-to-part level is established for the numerical inspection at spreadsheet, the connections contain relevant information of the nature of how they are attached to each other. On the spreadsheet, the BOM, product structure, and the established connections is used to form estimators and metrics according to the drivers of the DFMA found on the literature review to be able to evaluate the manufacturability and assemblability of the product.

In the context of this master's thesis was noted that the most common DFMA tools are not directly usable on principle level to the products of the study, mostly due the physical size and weight being out of the scope of said tools. At the inspection of the example product, current lack of production related data does force the adaptations of the DFMA drivers to be on relative scale instead of using, for instance monetary units on the analysis. The metrics do present an option for inspection on the structural level of the product, which is suitable if adopted at the earliest stages of PD process. Even though presented metrics estimated on top-down level, the used product representation method with a diagramming software and spreadsheet allows detailed bottom-up approach assuming accurate data input becomes available. At the current stage, the analysis was made to be as automated as possible for more efficient iterations of the product structure.

The research question of this master's thesis was on how can the DFMA synthesis be applied in the case of this paper. This question was supported by questions of DFMA drivers and on the reasoning behind existing tools and methods. As described in previous chapter, the literature review does not deliver directs answer to the main question, since majority of the material do not reflect well to the nature of the example product of this paper. The existing methods and tools may realise for example through part count reduction and assembling direction, simplification of processes et cetera, but all these individual aspects aim to make the processing flow more fluent. According to the Lean, processes can be divided into VA and NVA. As the perspective is to optimise the VA share, the processing flows more fluently. If this is derived to the applicability on the case of this paper, the DFMA can be applied as one understands how the design choices may affect the processing flow fluency. The main question was “how”, and the existing literature offers several approaches, which of most suit for the example product as the designer realises how to represent the issues. One way how the product structure can be represented and analysis metrics drawn is presented in this paper.

The presented approach still needs further development, for instance on data gathering to be able to turn relative values into monetary units, and on improving the visual readability of the product structure constructing and inspection. The result is currently a bit abstract, but that is what was possible within the limits of this paper. Further development according to the suggested topics will allow better realisation in more practical metrics and values, hence this should not be the end of this working method development process.

