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Utilization of production planning tools in design for manufacturing of electric machines

Thesis submitted as a partial fulfilment of the requirements for the degree of Master of Science in Technology.

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Abstract of master's thesis

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In electric machines manufacturing process, maintaining the quality of the machines is challenging due to the high complexity and variance of the products. Better tools for production planning are needed to manufacture the electric machines with high quality and on schedule.

The objective of this study was to examine how production planning tools can be utilized in manufacturing planning of electric machines. The other main objective of the study was to compare two production planning tools, Delmia and TeamCenter MPP (Manufacturing Process Planning). The goal was to determine which of the two tools studied was more suitable for manufacturing planning of electric machines in the target company. A literature review was conducted where the basics of production planning and traditional tools of production planning were introduced. Manufacturing process planning basics and factory modelling state of the art was introduced. The concept of virtual reality and virtual reality tools state of the art in manufacturing planning were also introduced. Current internal product design, production design and assembly processes in the target company were also presented. Bearing assembly of a vertical pump motor was used as a case study in order to find ways to utilize the production planning tools in electric machines manufacturing planning. In the study basic technical functions of the tools were tested and evaluated. The two tools were compared by rating the technical functions. Weighting coefficients were determined for the functionalities of the tools based on their importance to manufacturing planning of electric machines.

With the case study it was demonstrated that Delmia and TeamCenter MPP tools can be utilized in manufacturing process planning of electric machines. Overall, the work instructions created were found to be the most important benefit of the manufacturing process planning tools. The work instructions were the concrete result of the work done with the manufacturing process planning tools and they can offer actual aid in the manufacturing of electric machines. From the numerical scores it was deducted that TeamCenter MPP is a more suitable tool for manufacturing process planning of electric machines in the target company compared to Delmia. The key findings of the study were the importance of the work instructions and importance of the integration of the manufacturing process planning tool to the current tools used in the target company. Based on the results of this study continuing the implementation of TeamCenter MPP tool to the current design tools in the target company was recommended.

Keywords Delmia, Production planning, TeamCenter Manufacturing Process Planning, Virtual Manufacturing

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Sähkökoneiden valmistusprosessissa tuotteen laadun varmistus on haastavaa, koska valmistettavat tuotteet ovat monimutkaisia ja tuotteissa on suuri vaihtelevuus. Parempia tuotannonsuunnittelutyökaluja tarvitaan, jotta sähkökoneet saadaan valmistettua laadukkaina ja aikataulussa.

Tutkimuksen tavoitteena oli löytää keinoja hyödyntää tuotannonsuunnittelutyökaluja sähkökoneiden valmistuksen suunnittelussa. Työn toinen päätavoite oli vertailla kahta tuotannonsuunnittelutyökalua, Delmia työkalua ja TeamCenter MPP (Manufacturing Process Planning) työkalua. Tavoitteena oli selvittää, kumpi työkalu soveltuisi paremmin sähkökoneiden valmistuksen suunnitteluun kohdeyrityksessä. Tutkimusmenetelminä käytettiin kirjallisuuskatsausta, jossa tarkasteltiin tuotannonsuunnittelun ja siinä käytettävien perinteisten työkalujen perusteita. Kirjallisuuskatsauksessa esiteltiin valmistuksen suunnittelun perusteita ja virtuaalisen tehtaan mallinnuksen state of the art sovelluksia. Myös virtuaalitodellisuuden perusteita ja virtuaalisia valmistuksen suunnittelutyökaluja tutkittiin. Nykyisiä kohdeyrityksen sähkökoneiden tuote- ja tuotannonsuunnittelukäytäntöjä sekä loppukokoonpanoa tutkittiin. Valmistuksen suunnittelutyökalujen tarkastelussa käytettiin malliesimerkkinä pystypumppumoottorin laakerin ja liukurenkaiston kokoonpanoa. Tarkastelussa molemmilla työkaluilla suoritettiin valmistuksen suunnittelun työvaiheet. Työkalujen vertailussa työvaiheita ja ominaisuuksia tarkasteltiin ja arvioitiin erikseen pisteyttämällä. Jokaiselle työvaiheelle ja ominaisuudelle määriteltiin vertailussa painokerroin, joka kuvasi ominaisuuden tai työvaiheen tärkeyttä sähkökoneiden valmistuksen suunnittelussa.

Työkalujen tarkastelu osoitti, että Delmia ja TeamCenter MPP työkaluja voidaan hyödyntää sähkökoneiden valmistuksen suunnittelussa. Kaiken kaikkiaan valmistuksen suunnittelutyökalujen tärkeimmäksi ominaisuudeksi osoittautui työohjeiden luominen. Valmistuksen suunnittelutyökaluilla luotuja työohjeita voidaan hyödyntää sähkökoneiden tuotannossa. Numeerisen vertailun tuloksena voitiin todeta, että TeamCenter MPP työkalu soveltuu paremmin sähkökoneiden valmistuksen suunnitteluun kohdeyrityksessä. Tutkimuksen keskeisimmät löydökset olivat työohjeiden hyödyllisyys sekä valmistettavuuden suunnittelutyökalun integroitavuuden tärkeys muihin käytettyihin suunnittelutyökaluihin. Tämän diplomityön perusteella suositeltiin TeamCenter MPP työkalun käyttöönottoprosessin jatkamista kohdeyrityksessä.

Avainsanat Delmia, Production planning, TeamCenter Manufacturing, Virtual Manufacturing

Preface

This thesis was done for ABB Oy Motors and Generators department in Helsinki, Pitäjänmäki. The topic was suggested to me while working in the synchronous machines design department as a trainee during my studies and I am thankful for the opportunity. The topic of the thesis was meaningful and an interesting educational experience.

I want to thank my thesis supervisor Professor Petri Kuosmanen and my thesis advisor Petteri Ylenius (M. Sc.) for guidance and advice during the study process. I also want to thank all the ABB employees in Pitäjänmäki who have advised me in the study and in the writing process.

I want to thank my family and friends for support throughout my studies. A special thank you to my girlfriend for support during the writing process of the thesis.

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Roope Aho

Contents

Abbreviations

3D	Three Dimensional
AEC	Architecture, Engineering and Construction
AR	Augmented Reality
AV	Augmented Virtuality
BOE	Bill of Equipment
BOP	Bill of Process
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CAVE	Cave Automatic Virtual Environment
CFD	Computational Fluid Dynamics
CMSD	Core Manufacturing Simulation Data
EBOM	Engineering Bill of Material
FEA	Finite Element Analysis
KPI	Key Performance Indicator
N-END	Non-drive end of the electric machine
MBD	Multi-Body Dynamics
MBOM	Manufacturing Bill of Material
MPP	Manufacturing Process Planning
MR	Mixed Reality
MRP	Material Requirements Planning
PDM	Product Data Management
PERT	Programming and Evaluation Review Technique
PLM	Product Lifecycle Management
PPR	Product, Process and Resource
R&D	Research and Development
VF	Virtual Factory
VFF	Virtual Factory Framework
VISTRA	Virtual Simulation and Training
VR	Virtual Reality
VM	Virtual Manufacturing
XML	Extensible Mark-up Language
XSLT	Extensible Stylesheet Language Transformations

1 Introduction

This master`s thesis is done for ABB Oy Motors and Generators department in Pitäjänmäki, Helsinki. ABB is the world leading company in power and automation technologies (ABB, 2017). ABB operates in over 100 different countries and employs approximately 132 000 workers of which 5100 are located in Finland. In Finland ABB operates in 20 locations with factories located in Hamina, Helsinki, Vaasa and Porvoo. (ABB, 2017) In Pitäjänmäki factory large synchronous motors and generators are designed and manufactured.

1.1 Motivation

Continuous improvement in the quality of the products and simultaneously decreasing the time-to-market are important to any industry. In a global competitive business gaining an edge to competitors in lead times and in product quality is vital. New production planning technologies and applications have become one of the tools in traditional industry to reach these goals. More advanced tools are already used for example in aerospace and automotive industries production planning. 3D modelling and simulation tools have been used in product design for a long time. Ways to utilize these tools in production design are continuously developed to concurrent the existing traditional production planning tools and methods. Even virtual reality tools are used in some industries and ways to utilize them in more traditional industry is studied. Recently virtual reality technology and devices development has accelerated especially in the videogame industry.

In the summer of 2017 in ABB Oy in Pitäjänmäki a factory virtualization program was started. The virtualization process started with a 3D scanning of the factory. From the acquired 3D point cloud a 3D-model of the factory was made with the right dimensions. This layout model of the factory floor could be utilized in the production planning. A production planning software called Delmia was adopted for testing. The main reason for these actions was a challenging vertical pump motor order from the Indian government. These large motors were designed to drive large pumps that move water from flooded areas to dry areas through canals in India. The motors caused many challenges in the product and production design phase and in the final assembly phase. The main challenge was a tight schedule of the final assembly phase compared to previous similarly challenging motors. Roughly, the final assembly time had to be halved from previous similar projects assembly times. To achieve this, goal improvements in production planning of the motor were needed.

1.2 Objective

Large synchronous machines are low volume, high complexity unique products. This is challenging especially in terms of detailed production planning because the final assembly process of the machine varies between different projects. In the vertical pump motors new design solutions were applied in both product and production design. The large dimensions and masses of the assembled motor components caused many challenges in the production phase.

The objective of this master’s thesis is to study and test new production planning tools in synchronous motors and generators production planning. One of the main goals is to find the most useful way to utilize the tools specifically in synchronous motors and generators manufacturing planning. The other main goal is to study and compare two different production planning tools and evaluate their usefulness in synchronous machine production planning. The objective is also to study current product and production design and the assembly process and to find areas that can be improved with new production planning tools. The objective of the study can be presented in form of research questions. The research questions are listed below:

- How can production planning tools be used in synchronous motors and generators manufacturing planning?
- Is Delmia production planning tool or TeamCenter MPP tool better for synchronous motors and generators manufacturing planning?

1.3 Scope

The scope of this study should be enough to meet the objective and answer the research questions properly. On the other hand, the scope should be limited in a way that it does not exceed the appropriate contents of a master`s thesis.

In this study an overview of the current state of the art of production planning and factory modelling is provided and ways to utilize them in synchronous machine production planning is studied. This study concentrates on the production planning tools testing and comparing. Two production planning software alternatives Delmia and TeamCenter MPP are both studied and compared. In this study pump motors bearing assembly model is studied with the two production planning tools.

Integration of the studied production planning tools to the current design and PLM (Product Lifecycle management) tools is considered in the comparison but is not in the main scope of the study. Current design methods and design structure of the synchronous machines in terms of production planning tools is discussed but finding solutions and improving the product design structure and processes it is not in the scope of the study.

1.4 Methods

The research methods used in the study are a literature review, a case study and a comparison between two production planning tools. In the literature review the theoretical background and the state of the art of production planning and factory modelling are examined. Especially examples of factories and industries already using more advanced production planning tools are studied. The current product and production design process of the company is also introduced and the current final assembly process of synchronous machines in the factory is explained. ABB internal product and production design processes are studied from company internal material and using the designer’s expertise. The assembly process of synchronous machines is studied by utilizing ABB internal work instructions and the knowledge of the operators and production planning experts.

Bearing assembly of the pump motors is used as a case example in this study. The bearing assembly process is modelled and studied in both Delmia and in TeamCenter MPP tools. For the bearing assembly basic production planning steps are conducted with both tools. In the comparison of the production planning tools technical functionalities are compared. Scores and weighting coefficients are determined for each functionality to find out which tool is more suitable for manufacturing planning of electric machines.

This study is constructed in a linear fashion. Chapter 2 consists of the literature review. In chapter 3 the production planning tools are studied and compared. In chapter 4 the results of the literature review and the study done with production planning tools are evaluated. In chapter 5 the methods and results of the study are discussed. The results are reflected to the research questions defined in the introduction of the study. Key findings and recommendations for future research are presented. Summary of the study is given in chapter 6.

2 Production planning literature review and current state in the company

In this chapter a theoretical background and the current state of the art for production planning, manufacturing process planning, virtual manufacturing tools and factory modelling and simulation is introduced. Current ABB Pitäjänmäki internal product design, production design and assembly processes are also introduced.

2.1 Production planning

In this section the basics of production planning and the traditional tools of production planning are introduced.

2.1.1 Basics of production planning

Production planning can be defined as manufacturing activity planning by allocating resources such as factory production capacity, employees, tools and materials to create finished products according to specified schedule. Traditionally production planning consists of scheduling of future production. Production planning and production scheduling terms can be distinguished from each other by the time span of the plan. Production planning can be considered more general planning for longer period in to the future. It consists of broader decision-making of for example production equipment investments, workforce capacity and inventory sizes. The time period of planning can vary from months to several years as planning is needed for different purposes. Some production equipment purchases for example can require production plans covering even the next ten years. Plans covering next few months can be used for example to set total production rates to meet forecasted production demand. Production scheduling covers a much shorter time period. It can determine the production needs such as materials, operators and factory space for the next few days or weeks. Production scheduling is more detailed plan of the production and smaller operations of production are covered. For example, smaller workstations or assembly lines are scheduled and operators' shifts are considered in the planning. (Bock & Holstein, 1963, pp.3-4)

However, detailed production schedule does not guarantee that the production will go as planned. Unexpected changes such as machine breakdowns or operator absentees can disrupt the planned schedule. Managing the production schedule as changes occur is often called dispatching. This means making decisions according to the unexpected changes so that the production schedule can be realized. (Thomas & McClain, 1993, p. 333)

L.J Thomas & J.O McClain (1993, p. 336) identified six decisions to be made when constructing a production planning model:

- The time unit.
- The time horizon.
- Level of aggregation of the products.
- Level of aggregation of the production resources.
- Frequency of plan revising.
- Number and structure of production plans.

Time unit determines detail of the production plan. Time unit can be for example months, weeks or shifts. It is also possible to use time units unequally in the plan. For example, shorter time periods can be followed by longer periods in the production plan. Time horizon determines the time in to the future that the plan`s decisions influence. For example, time horizon for the plan can be two years or ten years. Level of aggregation of the products determines the detail of product or products that are considered in the planning. Resource level of aggregation determines the detail of which resources are considered in the planning. Frequency of replanning determines how often the plan is revised and updated. Several different plans with different levels of aggregation can be used and the number and structure of the plans must be decided. (Thomas & McClain, 1993, pp. 335-337)

The main goal of production planning is to reduce costs by optimizing production. The objective is to fulfill customer needs with minimum cost. Different optimization methods for production planning exist. The usual costs included in the production planning are according to L.J Thomas & J.O McClain (1993, p. 335):

- Cost of oversupply, inventory costs.
- Cost of not reaching the demand or cost of delay.
- Regular production costs.
- Costs of alternative methods of production.
- Costs of changing the production capacity.

These cost calculations or estimates are used when optimizing or comparing different options for production. All of the above costs are difficult to estimate but the estimation is still necessary for production planning optimization and decision making.

L.J Thomas & J.O McClain (1993) state that production planning models are usually a mix of two strategies. The first one is “chase” which is producing according to the demand in other words “chasing” the demand. This can mean for example reducing or increasing the workforce according to demand. This strategy is very similar to Lean philosophy, where one of the tools for reducing costs is pull control. Pull control means that production volume is controlled according to customer demand so that costs for excess production and warehouse inventory are reduced. The second strategy used with “chase” is called “smooth” where some inventory or backorders is used as backup for unexpected increase or reduction of demand. The production plan is “smoothened” and made more flexible for changes in production. (Thomas & McClain, 1993, pp. 338-339)

In production planning there is usually a limiting factor that limits the production to a certain volume. The limit can be factory floor space, equipment capacity or workforce limits. These fixed resources sometimes have to be expanded in order to make the production optimized. (Thomas & McClain, 1993, p. 333)

Depending on the type of production, increase or decrease of production is solved in either changing the production capacity or using inventory and backorders to smoothen the changes or as a combination of the two. Production increase and decrease can be seasonal which means that the production volume changes between time periods. The production volume change can also be continuously increasing or decreasing. Often cost tradeoffs are considered. A cost tradeoff can be for example increase of production by overtime or extra shifts versus warehouse costs of backorders or extra inventory. (Thomas & McClain, 1993, pp. 338-339)

2.1.2 Traditional tools for production planning

Different types of charts and figures have been used in production planning for many years. L.J. Thomas & J.O. McClain (1993) show two graphical representations for displaying and comparing different production plans. In figure 1 the production capacity requirement and different production plans capacity are presented cumulatively across the planning period. From the figure it can be seen that the production capacity is sufficient if the cumulative requirement curve is below the capacity curve. The closer the required production capacity curve is from the planned production capacity the better. The advantage of this graph is that several different production plans can be compared and it is easy to see the differences of each plan. The downside of this graph is that the production volume amounts for each period are hard to read. In figure 2 a bar of the demand, production and inventory are presented for each period. From this graph it is easier to read values shown, but comparing different plans is difficult because each plan would require at least two separate bars.

