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Reduction of Retrofit product lead time in production

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Abstract

The general objective of this thesis is to analyse the manufacturing process of ABB's Retrofit product line. The main focus is in finding production bottlenecks resulting from the incompatibility of the product architecture and structure with the manufacturing process. Secondary focus is in analysing the product documentation used in the manufacturing operations from the manufacturing perspective. The goal is to find and suggest solutions to issues that increase the production lead time.

Increased demand and expanding product portfolio have caused lead time and capacity challenges in Retrofit deliveries. The Retrofit products are manufactured in a workshop that has previously focused on frequency converter maintenance and spare part services. Current Retrofit manufacturing process is built on top of those existing systems. A systematic analysis of the Retrofit manufacturing was needed in order to increase and combine knowledge of the product design and the manufacturing process.

The analysis was done with qualitative study methods including observing production orders on the shop floor, interviewing involved personnel, and analysing product documentation. Most concerning manufacturing issues were found to be in the material handling at the shop floor. Root causes were identified as improper material definitions in ERP and the inability to sequence the order materials. Both of these complicate the planning and assembly of production orders. The production documentation was found to be insufficient.

The findings were categorized based on their effect on the manufacturing process. Possible solutions were generated by combining the detailed product and system knowledge existing in multiple organizations involved in Retrofit design and production. The solutions are presented in the thesis, but the implementation was left out of the scope.

Keywords Product structure, Product architecture, Assembly manufacturing, Lead time

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Tiivistelmä

Tutkimuksen tarkoituksena oli analysoida ABB:n Retrofit-tuotteiden valmistusprosessia. Pääpainona oli löytää ne tuotannon ongelmakohdat, jotka johtuivat Retrofit-tuotteiden tuotearkkitehtuurista tai tuoterakenteesta. Työssä myös tutkittiin tuotannossa käytettävää dokumentaatiota kokoonpanotuotannon näkökulmasta. Työn tavoitteena oli löytää ja luoda ratkaisuehdotukset niihin tuotannon ongelmakohtiin, jotka pidentävät valmistuksen läpimenoaikaa.

Retrofit-tuotteiden laajentunut tuoteportfolio sekä kasvanut kysyntä ovat johtaneet kapasiteetti- ja läpimenoaikaongelmiin tuotannossa. Tuotteiden kokoonpano tehdään korjaamolla, joka on aiemmin keskittynyt taajuusmuuttajien huolto- ja varaosapalveluiden tuottamiseen. Nykyinen Retrofit-valmistusprosessi on rakennettu korjaamon olemassa olevien järjestelmien päälle. Systemaattinen tutkimus Retrofit-valmistuksesta vaadittiin lisäämään ja yhdistämään tietoa tuotesuunnittelusta sekä valmistusprosessista.

Tutkimuksessa käytettiin kvalitatiivisia tutkimusmenetelmiä, joihin kuuluivat tuotannon seuraaminen korjaamolla, henkilöhaastattelut sekä tuotedokumentaation analysointi. Tutkimuksen perusteella merkittävimmät ongelmat tuotannossa liittyvät materiaalien hallintaan korjaamolla. Juurisyiksi huomattiin sopimattomat materiaalien määritelmät toiminnanohjausjärjestelmässä sekä se, että tuotantotilauksia ei ole mahdollista jaksottaa. Molemmat syyt vaikeuttavat tuotannonsuunnittelua sekä tuotteiden kokoonpanoa. Tutkimuksessa huomattiin, että tuotedokumentaatio on riittämätön kokoonpanon näkökulmasta.

Työssä selvitetyt tuotannon ongelmakohdat kategorisoitiin niiden vaikutuksen perusteella. Ratkaisut näihin ongelmiin luotiin yhdistämällä tuote- ja järjestelmätietoa, jota löytyy Retrofit-tuotekehitys- ja tuotanto-organisaatioista. Tässä työssä esitetään mahdollisia ratkaisuja tuotannon ongelmakohtiin. Ratkaisujen toimeenpano on jätetty työn ulkopuolelle.

Avainsanat Tuoterakenne, Tuotearkkitehtuuri, Kokoonpanotuotanto, Läpimenoaika

Table of contents

Preface

For me, the most important thing in writing the master's thesis was to find a topic that is interesting and relevant in some way or another. I want to thank my colleagues at Motion Service R&D team for listening to my personal interests and finding me such a meaningful topic. My advisor Pasi Puranen have provided great support for setting the course of this thesis. Other members of the thesis reference group have supported by providing knowledge that has been vital to the thesis. I also want to thank professor Esko Niemi for feedback and guidance during the writing of this thesis.

Of course, I must also acknowledge the support that I have gotten from my family. My parents Päivi and Esa have always emphasized the importance of education and have aided my studies in every possible way.

A special thank you must be addressed to student association Metal Club Mökä ry. The lifelong friends that I have gotten from this one-of-a-kind community have supported me during the entirety of my studies. Without Mökä I most certainly would not have gotten this far. Hevay is the way!

Helsinki, 20 May 2021
Lauri Saarela

Terms

Cabinet line-up	Multiple electrical cabinets side by side attached to one another.
Component	Mechanical part, electrical device, or wire harness used in an assembly.
Drive	Frequency converter used for controlling electric motors.
ERP-item	Component, document, or a kit defined in the company ERP.
ERP-number	Identification number for an ERP-item
Item definition	The way in which an ERP-item acts in the company ERP. Affects how the item is viewed by different internal and external organizations.
Item designation	Product specific identification for electrical component or wire harness.
Kit	A group of ERP-items defined under a single ERP-item.
Retrofit	ABB's Drive modernization product.
Routing group	Parameter determining how a production order is handled by manufacturing organization.
Routing value	Parameter linking an ERP-item to a specific assembly phase based on the routing group.
Single Drive	Drive where supply and output are integrated in the same module

Abbreviations

ATO	Assemble-to-order
ATP	Available-to-promise
BOM	Bill-of-materials
DFA	Design for assembly
DFM	Design for manufacture
DFMA	Design for manufacture and assembly
DSW	Drive Service Workshop. ABB's service workshop. Also used for Retrofit manufacturing.
EC	Engineering centre. ABB's organization in charge of OBE projects.

ERP	Enterprise resource planning
ETO	Engineer-to-order
FAS	Final assembly sequence
FMEA	Failure modes and effects analysis
JIT	Just-in-time
LSU	Local sales unit
MPC	Manufacturing planning and control
MPS	Master production schedule
MRP	Material resource planning
MRPII	Manufacturing resource planning
MTO	Make-to-order
MTS	Make-to-stock
OBE	Order-based-engineering. Customer specific design and delivery project.
OPP	Order-penetration-point
PA	Product architecture
R&D	Research and development
RPN	Risk priority number

1 Introduction

Producing low-volume and high-variability products is a demanding task from both design and manufacturing perspectives. It is especially difficult in ABBs Retrofit product line since the manufacturing process is built on top of existing flexible operations providing other services that differ in some key characteristics. This requires the design and the manufacturing organizations to know the constraints and the possibilities of the existing process. The combined product and process knowledge is a necessity for creating and maintaining effective production flow that is able to deliver products to customers within the agreed timetable.

1.1 Background of the study

ABB's product life cycle model is divided into four stages: active, classic, limited, and obsolete. In the active and classic stages ABB provides a full range of services including maintenance, repair, and spare components for the product. As the product moves towards the limited and obsolete stages the range of services is decreased. The exact length of the life cycle depends on the product sold. With cabinet build frequency converters, here-after referred to as Drives, the lifecycle is about 15 years. For renewing the Drive lifecycle status to Active, ABB offers direct drive replacement or modernisation services.

Drives are used to control electric motors or generators in wide range of applications. Direct replacement of a customer's Drive means that the whole cabinet line-up is disassembled along with the critical infrastructure such as cabinet frames, bus bars, and electric motor connections. Then new and complete drive cabinet line-up is delivered and installed. This process can take a considerate amount of time and requires relatively lengthy downtime of the customers process.

Modernization services include Drive Retrofit products. Retrofitting as a term means replacing existing equipment with upgraded systems. Retrofitting customer's Drive means disassembling the contents of the existing cabined and leaving the critical infrastructure untouched. The new technology, which is the Retrofit product, is then installed into the old cabinet. Retrofit brings two major benefits for the customer compared to direct replacement. Retrofits can be installed to the line-up one cabinet at a time which means that the initial investment is much lower than for complete replacement. The second benefit is that the required installation time is much shorter and requires shorter downtime of customers process. The complete line-up modernization can be done in sequences and according to the customer's own maintenance and production schedule.

In recent years the demand for Drive Retrofit products has steadily increased. The increasing number of installed Drives nearing the limited life cycle status and the constantly expanding Retrofit product portfolio has contributed to the rise in sales numbers. The Retrofit products are designed, manufactured, and delivered by Motion Service business unit of ABB. The main focus of the business has been in other life cycle service such as spare components and maintenance services. Essentially the manufacturing of relatively large products is a new area for the Motion Service. The early Retrofits, that were mostly customer specific solutions, were not manufactured in-house.

In order to compensate for the increasing demand and the divergent product portfolio, the manufacturing operation was moved to in-house. Suitable production area was found in a repair workshop previously focused on maintenance and spare part services.

1.2 Objective of the study

The goal of this study is to identify the possible product or process issues and propose improvement solutions that can decease manufacturing lead times for Retrofit products. The increasing sales numbers and the somewhat lacking combined organization understanding of manufacturing of large scale products have resulted in capacity and lead time challenges. The exact source of the long lead times is currently not well known. The existing consensus in product development and manufacturing organizations is that the product structure of Retrofits might not be compatible with the manufacturing processes in place. Even though customised Retrofit products have been delivered for many years, it can be said that the in-house manufacturing operation of standard products is still ramping up. This study is meant to increase the combined organization knowledge of the Retrofit products and the manufacturing process.

1.3 Research questions

This study aims to answer the following questions:

- What is the status of current Retrofit production process?
- What are the major bottlenecks that might be the result of incompatibility between the production process and product architecture or structure?
- Are R&D and order-based-engineering (OBE) project deliverables sufficient for production's needs?
- Can the product architecture and structure be improved to decrease the production lead time? (e.g. by decreasing the number of assemblies required to be produced in the retrofit production.)

These questions are aimed to provide answers to varying areas of product design from the production perspective. Product architecture and structure are the basis for many aspects of the manufacturing and their effect in the current process needs to be understood. The R&D and OBE deliverables consist of the actual product design as well as the product documentation used in the manufacturing process. Before this study the design and the sufficiency of the product documentation has not been assessed from the production's perspective. Finding the answers to these research questions increases the company's combined design and manufacturing knowledge which can be used to decrease production lead time and improve efficiency of the customer order delivery process.

1.4 Retrofit product

In order to give a better context for the reader of this thesis, a brief description of the Retrofit products is needed. Retrofit products can be delivered as a standardized product or customer engineered solutions (OBE). Standard Retrofits are designed to suit the needs of most customers. The delivered product is configured from a wide set of options that the customer selects based on the modernized Drive. These options relate the physical aspects of the cabinet infrastructure, such as cabinet size and location of motor cabling, as well as the electrical connections and controls of the existing Drive. Standard products are the output of R&D projects. Customer engineered Retrofit are always designed based on the exact customer need. These can be minor changes to standard Retrofit designs or completely new and one-off designs. Customer engineered deliveries are designed by order-based-engineering team.

Standard and OBE retrofits are constructed from pre-installed and wired sub-assemblies, individual components, and Drive modules that are delivered to the customer. The final assembly and wiring are done at the customer facility. Retrofit products can be delivered as a kit or frame solutions. Kit Retrofit delivers the formerly mention items to the customer. In frame Retrofit, many of the pre-assemblies and components are assembled into larger sub-frame assembly that is delivered to the customer. This is done to decrease the needed final installation time. The generally the Retrofit manufacturing consist of assembling the sub-assemblies and sub-frames as well as organizing the order materials for packing. Figure 1 shows the construction of a Retrofit product from sub-assemblies, sub-frames, and a Drive module. This particular product is a frame solution for ACS600 single drive.

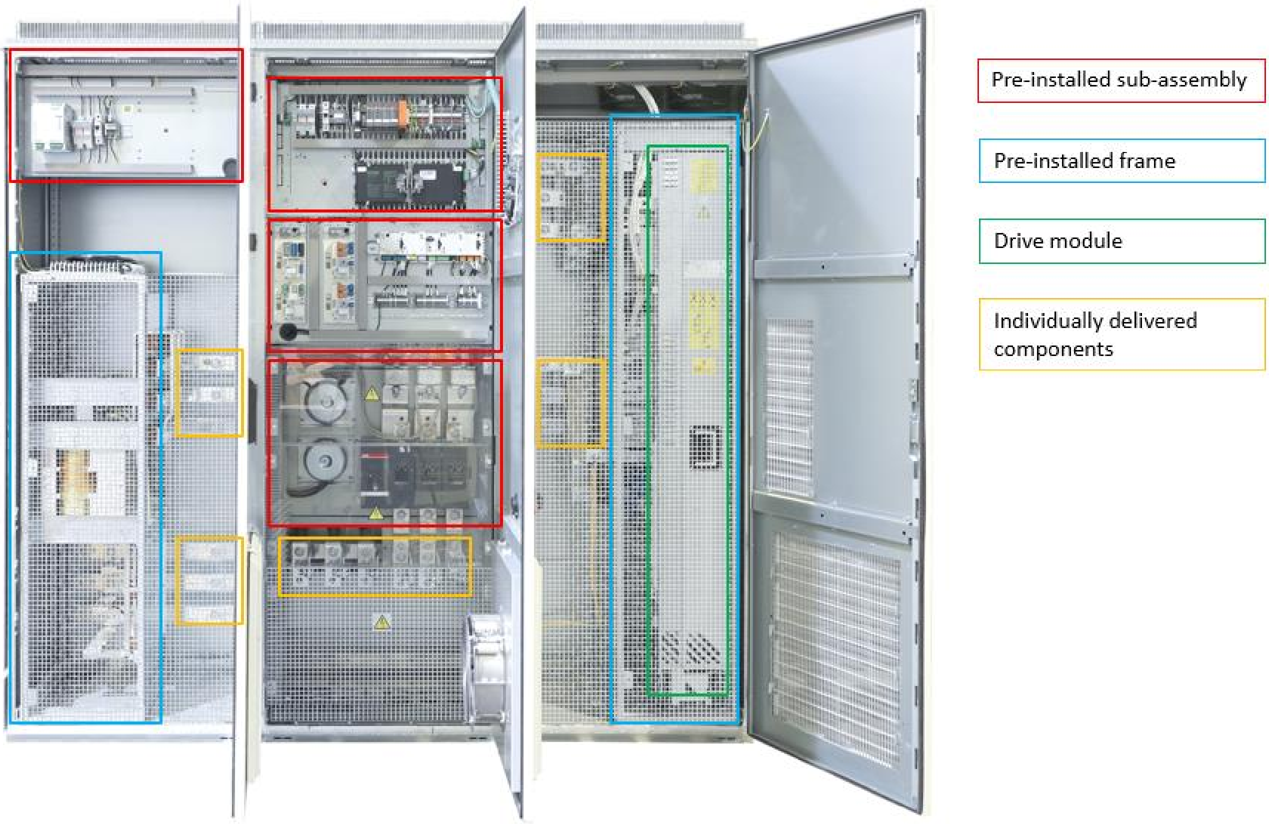


Figure 1. Construction of a Retrofit product.

1.5 Structure of the study

First part of the thesis consists of describing some of the existing research done in fields relevant to the research questions. Section 2 focuses on the higher level of product design. This includes the product architecture and the product structure and their effect on product lifecycle decisions. Section 3 presents how the assembly operations can be accounted for in the product design by using design-for-assembly methods. Section 4 describes different aspects of manufacturing planning in assembly-to-order environment. The focus this section is not in the shop floor actions but in planning of assembly operations.

The second part of the thesis focuses on the ABB's Retrofit products and the production process. Section 5 describes the current status of the production process. This includes describing the production facility, high level order completion, and the shop floor action in the Retrofit production. Section 5 also presents the current documentation used in the manufacturing and the product structure design of Retrofit products. Section 6 analyses the current production process and documentation. In this section the major production issues resulting in longer lead times are described and possible solutions to remove these issues are presented. The methods used in the analysis are also presented in section 6.

2 Product architecture

Product architecture plays a role in many of the lifecycle aspects of a product. The first part of this section presents the basic concepts behind product architecture. The focus in the section is in modular product architecture, and so the different considerations involved in building such product architecture are discussed. The second part focuses in presenting product structures and bill-of-materials as they are direct consequence of product architecture and can be seen as its practical applications.

2.1 Product architecture as a concept

According to Ulrich (1995), most products are constructed using a combination of individual components and sub-assemblies. Each component in the products provides a specified function that contribute to the functionality of the whole product. The product architecture can be seen as a scheme that allocates product components to serve the different functionalities in a product. In a product development project, the product architecture is commonly created after the basic concept for the working of the product have been identified but before the detailed design of components and sub-systems is started i.e. the system level design phase of the product development.

Ulrich (1995) suggests that the product architecture (PA) serves three main purposes. Firstly, PA is an arrangement of functional elements in the product. The Functional element does not refer to the actual physical properties of components or assemblies used in the product but describes the functionality that is expected of these elements. In other words, it is the functional requirement of that specific area of the product (Ulrich, et al., 2020, pp. 197-198). Individual functional elements are built into a complete functional structure that demonstrates the overall function of the complete product (Phal, et al., 2007, p. 31).

According to Ulrich (1995) the second purpose of the PA is to allocate components to specific functional elements in the product. Components implements the several functional requirements of the product. Component in a product architecture can be a separate part, sub-assembly, or distinct functional region within product. Based on this description not only physical parts are viewed as components, but non-physical elements such as software subroutines and regions of integrated circuits can also be viewed as components that can be allocated to a function.

Ulrich (1995) presents that, components can be mapped to the functional elements by one-to-one, one-to-many, or many-to-one relationships. The mapping depends on a whether the component implements single or multiple functions. The function-component mapping depends on the level at which the product is analysed. E.g. components inside a sub-assembly can experience many-to-one or one-to-many mapping while on the sub-assembly level, the final products exhibits one-to-one mapping between functions and sub-assemblies. The component-function mapping determines a general topology for different product architecture types.

Ulrich (1995) suggests that the third purpose of PA is to specify the interfaces or connections between interacting components. Interface can be physical, wired connection, or a non-contact connection such as a wireless signal (Ulrich, 1995; Fixson, 2005). Interface specification defines the primary protocol for interactions across component interfaces within the product. Interfaces can be standardized according to commonly agreed protocols such as standardized nut and bolt connection or signal protocol. Non-standardized interfaces may be used in products by the choice of the company.

According to Ulrich (1995) the component interfaces can be coupled or de-coupled. In de-coupled interfaces one of the interfacing components can be changed without also requiring a change to the other component. Coupled interface requires change to both components. Practically, very few physically connected components are fully de-coupled. Figure 2 presents coupled and de-coupled interfaces between parts A and B. Changing the height of the part A does not affect the part B when the interface is de-coupled. If the interface is coupled, then B must also be adjusted.

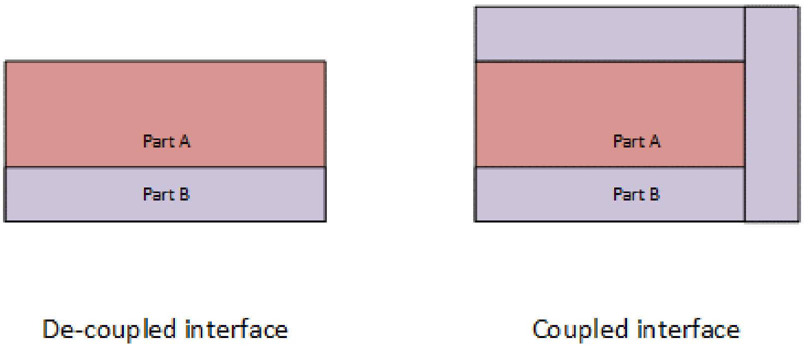


Figure 2. Coupled and de-coupled component interfaces.

2.2 Product architecture topology

In his work Ulrich (1995) suggest that on a general level, different product architecture types can be separated into two categories, modular and integral architectures. The division is done based on the mapping between components and functions as well as the degree of interface coupling within the product. Characteristics of a modular product are on-to-one mapping between physical components and functional elements and well defined de-coupled module interfaces. Modular architecture can be further specified into several sub-types such as slot, bus, and sectional based on how the interfaces are designed.

Ulrich (1995) presents that contrary to modular PA, integral products exhibit large amount of function sharing, i.e. a single component implements multiple functions within a product. The interfaces in integral architecture are typically coupled and do not adhere to a defined standard. Most products exhibit some combination of modular and integral architectures and no single architecture can be optimal in every case. Modular architecture has benefits e.g. in the areas of product change and variety and integral architecture can be used to achieve lower unit costs in mass produced products. The best way to measure the value of integral design versus modular one is to examine the customer requirements and needs (Stone, et al., 1998; Zamirowski & Otto, 1999). The different types of modular and integral product architectures are presented in Figure 3.

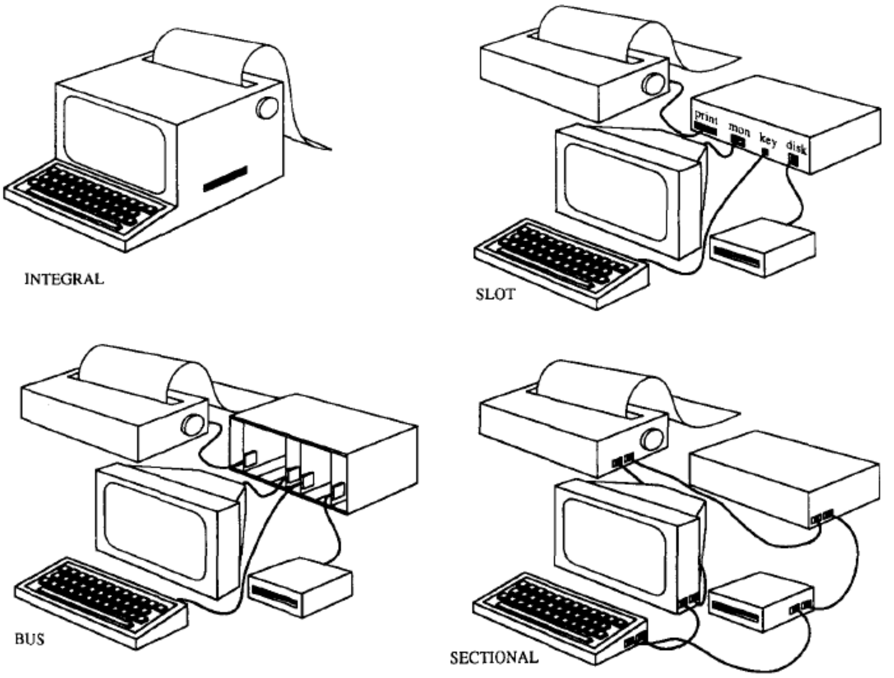


Figure 3. Different product architectures illustrated on a personal computer. (Ulrich, 1995)

2.3 Modular product architecture

Designing modular products means creating a high amount of independence between components (Sanchez & Mahoney, 1996). Phal, et al. (2007, p. 495) suggests that modular products are such machines, assemblies, and components that use distinct functional building blocks called modules to fulfil the overall product function. Key element in creating modularity is to achieve as much standardization in components and their interfaces as possible. The standardization of interfaces allows the certain components in the product structure to be substituted by another in order to create variation (Sanchez & Mahoney, 1996). Such changes are typically necessary e.g. because of variation in customer needs. According to Ulrich (1995) the modular architecture makes the overall design more flexible. The standard components and interfaces also allow the company to better use the capabilities of the suppliers as they are able to make improvements to their design during the lifecycle of the supplied component without affecting its use.

With the help of modular product architecture, companies can more quickly react to changing markets (Shamsuzzoha, 2011; Sanchez & Mahoney, 1996). Various individual customer requirements can be satisfied by reconfiguring modular products. Sanchez & Mahoney (1996) present that different functionalities can be provided by different variation of old and new product modules. The goal of modularization of product architecture is to achieve the requirements of the product or account for the production process (Phal, et al., 2007, p. 515). Ulrich (1995) mentions that for these and many more reasons the modular product architecture has been said to be a synonym of a good design.

2.3.1 Product functions

In their book Phal, et al. (2007, p. 31) present that product can be expressed as combination of functions. Function represent the relationship between the input and output of a system than is performing a specific task. Functions are expressed in a simplified verb noun statements or functional flow format and do not express any assumptions of the physical characteristic of that area of the product. Typical examples of functions are e.g. “transfer torque” and “reduce speed” (Ulrich, 1995). Functions express the conversion of energy, signals, or materials that takes place in individual tasks in the product.

Phal, et al. (2007, p. 32) present that functions can be categorized hierarchically based on the level of product examination. At the highest level in the function hierarchy are *overall* or *product functions*. Product functions express the overall input and output relationship of the complete product. The product function is achieved through a combination of *sub-functions.* Sub-functions represent more elementary tasks within the product performed by e.g. sub-assemblies or functional regions (Phal, et al., 2007, p. 31; Stone & Wood, 2000). At the lowest level in the function hierarchy are individual *functions.* These functions describe an operation performed by individual device or component within the product (Stone & Wood, 2000). Sub-functions can be divided onto *main functions* and *auxiliary functions*. Main functions contribute directly while auxiliary functions contribute indirectly to the product function. Auxiliary functions are supportive or complimentary and their necessity is determined by the nature of the main function.

2.3.2 Functional structure

The breakdown of the product function is called the functional structure of the product. According to Stone & Wood (2000) functional structure is a presentation of the product function as a set of sub-functions and their connectivity. Functional structure represents the design team’s understanding of the working principles of the product, but it does not necessarily contain every minor detail (Ulrich, et al., 2020, p. 198). It represents the conceptual design work and is a good way to communicate design information. Creating a functional structure is the first step in establishing the product architecture (Ulrich, et al., 2020, p. 197).

Phal, et al. (2007, p. 29) present that the connections between the sub-functions in the functional structure are called *flows* and they represent the inputs and outputs of each sub-function. There are three basic flows that exist between sub-functions that represent changes in matter, energy, and signal. The flow of matter is the transfer of physical material (solid, gas, liquid) within the system, signal is the flow of information between different sub-functions, and energy refers to the transmission of electrical or mechanical energy (Stone & Wood, 2000). Flows can be categorized as *main flows* that are dominant in the system and necessary for the correct operation of the product or *auxiliary flows* that are supportive in nature.

Phal, et al. (2007, pp. 170-171) suggest that the main sub-functions are formed from the main flow of the system. This means identifying the linkages that turn the main input of the system into the desired output. Once this is accomplished, the auxiliary flows can be considered in order to further break down complex sub-functions. The level at which the product is understood affects this process. In designing a new system, the subsystems and their connecting flows may not be well known. In designing new solutions based on existing products, the sub-functions can be determined by examining existing products.

In their work Phal, et al. (2007, pp. 31, 169-170) shows that the complete product functional structure can be presented in a solution neutral block diagram showing the different flows through the sub-functions within the system. The block diagram can be presented in varying degree of information. At most basic it is a “black box” model of the product function and the inputs and outputs of the product. As the main and auxiliary sub-functions are identified, more detailed diagrams can be built (Stone & Wood, 2000). According to Ulrich (1995) increasing the level of detail in a functional structure makes it present more assumptions of the physical working principles of the product. In order to keep the presentation manageable, the visualization of functional structure should aim to have fewer than 30 elements. In the case of complex systems, minor elements can be combined into higher level sub-functions that are decomposed in later design phases when the secondary systems of the product are determined (Ulrich, et al., 2020, p. 198).

Different levels of functional structure presentation for a hypothetical testing machine are presented in the following figures. Figure 4 shows the black box model of the overall function. In the middle is stated the required function of the machine. The expected system input flows are on the left side and output flows are on the right side of the model. Figure 5 shows the main sub-functions and the main flows of the machine that are needed to complete the overall function. Figure 6 presents the complete functional structure that includes the main and auxiliary sub-functions and flows. In the figures the functions are presented as rectangular shapes with the function statement. The flow of energy is presented with a solid black line. Material flow is shown as a solid blue line. The flow of signal is presented as a dashed line. Input flows are shown with an arrow pointed towards the function. Input flow of a function can be the output of another function.