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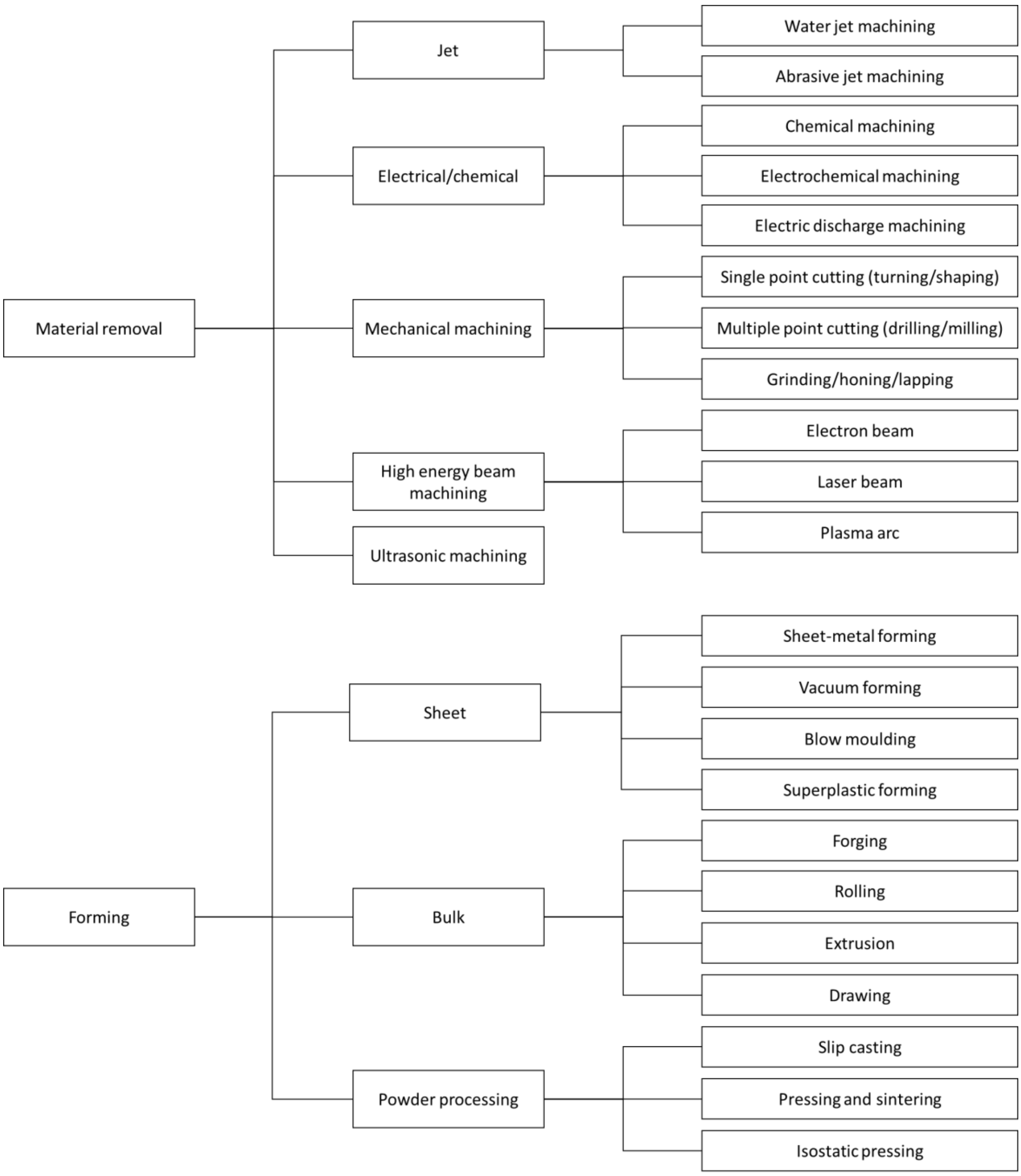
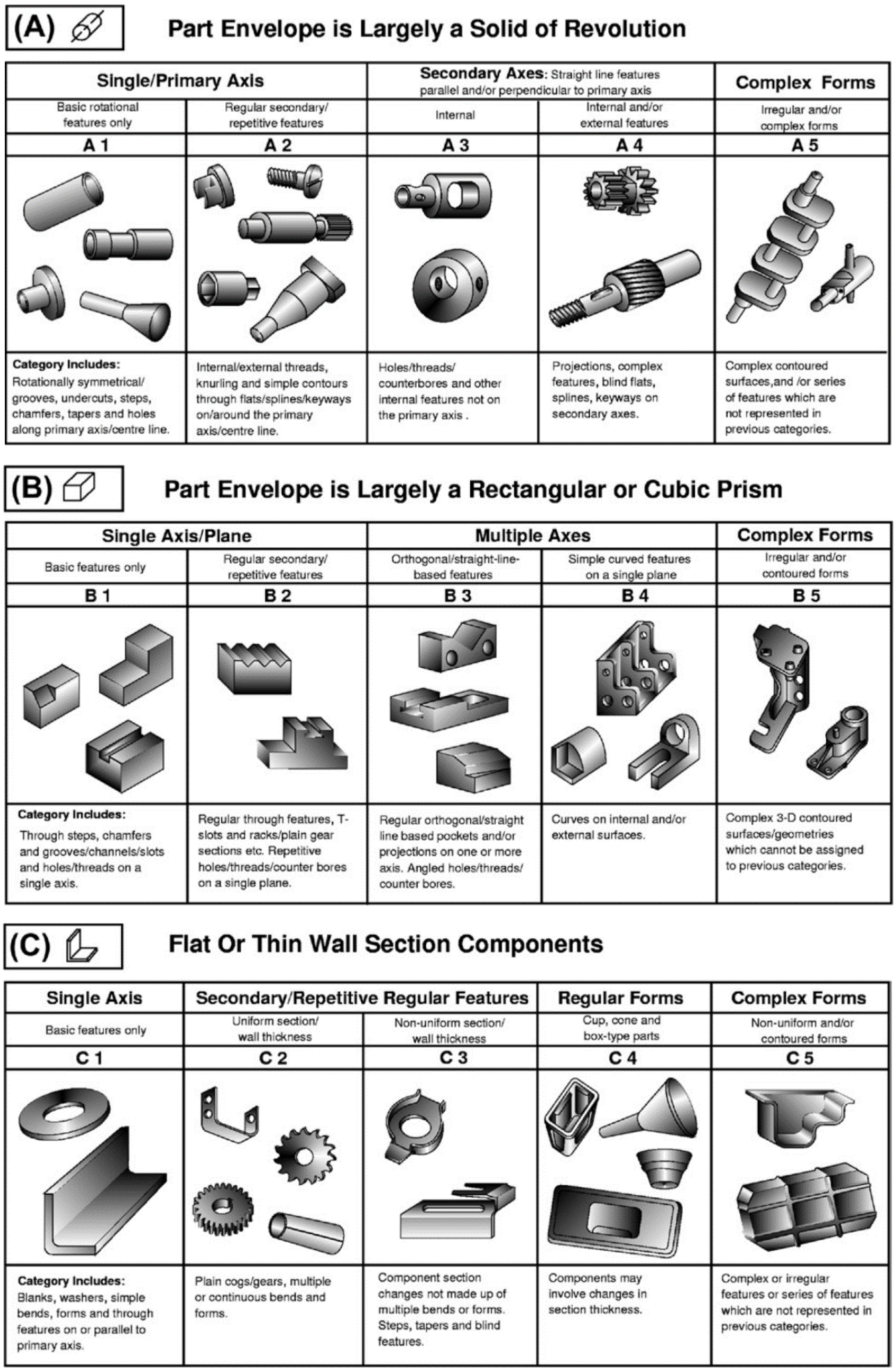
Manufacturing process selection