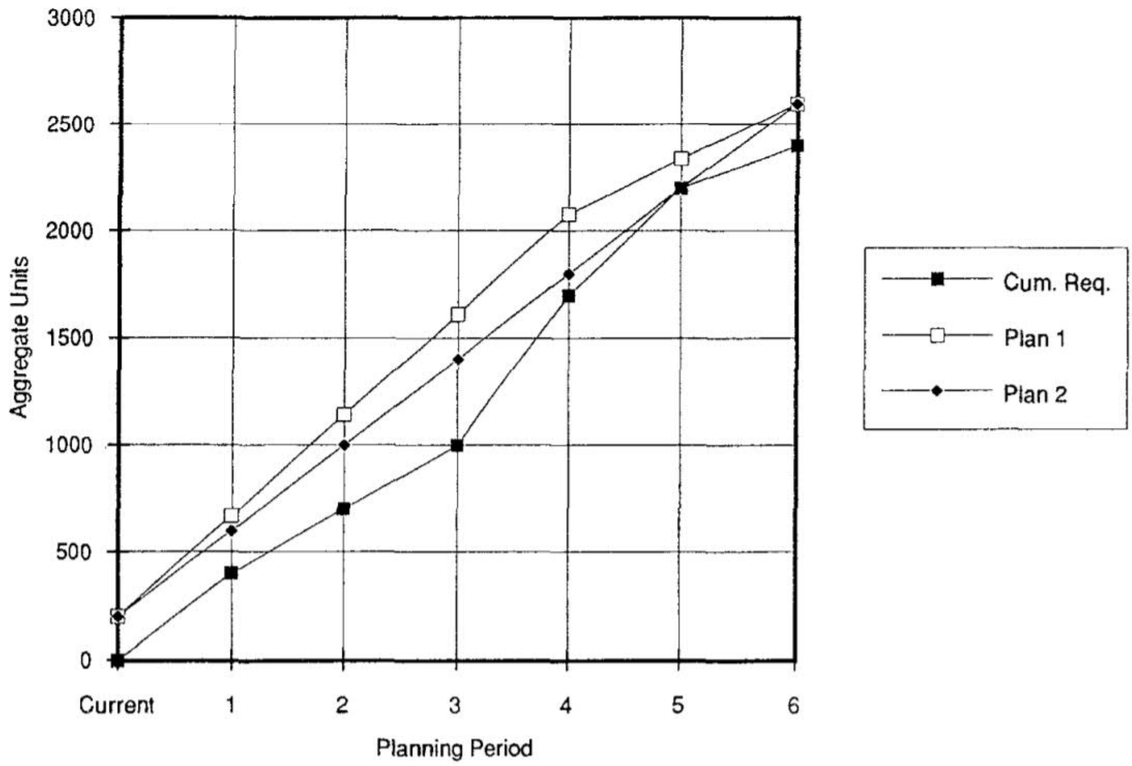

Figure 1. Cumulative requirements. (Thomas & Mclain, 1993)

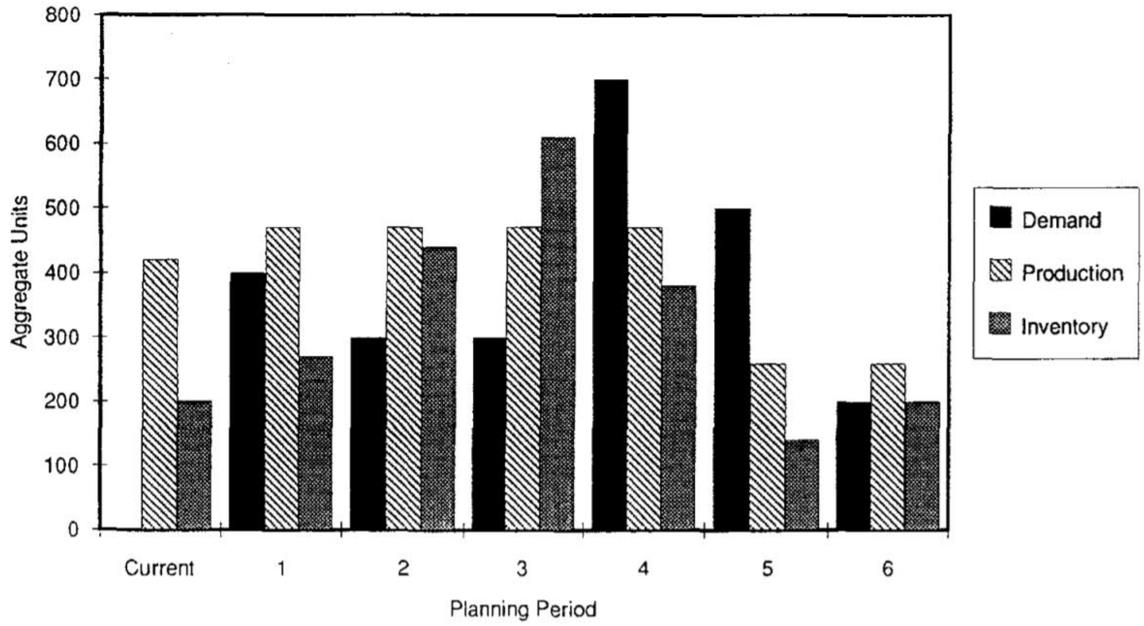

Figure 2. Periodical requirements. (Thomas & Mclain, 1993)

L.J Thomas & J.O McClain (1993) state that both graphs in figure 1 and figure 2 are better suited for presenting different production plan options rather than tools for more in depth analyzing.

One of the most notable visual tools used in production management is the Gantt chart. The Gantt chart is named after its developer Henry Gantt. Gantt chart is a bar chart that is used to illustrate a production schedule. In the Gantt chart tasks are illustrated in the vertical axis and the time in the horizontal axis. According to Polakov W. and Trabold F. (1922) the Gantt chart is a useful tool for management to make decisions by predicting the future by examining what has already happened in the past. A basic Gantt chart represents the workhours allocated to operations and the actual time used for performing the operations. The Gantt chart can also illustrate which operations are performed concurrently and which operations need to be finished before the next operation can be started. The Gantt chart shows the idleness of operators and machines and reasons why. From this information the problems that lead to idle time can be identified and corrected. (Polakov & Trabold, 1922)

At the beginning of its utilization the Gantt charts were drawn by hand and had to be redrawn when updated. In figure 3 a hand drawn machine record Gantt chart is shown. In the chart daily operation of different machines is shown as the thin vertical lines. The line shows how much of the planned daily work was done. The cumulative work done is shown with the thicker vertical lines. The letters in the chart indicate the reason for the idle time of the machine. For example, in figure 3 R represents repairs and P represents lack of power. Similar charts can be done for different resources and operators.

Nowadays electronic Gantt charts can be updated frequently. Usually in modern more frequently updating charts the progress of operations is visualized in percentages and current time is shown in the chart as a horizontal line. This enables easy visual tracking of how well on schedule the operations and the whole production is.

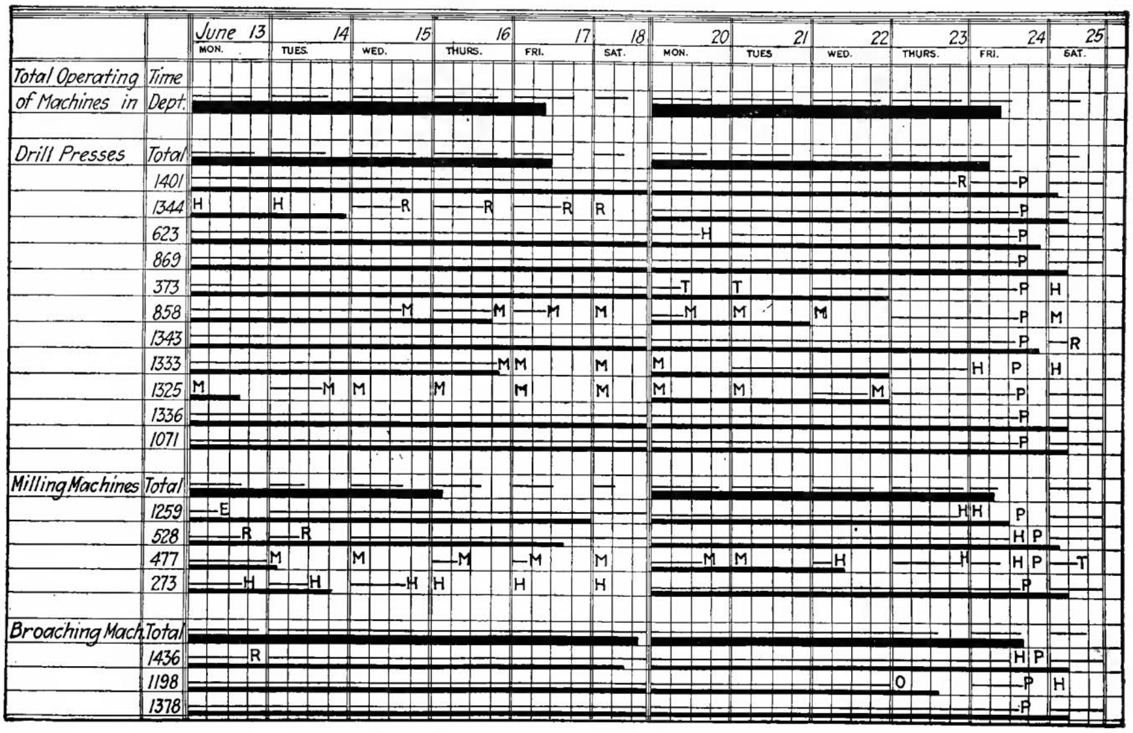

Figure 3. Hand drawn machine record Gantt chart. (Polakov & Trabold, 1922)

PERT (Programming and Evaluation Review Technique) chart is an arrow diagram that is used to plan the order of production steps. Similar diagrams and charts are still utilized in more modern production planning tools along with other visual tools. In figure 4 a PERT chart is shown where the numbered boxes represent events and the arrows between them represent activities. The number above the arrows are the amount of time units needed to complete the activity. The event is completed when all the activities related to it are completed. PERT chart is useful tool in finding the critical path of the production. In figure 4 the critical path consisting of events 2,6,10 and 11 is highlighted with thicker arrows. (Bock & Holstein, 1963, pp.10-12.)

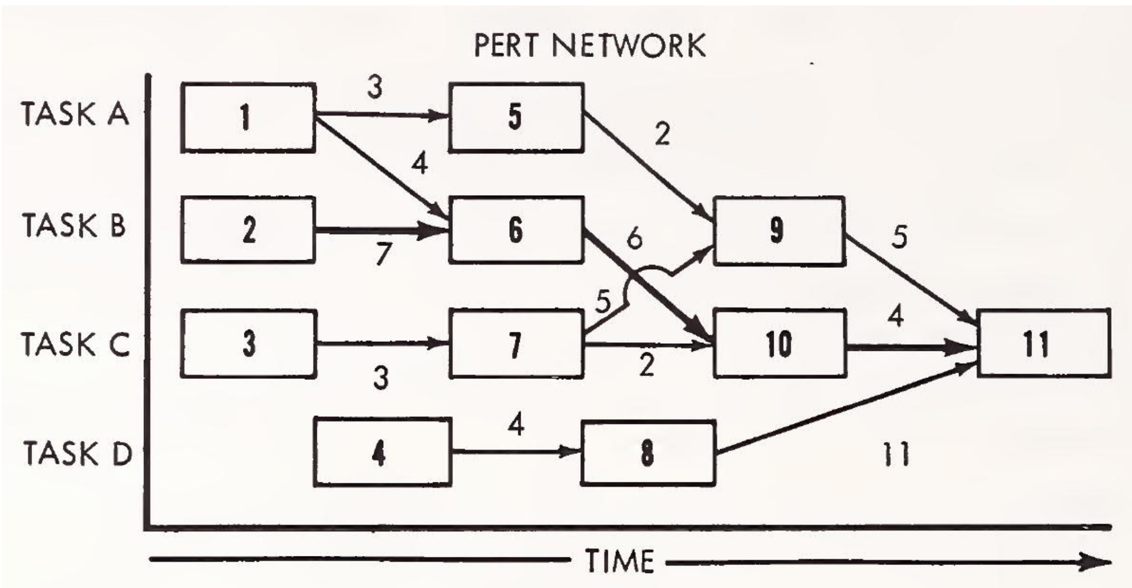

Figure 4. PERT chart. (Bock & Holstein, 1963)

2.2 Manufacturing process planning

In his book Groover (2010) defines manufacturing from economic and technological point of view. The technological definition of manufacturing is that material is threated with different chemical and physical processes to change its properties. Manufacturing is also a sequence of operations where a product is assembled with different tools. The processes and operations step by step transform materials into products. The economic definition of manufacturing is that materials are turned into products that are refined and more valuable than the original material, and thus manufacturing creates wealth. In figure 5 both technical and economic definitions of manufacturing are visualized. On the left a simplified path from raw material to refined product is displayed and on the right the value added in the manufacturing process is visualized. (Groover, 2010, pp. 3-4.)

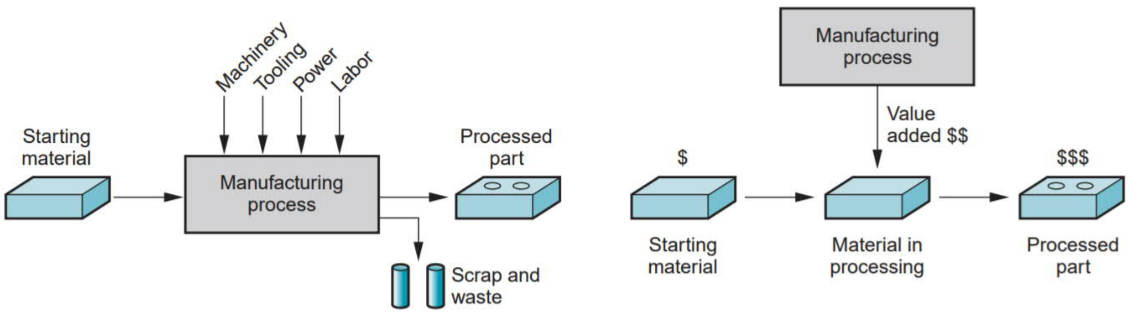

Figure 5. Manufacturing as technical and economic process. Groover (2010)

According to Groover (2010) the term manufacturing compared to production implies more specific processes. Term production is used in broader way when describing the making of products.

Manufacturing industries can be divided to primary industries, secondary industries and tertiary industries. Primary industries such as mining, agriculture and forestry use natural resources to provide raw materials for the production of products. Secondary industries use the raw materials by refining and manufacturing products. Products can be categorized by dividing them to consumer goods and capital goods. Consumer goods are products that consumers buy directly. Cell phones and clothes are an examples of common consumer goods. Capital goods are products that are used to provide services or to create more refined products. For example, aircraft and machine tools are capital goods. In addition to finished products, components and materials such as steel bars, sheets and electrical components are also manufactured items that are used when assembling products. Tertiary industries are services such as healthcare and commercial field. (Groover, 2010, pp. 4-5.)

This study focuses on secondary industries such as ABB Pitäjänmäki factory. Also, this study focuses on manufacturing planning for assembled products instead of processed goods manufacturing planning.

Production quantity is an important factor when considering manufacturing planning. Production quantity can be divided to low, medium and high production. Annually in low production 1 to 100 units are manufactured, in medium production 100 to 10 000 units are manufactured and in high production 10 000 to million units are manufactured. Product variety is another important factor that affects the manufacturing planning. Product variety is not as easy to determine as production quantity as the differences between different products can be minor or major. Manufacturing planning for high quantity and low production variety is very different from low quantity and high product variety production. (Groover, 2010, pp. 5-6.)

In ABB Pitäjänmäki motors and generators production can be thought as low volume and medium variety manufacturing. In some cases, the production can be even considered high variety manufacturing due to tailor made machines.

Manufacturing capability describes the manufacturing limitations and possibilities the factory has. The limitations can arise from technology available, the dimensions of the product and the facilities and from the production capacity available. Technological capabilities describe the available processes and manufacturing methods available in the factory. Technological capability also includes the expertise and knowledge of the factory staff. The size and weight of the manufactured product cause limitations to the production. Large and heavy products require more floor space and are also harder to move around the factory. Small products can also require floor space and can be challenging to move around if the production quantity is high. The manufacturing equipment must also be sufficient compared to the product size, which affects the manufacturing capability. Production capacity limits manufacturing capability by indicating the maximum number of units that can be produced in the factory for example in a year with normal operation of the factory. (Groover, 2010, pp. 6-7.)

In ABB Pitäjänmäki the manufactured products are large and heavy, which causes limitations to the manufacturing capability. The production capacity limits the manufacturing capability of the factory as the number of units manufactured in a year is relatively small. Technically the manufactured products are demanding and manufacturing requires special equipment and knowledge of the staff.

Manufacturing process consists of operations where step by step the raw material is changed to a more valuable product. Groover (2010) divides operations to processing operations and assembly operations. Processing operations alter the physical or chemical properties of the material and add value to it. Machining and heat treatment are examples of processing operations. Assembly operations join two or more material pieces together to form an assembly or subassemblies of the product. Assembly operation can be performed for example by welding or using fasteners. In figure 6 processing operations and assembly operations are divided into more detailed manufacturing steps. (Groover, 2010, pp. 10-15.)

In ABB Pitäjänmäki final assembly process assembly operations are mainly performed. Some processing operations such as surface cleaning operations and heat treatment are also performed.