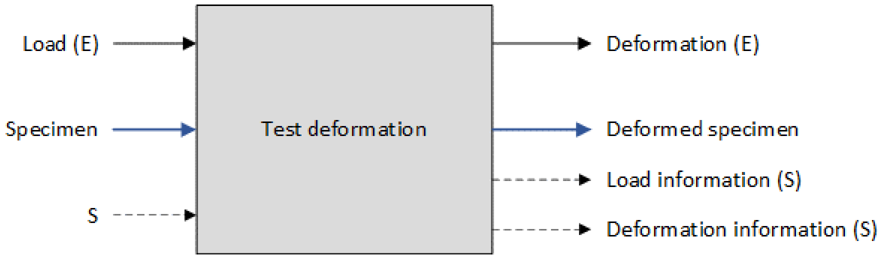


Figure 4. Black box model of a hypothetical testing machine.

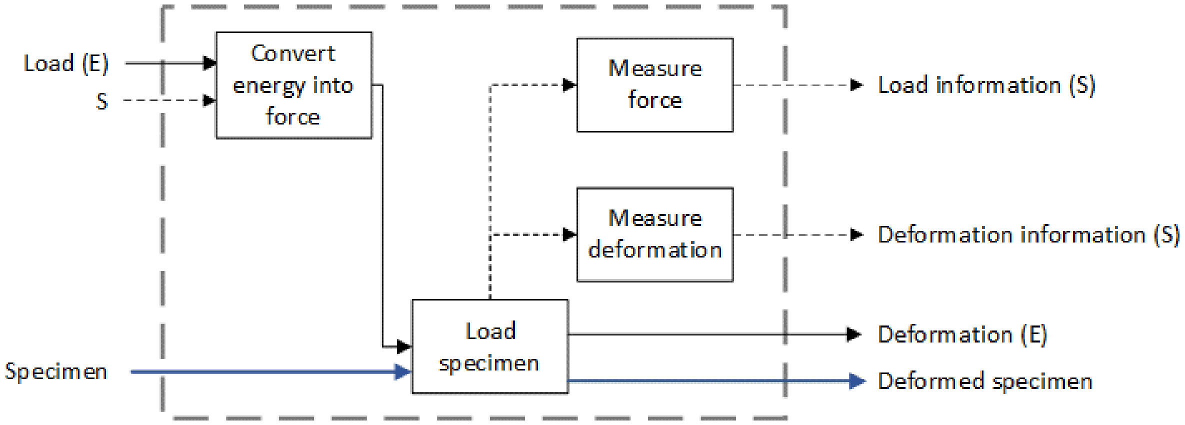


Figure 5. Main sub-functions of the hypothetical testing machine.

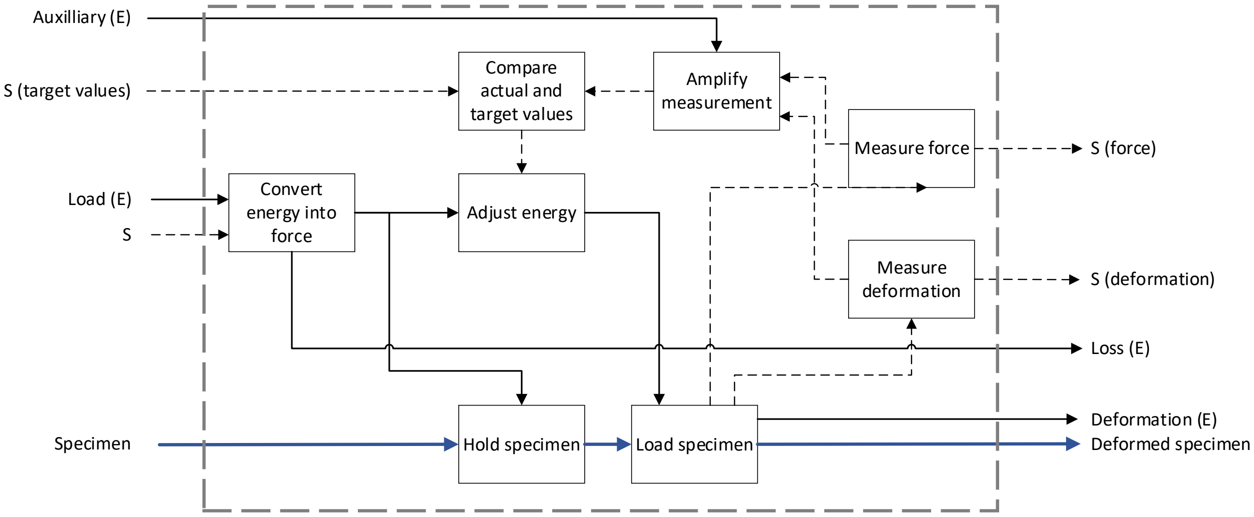


Figure 6. The complete functional structure of hypothetical testing machine

In the book *Engineering Design - A systematic approach* Phal, et al. (2007, p. 503) present couple of considerations for forming of functional structures. Firstly, the goal is to achieve the desired overall function with a minimum number of easily implemented basic functions. Furthermore, overall function should be divided into main functions, auxiliary functions, and interfacing adaptive functions in a way that more desired product variants can be made from the basic functions while less demanded variants are made with additional adaptive functions. In the case of vary rare product variants, it might be cost effective to provide solutions with non-module functions.

In the case that the product being developed is part of a larger product family, Dahmu, et al. (2001) present that a family function structure can be created. Individual product function structures are combined in a single diagram that shows every function and flow in the family of products. Those functions that are shared by many or all the products in the family can be used to modularize the product into a common platform. It is possible that some shared function is performed with differentiating flows depending on the product. Then the shared function is not an option for platforming. For example, the motor in compressed air and in electric motor driven screw guns in the same family provides the same function but with different inputs. As such the motor cannot be used as common element.

2.3.3 Determining a module

In their work Phal, et al. (2007, p. 496) suggests that after the product functional structure is established and the rough layout of the system is known, the formation of product modules can begin. Modules can be divided into *functional modules* and *production modules* based on the need for the module formation. Function modules are used to implement a technical solution. These modules fulfil their functions individually or as a group. Production modules are formed solely based on the module's production related aspects and are designed independently of the actual function they implement.

According to Phal, et al. (2007, p. 497) modules can be formed at a different level of complexity. Modules that are assemblies and can be divided into individual components can be classified as *macro* *module*s while modules that are individual components themselves are known as *micro modules*. This definition is one of the more production-oriented characteristics of a module. Overall, the level at which a module can be divided into individual components for functional or production reasons is known as the resolution of that module.

Modules are formed by grouping sub-functions together (Phal, et al., 2007, p. 496; Ulrich, et al., 2020, p. 199; Stone & Wood, 2000). Since there are large number of different combinations, it is important to consider where the grouping can yield most advantages. A possible rule for managing the number of alternative sub-function combinations is to assume that every module provides one sub-function (Ulrich, et al., 2020, p. 200). However, Phal, et al. (2007, p. 504) suggests that combining several functions in a single module may be more cost effective than individual modules for those functions. It is difficult to lay a specific set of rules that apply to module formation across industries because of the complex technical and economic factors included. However, some general guidelines can be used to ease the process. In their book *Product design and development* Ulrich, et al. (2020, p. 200) present a set of considerations that can be used to determine whether the grouping of certain sub-functions into modules is advantageous. These are based on different viewpoints of the product such as design, manufacturing, or product management. These considerations are presented in Table 1.

Table 1. Considerations when forming modules. (Ulrich, et al., 2020, p. 200)

Module formation guideline	Description
Geometric integration and precision	Functions that require close geometric integration or a similar precise location in the product could be combined into a module.
Function sharing	When multiple functions can be implemented by a single component, they could be included in the same module.
Capabilities of vendors	If a vendor has an expertise regarding certain functions, they could be included in the same module.
Similarity of design or production technology	Including functions that may be implemented by components sharing similar design or production technology into a same module can allow for more economical production.
Localization of change	If some form of a change is expected to a function or the component assigned to it, it is best to leave it on its own module to avoid disturbing other modules
Accommodating variety	Modules should be determined in a way that allows the creation of product variety that is valuable to the customer.
Enabling standardization	If a group of functions are used in multiple products, they should be included in the same module. This allows the possibility of standardization and benefits of economics of scale.
Portability of the interfaces	If a group of functions is implemented by components requiring close physical proximity, they should be included in the same module. Some interfaces, e.g. signals or wires, allow flexibility regarding component location.

2.3.4 Methods for module identification

Some systematic approaches have been developed for identifying possible product modules. The goal of these methods is to offer a simplistic definition for modules based on the functional structure and the flows in the system. In their 1998 conference publication Stone, et al. (1998) introduced three methods for identifying modules based on heuristic approaches. These methods are based on analysing the different flows in the functional structure.

Stone, et al. (1998) present the first methods as the *dominant flow* method. This approach is used to examine and identify the set of sub-functions that a certain flow runs through until it changes into another type of flow or it exits the systems. These sub-functions form a candidate for a module and sets the boundaries for that sub-system. Other flows, that might be involved with these sub-functions, are the interactions between the module and the rest of the product. In some cases, it is possible that a flow only enters one sub-function before changing or exiting the system never forming the needed sequential function chain to form a module.

According to Stone, et al. (1998) the second heuristic method, called *branching flows*, is based on identifying parallel sequential sub-function chains. A sequential chain refers to a set of sub-functions that must be completed in a particular order to get the desired output. Parallel sequential sub-function chains all depend on the same upstream sub-function as well as a common flow. These chains can accomplish their desired output independently without interactions between them. The method ranks these parallel chains and identifies each as a potential module. The benefit of this method is that products where modules are made with parallel sub-function chains are likely to be capable of component swapping and/or bus modularity since the interfaces of the modules are typically physical connections.

Stone, et al. (1998) calls the third heuristic method *conversion-transmission modules*. This method searches the functional structure for sub-functions that convert the input flow of material or energy into another form of material or energy. If this type of sub-function exists in the same sequential sub-function chain with a transmitting or transporting sub-function, it can be viewed as a module that implements the new form of energy or material. If a conversion-sub functions exists without the downstream transmitting or transporting sub-function, it can be considered a module on its own. Typically, these types of functions are implemented by a specific component themselves. If there is a transmitting or transporting sub-function right after the conversion sub-function, the pair is a candidate for a module. However, if there are sub-functions operating on the new flow between them, the whole chain needs be considered a possible module.

McAdams, et al. (1998) present that one additional rule for forming product modules is to identify causally linked pairs or groups of functions. These types of functions are obviously linked, and one function may require the existence of one another. These types of function pairs, that can be e.g. process inefficiency removing functions, are a possible candidate for modules (Zamirowski & Otto, 1999).

According to Zamirowski & Otto (1999) the former methods are focused on analysing a functional structure of a single product. When the goal is to modularize a family of products that might share modules, additional rules need to be defined based on the family functional structure. Then the rules are based on the repetition, commonality, and uniqueness of the sub-functions. When certain sub-function sequences share similar input and output flows and they are used multiple times in the functional structure, they should be included in the same module. This module can be used multiple times in the product in question. Also, sub-functions that are shared by multiple product variants in the product family are candidates for a modularization. If a set of sub-functions are only used by one product variant, they should be consolidation in their own variant specific module.

2.3.5 Product variety

In his article Ulrich (1995) presents that product variety can be defined as a diversity of products that a particular production system can deliver to the marketplace. From the customer perspective, variety is only valuable if it provides different functionalities to a product. From production systems perspective, high amount of product variety can be achieved from most systems if cost is not a limiting factor. The difficulty comes from providing product variety at a reasonable cost. Production equipment flexibility is often viewed as a necessity for producing variety. This is often equated with manufacturing flexibility. While equipment flexibility is a factor in determining economics of product variety in some production systems, a notable portion of the ability to produce variety resides in the architecture of the product itself.

According to Ulrich (1995) due to the nature of integral product architecture, production of variety would require increased inventory, setup, or tooling costs. High process flexibility, such as the use of CNC equipment, could allow for economical production of variety for some integral products. This is because with such equipment, integral components can be produced with relatively low setup costs as they are needed. These benefits exist also for modular products, but with modular architecture variety can be produced more easily without flexible equipment. This argument is focused on component level manufacturing, but it assumes that the finished product is also made in a flexible assembly system. This is commonly the case in manual assembly processes. In automated assembly, the flexibility of the system used is also a key driver in the ability to produce variety.

Ulrich (1995) presents that with a modular architecture variety can be produced by combining predetermined building blocks. In example if customer requirements for a product can be divided into 4 different functions for which 3 possible options could be selected, with completely integral design, were the functions are shared by components, this would mean 81 (3x3x3x3) individual products designed to the marketplace. With the use of modular design, the same amount of variation could be produced by only 12 types of building blocks. In some cases, modular architecture can allow variety to be created at final assembly stage of production or when the product is ready to be shipped to the customer.

2.3.6 Component standardization

According to Ulrich (1995) and Perera, et al. (1999) there are three possible situations where the component standardization can occur. In the first one, multiple individual components are replaced by a common one in a product. This is called standardization within a product. Second one is the standardization between different products. This means that unique components in a variety of products are replaced by a common one. Thirdly, some component can be standardized across product generations over time. These types of standardization can occur in the designs of a single company, i.e. internal standardization, or across multiple companies, i.e. external standardization. In internal standardization the components are designed by the company and can be manufactured in-house or procured from external vendor. In external standardization the vendor is also in charge of the design.

Ulrich (1995) proposes that a component can be standardized only if it implements a commonly useful function or it has an identical interface in multiple products. The probability of component being commonly useful is increased in modular architecture. Because of one-to-one component-function mapping, same components can be used in variety of products where the functions are needed. The decoupling of interfaces between components allows for interface standardization and the use of the same component in different settings.

Ulrich (1995) and Perera, et al. (1999) suggests that standardization of components has cost implication on many of the lifecycle phases of the product. In product development the different costs can be roughly divided into engineering, design modification, production preparation, computer processing, and management costs. The use of standardized components lowers the uncertainty in design since they represent already well known components. Furthermore, the development time, complexity, and costs of a product can be decreased since the design of multiple individual components for a variety of products is replaced with a common effort. The development costs of the standardized component are typically higher since they need to satisfy a multitude of requirements. On the other hand, the purchasing costs are lower compared to unique design components since economies of scales can be utilized. The higher volume can also attract and incite competition between possible suppliers.

Perera, et al. (1999) present that the manufacturing related costs of a product include material, facility, and production costs. Standardization reduces the variety in materials which in turn reduces all of the different material related costs such as unit costs, transport, procurement, and material management costs. The reductio of part variety also results in reduction in necessary production equipment. Furthermore, the set-up, processing, queue delay, and WIP related costs are decreased and the variability in production planning and scheduling is reduced. The decreased component variety also diminishes the need for multi-skilled labour. The variety of production activities are decreased which moves the process towards repetitive manufacturing. This improves the learning curve of personnel and maintains the skill of the employees more efficiently. The consequence of these factors is lower overall cost of manufacturing.

According to Ulrich (1995) and Perera, et al. (1999) the standardization of components has some disadvantages. Standardized components may be used in situations where they exhibit excess functionality compared to the product requirements. For example, this can lead to increased weight and volume that need to be considered in product design. Excess functionality can also increase the operation costs of the product for example by unnecessarily increasing power consumption. Excessive components can also have higher unit costs compared to solution engineered ones. The use of standard components with excessive functionality can be justified by the reduced complexity of material management, purchasing and quality control. From design standpoint, the use of known standardized components can slow down the development of new and better technology or its implementation to new products.

2.4 Product structure

According Saaksvuori & Immonen (2008, p. 30) a product structure is a presentation of relationships between separate components and possible assemblies in the product. A basic product structure is based on the design and direct product part lists. Product structures can be managed by a product life cycle management (PLM) software which is commonly integrated to the company's design software. Alternative representations are possible based on organizational viewpoint of the product. Management of multiple product structures for complex products is practically impossible.

Figure 7 presents the product structures of a bicycle based on engineering and manufacturing viewpoints. The top level of the structures corresponds to the end product and is show with a green block. In the engineering product structure, the second level shows the individual design areas of the product and possible sub-assemblies such as the frame. In the manufacturing product structure, the hierarchy represents possible assembly stages and not the design. For example, fender, tyres, seat can be manufactured concurrently but frame can be assembled after the chain and pedals have been completed.

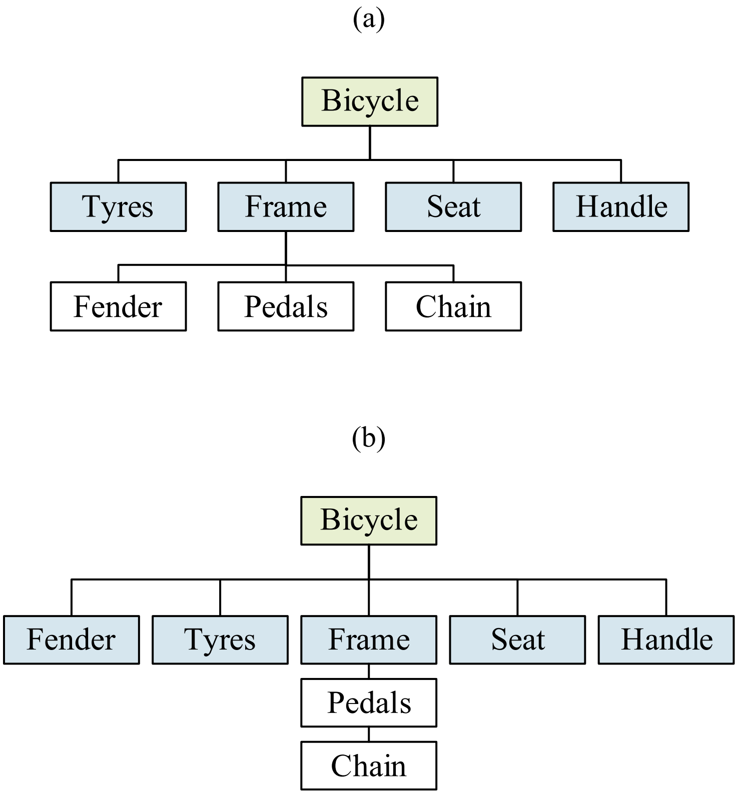


Figure 7. Product structure of a bicycle form engineering (a) and manufacturing (b) viewpoints.

Fry, et al. (1989) present that different product structure types can be roughly divided into three categories: flat, tall, and complex. In flat product structure, every component is on the same level in the structure. In the tall structure, components are placed on multiple levels in the structure. Complex product structures manifest characteristics from both flat and tall products structures. These types product structures are show in Figure 8.

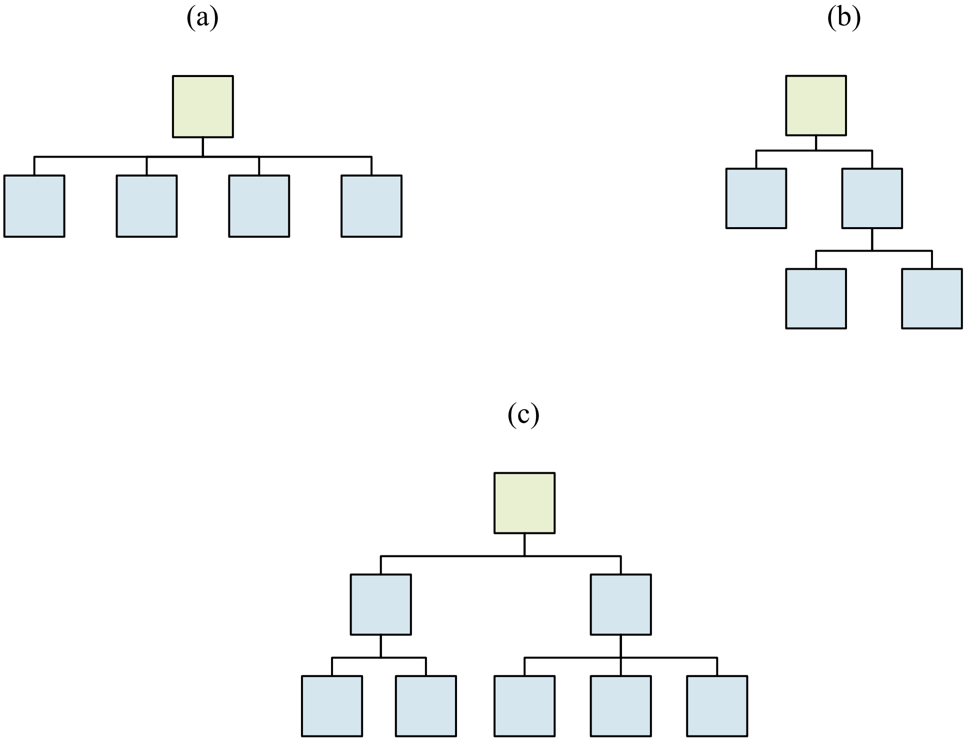


Figure 8. Product structure types. (a) flat, (b) tall, (c) complex.

In their study Fry, et al. (1989) showed that complexity of the products structure affects scheduling in assembly manufacturing. In an assembly shop environment, the tall product structures exhibit more tardiness compared to flat ones when the same due date allowance is used. This is because flat structures allow more concurrent processing of parallel components. Tall product structure was found to improve job due-date based scheduling. The shortest processing time (SPT) scheduling was found not to be impacted by the product structure. On general level, the study showed the importance of product structure consideration in manufacturing scheduling.

Collier (1981) presents the degree of commonality within a single product or between two or more products as one performance characteristic of a product structure. Degree of commonality can be expressed analytically by a degree of commonality index (*C*) that uses the component relationship information in the product in bill-of-materials. The degree of commonality index can be defined at any level of individual product structure or across the company's offering. For example, company can calculate the commonality in major sub-assemblies that are used across product lines. Product structure degree of commonality is strongly linked to component standardization and has similar benefits regarding inventory, and production related costs.

The degree of commonality index can be calculated with equation (1) (Collier, 1981).

$$Degree\ of\ commonality\ (C) = \frac{\beta}{d}, \qquad 1 \leq C \leq \beta = \sum_{j=i+1}^{i+d} \Phi_j \tag{1}$$

Where β is the number of closest parents for all different components in a set of end items or PS level(s), d is the number of different components in the product structure(s), i represents the number of end items or the parent items for PS level(s), and Φ_j is the number of parent items that component j has over a set of end items or product structure level(s).

Example of degree of commonality index for three pairs of products is shown in Figure 9. For example, the degree of commonality between product 5 and 6 can be calculated as follows. On the second level in the product structures there are total of three components of which two are common. The commonality on the second level is then 2+1. The third level has a total of seven components. Components c and e are used three times and d twice. The commonality in this level is 3+3+2. The total number of distinct components in the product structures is 5. The degree of commonality index can be calculated as 2,2. It is the total amount of components in the products divided by the number of unique components.

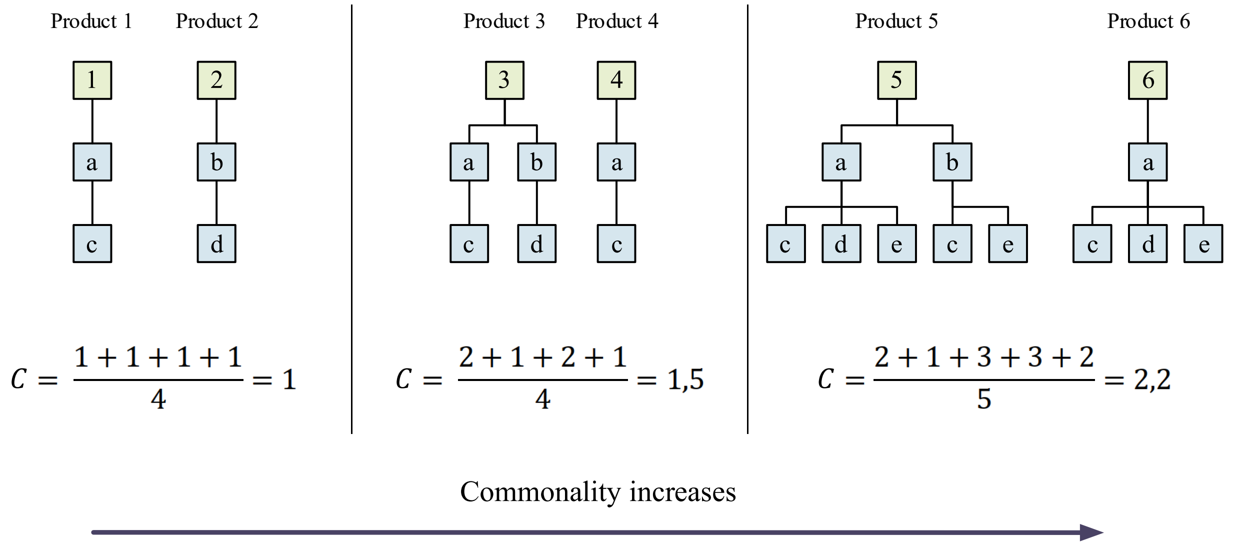


Figure 9. Degree of commonality in two product structures.

2.4.1 Bill-of-materials

Bill-of-materials (BOM) can be seen as the practical representation of the product structure. According to Van Veen (1991), Hegge & Wortmann (1991) and Jiao, et al. (2000) at the most basic level, the BOM shows a list of components and their corresponding quantities that are used in the end product. BOMs commonly include the "goes-in" relationship between parent items, such as assemblies, and the components needed in the parent items. Other information in BOM can include item number, description, price, make-or-buy, lead time, operation number etc. The exact product information presented in BOM can vary depending on the intended use of the BOM. Different organization within a company can have varying requirements for the BOM information. The downside of using multiple BOMs is that companies can struggle with the maintaining consistency and synchronization of the various BOMs (Jiao, et al., 2000).

According to Hegge & Wortmann (1991) items in a BOM can be defined at different levels of hierarchy. An item that has its own BOM and does not belong to any other BOM can be seen as the *top product* and is at the highest level in BOM hierarchy. An item that does not have a BOM but is used in other BOMs can be called primary products. These items are typically components that are purchased from a supplier and are on the lowest level in BOM hierarchy. Items located between the top and primary products are sub-assemblies in the end product.

Chang, et al. (1997) and Jiao, et al. (2000) present that the most practical BOM types in a manufacturing company are the engineering BOM (EBOM) and the manufacturing BOM (MBOM). EBOM is the end result of product design. It is a representation of the functionality of the product and shows the series of subsystems or assemblies that form the overall product functionality. EBOM is the most commonly used and is the traditional representation of a BOM (Jiao, et al., 2000).

Manufacturing BOM is constructed to show how the end product is built from physical sub-assemblies (Jiao, et al., 2000). According to Chang, et al. (1997) The structure of the MBOM consist of series of hierarchical assembly groups that reflect the assembly process in the shop floor. Information in MBOM includes the sequence in which the components are assembled and the possible constraints that need to be accounted for. Most benefit from using MBOM, regarding shorter production lead times, can be achieved if concurrent assembly groups, possible elimination or combination of useless assembly groups, and the lead times for components that are needed later in the process are considered. Although the elimination and combination can only be used if just-in-time (JIT) production philosophy is in place.

In his article Stonebraker (1996) notes that the reduced lifecycle requirements for products, process flexibility and delivery requirements, and use of automated inventory management encourage the change toward more modern representation of BOM. One such example is the modular BOM that show the product as a combination of product variant blocks. Modular BOM can be used to configure end items based on the needs of the customer and is also known as configurable or variant BOM. The some of the different kinds of BOMs are presented in Table 2.