Manufacturing methods for material removal and forming processes adapted according to Swift & Booker (2013, p. 11). The chart is modified to include only material removal and forming processes, for casting/moulding options see Swift & Booker (2013, p. 11).



Manufacturing complexity classification

Dividing the complexity of manufacturing into different classes depending on the material forming method (A, B & C) and difficulty (1, 2, 3, 4 & 5) as presented on Swift & Booker (2013, p. 362).



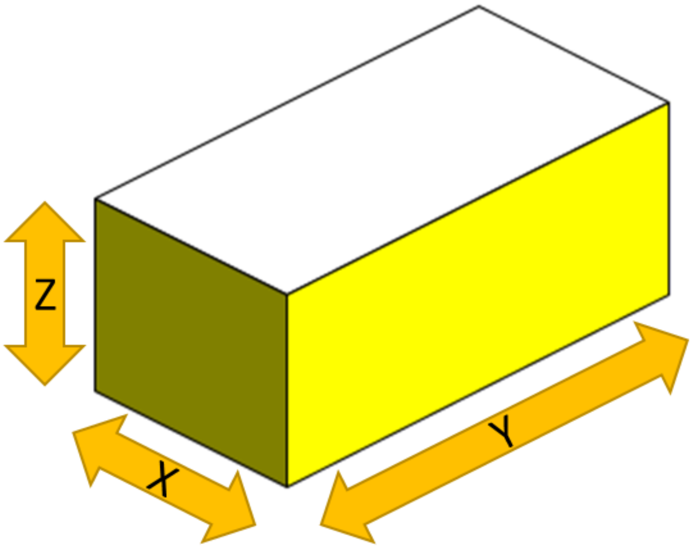
Data input types for assembling action -shapes