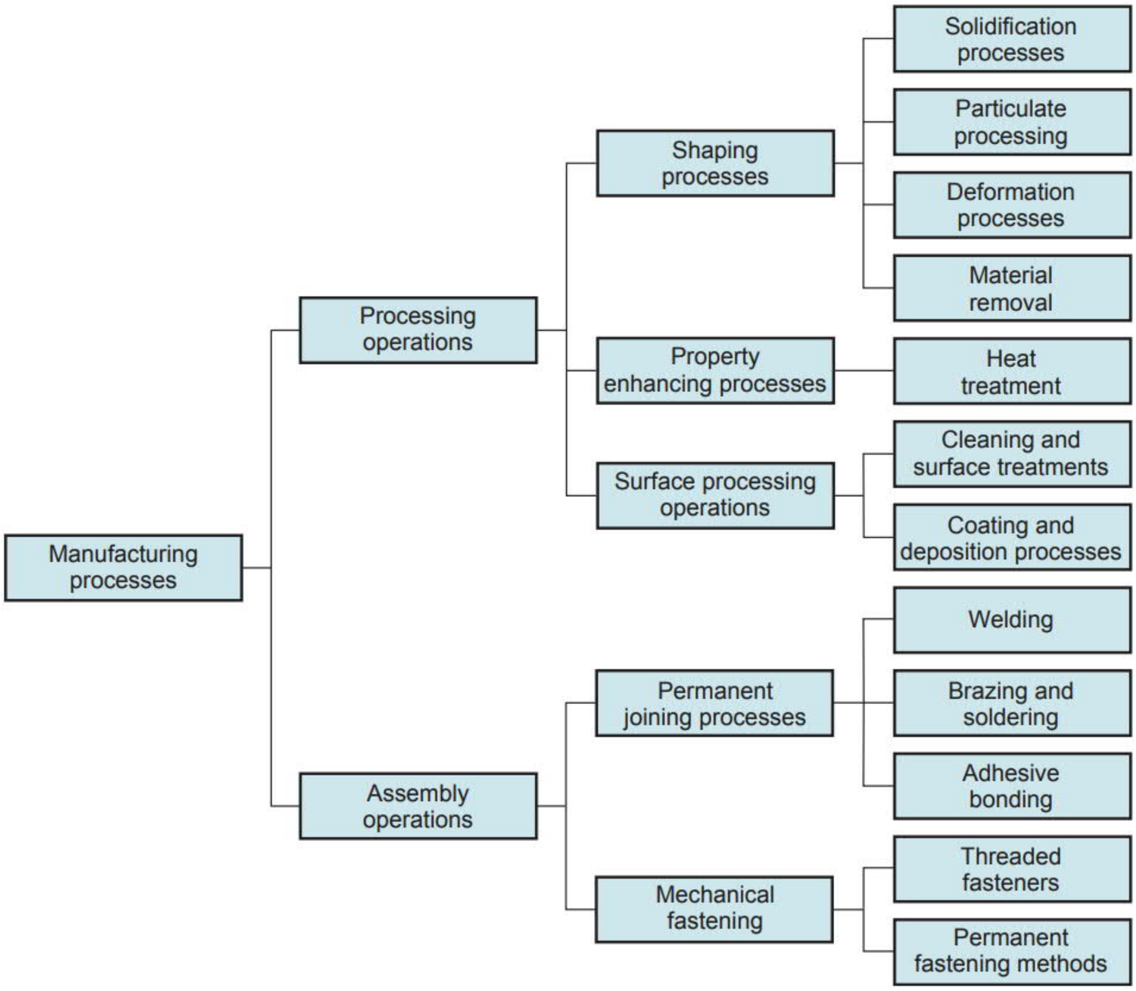

Figure 6. Manufacturing processes and operations. (Groover, 2010)

Production facility layout has to be taken into account when planning the manufacturing process. The factory floor layout depends on the production volume and variety. In low quantity production term job shop is used to describe the factory layout. A job shop is used to manufacture complex and heavily customized products. Usually the products are large and therefore the product is often stationary and the materials, workers and tools are moved to the product in the manufacturing process. In medium production volume batch production or cellular manufacturing can be used. Batch production means that the factory layout is planned according to the batch that is manufactured. The whole factory layout is changed when different type of product batch is manufactured. Batch production is used when the product variation is large. When the product variation is smaller the cellular manufacturing can be used instead. The manufacturing cells are planned so that products with small variation can be manufactured without excess time losses. In high production volume production lines and quantity production is used. Quantity production means manufacturing of a single part using a single equipment. Quantity production can be performed for example in cellular layout. Production line consists or multiple workstations and the product is moved from workstation to another. Production lines can be used for manufacturing of identical products and also products with small variations. Automotive industry manufacturing is an example of a production line where there are slight variations in the manufactured products. (Groover, 2010, pp. 16-19.)

In the facilities different combination levels of automated work and manual work done by the operators exist. Groover (2015) divides them to three categories: manual work systems, worker-machine systems and automated systems. Manual work systems have only workers performing tasks with only manual tools. For example, assembling with hand tools. In worker-machine systems the tasks are performed by a worker and some powered manufacturing tool. Examples of worker-machine systems are assembly lines where workers perform tasks in the workstations or a worker operating a lifting device. In automated systems tasks are performed by automated machines. The level of automation is divided to semi-automated and fully automated by Groover (2015). Semi-automated systems need some human interaction during or between cycles. Fully automated systems can operate an extended period of time without human control or supervision.

In ABB Pitäjänmäki factory the final assembly has a job shop based layout which is suitable for the low volume production of large and challenging products. The facilities in the final assembly area are a mixture between manual work system and worker-machine system. Automated tasks are not performed in the final assembly of large electric machines.

2.3 Factory modelling and simulation

A typical factory consists of many different areas of operation or subsystems. These subsystems can be for example a manufacturing system, a business system and a communication network system. Virtual factory can be considered as a simulation model of all these subsystems. With this model a real factory can be imitated. The virtual factory can be used as a kind of a test bed for the real-life factory. (Jain S. et al., 1995)

Different approaches to virtualization of the factory exist. Some focus on the visualization in a virtual reality environment and others focus on the simulation of the whole factory systems. Jain S. et al. (2001) divides four different definitions of virtual factory and expands them in his more recent study (Jain, 2014). Virtual factory can be thought as a simulation of a real factory, a virtual organization, a virtual reality representation or an emulation facility. A simulation of a real factory consists of all subsystems of a real factory and considers the factory as a whole. It provides data to support decision-making. A virtual organization definition of virtual factory links multiple real factories in different locations. A network of different processes and manufacturing phases of a product is generated. A virtual reality representation of a factory is a 3D representation of the factory facilities and the different processes in a virtual reality environment. This 3D environment can be used for visualization, simulation, design and communication. In their paper Kelsick J. & Vance M. (1998) built a 3D model of a factory in virtual reality environment. Their biggest challenge was the limited computational power, which led to limited model and texture quality. Nowadays the computational power is much greater and the models and textures can be made more detailed. An emulation facility combines the real world with the 3D representations of the factory. With pictures and other data gathered from the factory, the 3D virtual representation can be enhanced. This can be considered as hardware in the loop simulation where a part of the real system is substituted. (Jain, 2014)

Training and customer tours can also be performed in the virtual reality environment. Back M. et al. (2010) constructed a virtual reality representation of a chocolate development factory. It consisted of 3D virtual environment with 3D and 2D layers of information about the factory. The data in the layers was videos, sensor data, animations and display of 2D documents. Different users of the virtual factory environment from managers to visitors were identified and specific applications and presentations were designed for them. In their study a mobile app was also created to access the virtual reality applications. Ordaz N. et al. (2015) used virtual simulation and training system (VISTRA) to test how assembly workers in the automotive industry could be trained in VR environment. They discovered that people with gaming experience managed to complete the training faster than people without gaming experience. However, the number of mistakes made in the training program were similar between the two groups. Overall, the assembly workers participating to the tests found the VR training useful. Al-Ahmari A. et al. (2016) constructed a virtual manufacturing assembly simulation system (VMASS) that consisted of VR environment with visual and physical feedback to the user. According to the authors the VMASS can be used for manufacturing assembly training and assembly operations evaluation.

Tolio T. et al. (2013) discussed the concept of integrated factory design where different simulation, design and analysis tools were integrated to each other. In their paper problems and current solutions were discussed. They stated that although different PLM software tools integrate different planning tools, more is needed to meet the demands of the industry in terms of integration and interoperability. In more recent study (Jain S. & Lechevalier D. 2016), an automated generation of virtual factory model was studied. In their work the logic network and the 2D layout of the factory were generated automatically based on CMSD (Core Manufacturing Simulation Data) file information gathered.

Ivson P. et al. (2018) developed a visualization system for virtual construction planning for large constructions in AEC (Architecture, Engineering and Construction) industry. In their visualization system sequencing of tasks was integrated in the 3D visualization with a PERT/Gantt chart view. This helped the designing of large constructions such as oil & gas plants where many different systems and operations sequences exist.

Jain S. et al. (2001) state that virtual factory can be used to support continuous improvement. In Figure 7 the process is explained in more detail. In the figure virtual factory is used to evaluate proposed changes before they are implemented to the real factory. The improvements are implemented to the real factory. Data is collected from the real factory to evaluate if the improvements apply to the real factory.

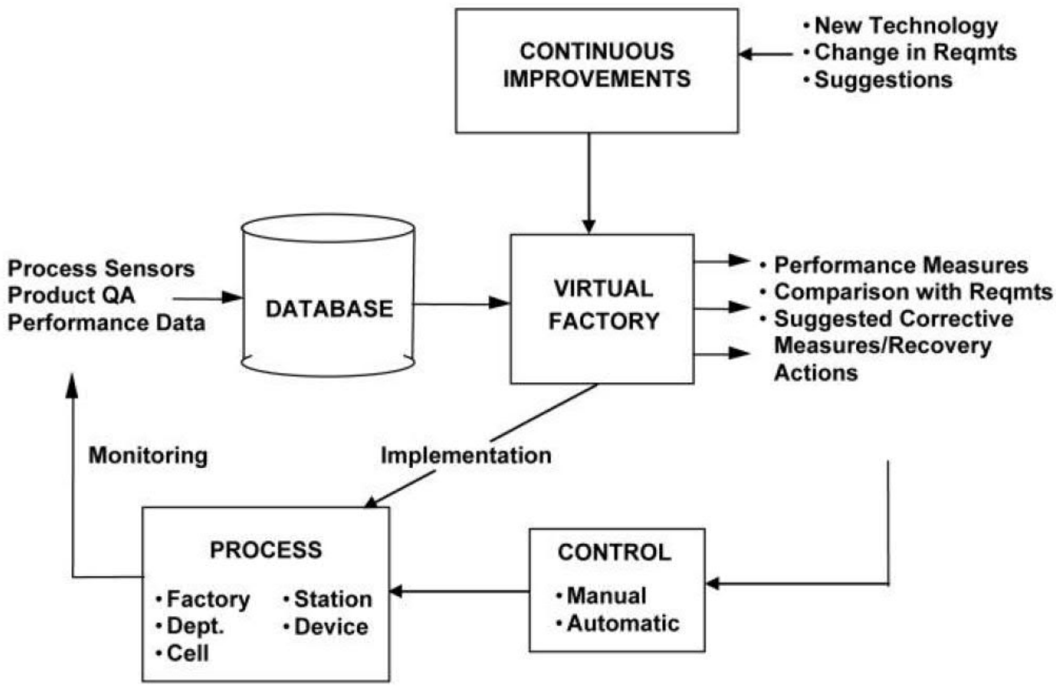

Figure 7. Virtual factory in implementing continuous improvements. (Jain S. et al., 2001)

2.4 Virtual tools in manufacturing planning

In this section virtual reality concept is defined and literature review of virtual manufacturing tools basics and state of the art is presented.

2.4.1 Virtual reality

Oxford dictionary defines virtual reality (VR) as "The computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors." Virtual reality is a virtual representation of a real world.

Different levels of real and virtual world combinations exist. The scale goes from real world to combination of real and virtual worlds to only virtual world. Virtual reality can be considered a continuum from real environment to the different levels of virtual environments. Milgram et al. (1994) first introduced the term reality-virtuality continuum that describes the path from real environment to completely virtual environment as in Figure 8. Between completely real and completely virtual environments are different levels of mixed realities. Mixed reality (MR) can be categorized to augmented reality and augmented virtuality. Azuma et al. (2001) defines augmented reality (AR) as a real environment where virtual and real objects are combined and aligned interactively in real time. This definition can be adapted to describe augmented virtuality (AV) as a virtual environment where virtual and real objects are combined and aligned interactively in real time.

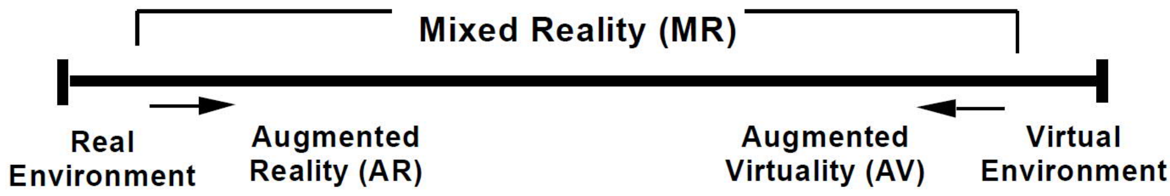

Figure 8. Reality-Virtuality Continuum. (Azuma, 2001)

2.4.2 Virtual manufacturing

Lin et al. (1995) define virtual manufacturing (VM) as use of computer aided design tools such as models and simulations of manufacturing processes to aid in product design and manufacturing design. Virtual manufacturing can be divided into three different areas of focus. Virtual manufacturing can be design focused, production focused or control focused. Virtual manufacturing provides tools for design of products and tools for production and process planning. It also allows simulation of the control process to evaluate the product design, production design and process planning. (Lin et al. (1995)

Khan W. et al. (2011) have a broader definition for virtual manufacturing that concentrates on production design: "Virtual manufacturing (VM) is considered to be an augmented reality (AR) environment exercised to enhance all levels of control in a discrete or continuous manufacturing system. Virtual manufacturing objects include both tangible and intangible functions of production, including manufacturing, costing, process planning, scheduling, quality control, and management information system." Virtual manufacturing can be considered to include both product design and production design in a virtual environment.

Virtual design can be considered as design work that is done in a virtual environment. Often the term computer aided design (CAD) is used to describe it. "Computer aided design (CAD) can be defined as the use of computer systems to assist in the creation, modification, analysis or optimization of a design." (Narayan et al. 2008. p3.) CAD is based on interactive computer graphics (ICG) where user communicates and commands the computer through inputs. With these different commands user can create 2D drawings or 3D part models and assemblies. (Narayan et al. 2008. p3-4.) Main advantages gained from CAD are identified as:

- Improved productivity of the designer.
- Improved quality of the design.
- Improved documentation for better communication.
- Improved documentation and data for manufacturing.

The productivity is increased because CAD software reduces the time for conceptual design drafting and analysis. CAD also shortens lead times considerably, which means that the time between customer order and delivery of the designed product is reduced. The design process is more flexible and design errors are reduced. The design is more easily analysed and changes to the design are easier to make. (Narayan et al. 2008. p17-18.)

Computer aided engineering (CAE) can be considered as a tool to analyse CAD geometry. CAE tools include finite element analysis (FEA), multibody dynamics (MBD), computational fluid dynamics (CFD) and optimization tools. Vermaak H. & Niemann J. (2015) used Delmia manufacturing planning and simulation software to simulate the movements and operations of a configurable manufacturing system. The simulating was validated with a real-life system.

In their study Mujber et al. (2004) discussed different VM applications and evaluated the advantages gained from them. In product design the advantages of design and prototyping in VR were mentioned of being the improved visualization of the product. Use of VR also enables the whole design team to work in the same environment and therefore the interaction between designers is improved. Also, the use of virtual prototypes instead of physical ones is more flexible and less time consuming. The number of prototypes needed is also usually smaller. VR provides benefits to different operations such as planning, simulation and training. In VR people with different areas of expertise can easier participate in the planning process and the understanding of the plans is improved. In simulations VM makes validation, verifying and understanding the results easier due to better visual presentation. Training in VR is beneficial as it allows the trainer to practice in a lifelike environment without risking themselves or the equipment. In VM assembly and disassembly verification is improved and for example collision detection can be done. (Mujber et al. 2004.) These advantages lead to overall higher quality of the manufactured products. The production costs are lower and changes to the production are easier and faster to make.

Brown R. (2000) uses a term digital manufacturing when describing virtual manufacturing planning. He states that especially companies with low production and complex products can benefit from digital manufacturing tools. The reason is the savings to be made by reducing the time to market. The assembly time of very complex and large products can be reduced with better manufacturing planning and analysing of the production process. The goal is to do the learning process with the virtual product beforehand in order to save time in the actual manufacturing process of the product.

Virtual manufacturing has mostly been used in automotive industry, aerospace industry and healthcare domain (Bharath & Patil, 2015). Gradually VM is becoming more common in other more traditional industries. In their paper Lawson et al. (2016) interviewed Jaguar Land Rover employees about the benefits and limitations of VR in automotive design and manufacturing. The VR technologies the employees use are the Cave Automatic Virtual Environment (CAVE), a dynamic simulator and a motion capture suit. The main use for VR is to evaluate and inspect the visuals, design and vehicle architecture. VR is also used to review driving position, ergonomics analysis and to study access to different parts of the vehicle such as tanks containing fluids. The main limitations according to the employees were problems with depth perception, a lack of weigh indication and force feedback, limited collision feedback and lack of hand motion tracking accuracy. Another study (Ordaz N. et al., 2015) done with the automotive industry focused on testing the VR training of factory operators. In this training program a welding station of a truck chassis was simulated in VR. The results showed potential in VR training although some limitations were also reported.

2.5 Current design process and tools in the company

In this section current product and production design processes and tools in ABB Pitäjänmäki are introduced. This study focuses on production planning but knowing the current design process for the product is important when evaluating possible benefits from the production design tools.

In the left side of figure 9 a simplified design process of the machines before the final assembly process is described.

2.5.1 Product design

Mechanical designers, electrical designers and partly the R&D department are responsible for the motor and generator design in ABB Pitäjänmäki. The electrical design of the machine starts when the sales department has completed a deal and gathered the initial information of the requirements of the machine from the customer. The electrical design consists of designing the connection diagrams and performing various calculations about the electrical properties of the machine. The mechanical design is started when electrical design of the machine is ready. The duration of the mechanical design can vary from a few hours for stock machines to over 1000 hours for highly customized challenging machines. The basic tasks for the mechanical designers that affect the production of the machine are creation of manufacturing drawings, part lists and purchase orders of the components of the machine.

The main mechanical design tool consists of CAD software that is integrated to PDM (Product Data management) software. Currently two different CAD software are still used simultaneously in the mechanical design department and in R&D because of a recent switch of CAD software. The migration from the older I-DEAS software to the new NX software is an ongoing process in the design department. The PDM software TeamCenter is integrated to both CAD platforms. The purpose of product data manager is to track and control the data of the product. The data can be for example a list of the components, drawings and other documents. PDM also supports change management, workflow management and project management. (Crnkovic et al., 2003) In electric machine design PDM is mainly used for managing the product structures and change management of the design data. The design data consists of items that can be for example different materials, standardized stock parts, or 3D designed custom parts of the machine. A structure of the product is formed from these items and from the structure all part lists of the product can be generated. PDM is also used to track the changes in the product design by revisioning of the items. The PDM software is connected to resource planning software SAP, where the product data is transferred for example when purchase orders of the machines parts are made.