Table 2. Some of the different types of bill-of-materials. (Jiao, et al., 2000) (Van Veen, 1991) (Hegge & Wortmann, 1991) (Jacobs, et al., 2011) (Stonebraker, 1996)

Name	Abbreviation	Functional description
Engineering BOM	EBOM	Traditional BOM representation based on the functionality and constructions of the product from individual components and assemblies.
Manufacturing BOM	MBOM	Bom used for the MRPII explosion. Contains information of the specific assembly sequences for the product.
Modular and configurable BOM	MBOM, CBOM	Shows component relations to product options. Construction is based on how the product is ordered.
Planning BOM	PBOM	A term used for a type of modular type bill-of-materials used in assembly scheduling.
Super BOM / percentage BOM	SBOM /PBOM	Shows all possible product options as components with their average decimal usage in an average end item. Can be used in the forecast of components and option modules.

3 Design for manual assembly

Just like architectural decisions, design decisions can have significant effect on the assembly of a product. This section discusses methodologies that can be used to guide design efforts in more favourable direction from assembly point of view. Most of the focus in this section is in method to analyse and guide the design of manually assembled products. The way in which the assembly of a product should be considered on the business and product development contexts is discussed I the last part of the section.

3.1 DFx, DFA and DFM

Multiple different methodologies for guiding the product design process based on some characteristic have been developed. These are typically referred to as design for X (DFx) methodologies. According to Whitney (2004, p. 379) DFx are aimed at improving the product by combining knowledge, procedures, analyses, metrics, and design guidelines in some specific domain such as, disassembly, repair, recycling, etc. Design for assembly (DFA) is one DFx method aimed at improving the assembly aspects of a design. Design for assembly is based on the idea that lowest possible assembly cost is achieved by designing the product in a way that it can be economically assembled by the production system (Kuoa, et al., 2001).

Many of the DFA methodologies have two main goals, minimization of the part count in the assembly and improving the physical aspects of the parts in order to improve “assemblability” (Boothroyd, 1987; Kuoa, et al., 2001). According to Boothroyd, et al. (2011, p. 10) and Stone, et al. (2004) the applications of different DFA methods have shown that the greatest improvements on assembly time and cost can be achieved with the reduction of part count which simplifies the product structure. For this reason, it is considered as a basis of many DFA approaches.

According Boothroyd, et al. (2011, p. 73) DFA is a clearly defined, systematic procedure that evaluates the design with respect to the ease of assembly operation. DFA methods measure the assemblability of the design objectively while considering the whole assembly process. In addition, an effective DFA method should include a way of estimating the assembly costs in conjunction with part manufacturing costs. Both aspects essential since multiple simple parts can be more costly to produce and assemble that fewer complex parts (Boothroyd, et al., 2011, p. 5).

In his book Whitney (2004, p. 380) notes that DFA methods provide the designer a way to evaluate their work. However, DFA is often rejected by designer in the fear of compromising product function. This can be because the designer does not have the manufacturing and assembly knowledge to see that improving the assembly aspects rarely impact the product function. DFA methods are meant to be used by the product designer, but often personnel from other areas of expertise need to be involved.

DFA improves the cost aspects of assembly operations. According to Boothroyd, et al. (2011, pp. 1-5) a notable portion of the total assembly costs depends on the cost of components. Because of this DFA can be used in conjunction with design for manufacturing (DFM) rules. DFM focuses on simplifying the parts in order make the manufacturing operations more effortless which in turn reduces the manufacturing and ultimately the part costs. DFA, DFM, and their combination design for manufacturing and assembly (DFMA) are best to be applied at the early design stages of a product development process. Figure 10 show the general application of DFMA in product development. In figure the DFA is applied in the early stages of the product development just after the product concept has been created. DFA is followed by DFM cost estimates. These create a feedback loop that is used to improve the product concept before any prototyping is done.

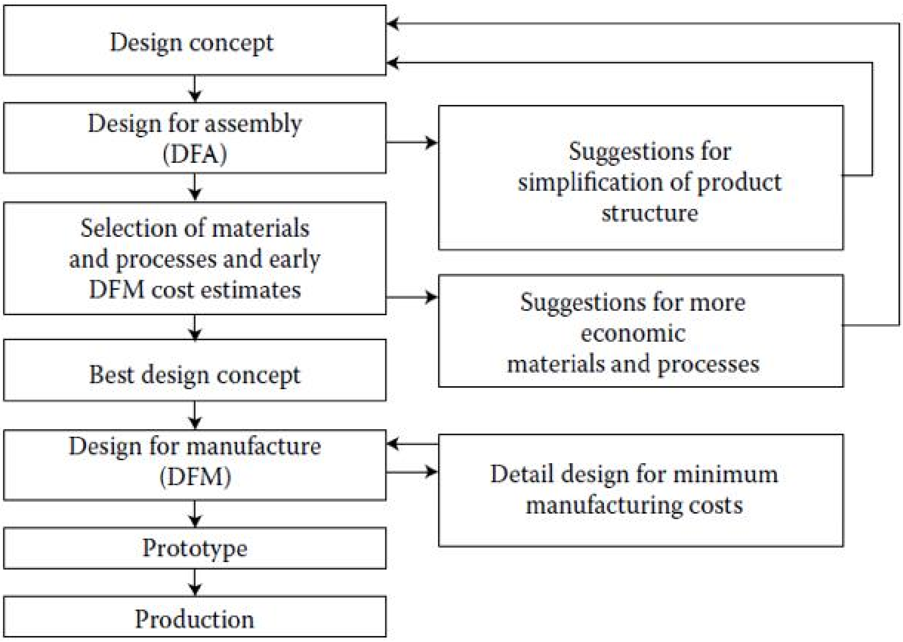


Figure 10. DFMA in product development. (Boothroyd, et al., 2011, p. 14)

3.1.1 Available DFA methods

According to Stone, et al. (2004) currently available DFA methods can roughly be categorised into four groups based on the method by which the analysis is conducted. The first of these are the design principles and rules. These rules are considered as the empirical truths that have been verified in practice. The second group analyses the assemblability of the design quantitively. The goal of these methods is to use a systematic process for determining a rating for the assembly process operation by operation. Quantitative DFA methods include for example Boothroyd and Dewhurst method, Hitachi method (AEM), and Xerox Producibility index. Out of these the Boothroyd and Dewhurst method is the most widely used. Quantitative methods offer repeatable and accurate way of rating the “assemblability” of the proposed design.

Stone, et al. (2004) present the third group, named knowledge-based systems, as those DFA methods that provide new information-processing capabilities combined with computer capabilities such as knowledge-based management or inference about the assembly. The fourth group is known as computer aided methods. In these systems the DFA evaluation processes are integrated in modern CAD software. The software uses the 3D geometry data such as symmetry or the centre of mass to determine useful information about the assemblability. Lucas DFA approach developed by Lucas engineering & systems is such a method.

3.2 Design for manual assembly (Boothroyd and Dewhurst method)

One of the most widely used systematic DFA methodology was developed by Boothroyd and Dewhurst (Stone, et al., 2004) (Whitney, 2004, p. 385). According to Boothroyd, et al. (2011, pp. 73-

74) this method specifically focuses on improving part and assembly design for manual assembly processes. The method aims to include manufacturing knowledge in a set of general design guidelines and to provide a systematic ease of assembly evaluation method for the designer. This method can be used in the design of new products or in the improvement of existing ones.

In their book Boothroyd, et al. (2011, p. 74) present that the manual assembly consist of two individual phases, part handling and part insertion. Handling phase of the assembly operation consist of acquiring, moving, and orienting the components. Insertion phase is the placing and fastening of components together. The B&D method evaluate every component in the both of these phases. The analysis is a two-step process that first evaluates if some components are candidates for elimination or combination and then determines the specific time it takes to grasp, manipulate and insert the part into the assembly (Stone, et al., 2004).

The B&D design guidelines for part handling and insertion are presented in Table 3 and Table 4. Table 5 lists additional guidelines design that are based on the reduction of parts in the assembly. According to Boothroyd, et al. (2011, pp. 74-78,110-113) these guidelines provide the basic information needed to design an easy to assemble product. However, by themselves they provide no means for quantitively evaluate the design nor are the rules ranked in any way. The designer has no way of determining which of these guidelines provide the greatest benefit for their design.

Table 3. DFA guidelines for part handling (Boothroyd, et al., 2011, p. 74)

Design guidelines for the ease of part handling.

1. Parts that have end-to-end symmetry should also include rotational symmetry about the axis of insertion. In the case this is not possible, try to include the maximum possible symmetry.
2. If part cannot be made symmetric, they should be designed to be as obviously asymmetric as possible.
3. Parts should include features that prevent jamming if they are stored nested.
4. Features that causes tangling if parts are stored in bulk should be avoided.
5. Parts that are slippery, delicate, flexible, very small, very large, or stick together should be avoided. Also avoid parts that are hazardous for the operator.

Table 4. DFA guidelines for part insertion. (Boothroyd, et al., 2011, pp. 74-78)

Design guidelines for the ease of part insertion.

1. Design parts so that there is as little as possible resistance in the insertion of components. Also, proper guidance for insertion such as chamfers should be provided. Insertion clearance needs to be enough, so that possibility of jamming should is considered.
2. Standardized components should be used as much as possible across products and product lines.
3. In case of a progressive assembly about one axis of reference, a “pyramid” assembly should be used. Generally, it is best to assemble from above.
4. The necessity of holding down parts in order to maintain the correct orientation should be avoided. The part should be secured to the assembly as soon as possible.
5. Parts should be located before it is released.
6. The relative assembly cost of common mechanical fasteners is (in increasing order): Snap fitting < Plastic bending < Riveting < Screw fastening.
7. Reorientation of partially completed assembly in a fixture should be avoided.

Table 5. DFA guidelines for part minimization. (Boothroyd, et al., 2011, pp. 110-113; Whitney, 2004, p. 388)

Design guidelines for part minimization.
1. Avoiding connections. If the sole purpose of a part is to connect two other parts, consider locating them at the same point in order to make the connection short and direct or to remove the need for connector part.
2. Provide sufficient space so that the operation and the use of tooling is not restricted.
3. Design parts so that they do not need adjustment. This is because adjusting a part takes time. If the need for adjustment is due to different materials used in the part, try to find a material that suits the application. Low costs associated with cheaper varying materials compared to more expensive one is compensated by the ease of the assembly.
4. Over constraining lead to operator dependant assembly procedures, quality, and assembly time (Whitney, 2004). This can be prevented by using kinematic design principles than can reduce the manufacturing and assembly costs of over constrained components (Boothroyd, et al., 2011).

In order to rate the “assemblability” of the proposed design quantitatively, Boothroyd, et al. (2011, pp. 81-82) introduce an assembly efficiency index, equation (2). The assembly efficiency index for a design is calculated by comparing the theoretical minimum assembly time with the actual or estimated time to complete the assembly.

$$Assembly\ efficiency\ index\ (E_{ma}) = \frac{N_{min} * t_a}{t_{ma}} \tag{2}$$

N_{min} is the theoretical minimum number of components in an assembly, t_a is the basic average assembly time for component, and t_{am} is the estimated time to complete the assembly in question. In order to estimate the theoretical minimum number of parts, each part in the proposed assembly should be compared against the following criteria:

1. Does the component move in relation to all other components in the assembly during the operation of the product?

2. Does the component need to be of different material than other components or otherwise isolated for them?

3. Is there a need to separate the part from others because otherwise the assembly of other components meeting the preceding criteria would be impossible?

According to Boothroyd, et al. (2011, pp. 81-82) the first question refers only to large relative motion between components as small movements can be compensated by elastic elements in the components themselves. The second question only consider fundamental material properties as a requirement for separation. Each component is evaluated without considering the design or service requirements. The idea behind this set of questions is to encourage the designer to think of ways in which the design can be simplified and consequently the assembly costs can be lowered.

Boothroyd, et al. (2011, pp. 82-85) suggest that basic average assembly time for a component is estimated to be on average 3 seconds. This value represents a component that is ideal from assembly point of view. This means that it presents no handing, insertion, fastening difficulties. In order to quantitatively estimate the effects of design changes, B&D methods includes a detailed classification scheme for estimating assembly times and costs for components. In the scheme general part features are used to assign a component to group that determines a standard handling and insertion times for the component. By assigning every component to a group, an estimated total assembly time can be calculated for the assembly. The complete classification system is presented in the works of Boothroyd and Dewhurst. The feature-based grouping of components and determining standard assembly times are based on expensive research. The classification is applicable for small components but can be scaled to suit larger parts (Whitney, 2004, p. 386). Some of the key part features that affect the part assembly times are part symmetry, thickness and size, weight, and clearance ratio (Whitney, 2004, p. 388; Boothroyd, et al., 2011, pp. 85-100).

Effect of part symmetry

Boothroyd and Dewhurst express the symmetry of a component with two symmetry angles based on on the different orientation actions needed to assemble a part:

Alpha symmetry, α: Required angle of orientation perpendicular to the insertion axis.
Beta symmetry, β: Required angle of orientation about the insertion axis.

According to Boothroyd, et al. (2011, pp. 85-87) the simplest parameter that expresses the time required to orient the part is the sum of the alpha and beta angles. It is the total symmetry of the part. The Boothroyd and Dewhurst classification divided the orientation time into four groups based on the total symmetry value ranges. Spherical parts are excluded from the interpretation as their total symmetry does not have an effect in practice. The Figure 11 shows the Boothroyd and Dewhurst graph of the part handling time based on total symmetry. X-axis shows the total symmetry level and y-axis the expected handling time. Shaded areas represent impossible total symmetry values. Different component geometries are shown with circle and square blocks.

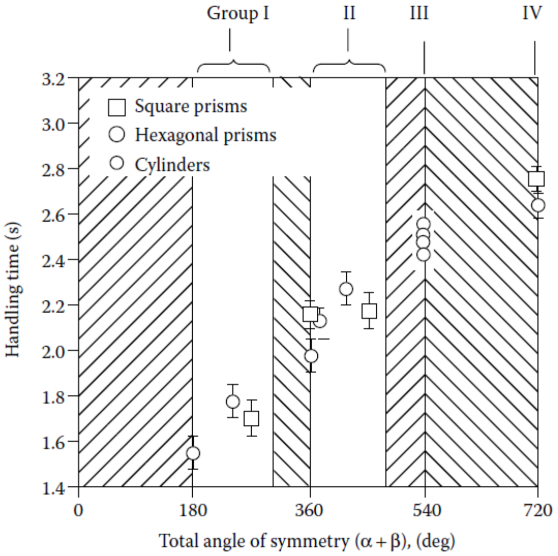


Figure 11. Effect of total symmetry of a component to the orientation time. (Boothroyd, et al., 2011, p. 87)

Effect of thickness and size

Boothroyd, et al. (2011, p. 88) note that part thickness and size are the most important factors that affect the part handling in manual assembly. Boothroyd and Dewhurst defines the thickness of a non-cylindrical part as *"the maximum height of the part with its smallest dimension extending from a flat* *surface"*. For example, this definition means that the thickness of a sheet metal component can be greater than the material thickness if bent features are included. The thickness of cylindrical part is its radius but if the diameter is greater than the its length, the part is considered as non-cylindrical. Part can be defined as a cylindrical if it has a regular cross-section of five or more sides or it is cylinder shaped. Part size is considered to be the *"largest non-diagonal dimension of the part's outline when projected on a flat surface"*. Figure 12 shows the effect of thickness and size to the expected handling time of a part. Horizontal axis represents the change in thickness or size of the component and vertical axis the handling time penalty. Curves represent different part geometries. It can be seen that the largest handling time penalty is associated with small and thin parts.

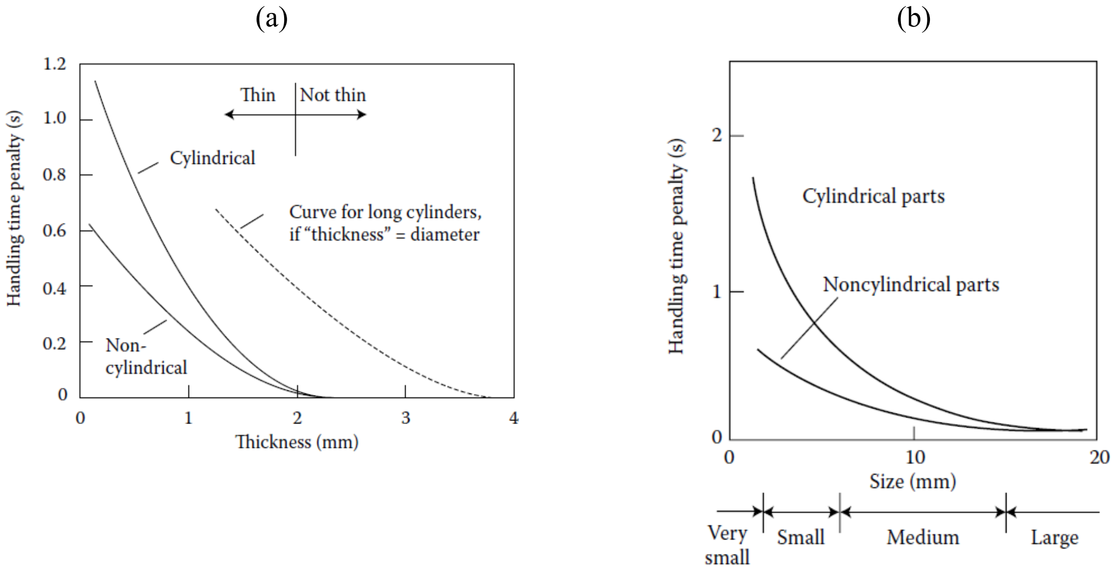


Figure 12. Effect of part thickness (a) and size (b). (Boothroyd, et al., 2011, pp. 88-89)

Weight

Weight affects the handling of components. According to Boothroyd, et al. (2011, p. 89) the time needed to grasp, control, and move parts increases linearly depending on weight. This is apparent in the case of relatively light parts that can be operated with one hand. In case of heavier components additional time penalty is needed to compensate for greater moving distances associated with such parts.

Clearance and Chamfers

Whitney (2004, p. 265) notes that a common assembly operation involves a peg being inserted to a hole. Possible error conditions in such operations are *wedging* where the peg is lodged in the whole as a result of compressive contact force or *jamming* where the peg cannot advance in the hole because insertion force is too far off the holes axis. These situations are affected by the angular and lateral errors between the components at the start of the mating.

A common way of reducing the possibility of wedging or jamming is the use of chamfers in one or both of the mating parts. Whitney (2004, p. 275) suggests that chamfers increase the lateral error tolerance in the initial contact between components. The typical chamfer profile is either curved or conical. Curved is the most effective when considering the insertion time of components but from manufacturing perspective might be more expensive to make (Boothroyd, et al., 2011, p. 94).

Boothroyd, et al. (2011, p. 95) note that another factor that effects the possibility of jams is the careful dimensioning of component. Most mating parts, excluding shrink fit mating, have some clearance between them (Whitney, 2004, p. 263). The effects of chamfer and the dimensionless clearance between parts, which is the difference between the hole and the peg diameters divided by the hole diameter, on the insertion time in one particular case can be seen from Figure 13. Horizontal axis is the dimensionless clearance between the pars and vertical axis is the expected handling time penalty. Lines represent different chamfer types.

Boothroyd, et al. (2011, pp. 92) present that following conclusion can be said about chamfer design:

1. Insertion time difference is constant between chamfer designs.
2. Chamfer on a peg is more effective that on the hole in reducing insertion time.
3. Effective Chamfer width is 0.1 times the hole diameter.
4. In the case of conical chamfer, it is best to use chamfer on both the peg and the hole. In this case the angle of the chamfer should be 45 degrees and width 0.1 times the hole diameter.
5. Manual insertion time is not affected when chamfer angle is between 10 and 50 degrees.
6. With small clearances, curved chamfer is more effective than conical.

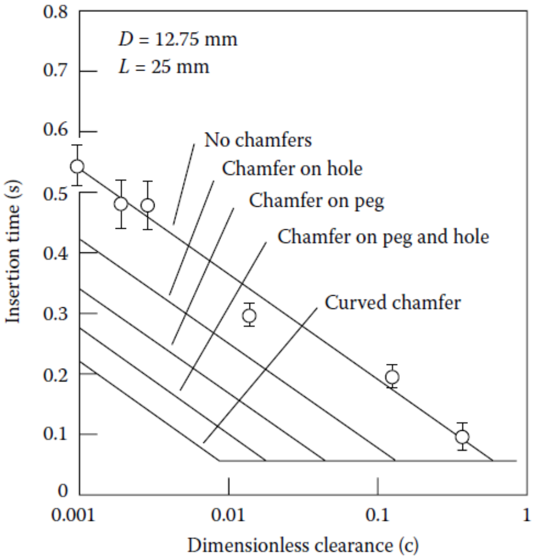


Figure 13. Effect of chamfer and clearance in ped-hole insertion time. (Boothroyd, et al., 2011, p. 93)

Assembly operational factors affecting assembly time

According to Boothroyd, et al. (2011, pp. 98-102) in addition to part geometry, some operational conditions have an effected on the component assembly time and consequently assembly costs. Most common ones are the restricted access or vision. In addition, holding down might be required during the assembly if the parts are not self-locating. Table 6 describes the effects of these conditions on the assembly time.

Table 6. Operational conditions affecting assembly time. (Boothroyd, et al., 2011, pp. 98-102)

Factor	Effect
Obstructed vision on threaded fasteners	• Restricted vision increases the insertion time when access is not restricted. • Restricted vision does not significantly increase the initial insertion time if access is also restricted. Result of tactile sensing.
Obstructed access on threaded fasteners	• If the distance between the hole centre and obstruction is below 16 mm, additional time is needed for the initial insertion. • Restricted access can increase the tightening time for each revolution.
Obstructed access or vision on pop-riveted parts	• Time penalty from restricted access is insignificant, unless clearances are small < 10 mm. • Restricted vision provides much greater time penalties compared to access.
Holding down	• Time penalty from holding down increases as the when the number of component interfaces increases. • The time penalty is greatest when the part geometries are difficult to align.

Effects of obstructed vision and access during the tightening of threaded fasteners are shown in Figure 14. Horizontal axis represents the tool clearance during the operation and vertical axis the expected times for initial the engagement and the tightening time for one revolution. On Figure 14 a) lines represent different threaded fastener ends and on Figure 14 b) different tool types.

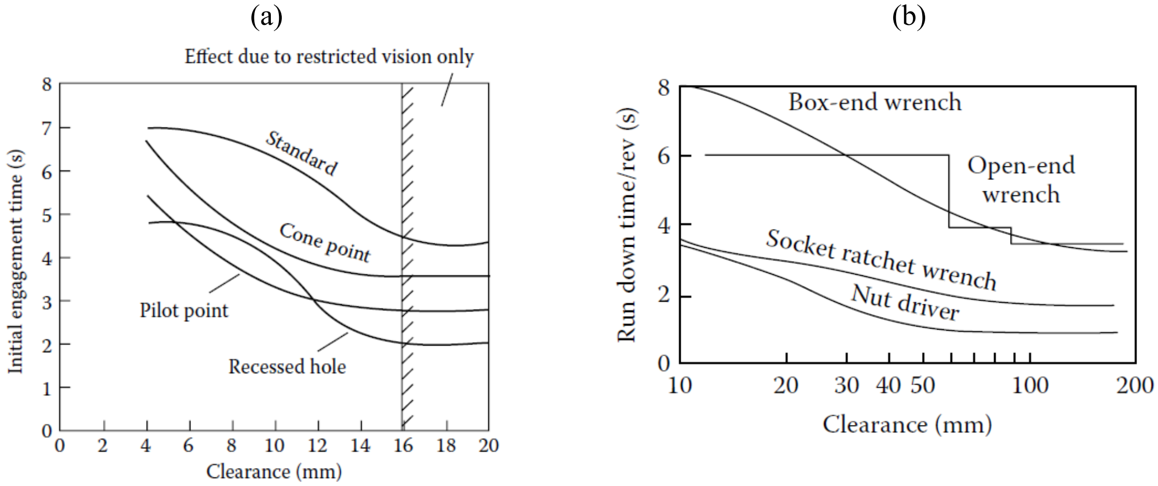


Figure 14. a) Time penalty from limited access and vision on threaded fastener insertion. b) Time penalty from limited access to tightening threaded fastener. (Boothroyd, et al., 2011, pp. 98-100)

Figure 15 shows the effect of restricted vison and access on pop riveting operations. Horizontal axis represents tool clearance from the head of the tool to the obstruction and vertical axis is the expected time penalty. Lines represent different clearance values from the side of the tool to the obstruction.

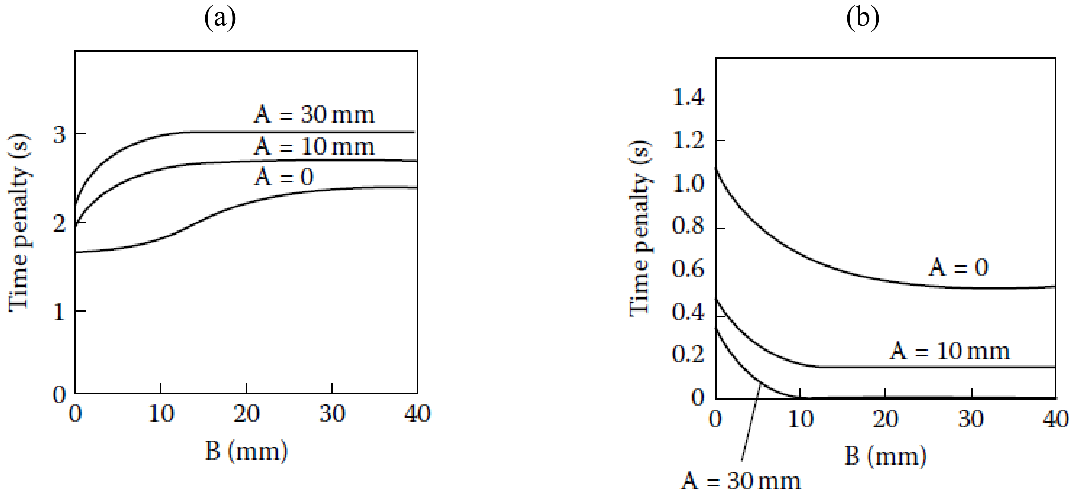


Figure 15. Time penalty with restricted vision (a) and without limited vision on pop riveting (b). A = Tool distance from side obstruction, B = tool distance from head obstruction. (Boothroyd, et al., 2011, p. 101)

Three different insertion situations where holding down is required is presented by Boothroyd, et al. (2011, p. 102). First is inserting a peg through easy-to-align parts that have been pre-aligned before the insertion. Second is similar but the parts are difficult-to-aligning. The final is aligning and holding down difficult-to-align parts while inserting a peg. Time penalties in these situations are presented in Figure 16. The horizontal axis represents basic time for a component that is easy to align and has been aligned before the insertion. It is a function of clearance between components, insertion depth and grip size. Vertical axis shows the time penalty for the insertion and alignment operation. Multiple graphs are shown based on the number of part interfaces in the operation.