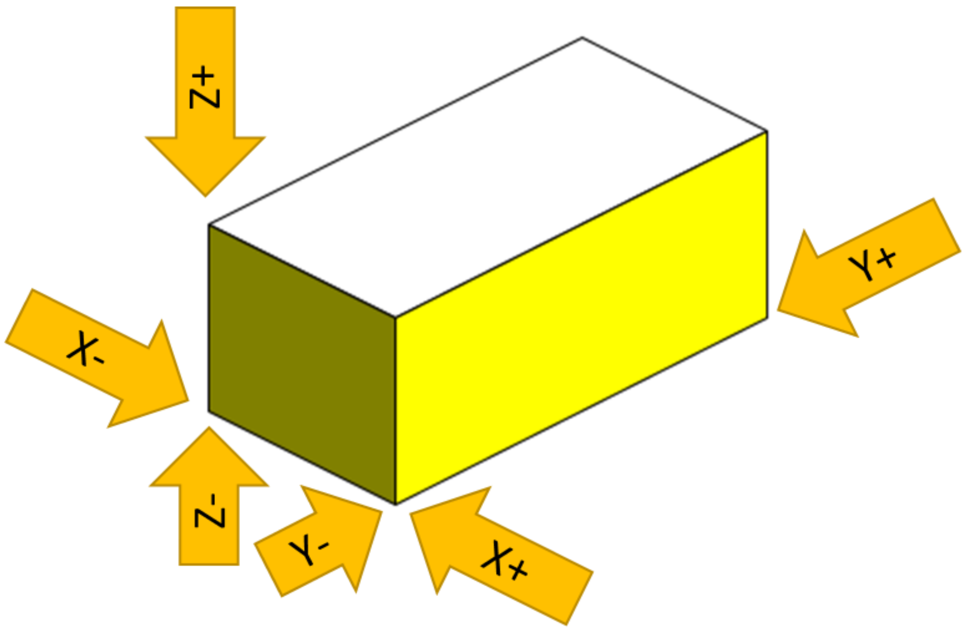
Parameters that are to input to the assembling action shapes at the diagramming software (in this master's thesis MS Visio). All parameters are added according to the CAD models and drawings of the product.

Parameter	**Unit in Visio**	**Input type**
Common for all assembling actions		
Global direction, which direction the assembling happens from		String
Related part, which are the parts this shape joins together?		String
Nature of part relation, is the assembling shape part-to-part, or is there several assembling shapes in chain?	TRUE/FALSE	Boolean
Reference assembly, which sub-assembly this assembling shape belongs to		String
Weld (diamond shape)		
a -dimension	mm	Number
Length on straight interrupted seam	mm	Number
Welding position according to EN-ISO 6947:2019, expecting parts not rotated in relation to full assembly orientation		String
Weld type (for example: fillet, butt…)		String
Is the weld on both sides?	TRUE/FALSE	Boolean
Mechanical (hexagon shape)		
Does joining require additional elements?	TRUE/FALSE	Boolean
If previous TRUE, how many?		Number
Fit (circle shape)		
Interference fit	TRUE/FALSE	Boolean
If previous TRUE, add temperature difference	˚C	Number
Other joining requirements?		String

Fixed axis for assembling directions

The axis of assembling directions. On upper figure is presented the axis in relation to the assembly (box) and on lower figure the positive and negative approaching directions along said axis.