Most of the modelling and designing of the motors is done with NX. However, some generators are still designed with I-DEAS due to only minor changes in the older reference projects. Currently a detailed 3D model of the whole product is made for some of the motors. For the “stock” generators there are standard models of the whole machine that are updated when changes occur in the design. Many generator designs are done without proper 3D models of the whole machine. This is possible because of automated structure creation of the product. This tool picks the right components for the machine. The designer’s task is often to check that the structure is correct and make some modifications to the product structure if there are special requirements from the customer.

In addition to CAD and PDM, designers use calculation templates made for specific calculations involving the mechanical design of the machine. Designers have also many instructions at their disposal made for different components and areas of the machine. The instructions are updated when changes occur and outdated instructions are not used. ABB Pitäjänmäki has their own internal standard codes for materials, standard components and manufacturing methods in addition to international material and manufacturing standards.

2.5.2 Production design

SAP ERP (Enterprise Resource Planning) software is used in production planning in ABB. In ABB Pitäjänmäki production planners use MRP (Material Requirements Planning) to schedule a machines production. The broad scheduling of the production phases of the machine is done alongside the designing of the machine.

A separate manufacturing engineering team is responsible for manufacturability checks of the machines. After the mechanical design of the machine is ready a manufacturability review meeting is held with the designer and the assembly workers. The purpose of the meeting is to check if the machine design has entities that may cause problems in the final assembly process. Assembly workers are also present in the manufacturability meetings to give their input to the designers about possible problems in production of the designed machine.

Detailed planning of shifts and worker schedules is done by the production managers. The production managers have the best knowledge of the current state of the factory floor. They know which machines are in which work area and the detailed scheduling of the machines in order to meet the required delivery time.

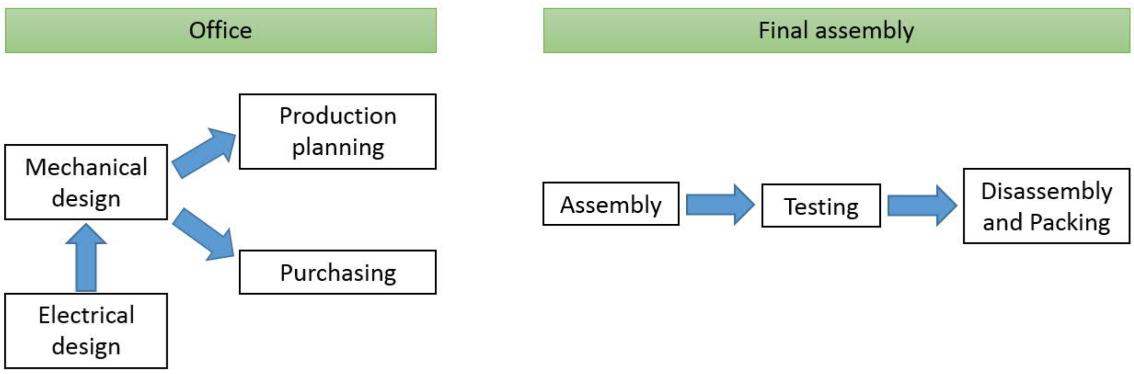

Figure 9. Simplified representation of electric machines product creation process.

2.6 Final assembly process

The final assembly of the machines is done in Pitäjänmäki factory in Helsinki. The final assembly process can be divided to assembly, testing, disassembly and packing of the machine. Detailed planning and scheduling of these phases is a key to streamlining the final assembly process and accelerating the delivery cycle.

In the right side of figure 9 the simplified final assembly steps performed after the machines design phases are shown.

2.6.1 Assembly

The main components of the electric machines are the stator and the rotor. These two components are prepared separately and are assembled together in the final assembly area. The frame machining of the stator is subcontracted and delivered to the factory. Winding of the stator core is done in the factory and the wound stator core is welded to the stator frame in the factory floor. Shaft forging and machining is subcontracted and the machined shaft is delivered to the factory. Rotor manufacturing that includes winding of the poles and attaching the wound poles to the shaft is done in the factory. The assembled rotor and stator are assembled in the final assembly area by inserting the rotor assembly inside the stator core. The aligning needed to assemble the rotor and stator components makes the process difficult and time consuming. In the case of vertical pump motors, the rotor position is vertical instead of horizontal. Therefore, the rotor must be lifted in place inside the stator core. The lifting of the rotor is challenging because of the length and mass of the assembled rotor. Special tools and simulations needed to be made beforehand to ensure that the lifting was possible.

Other main components of the machine assembled in the factory are bearings, cooling units, fans, cover plates, exciter, main terminal box and auxiliary terminal boxes. The cabling is also done in the factory final assembly. Many of these smaller components need preliminary preparation and they can be thought of as subassemblies of the main assembly process.

Most of the components are so heavy that cranes are needed to move the parts around the factory. This makes the planning of crane usage a key feature because of limited number of operable cranes in the factory. Also, smart utilization of floor space of the assembly area is the key to reducing the assembly time.

2.6.2 Testing and inspection of machine

The testing of machines is done in the test field area in the factory floor after the assembly phase is completed. At the beginning of the testing visual inspection for the machine is performed. The purpose of the visual inspection is to check if machine has any visible defects. The inspection is done according to internal inspection record instruction that lists all the things to be inspected. For example, bearing clearances, perpendicularity of the bearing housing and the tightening torque in the bearing cap are inspected.

Before any cables are connected to the machine insulation resistance measurements are performed. The purpose of insulation resistance measurements is to test that insulations between frame of the machine and components such as windings, connections, brush gear, bearings and other parts are in good condition. Low values of insulation resistance indicate that the insulation is defected, for example moist or damaged. Insulation resistances are measured twice, before any cables are connected to the machine and any test runs are performed. Measurements before the test runs ensure the safety of the machine during the high voltage test runs. The measurements are repeated right after the test runs to verify the final condition of the machine. (P-instruction, P-00773 Insulation Resistance Measurement)

The machines test runs are performed by rotating the machines with testing motors attached to the machines shaft. During the test runs of the machine measurements are performed for the temperature rise, moment of inertia, efficiency and vibrations. Test runs are done with different rotation speeds in order to test that the machine capable of operating in the intended range. After the test runs insulation resistance is measured again. After all the tests are performed the testing equipment is disassembled.

2.6.3 Disassembly and packing

After testing the machine is disassembled and prepared for shipment. The disassembly and packing process depends on the size of the machine. The machine is disassembled and shipped in smaller pieces if it is too large or heavy to be shipped as a whole. For the lager motors, it is common to ship the rotor and stator separately to the customer. Disassembly of the machine is basically done in reverse order compared to the assembly phase. The packing of the machines and the components is subcontracted. The subcontracting company designs the packages and packs the machine components in the factory packing area. Wooden boxes and tarpaulin are usually used as packing material. The lifting and fixing points of the machines and the components are designed by ABB employees.

3 Research material and methods

In this chapter the research material and methods are presented. The bearing assembly of the pump motors is introduced. Two manufacturing process planning tools are studied by using the bearing assembly as a case study example. The manufacturing process planning tools are also compared to each other in this chapter.

3.1 Bearing assembly of the pump motors

In this section the design and the assembly process of the bearing assembly of the vertical pump motors is introduced.

3.1.1 Design

The bearing assembly of the pump motors is located on top of the vertical machine in the N-end (non-drive end) of the machine. The bearing used in the pump motors is a radial bearing, which means that the bearing can only withstand radial loads. The bearings in the customer´s pumps take care of the loads in the direction of the axis of the shaft. In figure 10 the main parts of the bearing assembly are presented. The bearing assembly studied with the production planning tools consisted of:

- Vertical guide bearing.
- Bearing shield.
- Brush unit assembly.
- Water piping for cooling of the bearing.
- Slip ring assembly.
- Fixing plate.
- Cover for the slip ring and brush gear.
- Terminal box.

The bearing is attached to the bearing shield, which is attached to the frame of the machine. Slip ring assembly is located above the bearing in the end of the shaft. Slip ring is used for transmitting current to the rotating shaft with the brushes assembled around the slip ring. The brush unit assembly consists of the attaching plate and the supports for the brush gear assembly. Velocity transducers for the shaft rotational speed measuring are also attached to the fixing plate with supports. The pulse rings used for the measuring are located under the slip rings assembly. A cover for the slip ring and brush gear assembly is located at the top of the machine. Terminal box assembly is attached to the side of the cover.

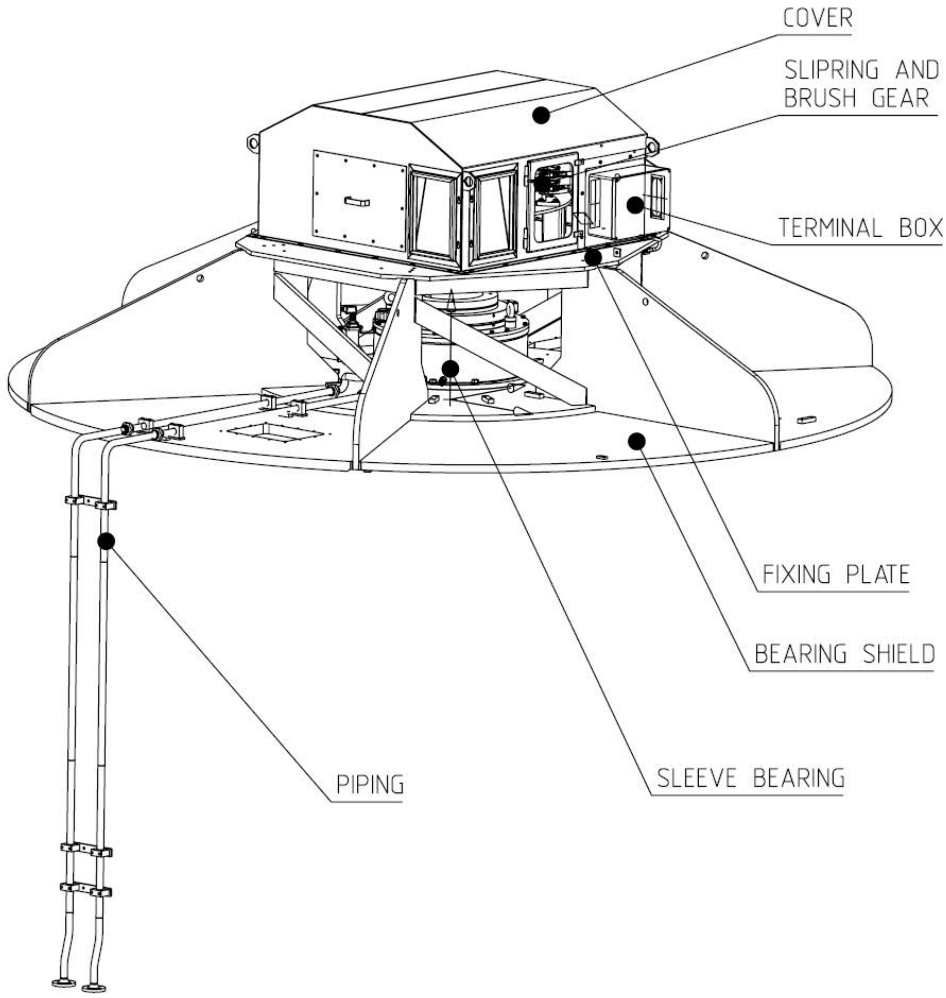

Figure 10. Main parts of the studied bearing assembly.

3.1.2 Assembly process

The main assembling of the bearing assembly for the pump motors is done at the assembly area and at the test field area. Before that the slip ring cover and the terminal box are pre-assembled on the assembly area. At First in the assembly area, the bearing seals are fitted to the shaft. After that the bearing shield is lifted and attached to the frame. The bearing is assembled and attached to the bearing shield. The fixing plate for the slip ring and brush gear is assembled. The slip ring and the brush gear are built on top of the fixing plate. The cover for the bearing assembly is assembled and fitted on top of the slip ring and brush gear.

After the testing is done for the machine the bearing assembly is disassembled and the rotor is lifted out for separate packing and shipping. After the rotor is removed the bearing shield is attached back to the top of the stator. The slip ring and the brush gear attached to the fixing plate are assembled back on top of the bearing shield. The slip ring cover with the terminal box is also attached on the top of the machine for packing. In figure 11 a simplified assembly process for the bearing assembly is shown.

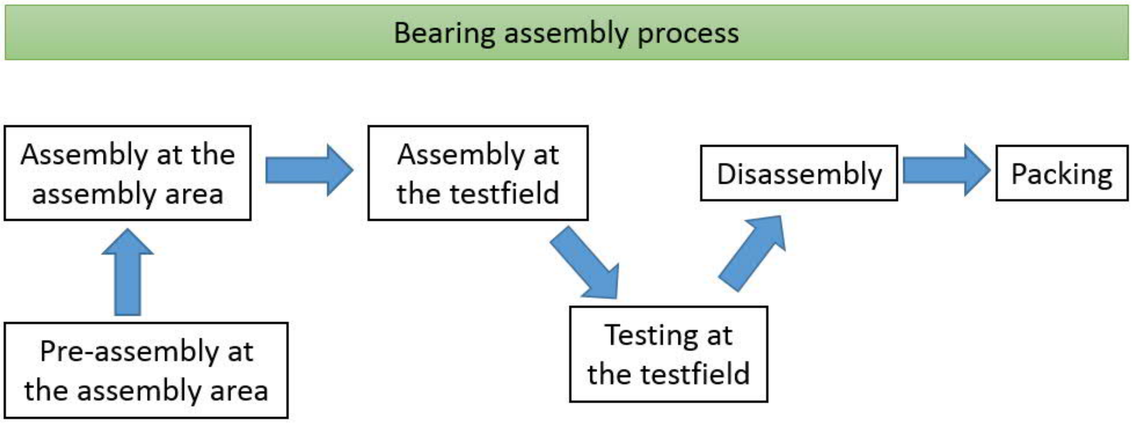

Figure 11. Simplified Assembly process of the vertical pump motor bearing assembly.

3.2 Bearing assembly study with production planning tools

Bearing assembly of the vertical pump motor was used as a case example in this study. Assembly model appearing in a real life application was used to test the features of the production planning tools to get a better understanding of the possibilities and shortcomings of the tools. Following steps were implemented in both production planning tools:

- Importing the engineering structure.
- Creating the manufacturing structure.
- Creating the resource structure.
- Creating the process structure.
- Allocating and balancing resources.
- Evaluating the assembly.
- Creating the work instructions.

3.2.1 Delmia

Delmia is a Dassault Systemes digital manufacturing software that is part of their 3DExperience platform. Delmia has many virtual design, manufacturing, process and operations management tools available. (Delmia Digital Manufacturing Fact sheet, 2018) In this study Delmia virtual manufacturing and process planning tool was studied and tested. The tool was also compared to another manufacturing and process planning tool called TeamCenter Manufacturing Process Planner.

Importing the product data to Delmia

First the 3D model and the EBOM (Engineering Bill of Material) of the bearing assembly structure was imported to the Delmia system. This was done by exporting the 3D model of the bearing assembly from NX CAD software. After that the exported 3D model was imported to Delmia software with an import tool. The import keeps the same structure of the 3D model as it is in the NX software.

PPR context

PPR (Product, Process and Resource) context contains all the data about the product, process and the resources in Delmia. The PPR context contents can be explored and opened with Manufacturing Context Builder command in Delmia.

Manufactured item definition

With the imported bearing assembly engineering structure, a MBOM (Manufacturing Bill of Material) was constructed by using Manufactured Item Definition tool in Delmia. A product is usually designed slightly differently compared to how it is manufactured so the MBOM is required for planning of production of the machine. First the manufacturing assembly was linked to the imported product structure. After that the MBOM was created by constructing a manufacturing structure. In Delmia different types of building blocks are available when constructing the MBOM. The basic building blocks are a manufacturing assembly block and a provided part block. The manufacturing assembly blocks are used for assemblies and subassemblies and they contain one or more provided parts. Provided parts consume products when parts from the EBOM are allocated to them. Provided parts have implemented link to the consumed products. In figure 12 manufacturing assembly blocks and provided part blocks are shown.

Other possible building blocks to use in MBOM structure creation are transform, fasten, remove material, manufactured part, manufactured material, manufacturing kit, manufacturing installation, continuous manufactured items and disassemble blocks. Transform blocks are used to describe actions that do not involve adding or removing of parts. For example cleaning, painting or inspection of parts can be included to the MBOM with transformation blocks. With fasten block fasteners can be consumed from the EBOM. Fasten block has implemented link to the consumed fasteners. Remove material blocks can be used for example to insert machining or drilling operations to the parts of the MBOM. Manufactured part block implements a design part and realizes a manufactured part that does not belong to the EBOM structure. Manufactured material block creates a part that has no connection to the product structure. Manufacturing kit provides a set of items that are needed for the next assembly step. Manufacturing installation block manages the installation of components to a larger assembly. Continuous manufactured items are materials that have quantities such as mass, length, volume or area. With this block the usage of stock materials can be described in the MBOM. Disassembly blocks can be used to disassemble or remove parts from the assembly. Disassembly block can be also used for reassembly of parts.