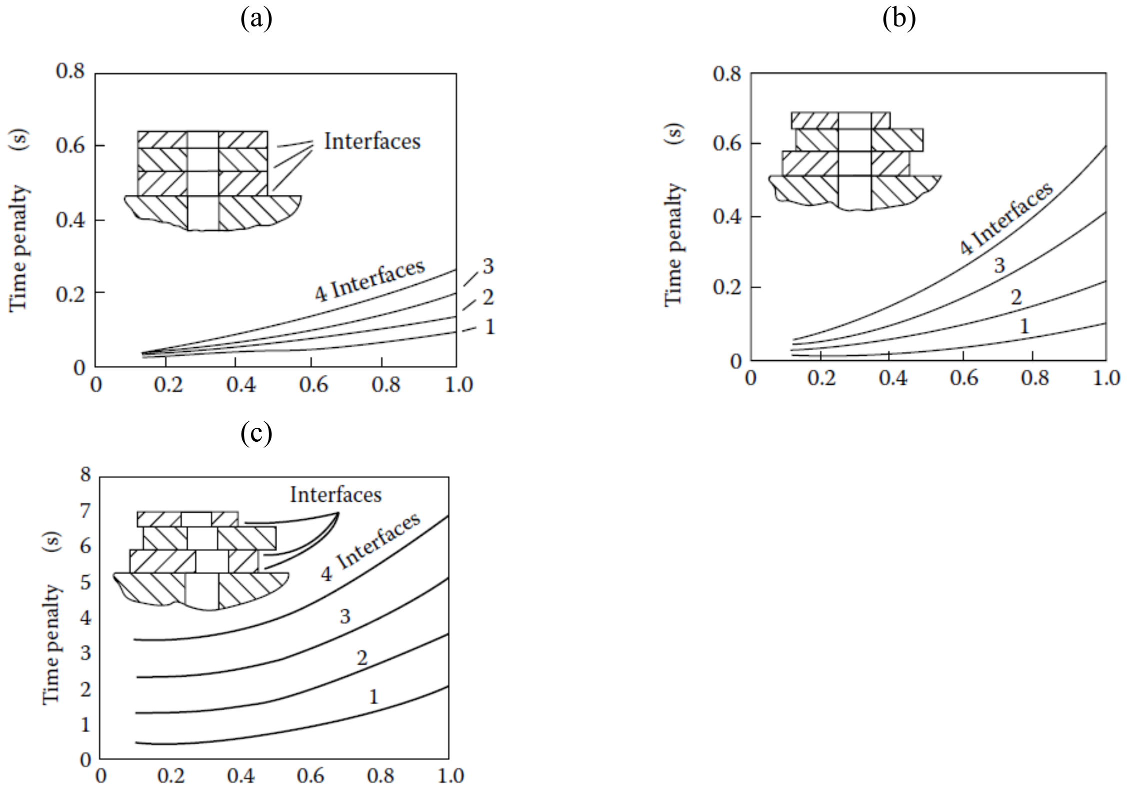


Figure 16. Time penalty when inserting a peg through hole while holding. a) With pre-aligned easy to align part. b) With pre-aligned difficult to align parts. (c) Penalty from aligning and fastening difficult to align parts. (Boothroyd, et al., 2011, pp. 102 -103)

3.2.1 Limitations of the Boothroyd and Dewhurst method

Boothroyd, et al. (2011, p. 103) acknowledges some limitations in the use of the B&D DFA method. As the standardized times in the systems are based on some distinct limit, e.g. in part thickness, the method can provide a vastly different time estimates for two components with minimal practical differences. This could lead to significant error in the assembly time estimates. However, they noted that such errors tend to be cancelled in typical assembly scenarios as some operation times are over and some underestimated resulting in insignificant net error.

Boothroyd, et al. (2011, p. 24) noted that only using design guidelines as a DFA can have negative effect on the design. They can increase the product complexity because the designer will focus on simplifying individual components. This can lead to more individual parts that will have greater inventory cost and consequently larger overhead. The correct application of DFA is through a systematic method that will quantifiably evaluate the assembly as a whole.

3.3 Assembly in business and product development contexts

According to Whitney (2004, p. 317) assembly can be viewed also as larger concept. The design for assembly methods such as that of Boothroyd and Dewhurst consider the assembly only from the viewpoint of the individual assembly actions for components. However assembly as a larger concept has some impact on decision making in company contexts and in the product development. The various organizations of a company and the different lifecycle stages present multiple varying demands for a product. The need to consider all of the diffident decision has resulted in concurrent engineering. It is the integration of all the different disciplines to the product design process in order to balance the various needs. Assembly as a concept can be used to integrate many areas of product development.

Whitney (2004, p. 321) presents that one of most important decision relating to assembly during product development is the one of product architecture. The architectural choice generally affects how the product is assembled by setting the key product characteristics, such as technologies or subassemblies, that determine the component interfaces. Analyzing the product assembly can show problematic areas in the product architecture that can be accounted for when making new architectural choices. This highlights the need to consider assembly in the early product development.

According to Whitney (2004, p. 322) assembly as a larger concept affects the decision making in the contexts of business, manufacturing, assembly process, assembly system as well as product design. In the business context many of the issues are concerning business flexibility as predicting the changes in the market can be difficult. For example, using only single supplier or one product design can be simpler but is also riskier. Flexibility can provide the ability to change from existing company situation to a new one based on the market changes. Table 7 lists different assembly related considerations from the business perspective.

Table 7. Business considerations affecting assembly. (Whitney, 2004, p. 322)

Business consideration	Decision relating to assembly
Product character: e.g. single use or maintained.	The choice of materials, fastening methods, assembly process.
Anticipated volume	How product is assembled, what kind of equipment is used and what are the production rates.

Product variety	The design of the assembly systems so that it can adapt from one variation to another.
Supply chain decisions and delivery	Make-or-by decisions for components, sub-assemblies, or complete assemblies. Supplier decisions, and supply chain management.
Geographical considerations	What are the costs of implementing production processes or delivering products in different parts of the world? Changes in currencies, politics, and local laws affect the possible location choices for making and delivering products. Labour laws and practises have an effect on manufacturing efficiency and costs.
Financial targets	Different assembly systems, e.g. automatic or manual, have varying costs on overhead, equipment, energy, and materials. Selecting the right one needs to be based on revenue targets even though another might look attractive for example for technology point of view.

In manufacturing contexts, Whitney (2004, p. 323) suggests that the assembly decisions are based on the need to assess the different factories in which the product will be assembled. Table 8 presents the manufacturing considerations relating to assembly. These are particularly important if the same product is assembled in multiple locations and with differing suppliers.

Table 8. Manufacturing considerations relating to assembly. (Whitney, 2004, p. 323)

Manufacturing consideration	Decision relating to assembly
Characters of the workforce	Worker unions, skills, and motivations of the workforce can vary between location. These affect the ability to do a variety of tasks and effect the flexibility of the plant. In addition, worker turnover and learning curve needs to be considered in difficult assembly tasks.
Factory experience.	What are the existing technical capabilities of a factory? Has the factory produced similar products before?
Facility related constraints	Is the layout and configuration of the considered factory suitable for the assembly process?

Whitney (2004, p. 323) notes that knowledge of different assembly systems is required to fully understand how the product's assembly process requirements affects the decisions making. It also requires understanding of the product designs in order to know the constraints that affect assembly. It is common that company already produces similar products, or a pilot assembly is conducted at the end of product development. While these can be used to test the assembly of the new product, they can be misleading in nature. Table 9 lists the process related assembly considerations.

Table 9. Manufacturing considerations relating to assembly. (Whitney, 2004, pp. 323-324)

Assembly process considerations	Decision relating to assembly
Know the assembly process	Study the assembly process in place at the factory being considered. Existing process can be tailored for the current product designs and facility. If the current product is assembled by exceptionally skilled personnel, they do not represent average assembly worker. The current process might contain knowledge that is not documented that cannot be easily communicated to another set of workers. Knowing the process helps to avoid the same issues in future products.

Process should be designed for the product	Existing assembly process should not be a driver for the product design. The process design should start with the product concept and its functional requirements. The process is then designed to meet these requirements. Product related change suggestion from manufacturing engineer that does not understand the product should be discarded if they compromise the performance of that product.
Design's effect on process sequencing	Factors including product architecture, design, and make-or-buy decision divides the product into distinct units such as sub-assemblies. This division can be used to partition the assembly process into smaller manageable units performing coherent tasks.
Design for assembly	Tools that help the product design for assembly should be utilized throughout the design process from early concept to the development of assembly methods.

According to Whitney (2004, p. 324) analyses of the manufacturing process should be done concurrently with the product development and as early as possible. Then they can be used to impact the product design. If the company is considering outsourcing some aspect of product design or the assembly process, it needs to be done carefully and with early supplier involvement. The late addition of suppler in these matters might risk uneconomic or inflexible assembly process. The different assembly considerations and process analyses presented in this section can be used to make design improvements that results in easier to assemble product and more flexible assembly process.

4 Assemble-to-order manufacturing

This section is focused on assembly-to-order (ATO) manufacturing. The first part of the section describes how the ATO differs from other production control environments based on customer order entry point. Then the basics of manufacturing process choice, make-or-buy decisions, and production lead times are presented as they are important considerations in ATO manufacturing. The second part of the section focuses on describing the important functions of the manufacturing planning and control systems (MPC) that can be used to plan assembly manufacturing. The final part of the chapter presents how the how the planning can be accomplished in ATO from the assembly and bill-of-material points of view. A brief section on planning in engineer-to-order (ETO) environment is also given since it is in the interests of this thesis.

4.1 Production control environments

The production control environment defines how the product is manufactured with regard to customer, inventory, and the manufacturing system. There are multiple choices for production control environment and many factors need to be considered in order to select the most suitable one. According to Chapman (2006, p. 3) few of the most critical factors that affect the choice of production control environment are the volume and the variety in which the product is manufactured. These factors are driven by the customer requirements and the amount at which the customer is involved in the design of the delivered product.

Jacobs, et al. (2011, p. 49) and Van Veen, (1991, p. 17) present that commonly used classification for distinguishing different production control environments is the location of the customer order decoupling point, also known as order penetration point (OPP), in the goods flow. This classification can be used to define the production environment as make-to-stock, assemble-to-order, make-to-order, or engineer-to-order. The different production control environments in regard to customer order decoupling point are represented in Figure 17. The Figure shows the storage type in the manufacturing operation where the OPP is introduced. In MTS the OPP is aimed at the finished goods inventory so the delivery lead time experienced by the customer is the shortest. ETO has the longest delivery time.

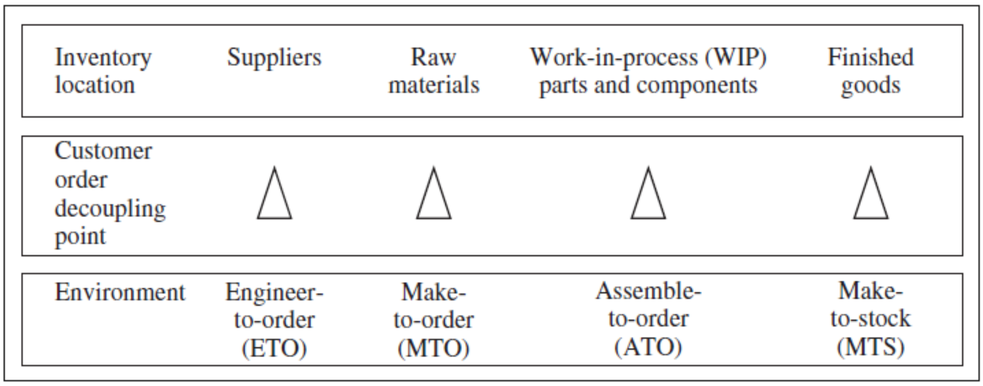


Figure 17. Production control environments. (Jacobs, et al., 2011, p. 49)

Chapman (2006, p. 3) describes that in make-to-stock (MTS) environment the products are manufactured completely before the customer order and final products are stocked in finished goods inventories. The expected customer base can have some influence in the design of MTS products in the early phases of product development, but individual customer can only select from final products. Mass produced goods such as clothes or office supplies are typical MTS produced products.

According to Chapman (2006, p. 4) in assemble-to-order (ATO) environment, the customers have some influence over the features of the purchased product. Customer can determine the specific final product by selecting a set of options and the final product is then assembled from predesigned subassemblies based on the customer needs. Stavrulaki & Davis (2010) notes that in ATO the order delivery times are shorter than the total manufacturing lead times, but a certain amount of waiting is implied from, the moment order is released to the time product is received. ATO companies can ship products to the retailers or directly to the customer. Typical examples of ATO products are personal computers or automobiles (Chapman, 2006, p. 4).

In their book Jacobs, et al. (2011, p. 186) note that due to relatively large amount of variety in ATO products, forecasting the demand for end items is very difficult and stocking them can be risky. In order to increase flexibility and decrease manufacturing lead time, company can release basic components and subassemblies to production, but the final assembly only started after customer orders is placed. In some cases, ATO can be referred to as configure-to-order CTO because customers can "configure" the product to their needs (Harrison & Petty, 2002, p. 9). Other industries, e.g. food, can use the term package-to-order to describe a similar operation where the goods are backed based on customer requirements, e.g. weight and size (Chapman, 2006, p. 4).

According to Chapman (2006, p. 4) make-to-order (MTO) and engineer-to-order (ETO) environments give the customer significant influence over the final product. In MTO the customer can determine the exact design of the products as long as it is manufactured from standard raw materials and components. In ETO the customer has complete control over the final design which is often not limited to standard components or materials. Stavrulaki & Davis (2010) note that in ETO the demand for individual products is almost impossible to forecast and the number of items that can be produced in anticipation of orders is non-existent. As such finished goods inventories tend not to exist. The products in ETO are highly variable and have very low sales volumes, typically just one unit. ETO product exhibit longer lead-times than products in other production control environments.

4.2 Manufacturing process choice

Manufacturing can be considered both business and technology related function. Products need to be delivered in a way that benefits the market in addition to satisfying the technical specifications. The choice of manufacturing method needs to consider both perspectives. The book *Manufacturing Strategy: Text and Cases* views the manufacturing process choice as a three-step action (Hill, 2000, pp. 111-112). First is for the company to decide what to buy and what to make. Secondly the proper manufacturing technology must be identified to complete manufacturing tasks for the product. Lastly is the choice of manufacturing process from various alternatives that best reflects the product volumes.

According to Hill (2000, pp. 114-115) the nature of the product is an important consideration in selecting the right manufacturing process. Generally, products can be categorized as standard, special, or customised products. With standard products the demand for individual end items is repeated and volumes are relatively high. Investment in special manufacturing equipment and tooling such as fixtures or jigs is often required. Special products are usually one-off deliveries and demand cannot be easily forecasted. Customized products are altered to suit the need of the customer and the demand can be repeated or one-off. An example of a repeated special product is a container made for the customers own product. For example, in the food industry. In these cases, the manufacturing process choice is not made based on customized nature of the product, but it is based on volume. From manufacturing point of view these types of products can be viewed as standard.

Hill (2000, p. 113) presents five generalized types of manufacturing processes to choose from: project, jobbing, batch, line, and continuous process. Project type of manufacturing is done to large scale one-off products. The manufacturing usually takes place at the delivery site because the project cannot be moved because of its type or size. The process inputs, such as materials and resources, are taken to the project site. The resources used in the project are released as soon as their tasks are completed. All aspects and activities are controlled by a centralized system. Example of this types of products are civil engineering projects.

According to Hill (2000, p. 114) jobbing is used when the goal is to provide one-off products for the customer based on their design or specifications. The process involves a skilled team of personnel to interpret the customer's needs and convert them into a delivered product. The exact end items of jobbing process are not likely to be demanded again. An example of this type of product is special tooling designed for the customer.

As stated by Hill (2000, pp. 115-116) batch manufacturing is used when similar types of products are expected to be delivered repeatably. The production is separated into a series of sequential operations that makes the products. Each operation is done for the whole order quantity (batch) before it is moved into the next operation. The station is then setup for the next order. Achieving the low costs of repeat and high-volume manufacturing is the basis of setting the production sequence. Batch manufacturing can be chosen when a wide range of volumes need to be covered.

Hill (2000, pp. 116-117) describes that line production is used when there is a need to deliver high volumes of a single or a range of products. In line manufacturing, products go through a predetermined sequence of operations that are designed to produce similar end items. Lines are used when standardized products are manufactured. Consequently, changes to products outside the original design or options cannot be made on the line. Production line flexibility and the accommodated range of products are determined by the investment in the production line. Higher flexibility requires higher investment. To accommodate other products, the manufacturing line must be stopped and reset. Lines are beneficial for make-to-stock production. However, some companies with a wide range of product options or large and costly products use lines to manufacture on order basis.

According to Hill (2000, pp. 117-118) continuous process is used when there is high volume demand and the materials involved can easily be moved from one part of the process to another. These types of materials are usually liquid or gas and the material transfer in the process is automated. The process involves feeding the material through different refining phases that produces one or more end products. The manufacturing process is meant to run constantly with minimal shutdowns. High investment and a narrow product range in continuous process manufacturing are justified by the volumes involved. Petrochemical refining is a good example of continuous process manufacturing. Different manufacturing process choices and product examples with regards to manufacturing volumes are represented in Figure 18. It can be seen that batch manufacturing can cover the widest volume range.

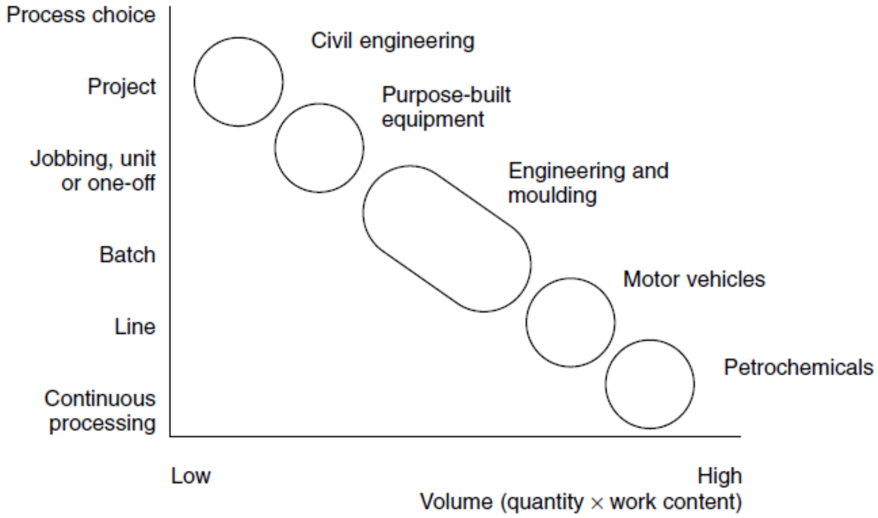


Figure 18. Manufacturing process choices based on volume. (Hill, 2000, p. 115)

4.3 Make or Buy

The decision whether the company should make components or assemblies in-house or whether to buy them from a supplier is a key strategic issue for manufacturing. According to Hill (2000, pp. 190-191) the make-or-buy decision should consider multiple business, product, and technology related aspects. In the big picture the decision needs to reflect the overall strategic plans of the company. Make-or-buy decision can have an effect on the critical customer requirements for the product such as price, quality, and delivery reliability. For example, long supplier lead times can affect the company's response to customer orders. Another broad view consideration is the globalization of trade and manufacturing. Searching suppliers from overseas has become easier making them a feasible option compared to investing in local manufacturing facilities.

Hill (2000, pp. 191-193) notes that the product and the manufacturing process plays important role in make-or-buy decision. From product perspective company can choose to make components in-house because it wants to control the product design, quality, or the customer relationship. For example, protecting the aspects of the design that contribute to advantages in the marketplace. Retaining control of the production process technology might also lead company to in-house manufacturing.

According to Hill (2000, p. 191) to another technology related consideration is that the company wants to apply new technology to its products. In some cases, the in-house resources do not support the requirements of the new technology. In these cases, the company has to turn to suppliers to provide the technology. This also narrows the upstream manufacturing process. The downstream manufacturing process is still kept in-house as it closer to the design and existing manufacturing knowledge of the final product. Product and component volume are also a key consideration. In low volume situations company can purchase components in order to decrease the complexity of in-house manufacturing. In high volume situation the companies can option for plant-within-a-plan (PWP) manufacturing of components.

Company's make-or buy choice might not always be based on these considerations. Hill (2000, pp. 194-196) acknowledges that majority of the procurement discussions in companies are still dominated by the technology and cost arguments. The lack of appropriate process capability often leads to outsourcing without further study or opposing arguments. If capability is not an issue, then solely provision costs are considered. The problem is that these do not consider the market requirements and relevant customer requirements. Unsuitable decisions can damage the company's short-and long-term strategic position. In addition, one common basis for make-or-by decision is how the company has done its manufacturing and procurement in the past. It is typical that company considers the possibility to avoid short-term problems and additional management tasks.

4.4 Manufacturing lead time

Manufacturing lead time is the time it takes from the issuing of the work order to the time the product is available to fill customer demand (Karmarkar, 1993). According to Jacobs, et al. (2011) the traditional lead time models consider the manufacturing lead time as a constant variable just like any other attribute of the part. In effective management of manufacturing the lead time should be viewed as an attribute of the whole manufacturing facility that can be managed. Karmarkar (1993) presents that lead time is not a constant value and can vary over time based on the capacity available. Lead time can be increased by production bottlenecks. Considering manufacturing lead time as a measure of performance allow the bottleneck to be defined as the resource that has the highest utilization or longest delay associated with it.

Jacobs, et al. (2011, p. 324) and Karmarkar (1993) present that there are four distinct elements that make up the total manufacturing lead time: run/processing time, setup time, move/transportation time, and queue time. Run time refers to the time something productive or value adding is done to the component or product. Sometimes run can only constitute 10-20% of the total lead time (Jacobs, et al., 2011, p. 324). Setup time is the time the component is being prepared for processing, e.g. setting up a machining operation. Transportation is the time that the component or product is being moved between processing stations or stock locations. Queue time is the product waiting to be processed or moved. In order to calculate the accurate manufacturing lead time, it is important to include the time from the moment the work order is issued to the actual time the production starts as it impacts the time experienced by the customer or the final product.

According to Karmarkar (1993) Multiple different models exist for modelling lead time. The types of models used depend on the manufacturing systems being synchronous or asynchronous. In synchronous system the production is based on a regular schedule and every stage of the systems is well coordinated. This results in small or non-existing queueing in the systems. The focus of lead time management in these systems is in controlling processing, cycle stock holding, and batch consolidation times. Most of the lead time models used for synchronous systems are static deterministic models. In asynchronous systems the production not completely coordinate as result of complex flows in the system. A batch production with multiple products is an example of asynchronous system. In asynchronous systems most of the lead time comes from queues which are associated with work-in-progress (WIP). This why the management of the lead time is the management of WIP. Lead time models for asynchronous systems are typically dynamic deterministic or stochastic.

Capacity utilization has a relationship with lead time. Karmarkar (1993) notes that this is known factor of queues and is apparent in asynchronous systems. Some models suggest that this is also experienced in synchronous systems. In these systems the high utilization implies the use of large lot sizes in order to minimize the setup time. As a result, delays in individual batches causes the cycle time for resources to increase. Capacity utilization is determined by product grouping, volume, and variety as wells as production equipment, routing, and planning of the total loading of the facility.

According to Karmarkar (1993) in asynchronous systems the queue lengths and delays also depend on the variability of arrival times, the variability of services, and the production batch size which affects all the previously mentioned factors. Batching decreases the variability of interarrival times for items but if the systems has a combination of two different item arrivals, large batches in one of them causes arrival variability to increase. Order release pattern also affects the variability of arrival times as well as total load of the system.

4.5 Manufacturing Planning and Control

Jacobs, et al. (2011, p. 2) present the Manufacturing planning and control (MPC) as a system of activities that manages the flow of materials and the utilization of people as well as equipment. It oversees the company's the response to customer requirements by effectively utilizing internal and external facilities. The most effective MPC systems can be used in coordinating the supply chains as well as creating joint efforts with outside companies. MPC is meant to provide the managers in the manufacturing company the necessary information for making effective decisions. Jacobs, et al. (2011, p. 497) and Harrison & Petty (2002, p. 210 & 215) present the most basic MPC is a material requirement planning (MRP) system. Introduction of feedback loop that allowed the system to react to changes in the manufacturing environment helped to create so called closed-loop MRP systems such as Manufacturing resource planning (MRPII). According to Jacobs, et al. (2011, p. 3) MPC is typically embedded in the company's enterprise resource planning (ERP) software. The exact design of MPC and its elements are depended on the company's place in the marketplace and the produced goods. Overall, developing and implementing an effective MPC is an important factor in creating a successful manufacturing company.

In their book Jacobs, et al. (2011, p. 4) present the general framework for the MPC system is divided into three areas that work in three time horizons. The long-term planning for the company is established by the "front end" of the MPC. This concerns the activities that set the overall company direction. The MPC provides information of the needed overall capacity to meet the expected market demand. This includes the appropriate mix of human and technological capacity as well as the best geographical locations to meet the future needs of the company. Long-term planning set the company constraints within which the company can respond to current demand and shifts in customer preferences.

According to Jacobs, et al. (2011, pp. 4-5) the middle "engine" part of the MPC addresses the intermediate term planning for the company. The main issue addressed is to provide the exact material and production capacity in order to meet the customer demand. Capacity planning activities concern employment levels, overtime, and subcontracting possibilities. The goal of material planning activities is to support production and distribution by planning for right quantities of material to arrive at the right time and place. This includes maintaining the needed amount of raw materials, work-in-progress (WIP) and finished goods inventories to match the market needs. Other tasks of MPC in the intermediate term is to communicate expected delivery times to the customers as well as to help coordinate supplier deliveries.

Jacobs, et al. (2011, pp. 5-6) present the “back end” as activities that are concerned with detailed scheduling of manufacturing resources such as people, material, equipment, and facilities in the short term. These actions determine the exact MPC execution system. Other task of the back end system is to react to sudden changes that affect production, such as customers changing their minds or things going wrong. This is done by providing the managers, customers, and suppliers the information on what has happened which supports the resulting problem solving. In addition, the back end provides the customers with the status of their order. It is also in the back end where key performance indicators (KPIs) for manufacturing are tracked. These can include output, utilization, order completion, manufacturing costs, customer satisfaction, on time deliveries, and possible quantity or other mistakes. Tracking of KPIs is a requirement for efficiently managing manufacturing operations.

The general MPC framework according to book *Manufacturing Planning and Control for Supply Chain Management* Jacobs, et al. (2011, p. 4) is presented in Figure 19. The figure shows the interconnection of the different functions within the MPC system as well as the three main areas of the complete system.

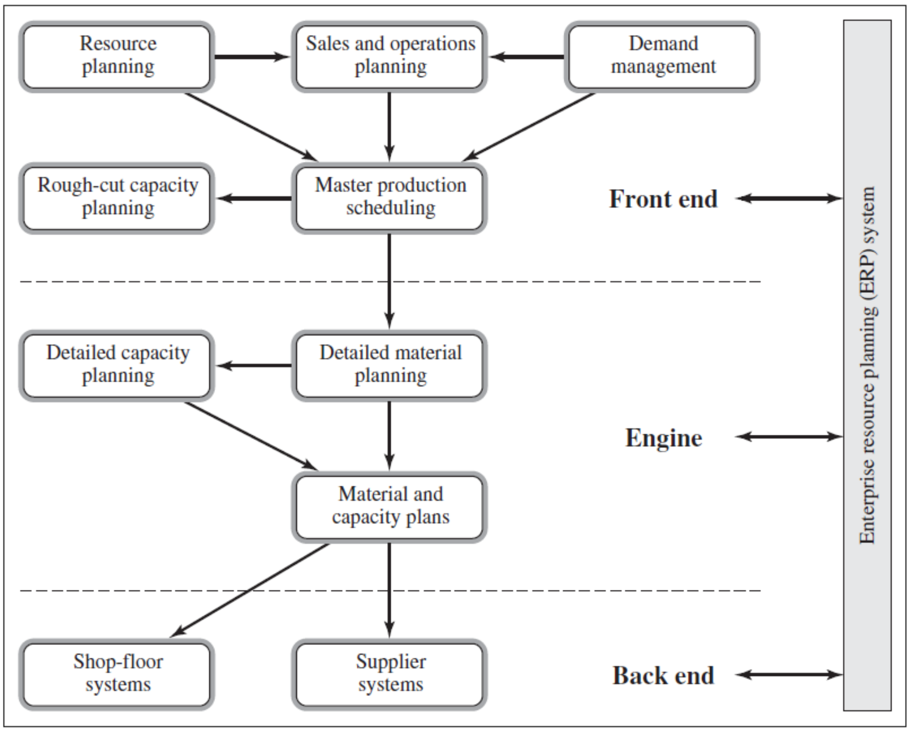


Figure 19. Manufacturing planning and control framework. (Jacobs, et al., 2011, p. 4)

4.5.1 Master production schedule

Jacobs, et al. (2011, pp. 183-184) and Harrison & Petty (2002, p. 222) consider properly defined master production schedule (MPS) as the basis for affectively using the available manufacturing resources as well as making accurate delivery promises to customers. The MPS is an important part in the company’s MPC systems because it turns the sales and operations plans into detailed manufacturing schedules. In practice many constraints limit the use of sales alone as a driver for manufacturing and MPS is meant to decouple the two (Harrison & Petty, 2002, p. 222). In addition, MPS accounts for capacity limitations, production costs, and resource considerations (Jacobs, et al., 2011, p. 185).