Restrictions for assembling structure constructing

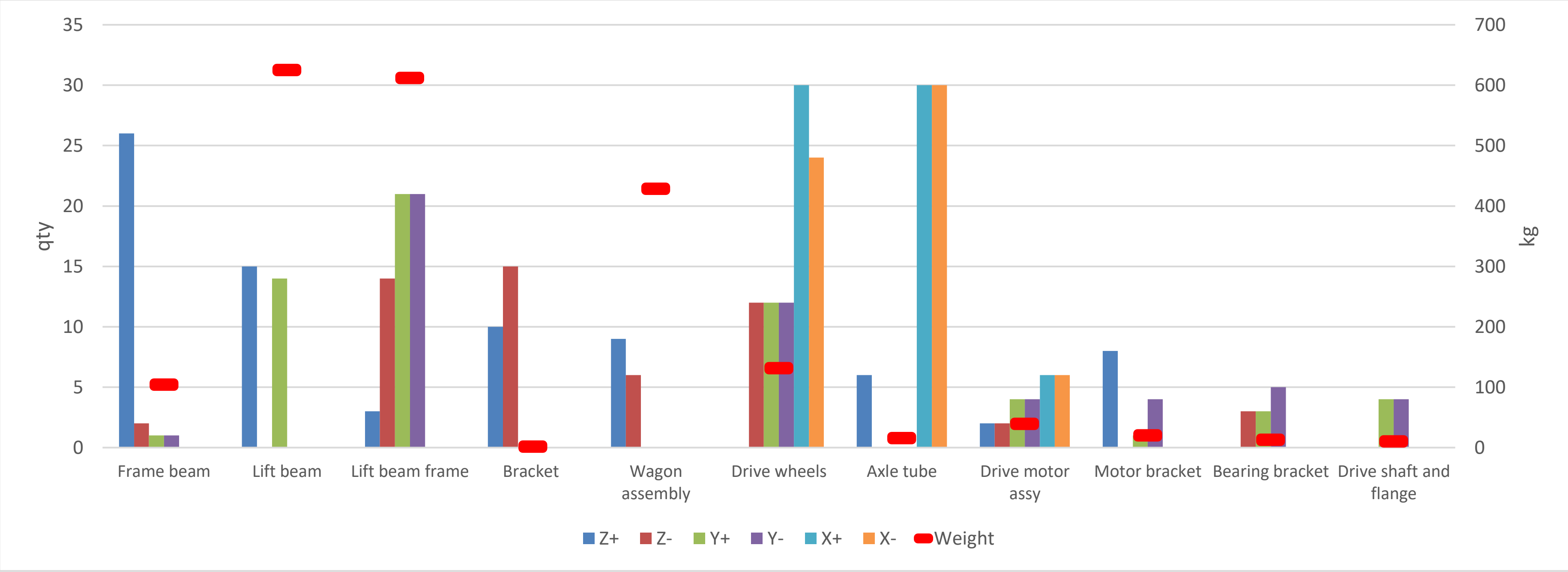
Following limitations were set to reduce and reduce the risk of altering the analysis's source data generated to the diagramming software by the opinion and experience of the user:

- Entire assembly orientation is fixed, and all parts are handled as they are orientated physically in the finished assembly
- Welding position is added according to the EN-ISO 4769:2019, expecting that the parts and weld seam is in the direction is forced by the fixed orientation of the entire product
- All assembling actions can happen only from one of the six different directions (X+, X-, Y+, Y-, Z+, Z-). Directions are defined by the fixed orientation of the product. If assembling action requires reaching from two directions at once (for example with bolt and nut) may positive and negative directions be added, such as X+ and X-
- If welding direction or position must be altered, new shape must be added
- A chain of assembling shapes must start and end to a part, but individual assembling shape may start and/or end to other shape
- The assembling action shape falls under Reference Assembly Number of the part the assembling action originates from
- Parts assembles toward the base parts and base assemblies that are earlier in the part- and/or assembly hierarchy. Decision process of the "base" part or assembly, in order:

    1. Assembly > part
    2. Base part for earlier parts > non-base part
    3. Higher quantity > Smaller quantity
    4. Heavier > Lighter (by weight)
    5. Larger volume (including hollow volume) > Smaller volume
    6. Designer's opinion, which one is more difficult to assemble *(This step should not be ever achieved)*