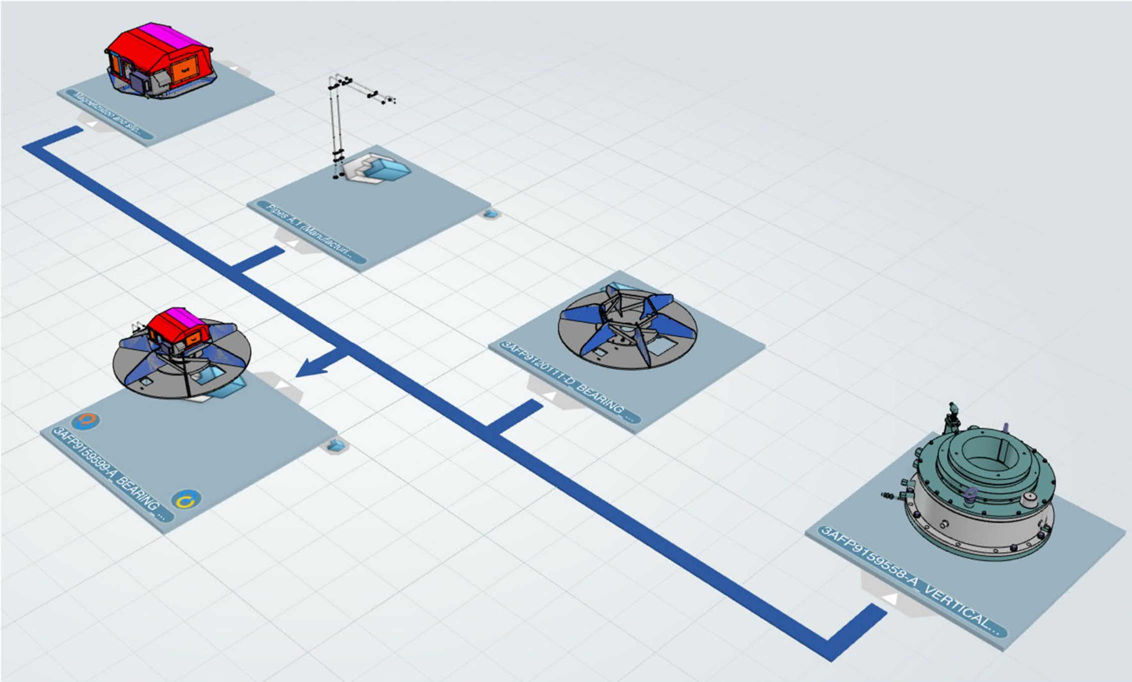

Figure 12. MBOM building blocks visualization in Delmia.

Products are assigned to the MBOM from the EBOM. In figure 13 the link between the product structure and the manufacturing assembly is shown. In the figure manufacturing assembly A is linked to product structure A and parts of the product A are assigned under manufacturing assembly A and its subassembly. Additional Links are also possible to create at lower levels of the structures to identify which manufacturing assembly parts produce which part of the product. In the figure subassembly B is linked to manufacturing subassembly 2 and product subassembly parts are allocated under manufacturing subassembly 2.

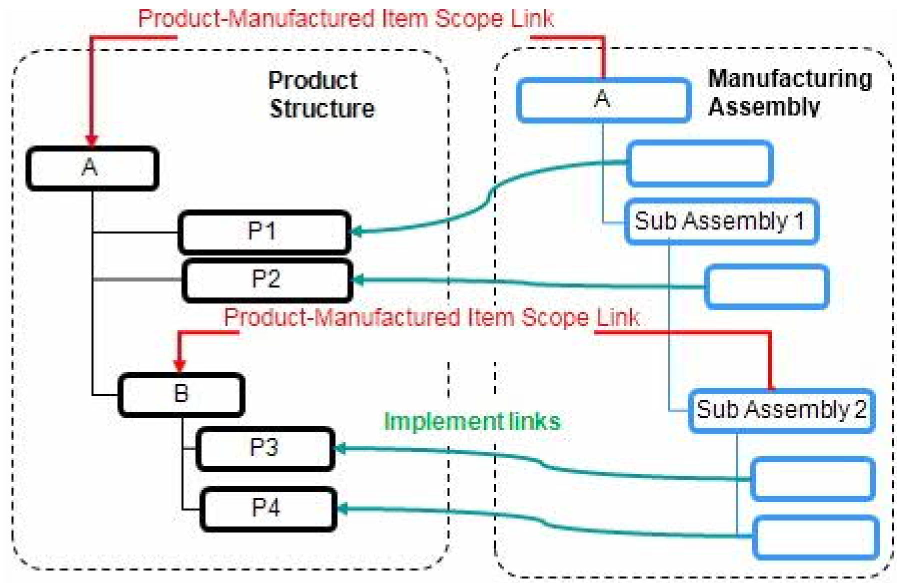

Figure 13. Product-Manufactured item scope. (Dassault Systemes 3DEXPERIENCE user assistance, 2018)

Allocation of product consumes the product and creates a link between the consumed product and the block that the part is assigned to. The link ensures that the data of the assigned part is carried over from the product to the MBOM. This includes the positioning of 3D model in reference to the main assembly. This enables the use of visual representation of the manufacturing assembly. The allocation can be done by dragging and dropping parts from the 3D model view or from the structure tree of the product. It is important that all the components in the EBOM are assigned to the MBOM and consumed. B.I. (Business Intelligence) Essentials tool is useful for inspecting the assignment status of the parts in EBOM. When B.I essentials tool is enabled, parts in the EBOM structure become colour coded based on their assignment status. With B.I. Essentials tool different information about the objects in the assembly structure can be inspected.

The manufactured item tool in Delmia displays the MBOM in a 3D representation where the consumed and linked parts of the EBOM are shown. A traditional hierarchy tree representation of the MBOM is also shown. These two representations give the user more options on how to build the MBOM. The visual representation of the MBOM is useful especially for people that are not familiar with the products EBOM structure. For example, the MBOM can be more easily created by some other than the designer of the product. On the other hand, the 3D visual representation can be heavy on the computer if the model of the product is large and detailed. The more traditional tree structure enables people experienced with the product structure to create the MBOM faster and more efficiently, than when using the 3D representation of the structure tree.

With 3D View tool a 3D model of the selected assembly or part can be examined in a separate window. Allocations of parts can also be done with the 3D view tool.

The level of detail of the MBOM is up to the user. The structure can be made by utilizing only basic building blocks and assigning all the parts of the EBOM to them. The more detailed the MBOM is the more detailed next phases in production planning can be made.

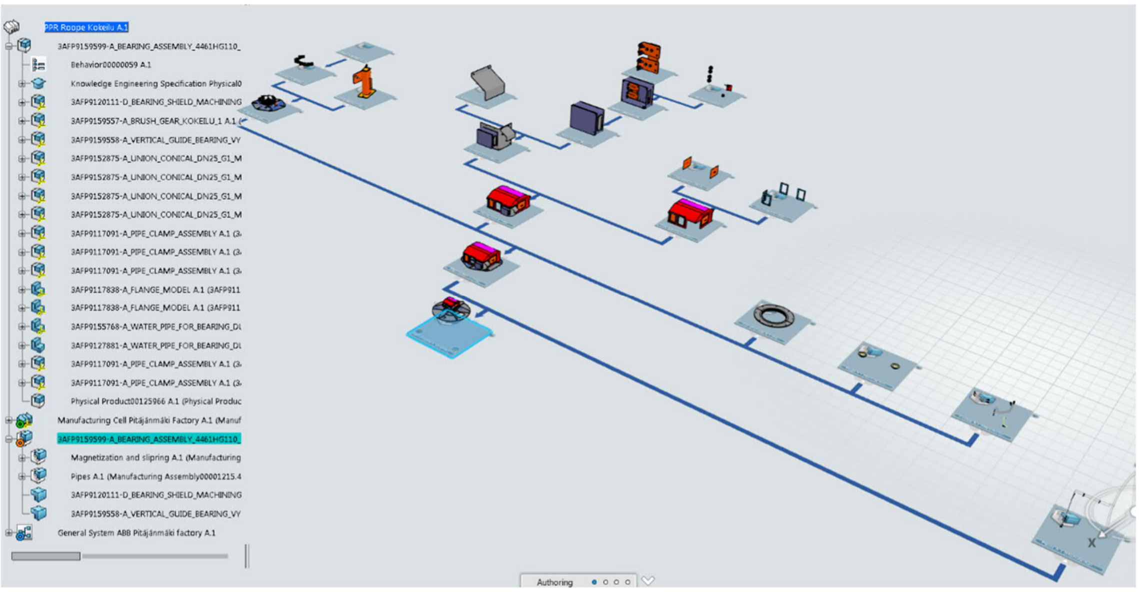

Figure 14. MBOM structure tree and visualization in Delmia.

When constructing the MBOM for the bearing assembly it was realized that using only the basic building blocks was the best method. The MBOM was created by using only manufactured assembly and provided part blocks. The use of other building blocks was tested but no clear benefit was discovered for the studied assembly. One block that might have been useful was the fasten block. However, in the assembly model studied fasteners were not specified as fasteners and therefore it made no difference whether they were allocated to provided part or fasten block. The bearing assembly MBOM was separated to two subassemblies: Piping assembly and magnetization and slip ring assembly. The bearing shield and the bearing were used as provided part to the main assembly. In the piping assembly all the needed parts were allocated. The magnetization subassembly was divided to smaller subassemblies containing: brush gear and slip ring in fixing plate assembly, slip ring cover assembly, top shaft seal assembly, plugs assembly and cables assembly. These were divided to even smaller subassemblies. In figure 14 the visualization of the structure can be seen. From the figure can be seen that slip ring cover assembly and brush gear and slip ring assemblies are divided to even smaller subassemblies.

Process planning

After the MBOM is done, the next step is the process structure creation. Delmia has a process planning tool where a process structure is created and linked to the MBOM. The process structure is created with different system blocks and operation blocks. Systems consist of different operations or subsystems. Systems can be considered as assembly locations or stations. In Delmia the highest level of the system structure is called root system. Root system type is usually general system. Other system types available in Delmia are workplan, transfer and transformation systems. Systems that have no subsystems are called leaf systems in Delmia. Operations inside the systems can be considered as steps needed to construct the assembly or subassembly assigned to the assembly area.

System and manufactured item scope is defined by the link between the system and manufacturing assembly structure. Scope outlines parts of the manufacturing assembly that can be realized with operations and subsystems of the system. In Figure 15 a simplified chart of the MBOM and system scope is given. In the figure, system and manufacturing assembly are linked and manufactured items are realized by operations of the system. Systems and operations can be renamed to make the structure clearer.

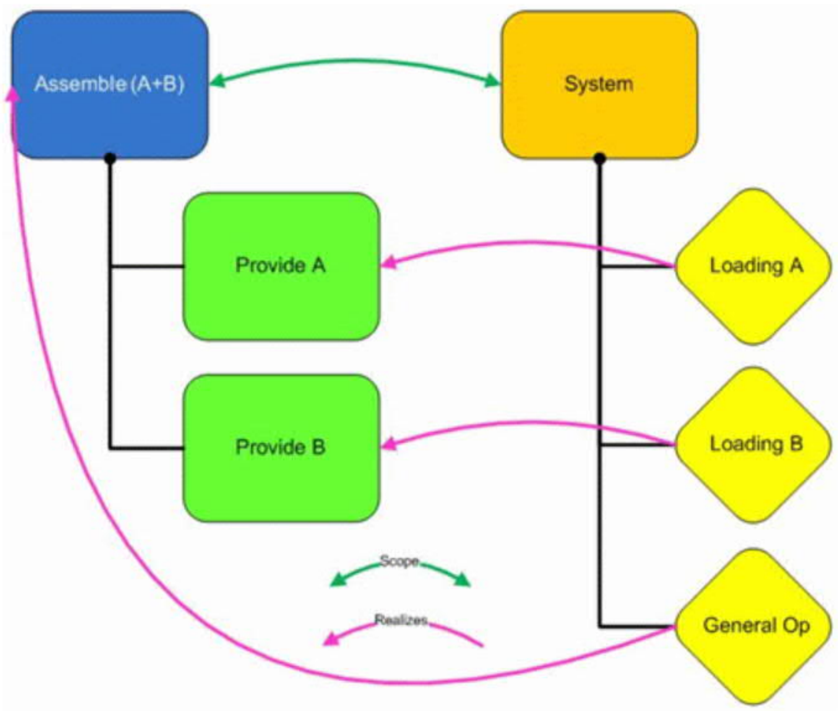

Figure 15. System and manufactured item scope. (Dassault Systemes 3DEXPERIENCE user assistance, 2018)

Manufacturing assembly parts can be allocated to systems in different ways. It can be done by dragging and dropping manufactured items to systems or by creating operations under the systems and linking them to manufactured items. When manufactured items are allocated to systems, operations are created automatically under them. Assigning tool can also be used instead of drag and drop functionality. The assignment status of the manufactured item parts can be inspected with the B.I Essentials tool similarly to analysing product assignments of the EBOM to the MBOM in manufactured item definition. The assigning must be done consistently by respecting the manufacturing assembly and system structures. In figure 16 correct and incorrect ways of assigning manufactured items to systems is shown. P2 and P3 are assigned correctly to systems S2 and S3 but P4 and P1 are assigned inconsistently to S1 and S4, because logically P1 cannot be realized before P4.

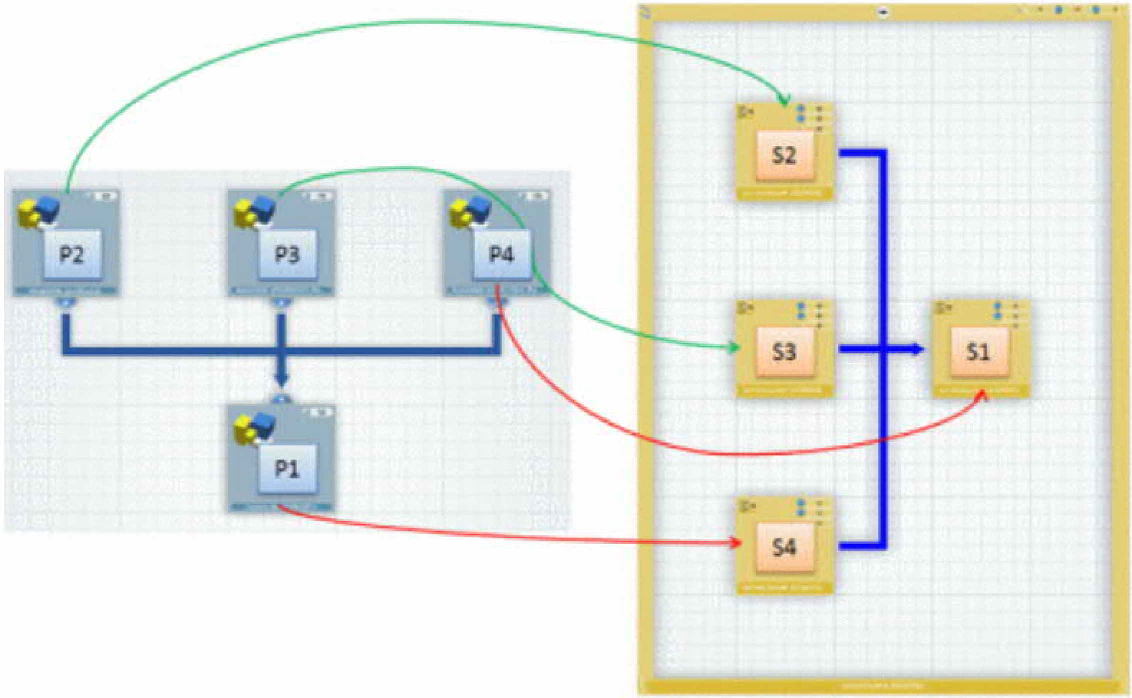

Figure 16. Manufactured item to system assignment in Delmia. (Dassault Systemes 3DEXPERIENCE user assistance, 2018)

After the systems and operations are determined for the process, product flow is determined with product flow tool. With this tool the order of operations performed in a system and the order of subsystems can be determined. Similarly to the manufactured item tool the process planning tool has a visual representation and traditional structure tree of the process chart. The visual 3D model representation of the manufactured product updates according to the product flow determined. For the operations, time constraint links can be created to determine start and end times accordingly. The operations can be for example determined to be started at the same time or to be finished at the same time. The operation can also be determined to start right after the preceding operation is finished or the start of the next operation can be delayed even when the preceding operation has been finished.

In the system properties cycle times can be set. Cycle time is the time needed to complete one cycle of the system. Times are also assigned to operations inside the systems that define the time needed to complete the operation. The duration of the operation can be determined by estimating, measuring, calculating or simulating. Operation time mode options for these options exist in Delmia and the user can allocate the most accurate time available to each operation. Cycle times are displayed in workload balancing panel, manufacturing system Gantt chart and in resource system Gantt chart. Manufacturing system Gantt chart shows the selected system and its subsystems and operations. The Gantt chart also shows the product flow and the times allocated to systems and operations. In figure 17 an example of a manufacturing system Gantt chart can be seen. It displays the duration of the whole system, subsystems and operations as numbers and bars. The beginning time of each operation is also displayed. The product flow can also be seen from the figure as arrows connecting operations and systems.

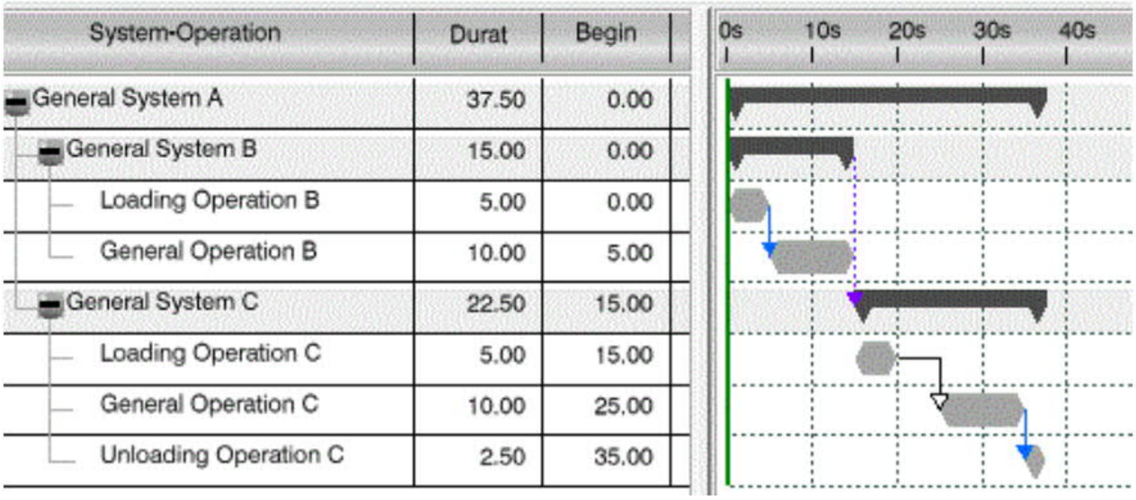

Figure 17. Manufacturing system Gantt chart in Delmia. (Dassault Systemes 3DEXPERIENCE user assistance, 2018)

The bearing assembly process structure consisted of the main Pitäjänmäki final assembly system. The subsystems of the final assembly were the assembly and disassembly in the test field area. The slip ring cover assembly and the slip ring and brush gear assembly to the fixing plate were also considered as separate subsystems. Inside these systems operations were created and manufacturing assembly parts and resources were linked to them. The order of systems and operations performed for the bearing assembly was determined with the product flow tool. Cycle times and operation times were estimated. The process planning structure was created by utilizing manufacturing planning engineer’s knowledge on where in the assembly area the subassemblies are assembled and disassembled. In figure 18 the bearing assembly process structure visualization is shown. In the figure the rectangles represent systems and the diamond shapes inside the systems represent operations. The blue arrows in the figure describe the product flow determined to the operations.