According to Harrison & Petty (2002, p. 222) and Jacobs, et al. (2011, pp. 184-185) master production schedule serves two functions. Firstly, MPS considers the sales and operations plans of the company and converts them into scheduled manufacturing plans. In addition, the MPS helps to balance the supply and demand. However, it is important to note that MPS is not a sales forecast nor statement of demand, but a description of the company's supply. This way MPS can be used to create a communication between marketing and manufacturing (Jacobs, et al., 2011, pp. 184-185). Demand alone cannot be used as a driver for MPS for multiple reasons, that may lead to excess stock of goods such as seasonal or month-end biased demand or demand overload (Harrison & Petty, 2002, p. 224).

In their books Jacobs, et al. (2011, pp. 189-195) and Harrison & Petty, 2002 (pp. 225-229) expresses MPS as a periodic plan for manufacturing. The plan contains information on the specific products or items as well as their quantities that are to be completed within certain planning horizon. As such the MPS considers the factory capacity and considers the product characteristics as well. The planning horizon determines the time frame for the operation of MPS by determining how far into the future manufacturing scheduling is done. Planning horizon is typically divided into smaller planning periods that are used for scheduling production runs. Changing the MPS withing the manufacturing lead time can have disrupting effects on production as it requires scheduling changes to already released work orders (Harrison & Petty, 2002, pp. 224-225). Overall, the master production schedule should be kept as stable as possible

Jacobs, et al. (2011, p. 183 &185) notes that the basis for setting up a master production schedule is to define an MPS unit. Typically, master production schedule is stated in product specified units and not global units of measure or currency. In product manufacturing, the MPS is typically expressed as component or end item numbers for which BOM can exist. These can be final products but also modules or options which are part of the final assembly. The MPS definition can vary between industries and the definitions of the MPS unit are the primary differences in how MPS is set up in different production control environments.

The employment of MPS can be accomplished by multiple techniques, most of which can be used with any kind of MPS unit definition. According to Jacobs, et al. (2011, pp. 189-190) Common MPS techniques include *time phased record, rolling through time*, and the *available-to-promise* techniques. Time phased records are used to show the relationship between sales forecast, manufacturing output and the expected delivery balance of completed items. The aim is to keep the expected balance positive with a predetermined manufacturing strategy. For example, keeping the manufacturing output constant in each period of the planning horizon is called the level strategy. The chase strategy contrarily determines the manufacturing amount for each period based on the forecast. The exact strategy is dependent on the process characteristics and other company constraints. If the same production process is used to manufacture a variety of items, company can employ lot sizing (batch manufacturing) to lessen the effect of change over time between variants. This creates cycle stock that lasts between scheduled production runs. Company can also use safety stocks for produced items to protect against demand uncertainty. It is important that the strategy used is the one that most effectively balances costs and benefits.

According to Jacobs, et al. (2011, pp. 190-191) the rolling through time technique includes changing the MPS schedule within the planning horizon. Compared to time phased records, this technique also considers the actual sales transactions that have happened from one period to the next. After each period the production schedule is re-evaluated and adjusted to prevent from running out of stock.

Production capacity and material constrains must be considered when making these changes. For example, whether the production capacity is enough to facilitate the changes and is the required material available if schedule is advanced. Only essential changes should be considered as high costs are associated with production changes.

Jacobs, et al. (2011, p. 192) and Harrison & Petty (2002, p. 226) present that the available-to-promise (ATP) technique considers the fact that customers may not require immediate delivery for the purchase, and they can place orders for future deliveries. In these cases, company can use order promising to specify for the customer when shipments can be made. ATP is then used for coordinating the production schedule and the order promising actions. This means ATP sets the number of products that can be promised to customers without affecting sales orders that already exist.

Jacobs, et al. (2011, pp. 192-195) shows that ATP amounts can be calculated by discrete or cumulative logic. In both cases, data on expected shipments before the next production run and the amount of available stock at the start of each period is used to determine ATP products. In discrete logic the orders for each planning period are considered independently from the planning view, i.e. time between production runs. ATP is then calculated from the difference between existing orders before the next production run and the projected available balance at the start of the planning horizon or after the previous produced batch.

In cumulative logic the ATP amount is carried from one batch forward to the next. Jacobs, et al. (2011, pp. 192-195) notes that even though the cumulative logic seems more feasible, it might overstate the actual availability of units depending on the time at which orders are booked. The actual situation in the company determines the effectiveness of discrete or cumulative ATP logic. Using ATP in the MPS reduces the possibility that customer delivery promises cannot be achieved. Overall, the acknowledgement of projected available balance and ATP are key to effective master production scheduling.

4.5.2 Material requirements planning

Jacobs, et al. (2011, p. 215) present the material requirements planning (MRP) as the part of MPC that takes the master production schedule for ordered end items and converts it to a time phased production and acquisition plans for sub-assemblies and individual components. This means creating detailed and time phased plans for each part number as well as raw materials. From managerial and production point of view the objective of MRP is to provide the right component at the right moment to meet the set schedule for completed products. In companies that produce assembled products form components that are produces in batches, the MRP is an important part in developing detailed part needs.

The main input for MRP is the master production schedule. Jacobs, et al. (2011, p. 217) notes that in addition, MRP requires the use of bill of materials and the inventory status for components and raw materials. BOM in MRP must represent how the product is manufactured by showing component relationships and quantities. The MRP data constructed from these inputs can then be used in the development of detailed production capacity plans. Material and capacity planning can be characterized as an iterative process that is completed level by level. This means developing plans for end items, sub-assemblies, components, and raw material individually by considering their relationships in the product structure.

According to Jacobs, et al. (2011, pp. 217-220), the practical level plans are expressed in MRP records for individual items. These time-phased records are similar in nature to the earlier described MPS plans and are also made for a set planning horizon that is divided into smaller periods. The information in MRP record consists of following:

- Anticipated usage of the item during each period in the planning horizon. Also called the "Gross requirement" for the item.
- Existing orders for stock replenishments that are due to arrive at the beginning of the period. This means items that have already materials and capacity committed to their production. These are also known as "scheduled receipts".
- Projected inventory status at the end of every period.
- The number of planned replenishment orders at the beginning of each period. If the gross requirement for the upcoming period exceeds the inventory of the period, replenishments that consider the production lead time must be planned to avoid running out of stock. These planned orders differ from the scheduled receipts since they are not yet released for production or purchasing, and no material or capacity is committed.

Jacobs, et al. (2011, pp. 223-224) suggest that the linking of MRP records for individual components is necessary in the management of production for complex end items. To achieve this, BOM, gross net explosion, and lead time offsetting are used. As described earlier BOM information is used to determine components and quantities for each sub-assembly. The gross net explosion is then used to transfer the product requirement into part requirements for production. This process considers the existing inventories and scheduled receipts for each part individually in order to determine the net requirements for component production or purchasing. Gross net explosion is an important communication link between parts and is a key element of MRP system. It also serves as the basis for dependent part demand.

Jacobs, et al. (2011, pp. 224-226) describes that lead time offsetting is used to schedule the part or sub-assembly manufacturing so that they are available when needed. It considers how items interact with each other taking in account the manufacturing or assembly sequence as well as manufacturing lead times for all items needed. To ensure availability of an item in later production stages, the item manufacturing can be front or back scheduled. Front schedule means that production for each item is started at the same time. This method leads to large work-in-progress inventories. Back scheduling starts the item production as late as possible. This way necessary items are available exactly when they are needed. Successful use of back scheduling requires accurate BOM and item lead time data.

4.6 Planning in ATO environment

Wemmerlöv (1984) suggests that there are two main considerations that relates to the material and capacity planning systems that must be considered in ATO environment. First is the level in the product structure at which the master schedule can be made and the demand for items can be forecasted. This determines the "break point" between master schedule and final assembly. Second consideration is the structure of the bill of material and its compatibility with the master schedule items and final assembly process. Van Veen, (1991 pp. 20-21) notes that in ATO manufacturing the definition of master production schedule and the construction of bill-of-materials should be considered concurrently since they are closely related. In addition, the commonality of components and sub-assemblies in different product variants affects the forecasting in MPS. Structure of the BOM is important as it can be made to show or hide commonality of semi-finished products from the viewpoint of finished assembly.

4.6.1 Assembly planning

In ATO environment it is vital that before deliveries are promised to the customer, all key components and subassemblies needed in the final product are available to the final assembly production. To make sure that this is achieved, company can employ two levels of scheduling (Jacobs, et al., 2011, pp. 199-200; Harrison & Petty, 2002, pp. 229-231; Wemmerlöv, 1984). The first level relates to scheduling saleable end items. This schedule is driven by the customer and refers to the control of final assembly schedule (FAS). FAS is used to coordinate the plans for picking components, assembling, testing, and delivering the exact set of end items for the customer.

According to Jacobs, et al. (2011, pp. 100-200) and Harrison & Petty (2002, pp. 229-231) the second level is the scheduling of lower level components and sub-assemblies that are needed in FAS. It is based on the forecast for components that can be derived from the planning BOM. In both levels ATP calculations can be done in similar manner that was explained in the section 4.5.1. The two-level MPS allows the sales of various product models to be coordinated with actual assembly schedule. This way the whole MPC process can be aligned more closely with the market.

Jacobs, et al. (2011, p. 186 & 196) suggest that the typical MPS units in assemble-to-order environments are not final products but options or modules that are used to create a large variety of end products. These items can be used as planning modules required by production orders (Van Veen, 1991, p. 22). From design perspective, MPS-items are usually semi-finished goods such as large components or significant sub-assemblies that are used in the final product. At the product level the specific MPS units are defined in the products planning bill of material. The company can estimate the usage of MPS items by determining the percentages at which each MPS units are used in the planning bill of material.

4.6.2 BOM structuring

The common types of BOMs used in ATO manufacturing have a modular structure and can be referred to as planning BOMs (PBOM) (Jacobs, et al., 2011, p. 196; Stonebraker, 1996). Stonebraker (1996) showed that using modular BOM structure rather than traditional one has a clear effect on cost, quality, flexibility, and delivery. Particularly modular BOM improved the productivity of manufacturing which in ATO is closely related to the manufacturing costs. The productivity improvements were apparent in inventory turnover and costs which were reduced to one-fifth and one-fourth respectively. The study also suggested that long set -up and lead times would be reduced by modular structure of BOM. However, the study found that quality was slightly reduced with modular BOM even though the evidence was not particularly strong. In simple terms the modularization of BOM means dividing the product into options or modules that in different combinations can be used to create variety of final products.

According to Van Veen (1991, p. 22) the way in which a traditional BOM can be transformed into a modular one depends on the level at which the MPS-items are defined in product structure. This is because MPS-items play part on the customer order decoupling point in the goods flow of the product.

While traditional BOMs are made on the level of final products i.e. complete list of components for each possible products variant, the modularization moves the BOM creation to the planning module level of the products structure. For each production order, a BOM consisting of needed planning modules is created based on customer selected options. The modular BOM structure then allows the requirements for a production orders to be defined at the level of planning modules instead of individual MPS-items. Jacobs, et al. (2011, p. 197) noted that the company can include the estimated decimal use for each MPS-item in an average product to create a so called super BOM (SBOM). This can be used to help with component and module forecasting.

The differences between traditional BOM and modular one are represented in Figure 20 and Figure 21. In Figure 20 the BOM and the product structure reflects the design including component and subassemblies such as the cabinet. This traditional BOM is made only one end item. In Figure 21 depicting modular BOM, the structure is based common items and customer selected options such as the face plate. Different end product can be created by changing only the option related modules.

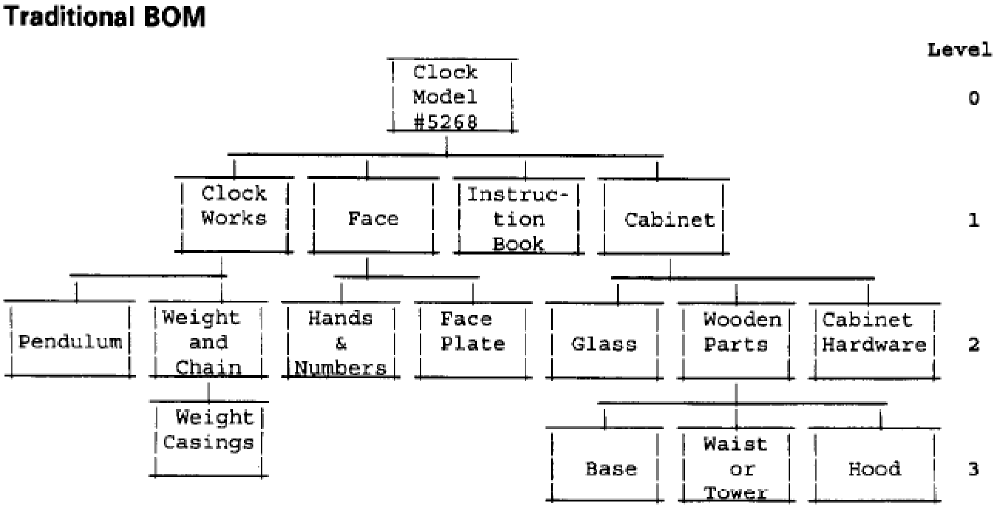


Figure 20. Representation of a traditional BOM. (Stonebraker, 1996)

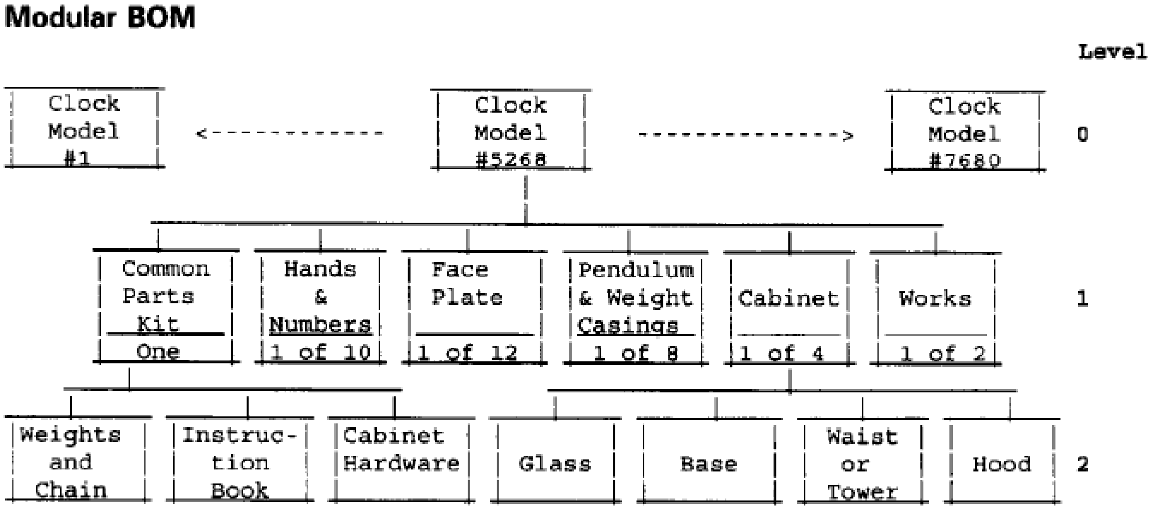


Figure 21. Representation of a modular BOM. (Stonebraker, 1996)

According to Van Veen (1991, p. 23) in complex product families the modularization of BOM has much more benefit than in products with only small amount of variation. In a simplified product each MPS-item is selected by one possible option. If a product has *n* features and each feature has two possible options, modularization can reduce the number of possible final by products 2^n and which then need to be planned to $2n+1$ planning modules. This represents one planning module for each option and one for items that are common for each product variant.

Van Veen (1991, p. 24) notes that from assembly point of view, one of the drawbacks of BOM modularization is that the possible information on assembly sequence is lost. This is because each production order BOM is determine by the customer selected set of options and final products are not defined earlier than the customer order acceptance. Thus, no manufacturing BOM showing the assembly routing or how the final product is built can be determined. Problem can be increasingly obvious in large complex products such as industrial machinery or automobiles.

4.7 Planning in Engineered-to-order production

The order completion process in ETO differs vastly from other production control environments. Every order can be considered as individual projects that contain concurrent activities (Bertrand & Muntslag, 1993). According to Van Veen (1991, p. 27) the main focus is on the planning and overall control of all the order related activities which include, engineering, purchasing, and manufacturing. Concurrent completion of all the activities is crucial for minimizing lead times in ETO.

(Bertrand & Muntslag, 1993) present that the accurate control of ETO projects is made difficult by the level of uncertainty involved in the process. In ETO uncertainty exists in product specifications, product volume and mix, and in the process. In the beginning of the ETO project, the parts and the product design are still unknown. Decisions relating to lead time, price and capacity cannot be determined precisely. For example, project lead time can be affected by some phase of the project taking more time than expected. In ETO it is difficult to estimate when an actual order is made and what are the specifications of the product. These reflects to the production process. As product specifications are unknown, the needed production resources and capacity are difficult to anticipate. MPC systems such as MRPII are not effective in ETO. One of the reasons is that no detailed information of the product is available in advance of orders which could be used in the manufacturing planning.

According to Bertrand & Muntslag (1993) manufacturing flexibility is required by the ETO. The production flexibility can be created for example with CNC machine tools. In manual assembly the skill of the workers plays important part in the assembly flexibility.

4.7.1 BOM in ETO

According to Van Veen (1991, p. 27) the low volume nature of ETO product makes the coordination of part stocks irrelevant. In addition, the product data required by manufacturing is not available on the order acceptance and will be created gradually as the project progresses. For these reasons, the product structure and the BOM will not be as important for the production control as in other control environments.

Bertrand & Muntslag (1993) and Van Veen (1991, p. 27) present that project BOMs are used in ETO. Every ETO product has its own BOM that is created during the product design. According to Van Veen (1991, p. 27) design data should be delivered to other organizations involved in the product delivery as soon as the design data is in somewhat finalized. From planning perspective, the finalized data and the data that is subjected to changes must be clearly indicated.

Van Veen (1991, p. 27) presents three types of data that are included in the project BOM. These are standard, customer specific, and historical reference data. Standard data refers to the existing product data that is not related to customer orders. If possible, project BOM are constructed based on some standard BOM and standardized components are used whenever possible. However, customers still have the possibility to customize the product to whatever degree possible. Customer specific data is generated for a specific order and created during the order completion process. Historical data is the reference product data from past projects. Past reference data is important for the improvement of ETO product design and manufacturing.

5 Current state description

This section of the thesis focuses on describing the current status of Retrofit production. The first part focuses on the Retrofit products and how the product structure for each product family is compiled. Understanding the product is a key element in finding bottlenecks in the assembly process that are the result of incompatibility with the design and production processes. The product information presented in the thesis is acquired from the internal as well as the public technical documentation made for the Retrofit products. It is also based on interviewing the R&D project managers. Product knowledge is furthermore expanded by the experience of the writer of this thesis who has worked in the Retrofit R&D for the past one and a half years.

The second part of the section focuses on the production process describing the material flow and shop floor actions of the assembly workers. One of the key goals of this thesis is to gain organizational understanding of the Retrofit production process. This means knowing the actions that different operators inside and outside ABB perform after production order is placed into the work queue. To achieve this goal, a mid-level process map of the assembly process was compiled. Mid-level map describes the generic lower level actions in a process but does not include every detail. For example, placing a component to assembly is considered a single action, e.g. "place component", and the actual acquiring of tools, fasteners, or the action of fastening are not differentiated.

The process map was compiled based on observing three individual production orders from start to packaging and interviewing the assembly and other personnel during production. The followed orders were a standardized single drive (SD) Retrofit product, order based-engineered delivery that was loosely based on the same of standardized SD product, and a completely customer engineered delivery. The aspects of the process that were closely observed during the production where:

- Arrival of the production order components.
- Assembly sequence.
- Handling of components.
- The use of product documentation.
- Assembly actions.
- Assembly or design related issues.

5.1 Existing production lead time data

The goal of the thesis is to find the problematic areas in the production that increase the production lead time. Currently detailed lead time data on Retrofit productions orders is scarce. Available lead time data consists of production start date, end date, and the number of products in the order. Active assembly, testing, and order finalizing hours are also reported by the assembly personnel. Figure 22, Figure 23, Figure 24, and Figure 25 show the production lead times for standardized and customer engineered orders during 2020. The data is presented in a production lead time run chart. The vertical axis represents production lead time for a single unit in the production order. The lead time values are presented proportional to the average lead time in the data set. They do not represent actual production times. Average lead time for the product family shown in a graph is 1. The horizontal axis shows data sample number. Datapoints on the graphs represent individual production orders.

The problems with the existing lead time data is that it does not differentiate between product variants within the product family. For example, in ACS600 standard inverter Retrofit the number of subassemblies completed at the Retrofit production and consequently the required production time can vary greatly between the main product variants. The same problem exists in the lead time data for customer engineered products where the differentiation of production orders is much more obvious. As can be seen from the graphs, the production time on all Retrofit orders exhibit large amount of fluctuation and no clear trend can be seen. Only exception is the graph for standard single drive Retrofit, but since it is a fairly new product with a small amount of datapoints no differing conclusions can be drawn from the data.

Figure 26 shows average active production reported by the assembly workers. The data is presented in a bar chart showing the percentile of the total PO lead time spend on assembly, testing and, finishing actions. The bar in the graph represent different standard product families as well as OBE orders. From the graphs can be seen that the majority of the lead time appears to be non-active time. Non-active time is not reported by the workers but can be calculated from the total lead time for the PO. In reality this data can impacted by the inaccuracy of the lead time data. For example, if PO is finished on the early hours of the workday, the rest of the day is considered as non-active time for the PO, even though it has already left the production. The data shows that majority of the active production time is spend on the assembly phase. The actions taken in each assembly phase are presented in section 5.5.

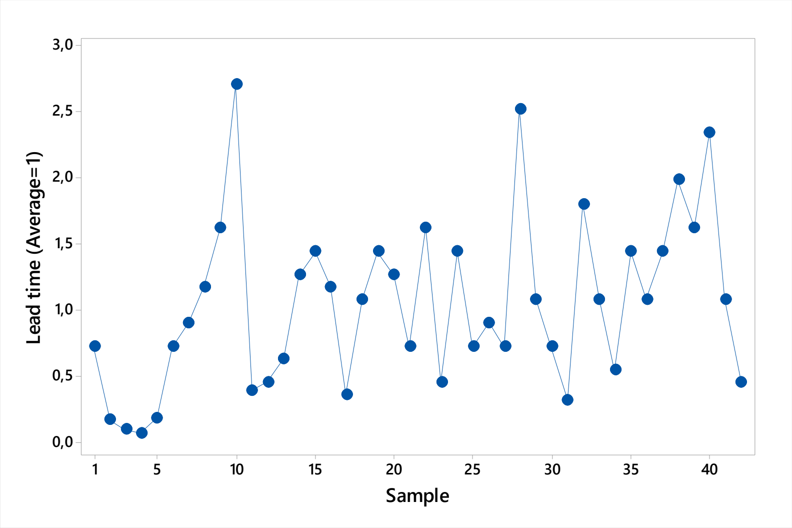


Figure 22. ACS600 inverter Retrofit production lead time.

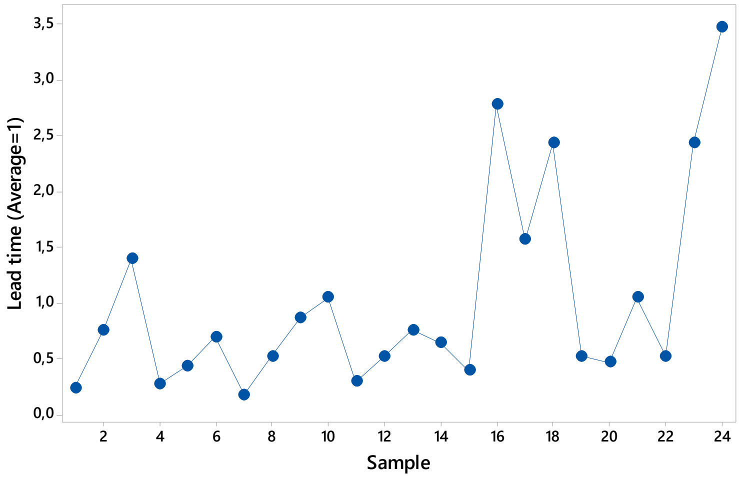


Figure 23. ACV700/Sami-Star inverter Retrofit lead time.

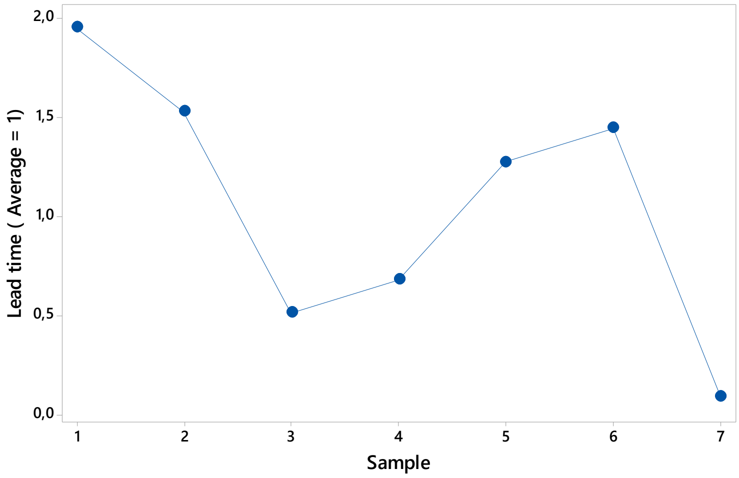


Figure 24. ACS607XT single drive Retrofit lead time.

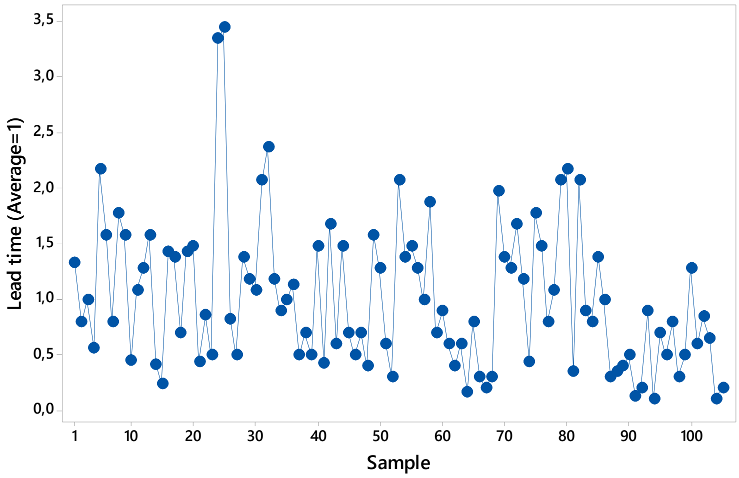


Figure 25. Production lead time for customer engineered solutions.

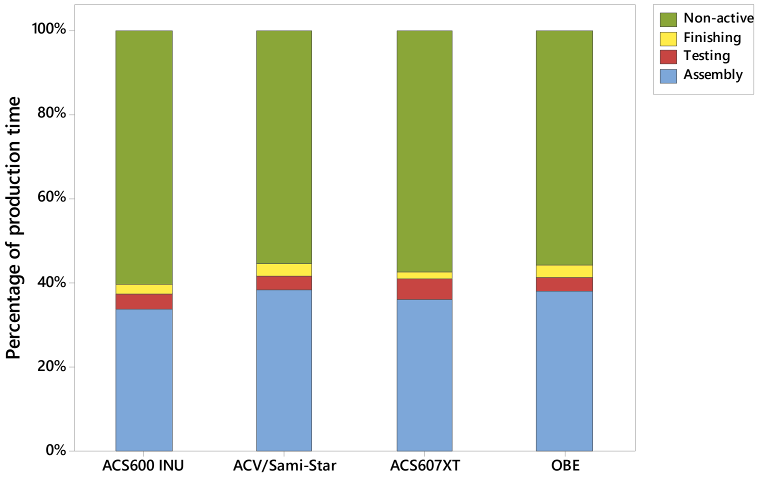


Figure 26. Average production time distribution in product types.