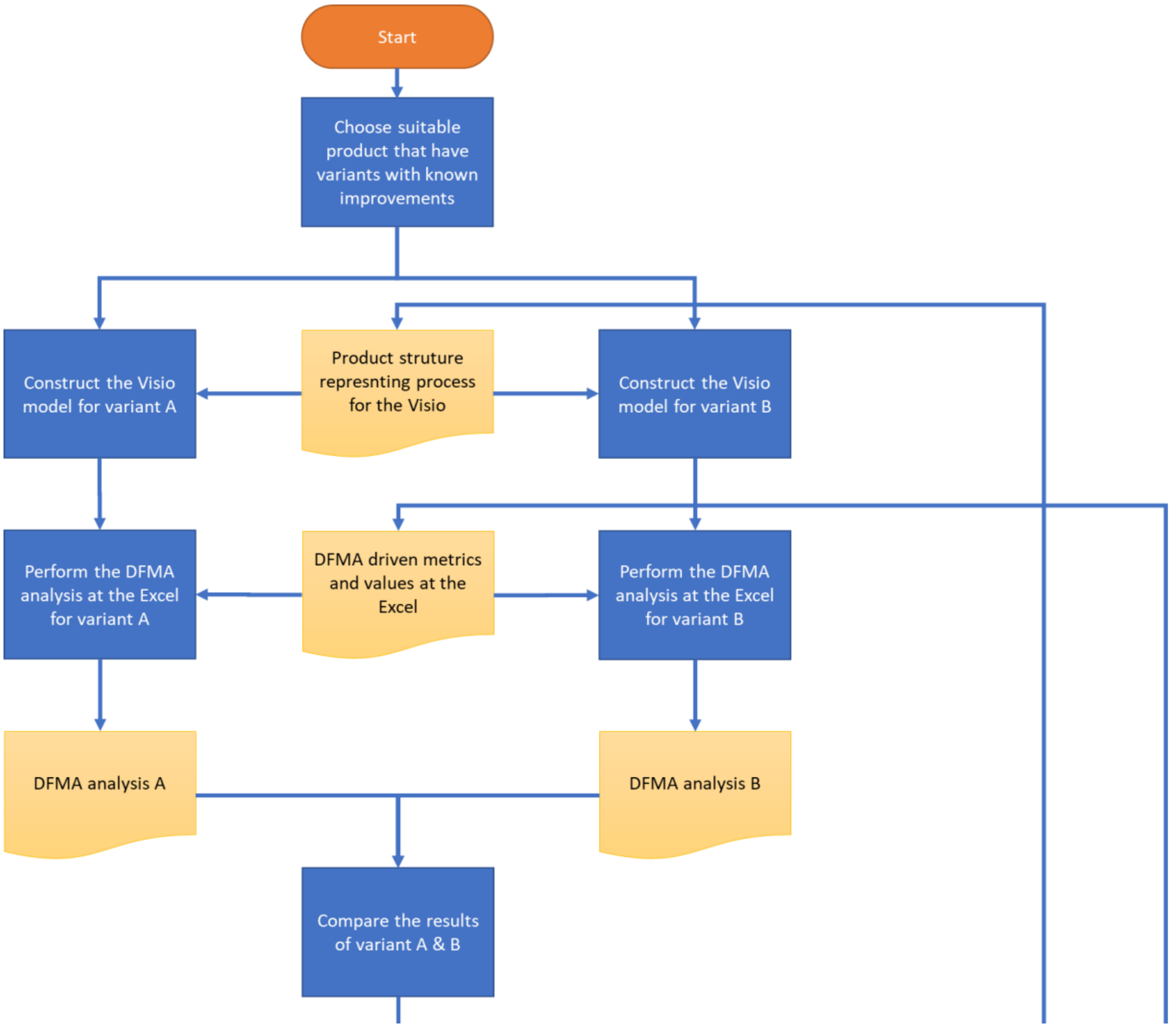
Assembling direction dependent actions per sub-assembly