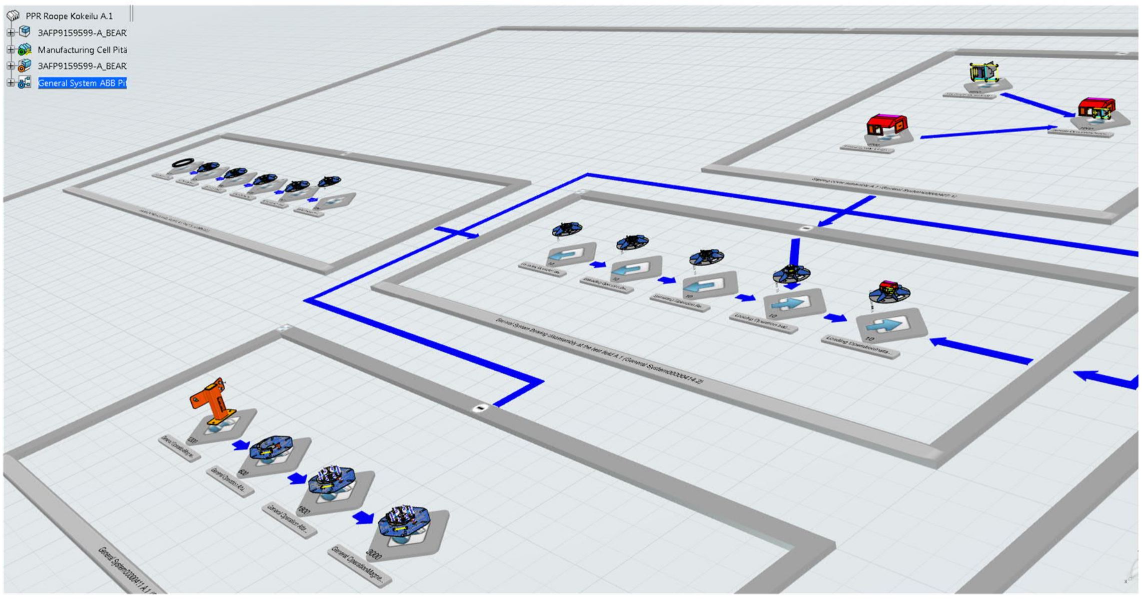

Figure 18. Systems, operations and product flow visualization of the bearing assembly.

Resource planning and factory layout

Resources in production planning can be anything from a machining tool or a workstation to an assembly worker. In Delmia all the resources are structured in resource management tool. With equipment allocation tool a link between the system and resource structure is created. This enables the allocation of resources to different operations in process planning tool. A resource can be for example an area, a robot, a worker, transport or a NC machine. In Delmia the resources are divided between working, non-working and organizational resources. Organizational resources define where the operation was performed. A work area is an example of organizational resource. Working resources define who or what performs the operation and the non-working resources define with what the operation is performed. Working resources are for example robots and workers. Non-working resources can be for example tools or sensors in Delmia. Resources can also be categorized as programmable or non-programmable resources. For example, NC machine is programmable resource and a simple wrench is non-programmable. In table 1 all resource types and the categorization of each resource are presented.

Table 1. Resource types in Delmia. (Dassault Systemes 3DEXPERIENCE user assistance, 2018)

Resource	Category	Logic
Area	Organizational	None allowed. Non-programmable.
Organizational	Organizational	Defined in reference only. Non-programmable.
Robot	Working	Programmable
Worker	Working	Defined in reference or in context; programmable
Transport	Working	Programmable
Conveyor	Working	Non-programmable
NC Machine	Working	Programmable
Industrial Machine	Working	Non-programmable, no contextual logic is allowed.
Inspect	Working	Programmable
Control Device	Working	Programmable
Logic Controller	Working	Non-programmable
Tool Device	Non-working	Non-programmable
Storage	Non-working	Programmable
Sensor	Non-working	Non-programmable
User-Defined	Non-working	Programmable
Manufacturing Setup	Non-working	Non-programmable

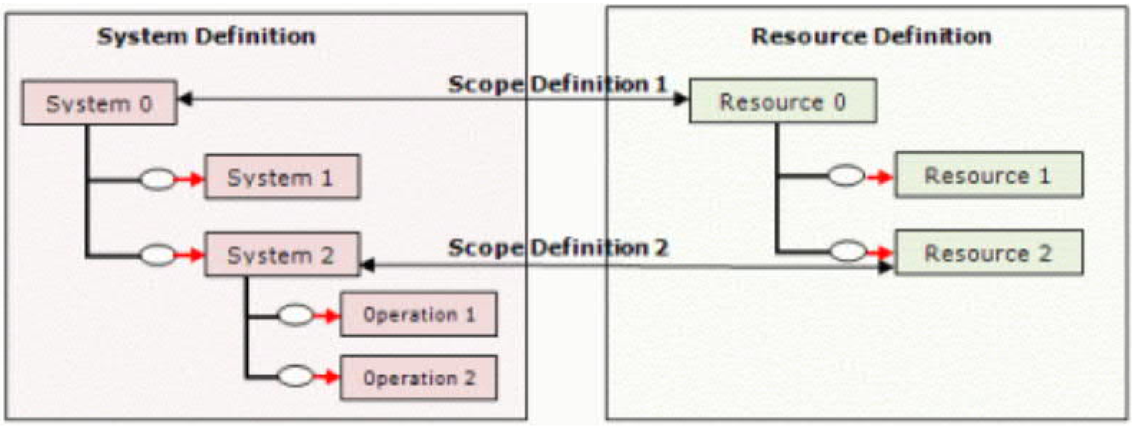

Figure 19. Resource-system scope in Delmia. (Dassault Systemes 3DEXPERIENCE user assistance, 2018)

The scope between resource and system is realized by an implement link between organizational resource and system. In figure 19 Scope Definition 1 link between System 0 and Resource 0 means, that Resource 0 is used in System 0. Possible operations under the System 0 are assigned to resources under Resource 0. Similarly, Scope Definition 2 links System 2 and Resource 2, and operations 1 and 2 are assigned to resources under Resource 2.

Resource utilization Gantt chart is used for inspecting resource and operation connections. Operations can be assigned to resources using the Gantt chart. The information displayed in the Gantt chart consists of a tree view of resources and assigned operations. Star time, end time and duration of operations are displayed. Idle time during which the resources are not used is also displayed. The utilization of a resource is displayed as a percentage of time which the resource is used in operations. Resource balancing can also be done with Delmia by using the Resource Balancing tool. With this tool operations assigned to resources can be inspected and balanced. For example, if some worker has too many operations assigned to them, the excess operations can be reallocated to a worker with fewer operations assigned. The goal is to balance the resources and reduce the idle time of for example a machine or an operator.

For bearing assembly resource planning in Delmia the factory layout 3D model was used. Different resources such as operators, cranes and larger tools were also tested with the bearing assembly.

Assembly evaluation

Assembly evaluation tool is used to analyse the part movements, sequences and manufacturability in an assembly. With assembly evaluation a manufacturing simulation in product, resource or PPR context can be made. In product context only the product is simulated. In resource context the product and the resources are simulated, which means that the simulation of the product build-up can be done operation by operation. Also, other resources such as workers or tools can be simulated along with the product.

In the manufacturing simulation tracks for part movements can be created and they can be organized into an assembly sequence. The part tracks can be anything from moving along the coordinate system axes to spline drawn with freehand. The tracks can be modified by for example changing the length or the angle of the track path. Kinematic tracks can also be created which are used to simulate mechanism movements. Assembly sequence simulates the order of operations in which the product is put together. The sequence can be modified by allocating and rearranging tracks. Editing of the sequence is done with a Gantt chart.

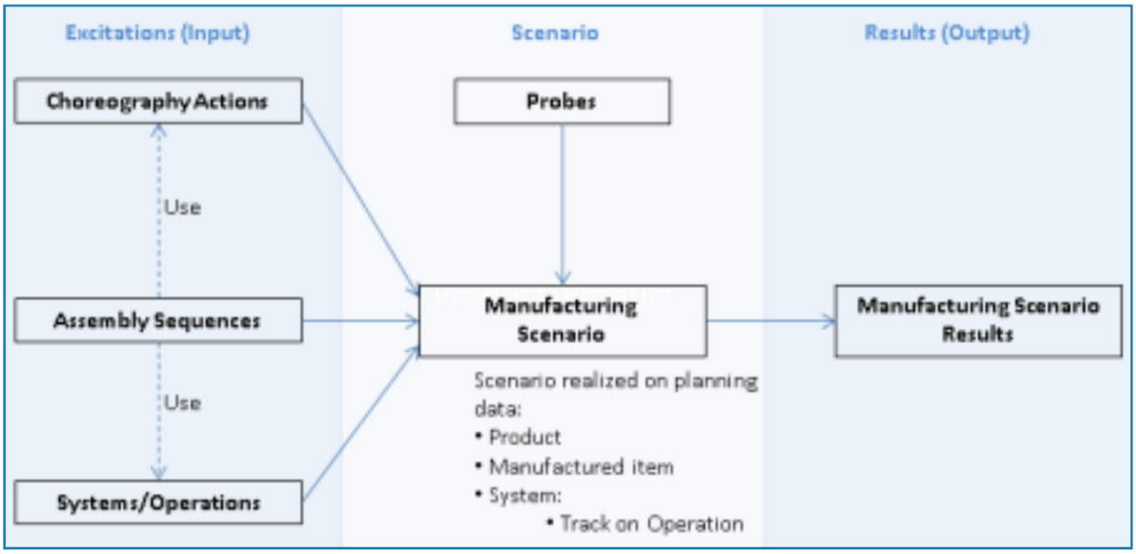

Figure 20. Workflow for assembly evaluation in Delmia. (Dassault Systemes 3DEXPERIENCE user assistance, 2018)

Collision checks can be performed to ensure that the part paths are valid and that the parts do not collide with each other during the assembly. Clearances between parts can also be measured. The paths of the parts can be optimized with path planning tool. The parts paths can be automatically computed to be collision free and optimized. The area in which the track path finding takes place can be defined by applying bounding box or axis rotation limits. Guiding points for the path start end and intermediate points can be determined to quickly find a solution. Individual tracks or whole assembly sequences can be played on the screen and recorded and imported to a video file. In figure 20 the workflow of typical assembly evaluation process can be seen.

With the bearing assembly model the sequencing was tested and an assembly sequence was created by generating individual tracks for parts of the assembly. Different track trajectories were tested from straight lines along coordinate axes to freehand splines. The modifying of existing tracks and the settings were also examined. The tracks were ordered correctly and the sequence animation was recorded. The video file of the sequence was exported but the media created by Delmia was not playable. The collision checking was also tested but despite following instructions the collision check tool did not detect any collisions. Testing was done with intentionally clear collision of two moving parts in an assembly sequence, but the software did not recognize any collisions of the parts.

The benefit for electric machines production design from assembly evaluation is the visualization of the order in which the parts are assembled. Also, the collision checks done with the parts of the machine and with the assembly tools can be useful. For example, inspecting if a wrench can be turned when tightening a screw in an assembly step is beneficial in terms of manufacturability evaluation. Optimizing the exact path of the assembled part on the other hand is not usually required due to the parts being assembled manually. Therefore, simulating accurate paths for parts of the assembly is too thorough approach compared to the benefits gained. Fitting rotor into stator is one exception where precise fitting and pathing is required. However, using Delmia assembly evaluation may not be the right approach in simulating the pump motor rotor fitting because the rotor is lifted inside the stator with a crane. This requires more specific simulations where the crane is included.

Work instructions

The final and probably the most important step in Delmia production planning was creating the work instructions. The work instructions are generated from the process planning steps allocated to the product. All the work done in manufactured item definition and process planning reflect to the quality of the work instructions. The work instructions are done for the operators who assemble the machine and perform all the designed manufacturing steps of the product. Therefore, the goal of the work instructions is to give as much useful information to the assembly workers as possible.

The creation of the work instruction begins by selecting operations for which the instructions are created. A system containing operations or a general operation can be selected. A selected operation sequence is displayed as if it was a film. Products implemented to the operations are shown as stamps in the pictures of the operations. From this operation sequencer individual operation can be activated and the products implemented appear in the work area. Also, already created work instructions for the operation are shown.

Work instructions can contain textual instructions, snapshots of 3D models of the product, linked documents, part lists and manufacturing drawings. For textual instructions a very basic text editor is available. Warning texts, data collect instructions and sign of requirements textual instruction types are also available. A name and information text can be added for all textual instruction types. Pre- made documents and instructions can be linked to textual instructions. This enables to include for example customer instructions for ordered parts or already made ABB internal work instruction documents.

3D Views for the operations can be created in addition to the textual instructions. The views of the 3D models in work instructions are highly customizable. Different parts of the assembly can be highlighted with different colours or made transparent for more visual information. Texts and pictures can be added to the views for further information about the operation. Sections can also be created for cross section views of the parts and assemblies. The parts in the assembly can be moved and exploded views can be created. This is especially helpful when visualizing many parts intersecting each other. Labels of the part names and item codes can be added to the views. Measurement and tolerance visualizations can also be used to use in the 3D views. The visualization tools should be used so that the images of the 3D assemblies give as much useful information to the assembly workers as possible. In figure 21 an example of 3D view created with Delmia is shown. In the view parts are exploded, labelled and highlighted with different colour. A good practice found for the 3D views was to use three images to display a parts assembly to main assembly. In first image the assembled parts are displayed. In the second picture the location and the path of the assembled parts in the main assembly are shown. In the last picture the assembly with the assembled parts is shown.

In the work instructions resources and factory layout can be used to inform and visualize the assembly operation to the operator. The tools used for the operation or the location where the operation is to be performed can be shown.

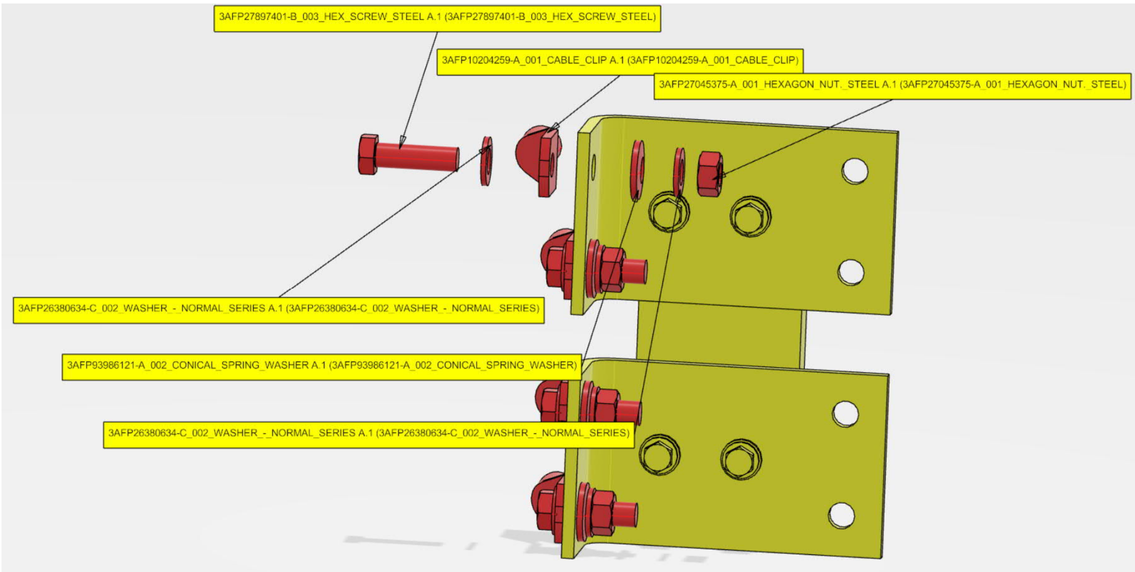

Figure 21. Example of work instruction view in Delmia.

Formatting of the work instructions is done by modifying default XSLT (Extensible Stylesheet Language Transformations) and XML (Extensible Mark-up Language) files. Formatted work instructions can be created and reviewed in the work instruction tool. The formatted work instructions can be published and then viewed with a web browser. The published instructions contain all the assembly processes created in process planning of the assembly. The work instructions in the processes contain all the textual and visual instructions allocated to the operations inside processes.

For the bearing assembly studied, work instructions were created for the operations. Textual work instructions and attaching documents were tested and proved to be an effective method of inserting drawings, part lists and standardised instructions to one location for the assembly workers to inspect. 3D product views were created and different visualization features were tested. The work instructions were presented to the assembly workers for feedback.

3.2.2 TeamCenter Manufacturing Process Planning

TeamCenter MPP (Manufacturing Process Planning) is Siemens PLM software tool for manufacturing planning. The tool is used to plan the manufacturing process of a product by utilizing visualization in managing operations, resources and other variants. (TeamCenter Manufacturing Process Planner Fact Sheet, 2018)

Importing the structure

The studied bearing assembly structure was transferred to the TeamCenter MPP test environment. All the TeamCenter data of the bearing assembly was transferred to the test environment. The data included different object types such as combo items with a 3D model and a drawing, items with only a 3D model and items without any 3D data such as material items.

Some parts of the transferred bearing assembly structure data caused problems in the visualization of the assembly. For example, the bearing shield had an item for the machined part and for the welded part. Both items had a 3D model and thus there were two similar 3D models of the bearing shield on top of each other in the bearing assembly structure. Another visual problem caused by the transferred structure was that some material items also had a 3D model which caused unwanted models of steel plates to appear in the visualization of the bearing assembly. The visualization of TeamCenter MPP uses JT-files of the 3D model objects. For some of the imported objects the JT-file dataset was missing which caused the 3D model of the assembly to be imperfect. Also, some object models were placed incorrectly in the assembly because of some corruption of the JT-files.