5.2 Product architecture & product structure

5.2.1 Current product architecture

Retrofit products are designed as a replacement for an ABB Drive or supply module that is at the end of the lifecycle. The replacement module for current Retrofit products is from the latest ACS880 product family. The old retrofitted and the new replacing modules are rarely directly replaceable. This means that most of the internal mechanics of the cabinet and majority of the electrical connections need to be re-designed for the Retrofit product. Consequently, the basis of the mechanical and electric design is the construction and connections of the old Drive cabined. From the new Drive family major design references are the mechanical connections of the Drive or supply modules, major sub-assembly or component locations, and the cooling of the cabinet. The general design principle is to make the overall Retrofit design as similar to the ACS880 family as possible.

Currently there are two distinct architectural approaches used in Retrofit design. They are derived from the customer needs and the important selling point of installation time. The firstly developed and more common of the approaches is so called *kit* Retrofit. This means that the product is delivered as a combination of pre-made sub-assemblies and individual components. These are then assembled and wired at the customer site into the final product.

In order to decrease the final installation time, a *frame* architecture was designed. In frame Retrofits most components and wires are pre-installed on a sub-frame at the Retrofit production. The idea is that in the final assembly at the customer site, the ready sub-frame is simply pushed into the empty cabinet, necessary connections are made, and then the Drive or supply module can be inserted. The frame architecture is presented in Figure 27.

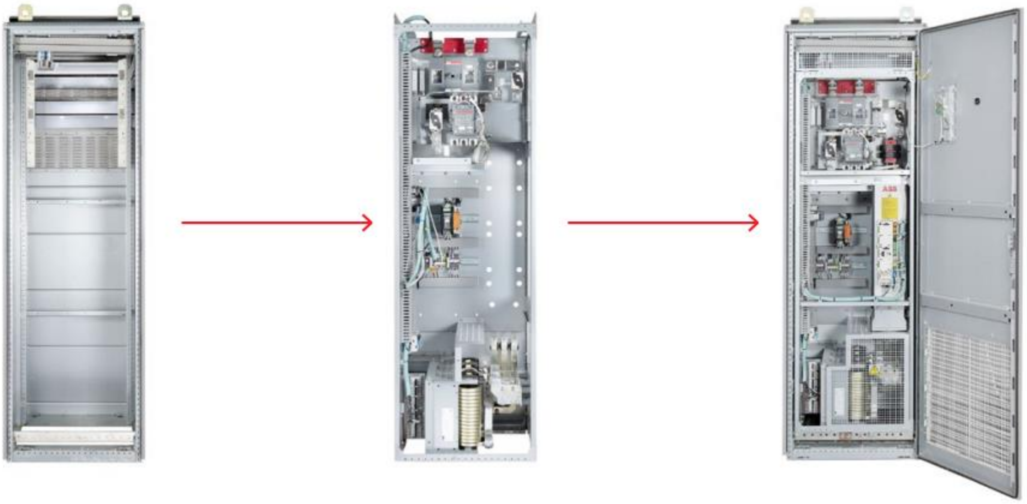


Figure 27. Example of a frame Retrofit. (ABB Oy, 2021)

Retrofit product development projects are started with a pre-study. The goal is to define the types of old Drives or supply modules that can be replaced with the ACS880 family products and to define the financial feasibility of the project. According to R&D project managers, the focus of the pre-study is on the business feasibility of the project determined based on the installed base for the retrofitted Drives as well as the customer needs for the Retrofit product. These aspects are used to make the decision whether product with a kit or a frame architecture is developed in the project. During the pre-study couple of mechanical concepts are introduced before the detailed design is started in order to find the best starting point for the design. This also helps in the architectural approach selection.

In mechanical sense the current product architecture can be defined as modular to some degree, but the overall design is more integral than modular. The modularity is apparent in the level of major sub-assemblies or components that are accessible from the front of the cabinet. For example, the drive or supply units are designed as easy to replace modules and Retrofit products have adapted this modularity. Other instances of modularity can be found in the electrical component pre-assemblies, mainly in the IO-plate assemblies. These are typically easily accessible and can be replaced or modified without major disassembly of the finished product. The integral aspects of the Retrofit design are apparent in components that are not accessible from the front of the cabinet. For example, in most Retrofit designs changing the main connector switch would require significant disassembly of the cabinet. The level of modularity in each Retrofit product varies greatly between product families. In Retrofit designs the use of same electrical components is common. This is because these components are directly related to the ACS880 family. Some mechanical parts are used in multiple product families, but the use of same sub-assemblies is uncommon.

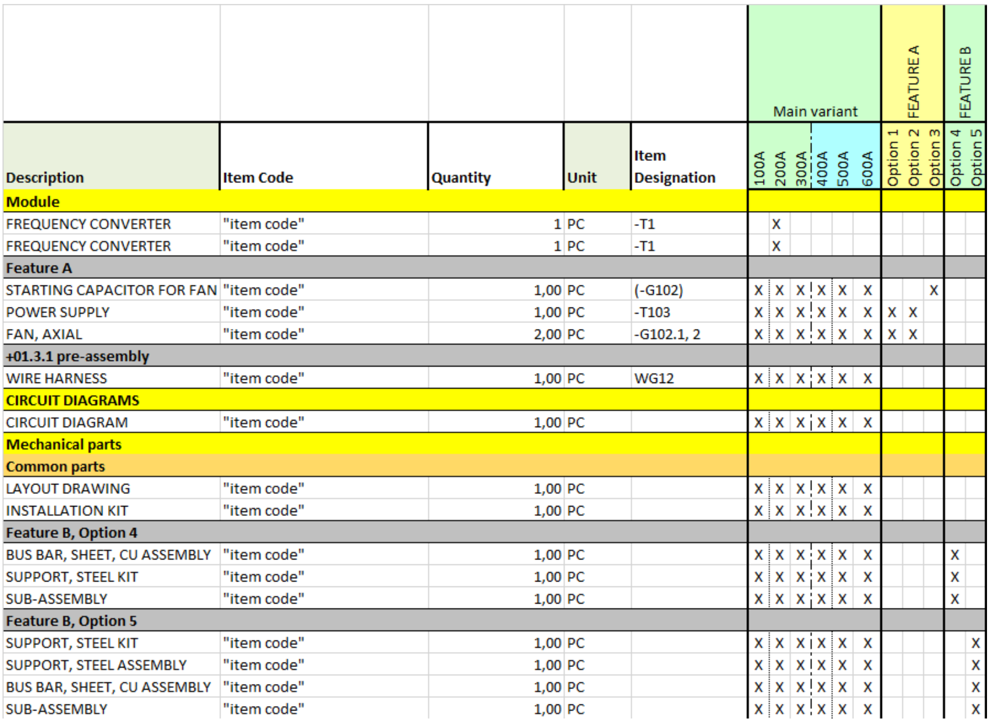
5.2.2 Current product structure

The product structure is compiled based on the 3d models and 2d assembly drawings after the detailed design is completed. In the final stages of the design, different combinations of components that are best suited for pre-manufactured sub-assemblies are selected. These sub-assemblies are meant to shorten the final installation time at the customer location. The components used in the sub-assemblies as well as corresponding sub-assembly documents are included in the same kits that are defined in the company ERP.

In order to simplify the product structure, individual mechanical components used in the final assembly are included in “scattered parts”-kits. Typically, sub-assembly and the scatter parts kits only contain mechanical components. They can be common to multiple product variants or single option dependant. Electrical components are placed in the product structure as individual components since they exhibit more option dependency than mechanical ones. The exact logic in the kitting varies between product families.

The Retrofit family product structure is compiled into a product structure table (PS-table). The PS-table shows the main level of the product structure. This means that kits, option dependant components, and final assembly documentation are shown in the table. Lower level components, such as components inside kits, are not visible.

The final Retrofit product structure is configurable and resembles that of the modular BOM presented in the section 4.6.2. BOMs for individual end product are generated using a variant code that includes the product family, main variant, and needed options. A simplified example of Retrofit product structure table is presented in Figure 28. On the left side of the figure are the component, document, and kit ERP-items that are on the main level of the product family BOM. On the right side are the configuration rules for the ERP-items. The configuration rules inside the main variant and feature columns work with OR-logic. Across the columns the configuration works with AND-logic. For example, the first “frequency converter” would be included only in main variant 200A, but the “Circuit Diagram” for any of the main variants. The “Starting capacitor for fan” would be included in all variants if the customer selected option 4, and the “power supply” if the customer selected option 2 or option 3.



					Main variant						FEATURE A			FEATURE B	
Description	**Item Code**	**Quantity**	**Unit**	**Item Designation**	100A	200A	300A	400A	500A	600A	Option 1	Option 2	Option 3	Option 4	Option 5
Module															
FREQUENCY CONVERTER	"item code"	1	PC	-T1		X									
FREQUENCY CONVERTER	"item code"	1	PC	-T1		X									
Feature A															
STARTING CAPACITOR FOR FAN	"item code"	1,00	PC	(-G102)	X	X	X	X	X	X			X		
POWER SUPPLY	"item code"	1,00	PC	-T103	X	X	X	X	X	X	X	X			
FAN, AXIAL	"item code"	2,00	PC	-G102.1, 2	X	X	X	X	X	X	X	X			
+01.3.1 pre-assembly															
WIRE HARNESS	"item code"	1,00	PC	WG12	X	X	X	X	X	X					
CIRCUIT DIAGRAMS															
CIRCUIT DIAGRAM	"item code"	1,00	PC		X	X	X	X	X	X					
Mechanical parts															
Common parts															
LAYOUT DRAWING	"item code"	1,00	PC		X	X	X	X	X	X					
INSTALLATION KIT	"item code"	1,00	PC		X	X	X	X	X	X					
Feature B, Option 4															
BUS BAR, SHEET, CU ASSEMBLY	"item code"	1,00	PC		X	X	X	X	X	X				X	
SUPPORT, STEEL KIT	"item code"	1,00	PC		X	X	X	X	X	X				X	
SUB-ASSEMBLY	"item code"	1,00	PC		X	X	X	X	X	X				X	
Feature B, Option 5															
SUPPORT, STEEL KIT	"item code"	1,00	PC		X	X	X	X	X	X					X
SUPPORT, STEEL ASSEMBLY	"item code"	1,00	PC		X	X	X	X	X	X					X
BUS BAR, SHEET, CU ASSEMBLY	"item code"	1,00	PC		X	X	X	X	X	X					X
SUB-ASSEMBLY	"item code"	1,00	PC		X	X	X	X	X	X					X

Figure 28. Example of simplified Retrofit product structure table (PS-table).

Two versions of the product structure exist at all times. First is the PS-table that is compiled and maintained by the R&D. The second exists in the company’s ERP and is used to generate customer order BOMs. When a new product is launched, the PS-table is converted to the ERP creating this product configurator. PS-table and ERP configurator are not linked in real-time.

The product structure is maintained in the “offline” PS-table. This means that if changes are made to the product structure, they need to be converted from the PS-table into the ERP configurator. The changes are included in customer orders that are placed after this conversion. It is possible that order is placed before PS change, but it will enter the production after it. In these cases, the production order might exhibit PS related issues that are already corrected.

The Retrofit product structure does not contain assembly related information such as operation sequences. The information in the table is only design and component related. Most of the component data is tied to the component’s ERP-item numbers and definition. This information cannot be changed for different product families. Only information not tied to the ERP definition of components is the item designations. They are based on electrical design for that particular product family.

OBE project BOMs

OBE deliveries use project BOMs. There are two types of OBE projects first of which is light OBEs. These are, to large extend, based on standard products designed by R&D. The customer requirements are usually related to electrical components or options that are not included in standard products. The design differences to standard products are minor. In these projects, the OBE engineer uses the PS-table to simulate a BOM for standard product that is close to the customer requirements and then makes the necessary changes.

The second types, referred to as full OBEs, are mostly customer engineer solutions. These projects are done for customers that have an uncommon Drive to be retrofitted. For example, non-ABB frequency converter or customised cabinet infrastructure. In full OBE projects major mechanical and electrical design is often needed and standard products and their PS-tables can rarely be used as a reference. During the design the OBE project BOMs are maintained in Exel format. Once the design is completed, the BOM is transferred to the company ERP system to be used in a PO.

5.3 Documentation

Retrofit product documentation made by R&D and OBE includes the following:

- Customer final assembly drawings (mechanical).
- Sub-assembly drawings (mechanical).
- Product circuit diagrams (electrical).
- Installation manual for site installation.

Customer final assembly drawings

Customer final assembly drawing are meant as detailed assembly instructions at the customer site. These drawings include information on the final assembly sequence (assembly steps), components needed in each step, and some specific instructions for the assembly. In Retrofit production, these final installation drawings are used as a reference to show the complete end product. They are also used in the so called “stepping” actions described in later sections.

Sub-assembly drawings

Sub-assembly drawings are used in the Retrofit production as production instructions. These drawing show the mechanical layout of components in a sub-assembly. Every component in the sub-assembly, including fasteners, are indicated by the company specific ERP-number. If the sub-assembly includes electrical components the drawings are made generic to multiple product variants. This means that a single drawing that of shows all of the possible electrical components is made instead of multiple variant specific drawings. The scale of these sub-assemblies and the corresponding drawings varies form a few components shown in a single page to large frame assemblies with multiple pages of information. Wiring of electrical components in the sub-assembly is not shown on the sub-assembly drawings.

Circuit diagrams

The product circuit diagrams are used both in the Retrofit production and the final assembly at the customer site. Diagrams show the electrical connections between components in the final product. The information on the circuit diagrams consist of item designations of components and wires as well as terminal identification. No ERP-numbers are shown in circuit diagrams as the exact components and wires used in the connection might differ between product variants. Typically, circuit diagrams are made generic to multiple product variants, but some product options have their own diagrams. The wiring that is done in the Retrofit production is not explicitly differentiated from the final assembly wiring. The physical aspects of the wiring done at the DSW, such as the cable routes in pre-assemblies, are not shown in the circuit diagrams nor other product documentation.

Installation manual

The installation manual is a supportive document for the site installation. It contains generic product family information as well as some detailed assembly and wiring instructions that are not show in the final assembly drawings. The assembly and wiring information in the manual consist of details noticed during prototyping or pilot installations. Other generic information in the manual includes basic product delivery information and commissioning guides. This manual does not include very detailed guides for the final assembly and commissioning but references some other related documentation produced by different organization of ABB.

5.4 Order fulfilment process

The order fulfilment process describes on a high level how Retrofit products are ordered, manufactured, and delivered to the customer. Within the ABB database exists a detailed process map of the order fulfilment process. The map describes the various actions that different departments in the motion service business organization take once a customer has placed an order with the local service sales unit (LSU). According to the process owner, the whole process and the map is reviewed annually or whenever the need arises. In this section only the key action that are essential for the thesis are described.

The process starts when a local sales unit (LSU) of ABB places an order for a Retrofit product. This order is based on quotation that the LSU has negotiated with the end customer and the Retrofit sales support team. A basic delivery time is negotiated with the end customer that varies between standard and OBE orders. The delivery time is adjusted after the order is placed based on the production capacity at the Retrofit production. Before production starts the quotation and the included products are checked by customer service and sales support team for discrepancies.

The actual production starts when production planner (PP) creates a production order (PO) for the delivery. The PO information consist of the production start date, delivery date, and the assigned assembly worker. After creating the PO, the components needed in the customer delivery are requested from the warehouse to the production area. Once components have arrived, the assembly can start. After the assembly is finished, the order is handed over to packaging. This closes the production process. After packaging the order is moved to external storage facility to wait for the delivery to the LSU and the end customer. A high-level process map of the order delivery process is presented in Figure 29.

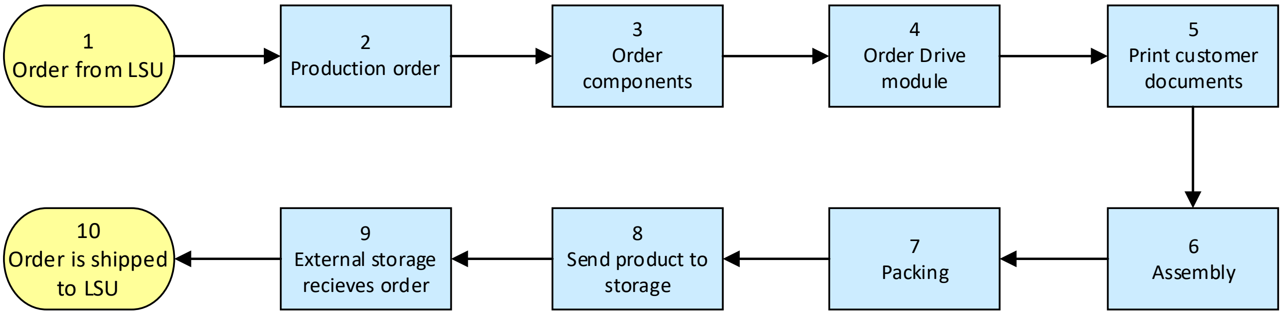


Figure 29. High level order fulfilment process.

5.5 Assembly process

The assembly process is the part of order fulfilment that concerns the shop floor actions completed in the Retrofit production. The assembly starts when the order material arrives to the production area and ends when the assembly worker has handed the order over to the packaging organization and has marked the order as completed to the ERP. This section describes the production area and the different phases of the assembly process.

5.5.1 Drive Service Workshop

Early modernization solutions that can be called Retrofits were customer specific designs and the delivery volumes were fairly low. The manufacturing of these deliveries was subcontracted. With increasing demand, it was deemed necessary to move the manufacturing closer to the design and sales personnel. A dedicated assembly area for Retrofits was created in a remote unit of Drive Service Workshop (DSW). The operation was small scale with only couple of assembly stations. The production was located adjacent of ABBs component warehouse and the assembly workers had the possibility to locate needed components themselves.

In recent years the demand has continued to increase, and the product portfolio has been expanded with standardized Retrofit products. In consequence the production was moved to the main unit of DSW located adjacent to the large-scale Drive factory in Helsinki. Before the Retrofit production, DSW served as a repair shop for Drive modules damaged during production or in use at the customer. The assembly of Retrofit product requires a certain level of electrical work knowledge. It was recognized that the DSW has the necessary production area and skilled personnel for the Retrofit production.

The layout of the DSW was configured so that it is separated into dedicated Retrofit and repair service areas. The layout and the workstations were made flexible to accommodate sudden increase in demand for either Retrofit or repair orders. The production of Retrofit orders has become a part of DSW's daily activities, and some aspect of the workshop and work methods have evolved around Retrofit production. According to the repair centre manager, the biggest change in the Retrofit assembly has been the move away for the component warehouse. The rough layout of the current drive service workshop is presented in Figure 30.

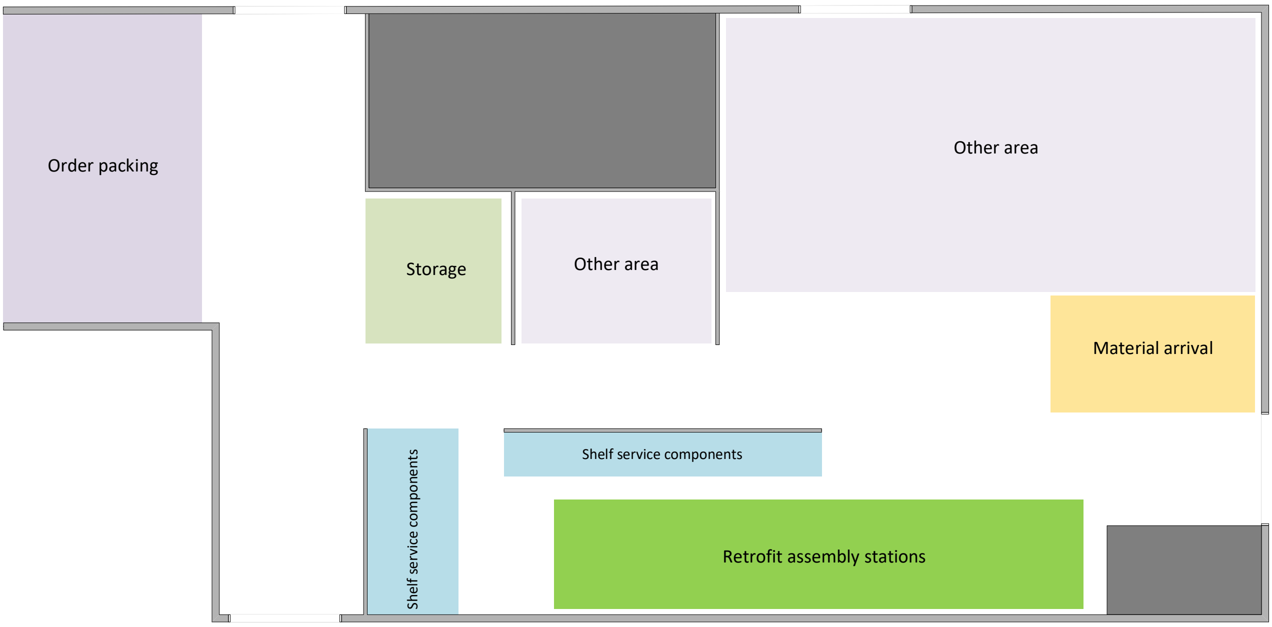


Figure 30. Rough layout of the Drive Service Workshop.

The production model in the DSW resembles that of a job shop or project production. Material flow and production scheduling is done on the production order level. Each production order is assigned to one assembly worker who is in charge of the completion of the order. Usually the order is completed in a single assembly station. If capacity allows and delivery time is limited, a production order can be divided among multiple workers and stations. No component fabrication, other that general wire harness assembly, can be done at the DSW. The tooling of the workshop includes basic assembly and fastening related tooling. One of the efficiency metrics measured in the DSW is on-time-delivery (OTD) for production orders.

5.5.2 Production managing

Retrofit production is managed with an ERP work queue tool. The tool is used by the production planner for requesting the components to the production area and tracking the progress of orders. The assembly worker uses the tool for viewing PO BOMs and for acquiring the order documentation. A new work queue tool was still being implemented during this study. When the production orders were observed, the assembly workers were using the new work queue tool and the previous one simultaneously which created some difficulties.

The work queue tool divides the Retrofit production process into five phases regardless of the order type: start, assembly, testing, finishing, and packing. Each of these phases contain multiple different actions that are completed by the assembly worker. These actions are further explained in the following sections. Generally, the Retrofit manufacturing consist of building, wiring, and testing sub-assemblies as well as organizing components for packing.

5.5.3 Production order components, documentation, & BOM

Components

The components needed in a PO are requested to the DSW by the production planner with the work queue tool. The tool explodes the PO BOM to be viewed at the component level and shows the available material quantities in warehouses. It is important to note that not all components are stored in the same location and delivery times ranges from couple of hours to a full workday.

In standard orders the components are mostly stocked items. If component is out-of-stock, the delivery time from supplier can be substantially longer. In OBE orders majority of components can be one-off and customer specific. For this reason, in OBE orders the lead time of components is a key scheduling factor for production planning. All of the order components are planned to arrive at DSW at the same time. In standard orders, usually the request for components is placed at the end of previous workday before the assembly is scheduled to start.

Components arrive to the production area in trolleys. The order of components in the trolleys is determined by picking logistics at the different component warehouses. From the assembly perspective the order of components is random. Large components or sub-contracted assemblies, such as cabinet doors and modules, arrive separately in their own trolleys. The first action in the Retrofit production is to move as much of the components near the workstation as possible.

All of the final product components are requested to the DSW even though only a portion is used in the sub-assembly manufacturing. Sometimes individual components are noticed to be missing during the production. To ensure that all necessary components are delivered to the customer, the assembly workers are instructed to compile a material checklist. This means that the worker goes through the order BOM line by line and verifies each component. The assembly phase in which the list is made varies between workers. Some make the checklist before starting assembly and others do the assembly and checklist concurrently.

Documents

Before starting the assembly, the worker acquires the PO documentation. With the work queue tool, the documentation can be printed based on assembly phase. The previous tool required the worker to select documents from the BOM and print them individually from the ERP. Some OBE specific documentation cannot be acquired from the work queue tool. OBE documentation is stored in the project folder. OBE design and documentation can be revisioned during the production. Accessing and updating the project documentation is more efficient through the project folder than the ERP. Effectively managing such changed required good communication between OBE design engineers and the assembly worker.

Production order BOM

In addition to component ERP-numbers, the Retrofit PO BOM contains two pieces of information important for the assembly actions: component “goes-into”-relationships (also known as the kit structure) and the item designation for electrical components and wires. The “goes-into” information is needed to easily check which components are needed in a certain sub-assembly. This is useful during the assembly and in the creation of material checklists. Item designations are used during wiring to check the ERP-item numbers of components as they are not shown in the circuit diagrams.

BOM acquired from the current work queue tool shows item designators for components but does not include the "goes-into" information. On the contrary, BOM from the previous work queue tool contains the "goes-into" relationships but did not include the item designators. As the implementation of the current tool was still in progress, during the observation of the first production order, the worker had to use two BOMs in order to have all of the necessary information.

5.5.4 Component assembly & testing

In this sub-section the different shop floor actions completed in the Retrofit assembly process are described. The process information was gathered during the thesis and is presented in mid-level process maps in figures Figure 31 to Figure 35.

Component assembly
Currently no pre-determined sequence exists for the sub-assembly production. The assembly worker selects any sub-assembly that is included in the order to take under construction. Larger frame sub-assemblies are typically built first. Before starting the assembly, the worker prints item designation stickers for the electrical components as well as serial number stickers for each sub-assembly.

The next step is to find the sub-assembly related components. The assembly worker checks the sub-assembly drawing and then searches the component trolleys. If the component is not found, it has to be ordered by the PP. This can halt the production, if the worker is not able to continue working on other sub-assemblies during the component delivery time. It is also possible that a wrong material is delivered from the warehouse. This is a fairly rare occasion but happened during the following of the standard production order.

During the assembly, the worker inspects components to determine whether they can be assembled. If a defective component is found, the assembly person can modify it or wait for the corrected component to be delivered. The decision is done based on the expected delivery time for the component and the scheduled assembly time for the order. Some components cannot be modified in the DSW and the only option is to wait.

Reasons for defective components are simple design mistakes or wrong delivered component version. Due to large number of product variants in a Retrofit product family, fairly low number of the mechanical components are tested and verified before product is launched to the market. For this reason, some component flaws are noticed only during production orders. If the design of an existing component has changed at some point, there might still exist stock of the old version. This happens when engineering changes are made as a "running" changes and old component versions are not removed from warehouse. Due to the low volume of Retrofit components old version can still be delivered from the warehouse a relatively long time after the issue is noticed and component is corrected.

Wiring is done after all mechanical and electrical components are installed to the sub-assembly. Worker checks the circuit diagrams and assesses which of the connections are done at the DSW production. As mentioned earlier, circuit diagrams show the item designations for the wires and components but not the ERP-item numbers. In order to find the correct wire, the worker compares the item destination in the diagram to the order BOM. The best wire routes are determined by possible cable conduits in the sub assembly and the personal preference of the worker. After wiring is completed, the worker places the item designation and pre-assembly serial number stickers. Then the completed pre-assembly is moved to a trolley to wait for testing. Some workers take pictures of ready pre-assemblies that they can use as reference in similar future production orders.

Once all sub-assemblies are finished, the worker checks if additional wires need to be made for the sub-assemblies or the final assembly. In standard products, most of the wires are manufactured by suppliers. In some older standard designs as well as in OBE orders, the wires are produced at the DSW. A mid-level process map of component assembly process is shown in Figure 31. The process map is generic for mechanical or electrical components as well as subcontracted wire harnesses. Oval blocks represent the start or the end of a process, rectangle blocks actions, and rhombus blocks decisions.