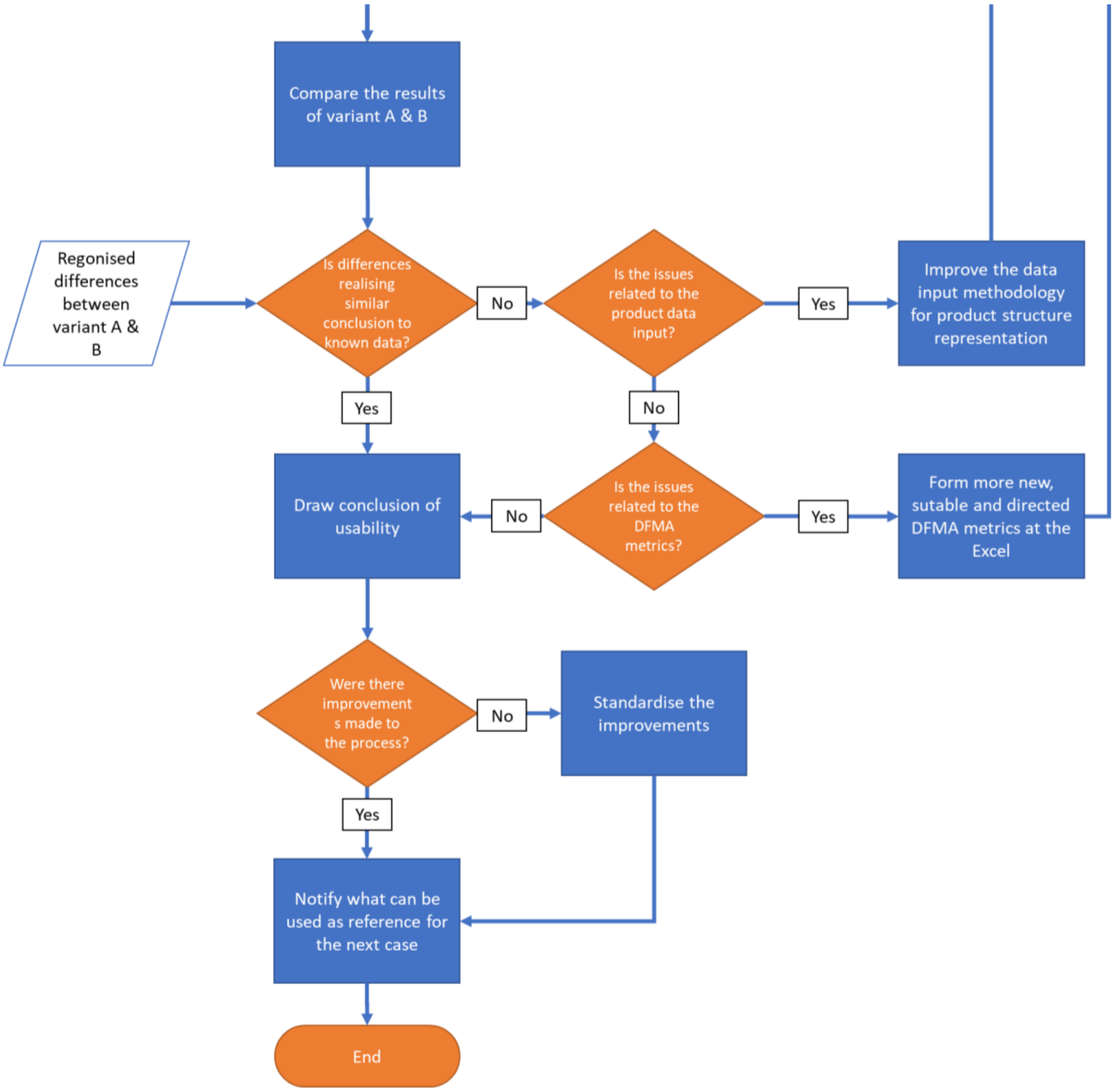
Assembling actions per sub-assembly divided into separate assembling directions. On the left vertical axis is quantity of assembling actions from individual direction (coloured bars) and on the right vertical axis weight of the sub-assembly (short horizontal red lines). Above each sub-assembly is set of bars representing how many assembling events happens from each direction.



The test structure for the DFMA analysis

A flowchart for testing the DFMA process for existing product. Assuming there is a product with older variant (A) and newer, improved variant (B), which can be compared to each other. The benefits of the improvements on the variant B should be known to be able to compare how the DFMA process represent those. The flowchart continues to the next page. For this flowchart is assumed that used diagramming software is MS Visio and spreadsheet program MS Excel.





Compare the results of variant A & B
Regonised differences between variant A & B
Is differences realising similar conclusion to known data?
No
Is the issues related to the product data input?
Yes
Improve the data input methodology for product structure representation
Yes
No
Draw conclusion of usability
No
Is the issues related to the DFMA metrics?
Yes
Form more new, sutable and directed DFMA metrics at the Excel
Were there improvement s made to the process?
No
Standardise the improvements
Yes
Notify what can be used as reference for the next case
End