In figure 22 the 3D models of material items can be seen as plates floating in illogical places. Also, the two 3D models of the bearing shield on top of each other can be seen in figure 22. In figure 23 a terminal box assembly model with missing parts and incorrectly placed parts are shown. In manufacturing process planning 3D data of the parts is needed for the visual planning and instructions. To make the visualization clearer unwanted 3D models were removed from the bearing assembly structure.

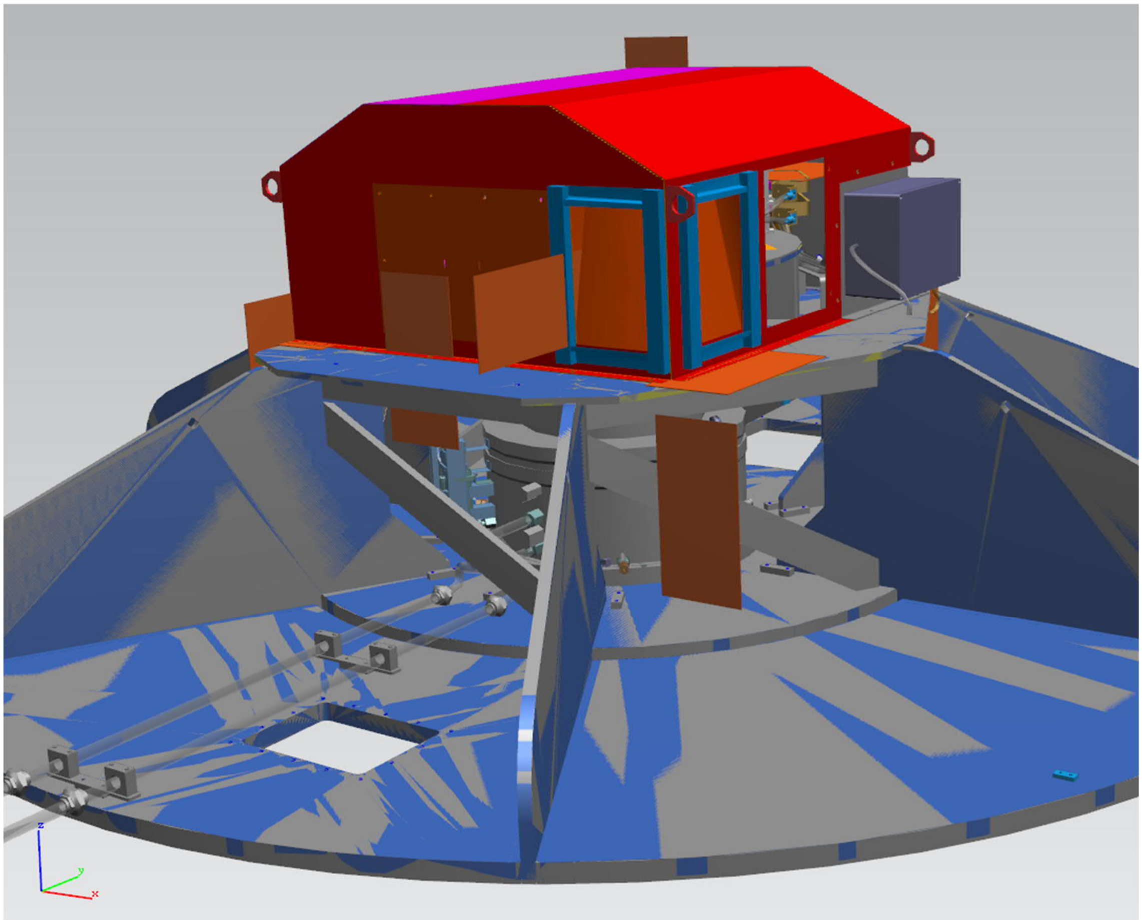

Figure 22. Visualization errors of the bearing assembly structure.

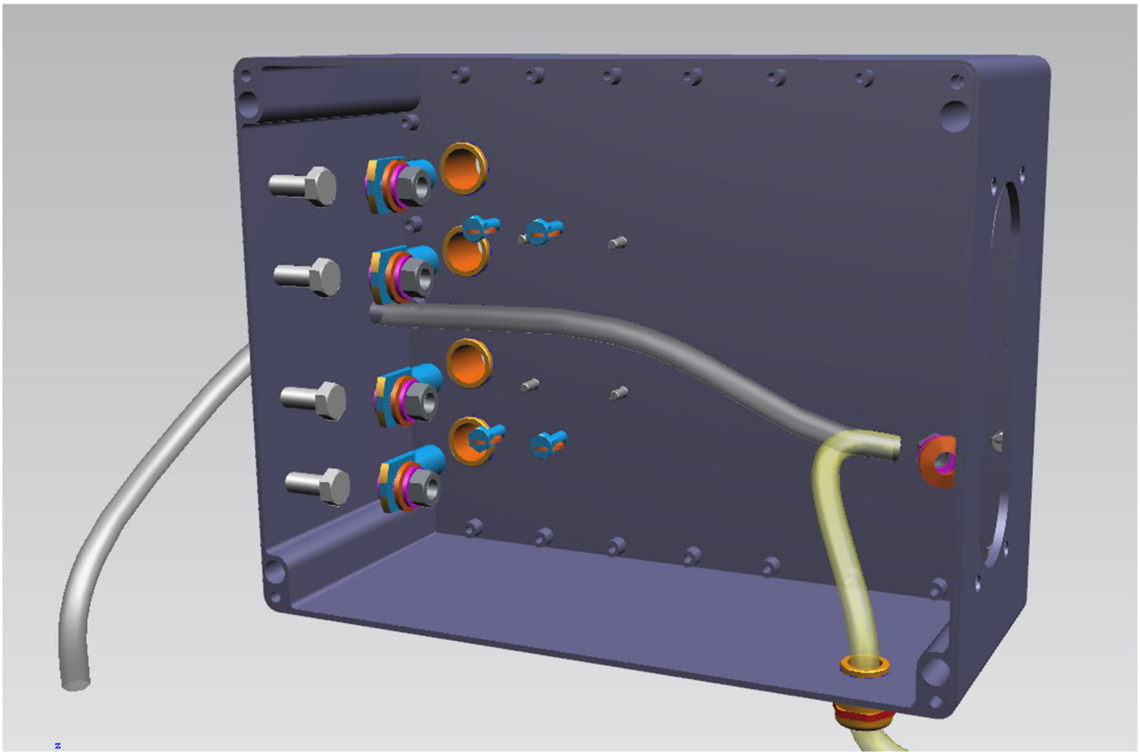

Figure 23. Visualization errors caused by missing or corrupted JT-files.

Collaboration context

Collaboration context is used to save a collection of data about the product, resources and the process in TeamCenter MPP. Collaboration context tree view is used to control the objects in the collaboration context. Collaboration context can be thought as a kind of main project file that contains all the information about the manufacturing process. Collaboration context consists of one or more structure contexts and a configuration context. A structure context can contain for example a BOM and configuration context contains for example revision rules and other configurations that affects the object in the structure tree. The collaboration context can be created with a top-down or with a bottom-up method. In top down method an empty collaboration context and structure context is created and objects are gradually added to the structure context. In bottom up method desired objects are first created or searched and then saved as structure contexts and the structure contexts are then saved to a new collaboration context. In figure 24 collaboration context tree of the bearing assembly testing is shown.

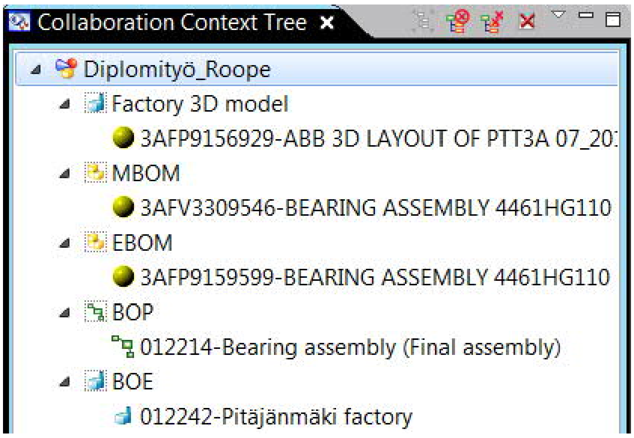

Figure 24. Collaboration context tree.

Manufacturing bill of material creation

The first step in TeamCenter manufacturing process planning is to create an MBOM from the EBOM of the structure. At first a product context is created to the collaboration context for the EBOM structure and for the MBOM structure. The imported product structure is placed to the EBOM product context. The main structure of the MBOM can be created to the MBOM product context with different items. The EBOM and MBOM are linked together by linking their root structures. Parts from the EBOM are assigned to the items created to the MBOM. The linking of the root structures ensures that the assigning of parts from EBOM to MBOM creates a link. The parts assigning can be done by dragging and dropping or by copying and pasting the parts. The parts can be selected either from the structure tree or from the 3D visualization of the structure.

It is important that all the parts of the EBOM are consumed in the MBOM structure. A tool called accountability check can be used to examine the assignment status of the EBOM parts. The tool shows with colour coding if the parts are assigned or unassigned to the MBOM. Also, multiple assignments and partially assigned parts are shown with different colours. The accountability check tool makes the MBOM evaluation easier. If part of the EBOM is modified, the changes are also realized in the linked part in the MBOM. However, if parts of the EBOM are changes the link to the MBOM breaks and the new part has to be assigned again. Accountability check can be performed to find broken links between EBOM and MBOM items.

For the studied bearing assembly similar MBOM structure was created as in Delmia. The base structure of the MBOM was created with ABB Combo items and the objects from the EBOM were assigned to them. The assignment status of the objects was inspected with the accountability check feature.

In figure 25 visualization of the bearing assembly EBOM and the MBOM is shown. The upper views show the EBOM structure and the lower views show the MBOM structure. The visuals can be used to find parts, assign parts and to inspect and compare the structures.

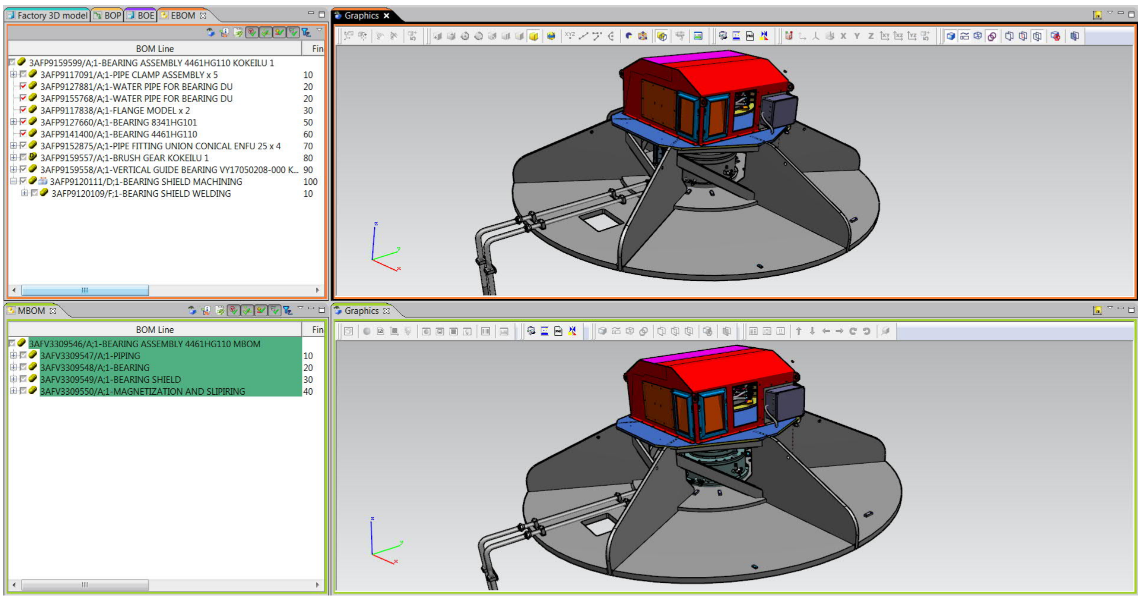

Figure 25. Visual comparison in MBOM creation.

Bill of equipment creation

In TeamCenter MPP resources such as tools and work areas are defined in BOE (Bill of Equipment) structure. The BOE structure created can represent the whole plant or a smaller part of the production facility. Different work areas, work stations, production lines and sections can be used to describe the production area architecture. Work areas can have resources that are fixed to the specific location. The work areas can be sequenced to represent the flow in the factory floor.

The resources can be balanced if the number of workers in the workstation is specified and the operations durations are specified. Then the balancing can be done by switching operations between workstations to move the load between working areas and operators.

For the studied bearing assembly, a BOE of the factory layout was build. First a plant context was created to the collaboration context. The factory layout was constructed by creating different work areas in the plant context. The 3D model of the factory layout was inserted to the root work area, which represents the whole final assembly area. In figure 26 the BOE structure and visualization of the Pitäjänmäki factory final assembly area can be seen.

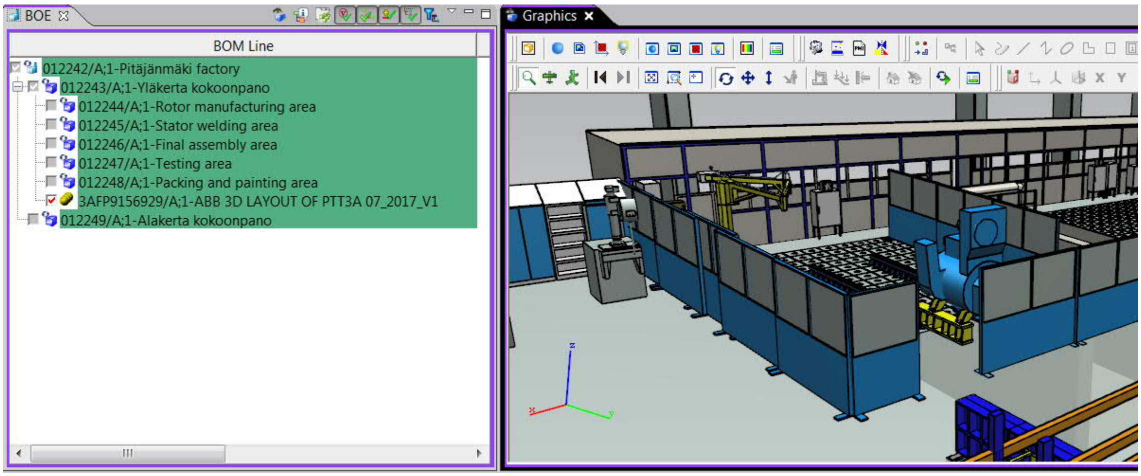

Figure 26. BOE structure and visualization in TeamCenter MPP.

Bill of process creation

The BOP (Bill of Process) is created after the MBOM and BOE have been finalized. Bill of process in TeamCenter MPP describes the steps needed to manufacture the designed product. At first a process context is created in the collaboration context. The BOP is built by creating process structure and creating operations inside the processes. The link between the product structure and process is formed by associating the MBOM of the product as target for the BOP structure. Operation types in TeamCenter MPP vary from machining to painting. Parts from the manufacturing structure are assigned to the operations similarly to assigning parts to the MBOM from the EBOM. Assigning a part to operation consumes the assigned part. Parts or items can also be linked to operations as required. This can be used when a part is needed for an operation but the operation does not consume the part. Resources such as work areas and tools are also assigned to the operations.

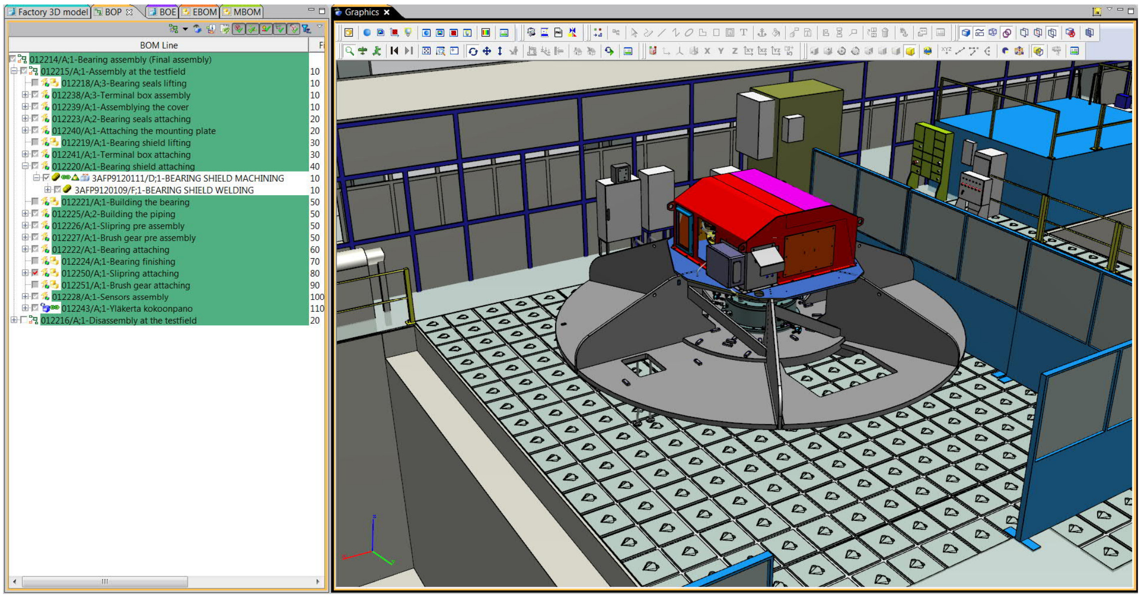

Figure 27. Visualization of the bearing assembly BOP in the factory layout.

Operations contain product data, work area data, resource data and analysis data that includes for example time. Operations also contain work instruction data that is used on the input data to generate output data of the operation. The input data can be for example a model of the previous operation step. The output data is used on the next operation of the manufacturing process. The amount of processes and operations depends on the manufactured product and the process structures can vary heavily.