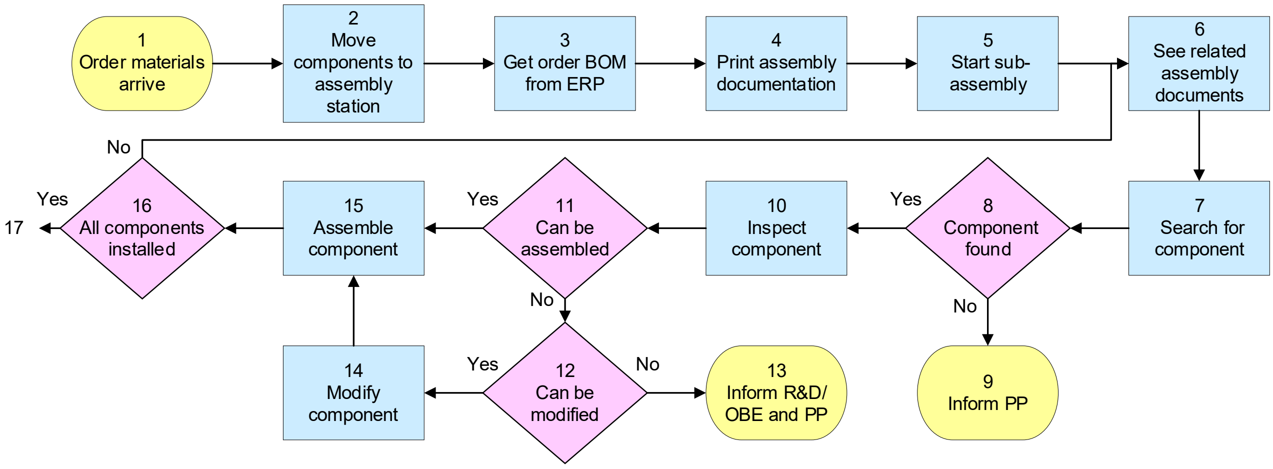


Figure 31. Component assembly process.

Testing

After all sub-assemblies and wires have been completed, the production moves into testing phase. Testing is done applying an internal test specification document that details every aspect of Retrofit products that need to be verified. The testing consists of two stages first of which is insulation and dielectric tests for the circuits in the sub-assembly. These tests require small changes to the connections that needs to be re-done after the testing is completed.

The second stage is to verify connections by comparing them to the circuit diagrams, measuring connectivity, and checking the tightness of the connections. The testing does not include verifying the product functionality with operating voltages. This is because sub-assemblies cannot function independently from the complete final products. The testing process acts as a quality control and is done to assure correctly functioning end product. It is also a way to find assembly or design related mistakes. The wire manufacturing and testing process steps of the Retrofit production are shown in Figure 32.

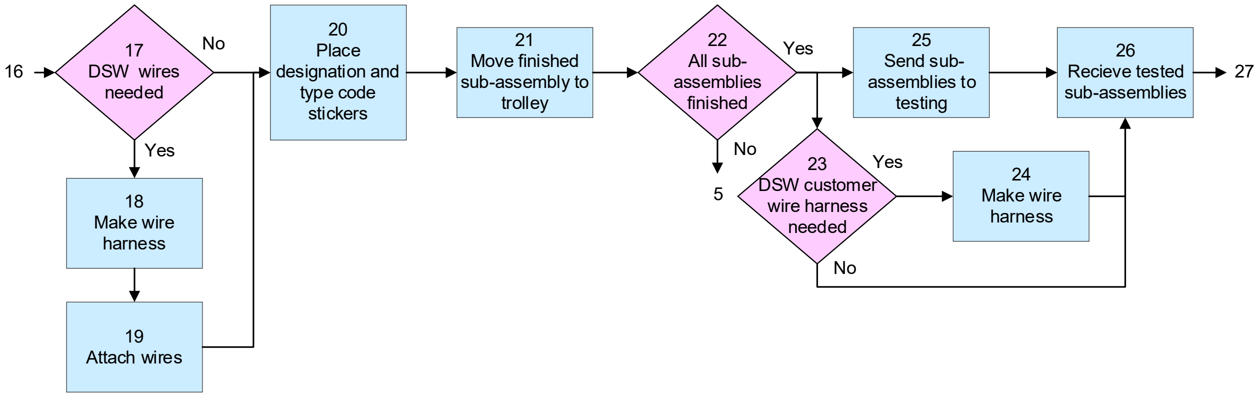


Figure 32. Wire harness manufacturing and testing process.

Fault reporting

During the component assembly or testing the worker might notice faults in the overall design, individual components, or sub-assemblies that interfere with the production. Workers are encouraged to report all mistakes, but the level of information and the reporting medium is not standardized. If these problems do not require immediate actions, the fault are typically listed in a “production log” Excel file. Some assembly workers will also inform the R&D or OBE directly of the problem. If the problem stops the production, the issue is quickly escalated to production planning, R&D or OBE, as well as other necessary organizations so that actions can be taken to solve the problem.

5.5.5 Stepping, production order completion, & packing

Stepping

After testing the production moves into finalizing phase. One of the actions in this phase is “stepping” which means systematically organizing the order materials for the packaging. The worker checks the final assembly drawing for assembly sequence (assembly steps) and organizes all of components and sub-assemblies accordingly. The components used in the same final assembly step are placed in the same trolley along with an assembly step identification sticker. The sticker is later used in the packing of the order. Components that are not shown in the final assembly drawing, such as wires, are placed into common “auxiliary component” trolley.

Standard products always show the final assembly steps in the drawing. In OBE orders the document information varies from order to order and the steps might not be indicated. In this case the stepping action is not done in the Retrofit production. The material checklist for the order is reviewed and finalised during the stepping actions. The stepping process is shown in Figure 33. Worker data input to an electrical document is shown with cylinder blocks.

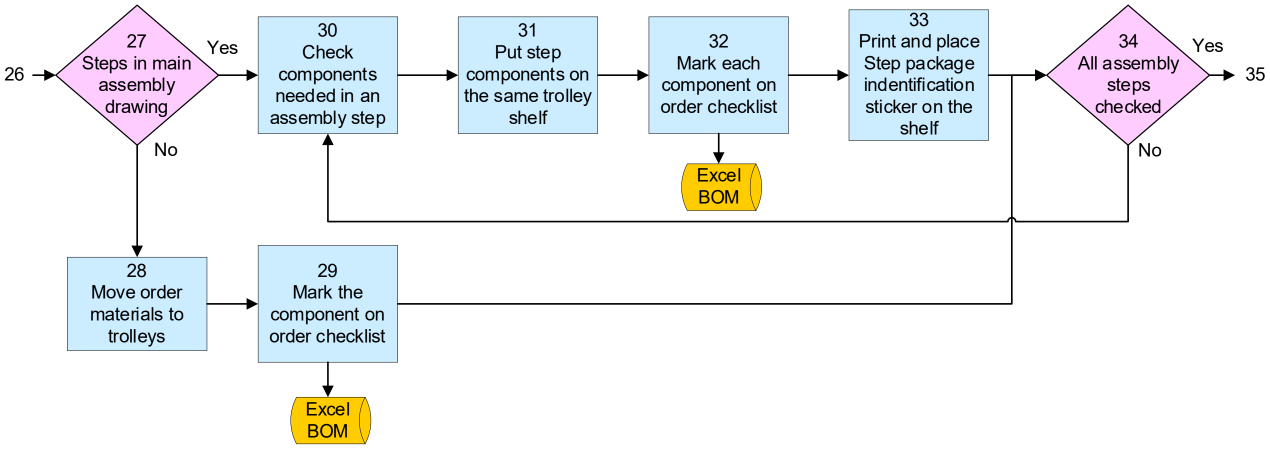


Figure 33. Material stepping process.

Production order completion

The final actions in the Retrofit production are compiling the order documentation, handing the order over to the packing organization, and updating the order folder in the shared drive. All of the order documentation is compiled into a binder that is included in the delivery. The binder contains the documents presented in Section 5.3 along with BOM, product compliance certificate, and general order information. Compiling and checking the binder is an important action in the Retrofit production. The binder acts as a main source of product and assembly information for the LSU and the end customer.

Before handing order components to the packing organization, the worker fills a packing list. The list shows the number of component trolleys, frame sub-assemblies, doors, and inverter modules in the delivery. Individual components are not listed in the packing list. The trolleys and the list are handed over to the external packing contractor operating within the factory. Assembly workers are instructed to take a few photos of the material trolleys in order to have proof of delivered components in case of warranty claims.

Every production order has a dedicated folder in the company's shared drive. Before closing the production order, the worker updates this folder with the finalised material checklist, pictures taken during the assembly, and other relevant documents. After this the worker closes the production order and is free to start the next one. Order completion actions are shown in Figure 34.Worker data input to physical document is shown with a purple block. The step 42 is the final action of the assembly worker that marks the end of the production order. This is also the point at which the production lead time for the order is reported.

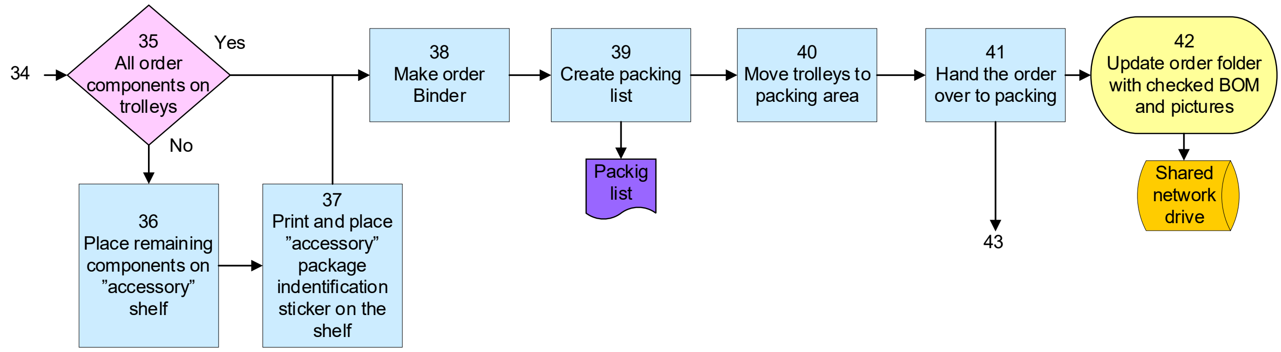


Figure 34. Production order completion.

Packing

The packing of Retrofits is done by an external contractor. In the lead time data, it not considered as a part of the Retrofit production. A short description of the packing process is still included in the thesis since it affects how the order arrives to the final installation.

Packing starts by checking the packing list and moving the trolleys to a dedicated packing area. Sub-assemblies and individual components are placed into suitable sized boxes with packaging material. If stepping is done at DSW, the packing workers are instructed to place the step related materials in the same boxes and place the step sticker on top. If step stickers are not included in the trolleys, packaging is done randomly. After packing, the check list is signed and returned to the DSW. The order is sent to an external warehouse to wait for delivery to the LSU and end customer. The packing process is shown in Figure 35.

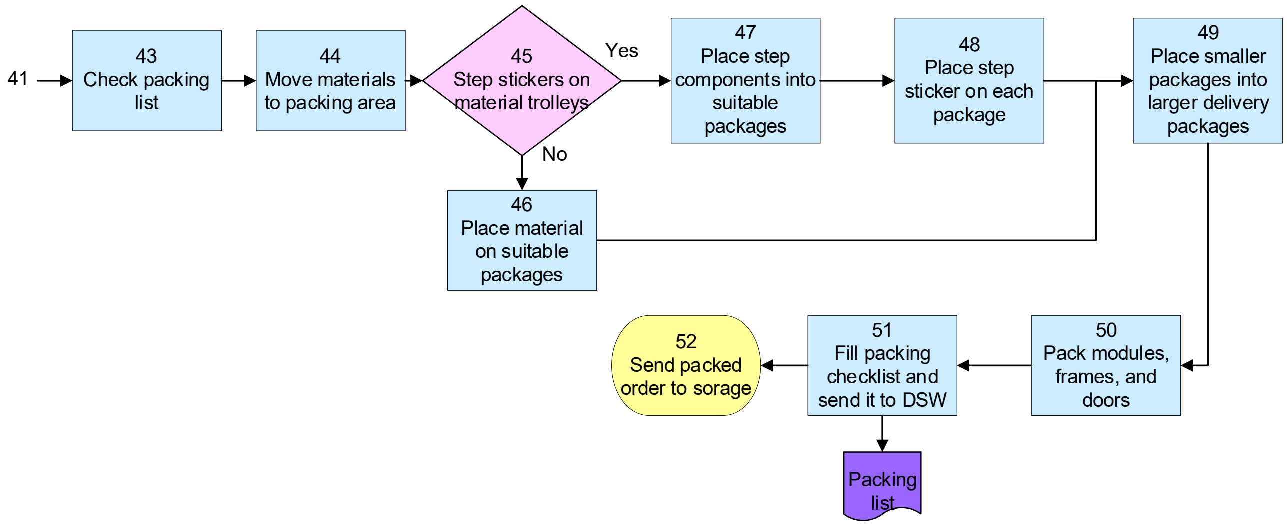


Figure 35. Packing process.

6 Analysis & solutions

The previous section described the existing Retrofit product structure and how the production of customer orders is executed at the DSW. In this section the product structure and design are evaluated from the manufacturing perspective. The goal is to find and categorise possible incompatibilities with the production process that might result in increased production lead times. The product documentation is also analysed from the production perspective.

First part of the section describes the methods used to find the pressing production issues and the possible solutions for them. Rest of the section is divided based on the focus areas of the thesis which are the product architecture, product structure, and the Retrofit documentation used in the production. In each section, related production issues are described, and possible corrective actions are presented.

6.1 Methods

No quantitative data relevant to this thesis is available from the Retrofit production process other than the lead time data presented in section 5.1. As the available data consist only of the total production time in full days it cannot be used to find actual problem areas or bottlenecks in the production process. A large portion of the production activities relies on the expertise of the assembly workers and most of the process knowledge transferred by word of mouth. For this reason, the best way to identify and rank the production issues is to conduct qualitative analysis of the process.

6.1.1 Personnel interviews

The methods used to identify production issues were the observation of production orders described section 5 and conducting interviews on assembly workers, production planner, and the process owner. Observing the production orders served as a way see first-hand the type of production issues related to the product or the process. The interviews were used to gain understanding of the issues that are viewed as major disruptions by the assembly personnel. The interviews also served as a way to determine which phase of the production is viewed as the most time consuming. A total of 3 assembly workers, 1 production planner and 1 process owner were interviewed in the study.

The interview questions where divided into three groups. First one focused on the Retrofit production from a general viewpoint. Second and third parts of the interview focused on the differences between standard and OBE orders. In the process owner interview, the questions were changed to reflect the complete process and not the shop floor issues. The answers were used in categorizing and ranking the issues in a failure modes and effects analysis (FMEA) shown in the following section. The questions used in the interviews are shown in Table 10.

Table 10. Interview questions.

Question	Interviewed personnel	Question Focus
What are perceived to be the major issues related to Retrofit production?	Assembly workers, Production planner, Process owner	General assembly
What aspects of the products or production process could be improved?	Assembly workers, Production planner, Process owner	General assembly
What is the quality of documentation in standard/OBE Retrofit products?	Assembly workers, Production planner	Standard/OBE product design
How is DFA considered in the design of standard/OBE products?	Assembly workers, Production planner	Standard/OBE product design
What are is most time-consuming actions in the assembly of standard/OBE orders?	Assembly workers, Production planner	Standard/OBE product design
What are the responsibilities of the process owner?	Process owner	Process owner tasks
What is the level of transparency of the shop floor actions to the process owner?	Process owner	Process owner tasks
What kind of feedback does the process owner receive from the shop floor?	Process owner	Process owner tasks
How was the order fulfilment process created?	Process owner	General process
How often is the order fulfilment process map revised?	Process owner	General process

6.1.2 Categorising findings & FMEA

The production issues noticed during the observation of production orders were listed and categorised. Figure 36. shows the different fault categories and the corresponding number of issues in one standard Retrofit production in a cumulative impact chart, also known as pareto chart. The horizontal axis represents the different issue categories. Left vertical axis is the number of times the issue was encountered, and the right vertical axis is the percentile of all the noticed issues. The line shows the cumulative impact of the issue categories.

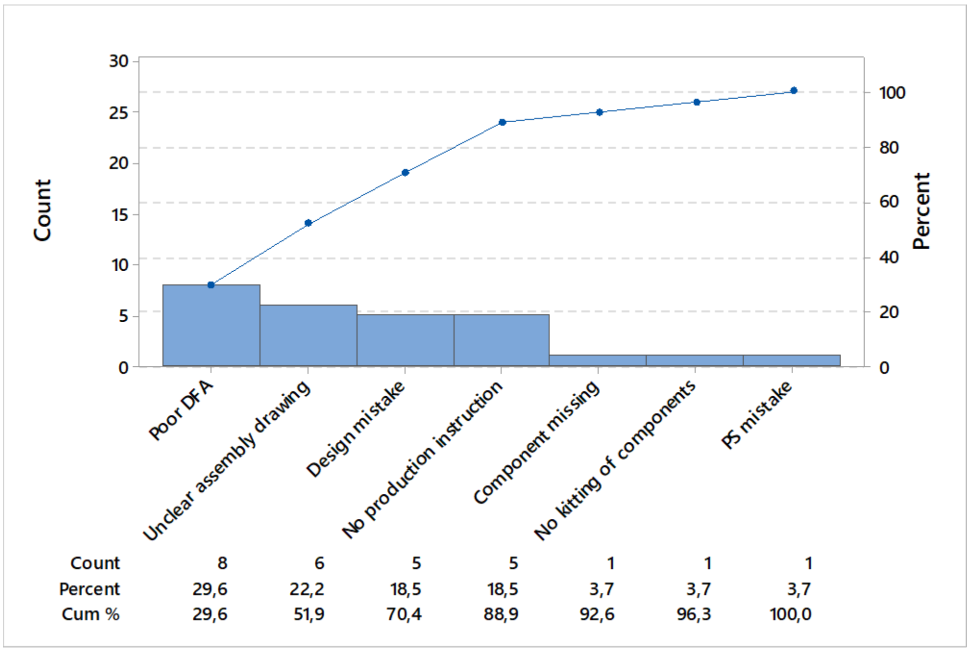


Figure 36. Single production order issues.

Pareto chart can be used to prioritize different issues based on their occurrence. From the graph can be seen that the first four categories have the greatest occurrence. Issues related to DFA were the most common. The pareto chart is a great tool for finding the most significant product design related issues but it does not show the major process issues. For example, the lack of kitting in components is only included once in the data but it affects every component of the production order.

For identifying the most significant problems in the complete production process, a failure modes and effects analysis was created. In FMEA the observed issues are ranked based on severity, occurrence, and the effectiveness of current issue detection methods. The final ranking is provided by a risk priority number (RPN) that is the product of the previous factors. In this study, the ratings for severity, occurrence, and detection were assigned based on the interviews as no quantitative means for determining the ranking is available. The FME analysis is show in Table 11.

Table 11. Production issue FMEA analysis.

Potential Failure Mode	Potential Failure Effects	Severity	Potential Cause(s) & Mechanism(s) of Failure	Occurrence	Current Controls	Detection	RPN
The materials do not arrive according to predetermine pre-assembly kits.	Increases the time spend on searching for right components.	9	Reason for the problem is the way materials for a production order are procured from ERP as well as material definition.	10	N/A	5	450
The materials do not arrive at same time.	Increases the time spend on searching for right components.	9	Reason for the problem is the way materials for a production order are procured from ERP.	10	N/A	5	450
Creation of material checklists.	Due to missing materials, the necessary checklist creation is very time consuming.	7	Material arrival. Reason for the problem is the way materials for a production order are procured from ERP.	10	N/A	5	350

Each worker assembles deliveries based on their own expertise's and practices.	Same products can be assembled to a varying degree of completeness and non-identical wiring routes. -> assembly time variates.	7	Standard work instructions and protocols are missing from Retrofit production.	7	Not existing?	6	294
Production specific documentation is currently missing (Wiring instructions, Standardized work instruction, pictures of example sub-assemblies).	This can cause assembly errors, delays (it is not clear how certain component /wiring should be installed) etc.	6	The responsible person/organization to produce this documentation is currently not defined.	8	N/A	6	288
Same mistakes in products keeps appearing.	Problems needs to be solved/fixed -> assembly time is increased.	6	Lack of communication between OBE and production, feedback channel does not work as intended.	7	Not existing?	6	252
Quality of OBE documentation is insufficient.	Assembly order, BOM etc not clear ->Issue needs to be clarified/solved with OBE -> assembly time is increased.	8	OBE design guidelines missing/insufficient for Retrofit products.	6	Not existing? Peer review?	5	240
Mistakes solved in R&D design appears in OBE order.	Problem needs to be solved/fixed in production -> assembly time is increased.	6	Lack of communication between OBE and R&D.	6	Not existing?	5	180
Same mistakes in products keeps appearing.	Problem needs to be solved/fixed -> assembly time is increased.	6	Lack of communication between R&D and production, feedback channel does not work as intended.	5	Enhancement project	5	150
Degree of completion for sub-assemblies not clear / not done according to assembly drawings.	Assembly workers rely heavily of personal experience in assessing suitable degree on completion (size and weight of sub-assembly) -> causes delays and variation in assembly.	5	The degree of completion information for sub-assemblies are missing from documents.	5	R&D design/prototype reviews	5	125
Mistake in R&D documentation/component design.	Correct way for assembly needs to be investigated/fixed component needs to be ordered -> causes delay.	6	Mistake not noticed during R&D project.	4	R&D design/prototype reviews	4	96
Design is difficult to assemble.	Assembly takes longer time than expected.	3	Poor design for assembly (Fastening and fastening methods, tool space considerations, wiring harness design, large component handling).	6	R&D design/prototype reviews	5	90

Product architecture vary between different Retrofit products.	Because of high number of product variant/ sub-assembly variants, it is difficult to standardize production process -> causes delay.	3	Product architecture is not defined in product family level.	4	Product architecture review.	4	48

6.1.3 Improvement workshops

In order to find viable solutions for the problems in the production process, two improvement workshops were organized. In the first one participated personnel from Retrofit product development team and the engineering centre (EC) team responsible for OBE design. In this workshop the focus was on the issues related to product design. The second workshop was held between product development and the production organization. This session focused on the issues related to production process. The workshops started with describing the issues identified during the study which was followed by brainstorming possible solutions. The discussed issues and the possible corrective actions are presented in the following sections.

6.2 Product and process compatibility

The existing consensus at the start of the study was that the current production process might not be compatible with the current product structure or product architecture. During the study it was observed that the major issues are related to the practical visibility of the PS. This means how the production planner and the assembly workers see the PS in their activities.

6.2.1 Product architecture analysis

Architectural thinking has not been a major driver in Retrofit product development. The final architecture of the Retrofit products has been the result of detailed mechanical and electrical design focusing on the correct functioning of the end product. The lack of mechanical and electrical compatibility in the retrofitted Drives and the new ACS880 drive product family has constrained the detailed design which has affected the resultant product architecture. No common architectural concept has been developed for different Retrofit product families. This resembles the situation described in the article by Karl Ulrich where product architecture is not the result of deliberate choice but incremental evolution of the product (Ulrich, 1995).

From modularisation perspective, the sub-assemblies are the closest thing that can be considered functional or production modules in the Retrofit design. However, these are highly dependent on the product family that they are designed for and it is rare to find sharing between product families. This has resulted in a large amount of variation in production orders. Because of this the production must be able to operate in a highly flexible manner which creates difficulties in standardizing the assembly procedures across multiple product families. These factors contribute to the highly variable production lead times that can be seen in the initial data presented in section 5.1.

According to a R&D manager, one architectural problem concerning currently retrofitted older product families is that original design is optimized towards functionality and power provided by the Drive. This has limited the capability for designing modular Retrofit products. In the newer product families, the original design moved towards modularisation. This characteristic can be used in future Retrofit products.

The current Retrofit product architecture was discussed in the solution workshop held with the R&D and EC team. It was concluded that improving the product architecture of the currently available Retrofit products would require too much time and resources that it would not be feasible. However, the architectural thinking is considered in current and future product development projects. Using modular architecture in Retrofit would enable the design of smaller individual upgrade units opposed to complete cabinet Retrofits. A combination of these units could then be used to provide the full Retrofit if the customer so chooses. The current plan in Retrofit product development is to assess the business and the technical possibilities of such modules.

From production perspective the modular approach would mean smaller and more generalized production orders in regard to component count and manufactured units. It was discussed that the standardization of complete sub-assembly designs across multiple product families would not necessarily be technically possible. However, standardizing them based on the functionality in the end product could be used to create more commonality in the manufactured units.

In addition to modular thinking, the creation of product block diagrams is taken as part of the future R&D projects. The goal is to map the different electrical components and interfaces that need to exist in the final product in a clear visual manner. Event thought the product block diagrams are not totally similar to the functional structures introduced in the section 2.3.2, they can be used to identify possible common functional modules in the products.

6.2.2 Product structure analysis

Retrofit product structure resembles a general modular BOM where the final products are configured based on options. From assembly perspective this type of BOM is not ideal since the assembly sequence information is not present. The configurable BOM is still feasible in Retrofit products due to the large number of product variants. In the current PS, the production aspects are considered by grouping mechanical components needed in the same sub-assembly in a kit.

One of the minor issues relating to PS was the discrepancy of information in BOMs available to the worker. The two key pieces of information in PO BOM are the item designations and the kit structure. At the time of the study workers had to utilize two different BOM lists to gain this information. Soon after the production order was followed, the old work queue tool was made inaccessible. This means that the kit structure of PO BOM is currently not available for the assembly personnel. The new work queue tool is still under development and the goal is to make this information visible to the assembly workers.

The major issues in current Retrofit production are related to the component arrival and handling at the DSW. This was evident from the interviews as wells as shop floor observations. In addition, the creation of material checklists was viewed as unnecessary and time-consuming part of the production process. Component arrival related problems can be broken down to three specific categories that are addressed separately in the section:

1. All of the PO components are ordered at the same time to the DSW.

2. Arriving components do not conform to the kit structure of the PS.
3. Components arrive with variable lead time.

Problem 1: All of the PO components arrive at the same time
A typical Retrofit product can have more than a hundred individual components but only a portion is needed in the sub-assembly manufacturing. From the assembly workers perspective there is a noticeable excess of components at the workstation. This creates difficulties in finding the right components when they are needed. The excess of components also decreases the available space at workstations and the storage areas in the DSW.

Solution
A possible solution would be to order the PO components in sequence based on the assembly phase or task. According to a systems development specialist working with Retrofit production this can be accomplished with an ERP logistics tool currently being developed for other manufacturing lines at the Drive factory. The tool is designed to be flexible and tackle similar problems in various production lines.

This logistics tool allows the production planner to view the ERP-items in the production order based on the assembly phase in which they are needed. It also shows the stock status for the ERP-items improving the production planning and scheduling. The correct use of the logistics tool would allow the production of PO to be divided into more manageable stages from the perspective of component count which improves the assembly efficiency.

A precondition for the use of the logistics tool is to allocate every ERP-item to a specific phase of the assembly. The logic in which assembly phase is determined for ERP-item in PO BOM is the following:

1. Every PO is automatically assigned to a routing group based on the product type.
2. Within a routing group a certain routing value is assigned for the order. The assignment is done based on some information linked to the PO.
3. For every ERP-item in the PO an assembly phase is determined based in the routing value. ERP-items can have multiple different assembly phases assigned to them but only one for each routing value.

The logistics tool automatically divides the PO BOM based on the routing value and corresponding assembly phase information assigned the ERP-items. This allows the production planner to view separate assembly phase BOMs for the order and to request the ERP-items to the assembly area accordingly.

The routing value-assembly phase data for ERP-items is maintained separately from products structure. This means that a change to the product structure that affects the assembly phase of an ERP-item is not automatically updated to the ERP. Because of this, concurrent maintaining of the PS and assembly phase data is required. The exact definitions of the different assembly phases can be done based on the requirements set by the production organization.

Figure 37 shows how the assembly phase for an ordered ERP-item in Retrofit PO is currently determined. Every standard Retrofit is assigned to the same routing group. This group is then divided into two possible routing values. This value then determines the assembly phase of the component in that order based on assembly phase definition set on the item level. The attribute used in selecting the routing value for the PO is the expected work hours. This divides the orders into long and short production time categories. The use of expected production hours is purely related to the estimated costs of the assembly. The product information for this selection is acquired from the product variant codes in the PO.

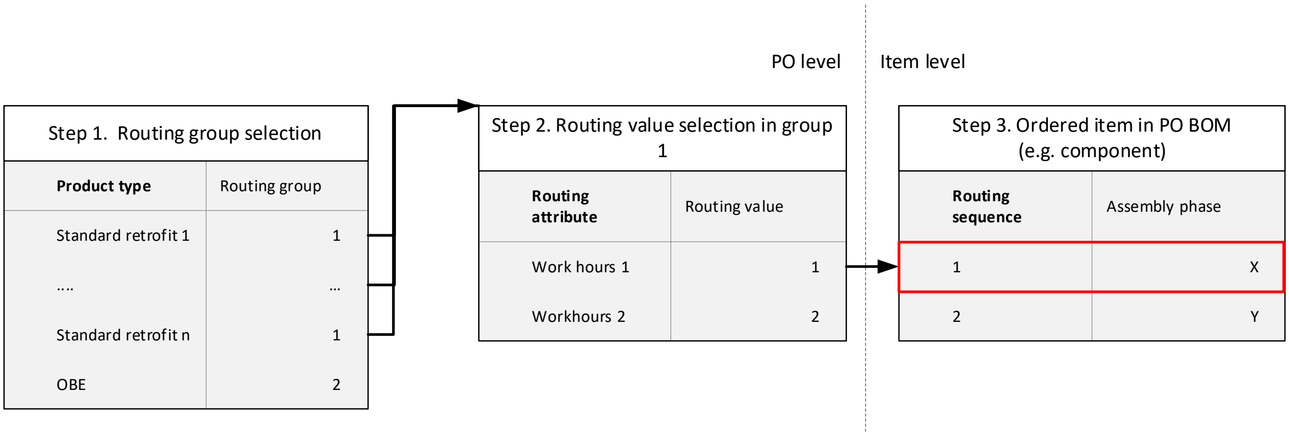


Figure 37. Assembly phase determination for ordered component in standard Retrofit production.

Currently four assembly phase definitions are used for Retrofit ERP-items. These definitions do not reflect actual phases of the assembly process but the ERP-item types. These are documents, bulk items, ordered items, and Drive modules. This means that the actual product or assembly information is not used. The routing value and ERP-item assembly phase information only serves as a way to separate the components based on their procurement type. This helps the production planner sort the component in the PO BOM when they are requested from the warehouse. The current method does not solve the component arrival problems in the production. With the current procedure ERP-items cannot be assigned to different assembly phases in each product family they are used in. The reason for the current way of determining the assembly phases is the lack of product knowledge in the organization maintaining the information. Figure 38 shows how the production planner currently sees the Retrofit production order BOM.

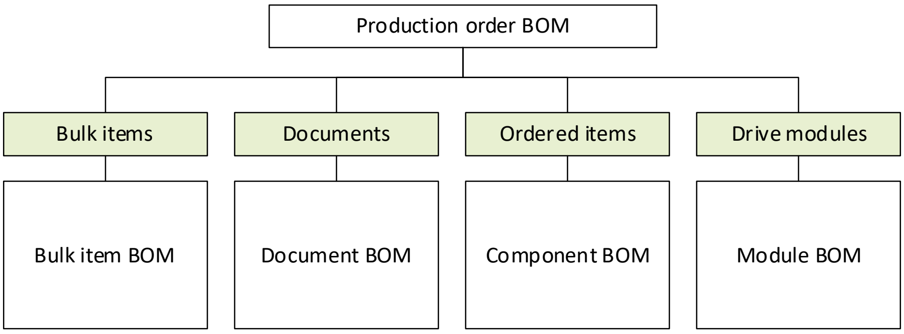


Figure 38. Current planning view for Retrofit orders.

According to the systems development specialist, a possible solution for sequencing the Retrofit production is to determine the routing value for the PO based on the product family information rather than the expected workhours. This would allow same ERP-items to be used in different phases of assembly regardless of the product family. On the system level this solution would be currently possible to implement and would not require large initial workload. The information on expected work hours and costs for the PO would not be lost as they can be defined for the new routing values similarly to how it is done currently.

In product level, the implementation would require assigning family dependant assembly phases for each ERP-item in every Retrofit product structure. The assignment for a specific product would need to be implemented simultaneously for the whole product structure so that it would not disturb the ongoing production orders. The initial workload would be significant. From design and maintaining point of view this items assembly phase allocation should be done in the main BOM level of the product structure. This means determining the assembly phases for complete kits in the product structure and not the components inside the kits. This would of course have implication on how components are kitted in the product structure based on the definitions of the assembly phases. Determining the item-assembly phase allocation would require combined understanding of the different Retrofit products, product structures, and the requirements of the production organization.

One possible practical application of the solution would be to determine assembly phases based on the component use in Retrofit production. For example, by allowing sub-assembly components to be ordered separately from other items. This would reduce the number of components in the workstation during the sub-assembly manufacturing.
Figure 39 shows the information flow in the solution systems. Figure 40 shows the production planner view were components are divided based on use.

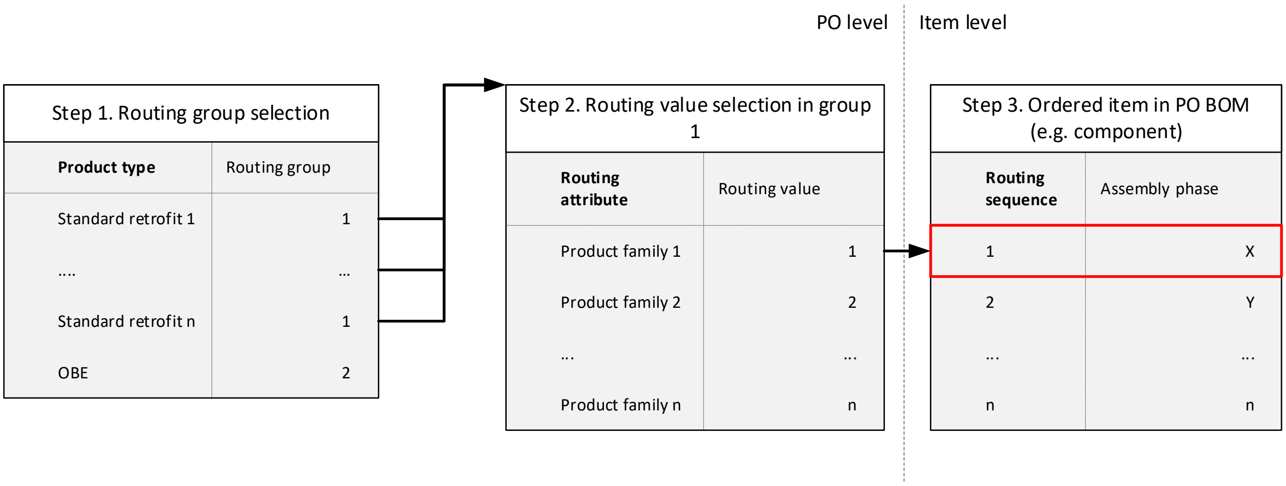


Figure 39. Assembly operation based on product family for ordered component.

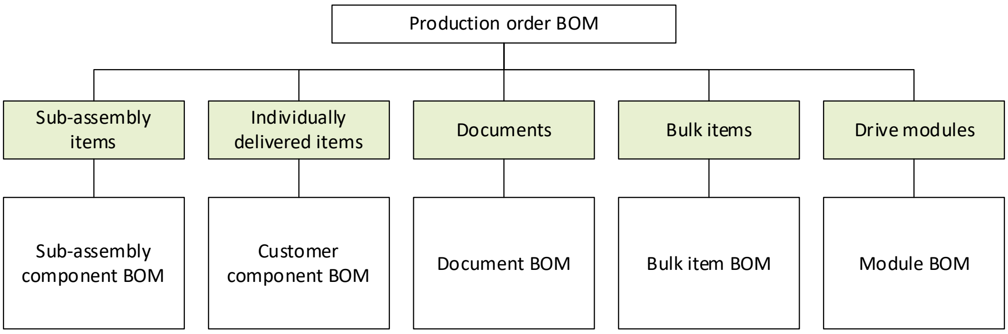


Figure 40. Planning view were components are divided based on the use at Retrofit production.

This solution is focused on the routing value determination step on the information flow. For standard Retrofit products the division could also be done at the routing group determination step. However, this would not be possible for OBE orders since they can share product type information and be completely different from the design and production perspectives.

The proposed solution would be difficult to implement for OBE orders as it is presented. This is because the OBE BOMs are always order specific and not generated through standardized product configurator. A common set of routing values for all OBE orders would be difficult to establish. Making order specific routing values and assigning the assembly phase information for all items on the BOM would be time consuming and as such not feasible.

The assembly phase information can be only assigned to ERP-items that are defined to be an ordered by the DSW. Currently only individual mechanical components, wire harnesses, and electrical components in the product structure are defined as such. The current ERP-item definition used for the Retrofit kits does not allow for the kit to be allocated to an assembly phase. This issue also related to the components not arriving to the production area according to predetermined kit structure.

Currently the assembly phase allocation in Retrofits can only be done at the component level. This creates an issue if an ERP-item is needed multiple times and in varying phases of assembly in the same product. This problem could be avoided by including these types of items in assembly phase dependent kits. These kit items would then have a routing value dependant assembly operation assigned to them.

Problem 2: Arriving components do not conform to the kit structure in the PS

The lack of kitting means that the pre-determined product structure for PO is lost when the components are ordered from the warehouse and delivered to the DSW. Referencing section 2.4, the complex product structure made by the designers is transformed in to a flat one when the PO is generated. This slows the assembly process significantly because components needed in a certain sub-assembly need to be found amongst all the of PO components. This can also lead to falsely reporting that a component was not delivered if the search is not done meticulously enough. In addition, it slows the creation of material checklist especially for components that are not used in the sub-assembly production.

According to the systems development specialist, the source of the issue is the ERP item definition used for Retrofit kits. Currently Retrofits component kits are defined to be manufactured at the DSW. It is important to note that manufacturing a kit refers to collecting individual items in the same package and not the assembly of the components. This means that from production planning point of view the kit code is nothing but a phantom item that DSW is collecting and delivering. DSW cannot order the kit items pre-made for the warehouse and can only order the included components. This definition is can be used for small spare component kits that are compiled at the DSW, but it is not suited for the needs of Retrofit production.

Solution

In order to have Retrofit materials arrive according to kit, the ERP-item definition should be changed to warehouse made-to-order kits. This would allow the production planner to view the kit as an ordered item rather that manufactured one. The components for the kit would then be picked and combined at the warehouse before they are delivered to the DSW production. Furthermore, this would allow an assembly phase to be determined for the kit as was described earlier.

According to a product information specialist similar type of definition are already in use in other production lines at the Drives factory. The suitability of existing ERP-item definitions for Retrofit kits would need to be assessed jointly by product information management, production, and system development organizations. Production and systems development organizations are able to provide the requirements for the kit item definition from the assembly and production planning viewpoints while the product information management has the necessary knowledge of defining ERP-items. If no suitable existing definition is found, new one needs to be created. Process for defining and testing new ERP-item definitions is already in place.

Problem 3: Components arrive with variable lead time

Currently it is difficult for the production planner to estimate when the assembly of the previous Retrofit order is completed. Because of this the components for the following order are ordered at the end of previous workday when the assembly is scheduled to start. Consequently, components arriving from long distance warehouses will not be available when the production starts. The differences in component delivery times are not visible to the assembly worker. This can lead to confusion when searching for components. If components are not available when they are needed the production could be stopped.

Solution

The possible solution for this is to order components at least two days before assembly is scheduled to start. This would require more storage area at the DSW to compensate the difficult production time forecasting. Dividing the PO into more manageable pieces along with having materials arrive pre-kitted at the warehouse would decrease the need for storage and improve the forecasting of the assembly duration.

Product structure and PS-tables

Creating a product structure is balancing between R&D workload, maintaining workload, and process functionality. The current product structure used in Retrofits is feasible from the R&D and product maintenance point of views for large variety products. However, the production and assembly considerations in the product structure are lacking. From the production point of view the current way of kitting sub-assembly components is satisfactory. From the final assembly point of view, it would be more reasonable to create component kits based on the assembly steps rather that to include all individual mechanical components in a “scatter parts” kit. A downside of this would be the need to create and maintain larger amount of kits in the PS.

Inclusion of final assembly sequence related information to the PS-tables would be beneficial to the Retrofit production. The current PS-table functionality would allow this information to be shown in the PO BOM in the same way as the item designation information. The information could help the stepping action described in section 5.5.5. Furthermore, the information could be used to crate final assembly step specific materials lists for the LSU and the end customer.

Lastly the way of creating the PS-tables should be standardized. Currently the similarity in the PS-tables for existing products is low. This makes maintaining the product structures difficult when the personnel maintaining the tables were not involved in its creation. Currently no guidelines for presenting the product information in the tables exist. Creating such guideline would make maintaining multiple product structures easier since the information is presented in a standardized manner.

6.3 Document analysis

This section focuses on the documentation used in the assembly process. The first part focuses on how the production personnel view the quality of the documents provided by R&D and OBE. The second part analyses the sufficiency of the current documentation based on the needs of the production. This means evaluating if all the necessary information that is needed in the assembly tasks are presented in the documentation. The analysis is based on the assembly worker interviews conducted in the study.

6.3.1 Document quality

Overall, the quality of the mechanical sub-assembly drawings and the electrical circuit diagrams were found to be fairly good. Some mistakes do exist in the current documentation, but they are generally minor and do not cause delays in the production. Such mistakes include for example wrong terminal markings in circuit diagrams or wrong material codes in mechanical drawings. The minor mistakes in drawings were said to be more common in OBE deliveries than in standard products. According to assembly workers the mistakes found in OBE drawing are obvious and should be noticed if the drawings are checked before they are released to production.

The workers gave more attention to the readability of the mechanical sub-assembly drawings. Especially in mechanical drawings for large sub-assemblies too much information is often presented on a single page. This means that too many components and their locations are shown on the same page. This makes the drawing and hard to interpret. The general assembly sequence in the drawings typically follows the page numbering and no detailed order for components are presented. These factors have caused the workers to assemble components in a wrong order that later needed to be disassembled and reassembled.

The document quality could be improved with a well-defined document reviewing process during the product design. In standard product design the reviewing process is divided into two steps. Firstly, the designers are responsible to cross examine the documents they create. The cross examination is aimed to catch small mistakes in the documents. In the second step the project manager organizes a document review meeting where the overall design and drawings are checked with a selected group from R&D, technical product management, and EC. The goal is to catch errors in design that affect the functionality or assemblability of the final product. These reviews are done well before prototypes or pilots of the products are built. Paying more attention to the assembly order, readability, and clarity of the sub-assembly documentation should be focused on future reviews.

The complete reviewing process is not as well defined in OBE projects. The designers are instructed to cross examine the documents and sales engineer responsible for the project might check them. The problem in OBE is that the timetable for the project can be fairly tight and it is unclear how often the reviews and cross examinations are actually conducted. In the R&D and EC solution workshop it was determined necessary to re-evaluate the current review process and make sure that it is followed correctly.

Another issue in the drawings is the lack of degree of completion information for the sub-assembly. This was particularly mentioned in the case of heavy sub-assemblies. Retrofits are designed to include as much sub-assemblies as possible in order to decrease the final installation time. This means that whenever possible, components are designed into a sub-assembly regardless of individual and combined weight.

Much of the Retrofit production relies on the expertise of the assembly workers and some have experience from the field assembly. Each worker evaluates the feasible level of completion from the final assembly perspective while working on a sub-assembly. Too heavy sub-assemblies need to be disassembled at the final installation which in turn increases the workload. It also makes the assembly done at the DSW unnecessary. Result is that the same sub-assemblies are completed to a varying degree of completion based on the assigned worker.

In the workshops was decided that all of the sub-assemblies should be built as they are shown in the drawings. From the quality and the customer point of view it is undesirable that the output of the production process for the same sub-assemblies depending on the assembly worker If a worker considers a sub-assembly too heavy, the issue should be communicated to R&D or technical product management so that the design can be revised. In the future designs, more attention is given to the weight of components and the sub-assemblies.

6.3.2 Sufficiency of the assembly documentation

By themselves, assembly documentation made during the product development R&D was deemed to be insufficient from the production viewpoint. All of the interviewed assembly workers mentioned that more detailed instructional documents tailored specifically to the production are needed. Especially detailed wiring instructions were requested. The wiring routes are currently done based on the personal experience of the worker which can lead to variable wiring in same sub-assemblies depending on the worker. Wiring was said to be one of the most time-consuming tasks in the assembly. The lack of detailed instructions makes it even more difficult. Some workers take pictures of the wiring they have done for a sub-assembly, but these pictures are not widely distributed or categorised based on product type.

Instructions and protocols for standardized work processed were highly requested. Without standardized work the output of the production process varies depending on the worker. In addition, if a worker has to leave during the production order, it is difficult for another worker to continue the work. There might not be enough information of the status of the PO or in which specific order has the previous worker completed assembly tasks.

Currently the responsibility of making detailed production instructions and standardized works is not defined. Making such documentation cannot fall into the responsibilities of the designers in R&D projects. The design engineers do not have enough knowledge on the specifics of the production environment or the instructional requirements. This concerns for example tooling available, bulk components at the workstations, or the general work principles.

The workshop manager of DSW described that the organization for Retrofit production is still fairly young. The history of DSW is in repair and spare component business and the organization is not used to manufacturing complete products such as Retrofits. The knowledge of production and production improvement is still developing because the Retrofit assembly started only in the recent years. The production of Retrofits has always relied on the expertise of the assembly worker. This has diminished the need for detailed production documentation. As the product portfolio and demand keep increasing there is a clear need for dedicated resource for production and instruction improvement based on this study.

6.4 Design for assembly in Retrofits

None of the workers expressed explicit concerns regarding DFA in Retrofit design. The workers view the overall assemblability of Retrofit designs as acceptable. During the production observation, several instances of poor design for assembly were noticed. Weight of individual components and the completed sub-assemblies is not fully considered during the design. The workers at DSW sub-assembly production have access to lifting equipment. The real issue is in the final assembly at customer facility. The final assembly is done in a technical room holding multiple line-ups of electrical equipment. Lifting equipment needs to be brought into the installation site and is limited by the space available.

Second common DFA issue was the use of non-ideal fastening methods. A typical Retrofit sub-assembly is a sheet metal base component onto which components are attached. A common fastening method is a nut and bolt connection through the sheet metal component. The worker has to hold the nut in place with while fastening the bolt making it a two-hand operation. Depending on the size of the components, dimensions of the base component, and the number of components in the sub-assembly this operation can be difficult to accomplish. This type of fastening also limits the ability to assemble components from the top of the assembly. These types of sub-assemblies should be completed while the base is constantly in a horizontal position and other component are then attached from above. In many of the observed cases this issue could have been corrected by using sheet metal insets such as hit nuts and threaded studs.

Third issue noticed relating to mechanical design was the lack of adequate space for tooling. According to the workers all of the required assembly operations in Retrofits can be accomplished but some require the use on non-conventional tooling. For example, by employing long extensions on screw guns to gain flexibility in the tool positioning. Other example is the tightening of bus bars bolts and the lack of required space for torque wrench. These types of issues were created either by the actual design or incorrect assembly sequence in the documentation.

Most assembly difficulties in electrical design came from the wire harnesses. The wires are often too short to make to connections or excessively long which makes the wiring difficult. Currently wires are not included in the product 3d models. Electrical designer estimates the approximate wire length with the help of mechanical designer from the model. Some wires can be used in multiple designs where the distance of components might vary.

One reason why the assembly workers did not consider the DFA aspect as an issue is that they are focused on the issues at operational level. The assemblability affects both DSW production and the site installation. In the solution workshops was suggested that some DFA information should be added to the current mechanical design guidelines. The goal is to increase the DFA knowledge of the mechanical designers and move the assembly considerations to the detailed design phase instead of prototyping. Overall, the DFA related issued were not given a high priority in the FMEA analysis.

6.5 Communication

Many of the assembly workers expressed concerns about communication between the assembly personnel and the product designers. More detailed feedback loop on reported design mistakes was requested. Currently the assembly personnel report the noticed design issues to R&D or OBE. However, they rarely know if the issues are taken under consideration. This leads to frustration when same issues keep appearing in the production.

In standard products the repetition of design mistakes noticed in production can be caused by how the engineering changes are managed as was explained in section 5.5.4. In OBE deliveries the repetition of design flaws is more common. Often OBEs are viewed as one-time designs and there might not be enough incentive or time to correct the faulty design after the delivery. The problem is that old OBE designs are commonly used as a base for new deliveries. As the mistakes are not corrected and adequately documented, they are forgotten and copied to future designs.

For correcting mistakes in standard Retrofit product, a dedicated project with certain amount of annual funding has been established. A dedicated person from the production organization is assigned to the project which is meant to improve the feedback and reporting between designers and production. In OBEs the documentation of issues is improved so that they can be corrected if the design is used again. The goal is to constantly improve the communication and feedback with the production organization and make the process of correcting design related issues more transparent.

7 Conclusions

This study analysed the production process for ABB's Retrofit frequency converter modernization products. The focus was in finding issues in the production process that might be caused by the product structure of the Retrofits. The quality and sufficiency of documentation made in the standard and the customer engineered solution projects were evaluated from the production viewpoint. The main goal of the thesis was to identify problems that increases the total production lead time for Retrofit products. The analysis was conducted using qualitative methods.

The most significant issues affecting the production process were caused by the component arrival to the assembly area. The study found that the production planning only sees a flat product structure where all the components are on the same hierarchy level. This means that pre-determined product structure and the kitting of sub-assembly components is not apparent in production planning or assembly operations. This increases the time spent on searching for the required components. It also increases the complexity and uncertainty in validating the delivered components. Cause of the problem is the ERP-item definition used in the Retrofit sub-assembly kits. Current definition assumes that the kits are made at the Retrofit production. Changing the definition so that the kit items can be viewed as ordered by the DSW moves the creation of the kit to the warehouse. The suitability of existing ERP-item definitions or the possibility of creating a new one needs to be assessed jointly by product information management, production, and the system development organizations. Item definition for Retrofit assembly kits needs to be created based on the production environment requirements.

Another issue in the component arrival was that all of the PO components arrive at the same time to the production area. Only a portion of the components are used in the sub-assembly manufacturing. The excess of components during the manufacturing of sub-assemblies contributes to the obscurity of the assembly actions. Other components are delivered to the customer individually but need to be verified in a material checklist. This was viewed as a time-consuming part of the process. This issue could be diminished by sequencing the acquiring of components based on the phase of the assembly.

This thesis presented a possible solution that showed how the ERP-items in a standard Retrofit product could be assigned to pre-determined assembly phases. This is done by creating new routing values to the ERP based on the Retrofit product families. The proposed solution is flexible and allows the assembly phases to be determined according to the needs of the production. The solution could be used to divide the PO materials into sub-assembly components and individually delivered components or the assembly phases could follow the final assembly sequence at the customer. The former allows the production to complete order's sub-assemblies before the rest of the components arrive. The latter allows the sub-assembly manufacturing, stepping, and checklist to be done independently for each final assembly step. The solution also considers the possibility that components may be used in multiple product families or in varying phases of assembly.

Implementing the proposed solution requires the assembly phase information to be assigned for every ERP-item in each product structure independently. This would require sufficient understanding of the product structures and the production sequencing. Currently the components are only divided based on the procurement type. The combined product and production knowledge have been inadequate in order to use the proposed method before.

The document analysis found the overall quality of the assembly documentation to be acceptable. Some enhancement for the existing mechanical assembly drawings were suggested by the assembly workers. First was the division of assembly steps containing multiple components into additional pages. This would make the component assembly order clearer. Second suggestion was to show the desired degree of completion for heavy sub-assemblies. This would reduce the guess work in the sub-assembly manufacturing because the worker also considers the ease of the final assembly at customer site. Even though the second suggestion was made for the documentation, the actual problem was found to be in the guidelines for the assembly process. R&D and OBE expect the sub-assemblies to be completed as they are shown on the drawings. If a problematic assembly is noticed, it is reported to and corrected by the design organization.

More significant issue was the lack of detailed production oriented assembly instructions. Large portion of the assembly process is the wiring of sub-assemblies. Currently the wiring is done based on the personal preferences of the worker because it is not shown in the documentation. This issue could be addressed in many ways. One of the suggestions from the assembly personnel is to create a common picture database containing example sub-assemblies. The database would be divided based on product families and would need to be easily accessible. The reason for the lack of detailed production instructions is the unspecified resource for their creation.

The lack of detailed production instructions relates to the absence of standardized work protocols in Retrofit production. The study found that much of the assembly process rely on the personal expertise of the assembly workers. This leads to varying output of the production process for the same assemblies depending on the worker. From the quality and the customers viewpoints this is undesirable. It also makes continuing the work difficult in the case of worker change.

The design for assembly aspects of the Retrofit products were not considered as a significant issue. During observation of production orders several instances of poor design for assembly were noticed. Considering DFA in the detailed design phase of the project development reduces the possibility of redesign in later stages and can decrease assembly time. The study suggests that a basic DFA addition is be made to the current mechanical design guidelines.

One general issue brought up by the assembly personnel was the difficult communication between the design and the production organizations. This was particularly related to the transparency of design issue correction feedback. The workers have noticed same design flaws in the production orders even though the issues have been reported. In the standard Retrofits the reason for the repetition of issues can often be found in the management of design changes. Commonly the old stock of changed components is used before the corrected version is available. In OBE projects the designs are often viewed as one-off and there is no time or incentive to correct mistakes. The issues are then repeated when old projects are used as a base for new OBE design. The feedback loop between designers and the assembly workers is constantly being improved.

Most of the presented solutions can be used to improve the production of already released products. The workload would be somewhat greater than in normal product enhancement tasks. For the future products, most of these solution could be applied during the product development and the amount of work would be much lower. Enhancing the old products could be justifiable as long as they are assembled in the same system as the future products. This would benefit the production by lowering the variability in the assembly procedures and further contribute towards the standardization of the whole Retrofit production.

The largest reduction to the production lead time could be achieved with the solutions improving component arrival. It can be estimated that the search time of components can be reduced more than 50% if they arrive according to the sub-assembly kits. This could be further impacted by sequencing the component arrival. Dividing the PO into smaller unit improves the production planning and reduces uncertainty in the production orders. Wiring and checklist creation were identified to be the most time consuming production actions. The proposed solutions would reduce the time needed to compile the component checklists. The creation of standardized work and wiring instructions would reduce the wiring time.

These solutions can be estimated to lower the variation in assembly times and to reduce the total manufacturing time of standard Retrofit products by 10-15%. In OBE deliveries the effect would not be as significant due to the fundamental differences in the design and manufacturing processes. These estimates are made based on the qualitative analyses of the process and as such need to be considered accordingly. The validation of the solutions was not part of this thesis. The possible lead time effects can only be seen in the long term due to the high variety and still relatively low production volumes for each individual product family.

This study was impacted by the lack of accurate quantitative data from the process. The production lead times are reported as full workdays, which decreases the overall accuracy. The workers only report the active production hours on the top-level of the production process. This means that for example in the assembly phase of the production, times spent on mechanical assembly and wiring are not individually reported. Furthermore the workers conduct actions from different top level assembly phases concurrently. As such the available data cannot be used to accurately determine production bottlenecks in the current process. Qualitative methods can be used to roughly estimated the problematic areas in the process. However, they cannot be used to accurately show the lead time and cost impact of these problems.

Retrofit products are a part of Motion Services modernization product offering. Motion Service and the DSW production has mostly focused on repair and maintenance services as well as spare component business. The ERP system currently used in the DSW has been well suited for low component count repair and maintenance production orders. It is evident that they have not been optimal for production of high component count products. Based on the study and the workshop manager, the production related knowledge in regard to manufacturing such products is still evolving and the ERP systems are constantly being improved. This study has served as a way to further increase the combined product, production, and information system knowledge that can be used to improve the production and the decision making during product development projects

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