The right assembly order is generated by sequencing the operations. The sequencing is done by utilizing a PERT chart to create a sequenced tree structure of the operations. The sequencing is done by drawing flow lines between entities. With sequencing the order of operations and the critical path of the manufacturing process can be planned.

Operations can be described in more detail by creating activities inside them. Activities are used when the operation steps need more detailed explanation. A fastening operation can be divided to part collecting activity, the fastening activity and to cleaning activity for example. The activities can also be sequenced with the PERT chart. After modifying the PERT chart, the process structure view can be updated to the latest structure. The PERT chart can also be updated according to the current process structure view. In figure 28 the sequencing of the bearing assembly operations at the test field is shown.

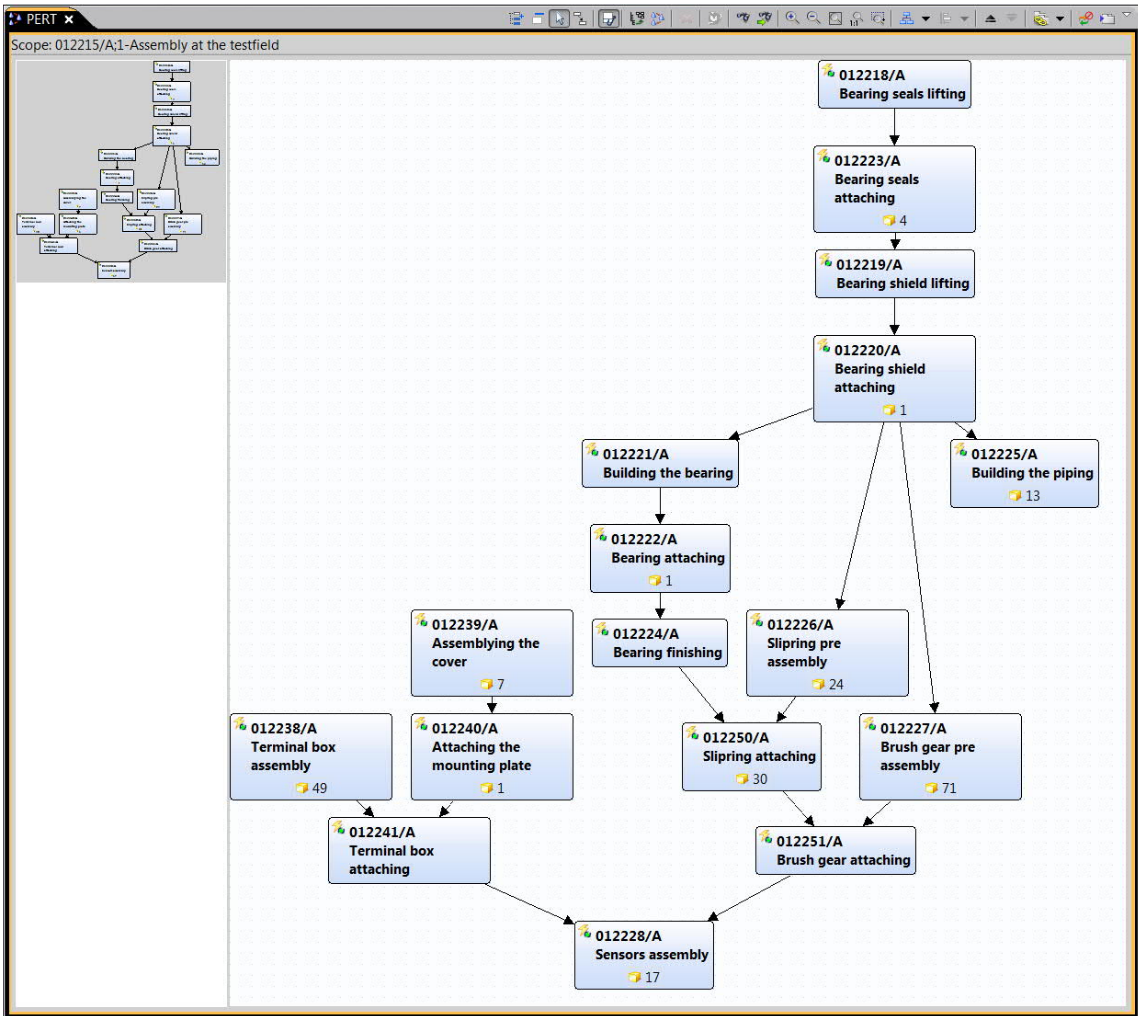

Figure 28. PERT chart of the bearing assembly operation sequencing.

The activities are created in time management window where the duration of individual activities, operations or processes are determined. The activity durations can be for example estimated times, simulated times or gathered from the workhour data. The activities or operations can be categorized according to whether they add value to the process or not. A time analysis is performed after the times are assigned. It calculates the time needed for each activity, operation and process. A pie chart displays the time used in value increasing activities and the time spend in activities that add no value to the process. This aids the detection of inefficient or even useless operations and activities in the manufacturing process. If time values are modified the calculations need to be redone. Allocated times can be set manually for processes or operations or they can be populated from other time fields. The population calculates the allocated time for process or operation from the child items of the populated structure. In figure 29 an example of activities created for an operation is shown. Allocated times and the ratio of value adding work to non-value adding work is also shown in the figure. Reports of the time analysis and allocated time can be created. The reports are created as Excel files and the files are attached as datasets to the object to which the report was created.

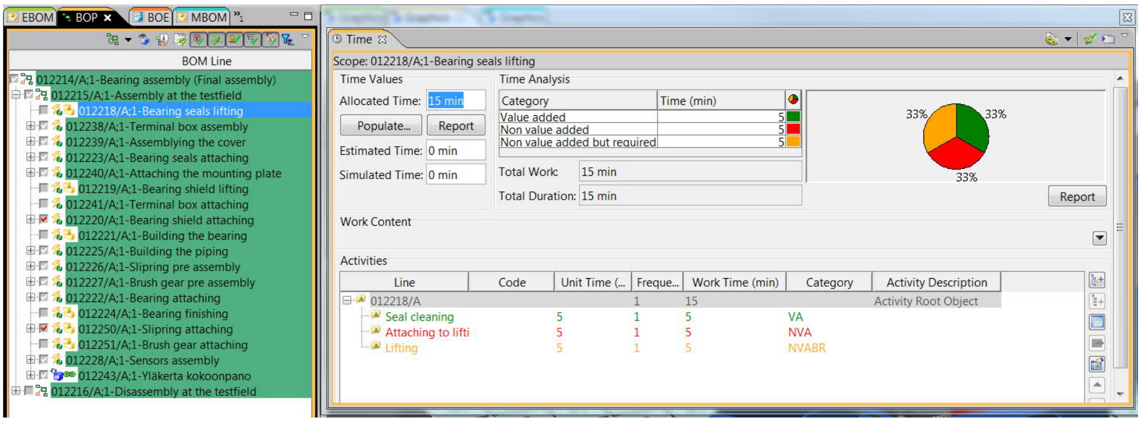

Figure 29. Creating activities and allocating time to operations.

A process Gantt chart can be used to visualize the allocated times of operations or processes. The Gantt chart also presents the sequence of the operations which enables tracking of the total time used for the process. From the Gantt chart it is easier to plan possible changes to the operation sequences in order to reduce the total manufacturing process time. From the process Gantt chart the user can modify the flows, change the time durations, populate the time durations and view the critical path. In figure 30 a process Gantt chart of the bearing assembly is presented. All the operation sequences and allocated times are presented. The critical path of the process is shown with red arrows connecting the critical operations. From the figure 28 and figure 30 it can be seen that some operations can be done simultaneously and some operations require one or more operations to be finished before they can be started.

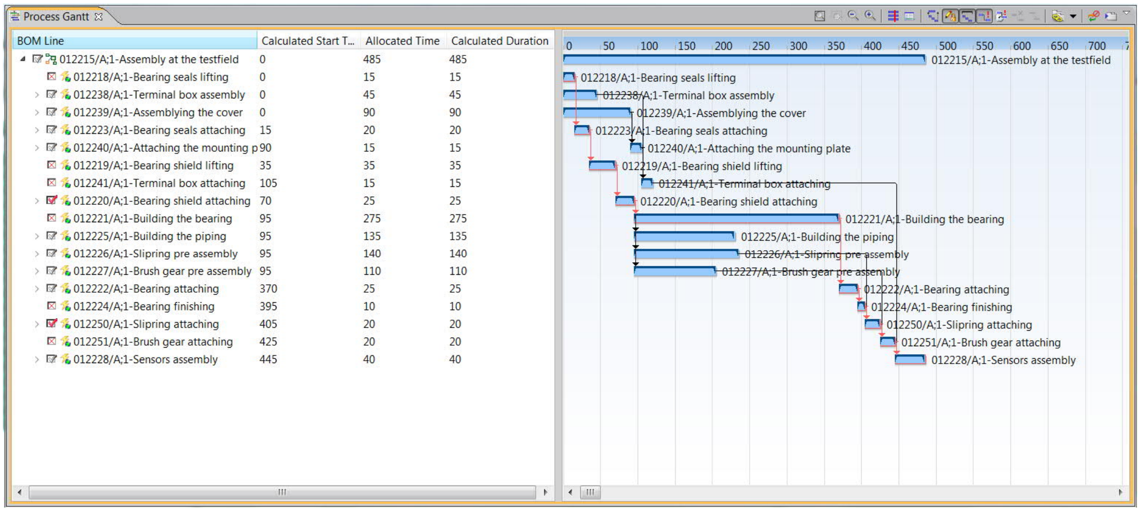

Figure 30. Process Gantt chart of the bearing assembly.

Work instructions

After the BOP of the assembly is finished, work instructions of the operations performed in the process are created in TeamCenter MPP. Work instructions of the operations are created for the assembly workers to utilize. Textual work instructions and 3D product views of the 3D models can be created for operations. The textual instructions are created and edited with Microsoft Word plugin in TeamCenter MPP. Textual work instructions can include plain text, images, charts and tables for example.

3D product views are created from the graphics display of the BOP. Different visualization tools can be used to increase the information provided by the 3D product views. Different markers can be used for example to highlight areas of interest or to display information. Text boxes with part names, codes or other information can be displayed in the 3D product views. Parts of the assembly can be moved to create exploded views. Section views can be created from assemblies or individual parts. Individual parts colour can be modified to highlight desired areas of the assembly. The transparency of the parts can also be modified to display for example what is behind some structure. Utilization of the factory layout model or other resources is also possible when creating 3D product views.

Different documents such as 2D assembly drawings, BOM lists and standard instructions can be attached to the operations. The attaching is done by dragging and dropping the documents to the operation by using the attachments view in TeamCenter MPP.

Work instructions are viewed using TeamCenter Active Workspace interface. The standard interface displayed for operation includes the textual work instructions and the created 3D product views. A list of the parts used in the operation is also displayed. Attached document are also available to view in the active workspace interface. In figure 31 the work instruction viewer interface is presented. In the instructions window the textual work instructions are presented. Parts window lists all the panels assigned to the operation. Viewer window displays the created 3D product views. Documents window next to the viewer is used to display documents attached to the operation. The advantage of the interface is that different types of information can be displayed simultaneously and the information is easily accessible.

For the bearing assembly studied, work instructions were created for the operations. Textual work instructions and attaching documents were tested and proved to be an effective method of inserting drawings, part lists and standardised instructions to one location for the assembly workers to inspect. 3D product views were created and different visualization features were tested. The work instructions were presented to the assembly workers for feedback.

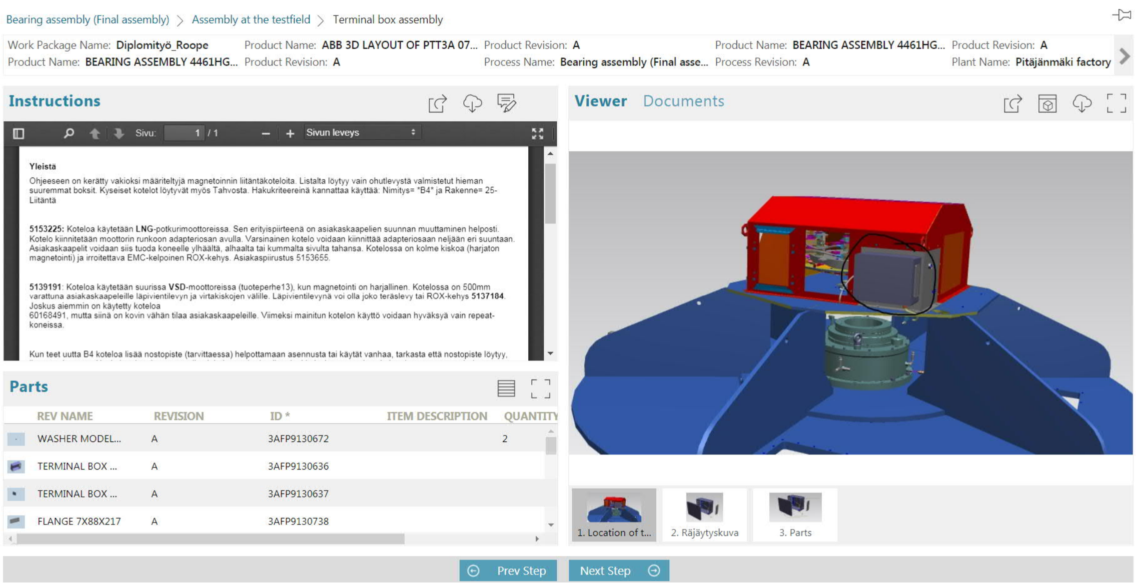

Figure 31. Work instruction viewer in Active Workspace.

3.3 Comparison of the tools

In this section the Delmia tool and the TeamCenter MPP tool are compared to each other. The comparison methods are also introduced.

3.3.1 Comparison method

In order to compare the two software tools, the objective and requirements of the tools must be carefully defined. The main objective of the manufacturing process planning tools tested in this study was to reduce electric machines assembly times. The sub-goals to achieve the main objective were identified as:

- Improved work instructions for assembly workers.
- Better manufacturability planning.
- Better preventive detection of possible problems in the assembly process.
- More detailed planning of the assembly process.
- Improved resource management.

The technical functionalities of the two tools were studied and the effectiveness of how they achieve the above goal and sub-goals was evaluated. The main technical functionalities compared were:

- MBOM structure creation.
- Process structure creation.
- Resource structure creation.
- Assembly evaluation.
- Factory layout.
- Visualization.
- Work instructions creation and viewing.
- Integration to current software tools.

The tools were scored from 1 to 5 points for each category, where 5 points was the maximum score. The scores were determined mainly from the author´s own experience of the tools as no one else in the company had been examining the tools as thoroughly. Some discussion about the scores was done with a few ABB employees with experience of the two tools compared.

Weighting coefficients were determined for the technical functionalities by estimating how important each functionality was to achieve the determined goal of the tools. The coefficients were determined by discussing with people who had been also testing the two tools. The final weighting coefficients of the technical functionalities are presented in table 2. The consensus was that the most important categories were the work instructions and the integration to the current system. The work instructions were seen as the most important category because the instructions were the outcome of all the work done in the other categories. If the work instruction creation or viewing functionalities are lacking it is hard to correct with the other functionalities. The other important functionality determined was the integration to the current tools. In his book Stark (2015) Identifies KPIs (Key Performance Indicators) of product data in PLM software. Some of the possible KPIs are listed in figure 32. The KPIs can be used to compare the two manufacturing process planning tools integration to the current system in ABB Pitäjänmäki. The better integration results in better KPIs presented in figure 32. The visualization functionalities of the tools were also determined to be more important than average. The reason is that the tools rely heavily on the visualization when performing other technical functionalities with the tools. Assembly evaluation and the factory layout features were determined not to be as important. The reasoning was that assembly evaluation such as collision checks could be performed more efficiently with other tools, for example using NX CAD tool. The factory 3D layout was hard to utilize in practice when working with the tools. A huge amount of work would be required to have practical benefits from the factory layout for the low quantity and high variance electric machines manufacturing.

Another way to compare the two software tools is by analysing the quality of the flow of information according to Lean principle. In Lean philosophy the goal is to remove everything that is not adding value. This principle of removing non-value adding activities can be applied to information flow as well. The better the tools are integrated to each other the better the quality of the information flow.

% of product data that is duplicated	% of product data that is electronic
% of product data that is incorrect	% of product data that is not under change control
% of product data that is incomplete	% of product data that has been lost
% of product data that is never used	volume of data that is re-entered manually
% of product data that has no owner	number of different copies of same document

Figure 32. Product data KPI examples. (Stark, 2015)

Table 2. Weighting coefficients for the technical functionalities.

Functionalities	Weighting coefficients
MBOM structure creation	1
Resource structure creation	1
Process structure creation	1
Assembly evaluation	0,6
Factory layout	0,6
Visualization	1,5
Work instructions	2
Integration to current tools	2

3.3.2 Technical functionalities comparison

In this section technical functionalities of the tools are compared. In table 3 the scores for all different technical functionalities are presented. The reasoning for the scores is explained separately in below.

Table 3. Scores for functionalities.

Functionalities	TeamCenter MPP	Delmia
MBOM structure creation	4	4,5
Resource structure creation	3,5	4
Process structure creation	4,5	4
Assembly evaluation	2,5	4
Factory layout	4	4
Visualization	4	4,5
Work instructions	4	2,5
Integration to current tools	4	1,5

MBOM structure creation

Both Delmia Digital Manufacturing and TeamCenter Manufacturing Process Planning tools had very similar MBOM creation process. Both tools required the linking of the EBOM and the MBOM structures. In Delmia there were a better variety of building blocks for the MBOM structure. Also, the structure visualization was slightly better in Delmia because of the visualization of the tree structure seen in figure 14. The assigning of objects from the EBOM to the MBOM was equally simple in both tools. Also, both tools had good instruments for checking the assignment status of the objects. The advantage of TeamCenter MPP over Delmia was a BOM recipe tool which enabled some automation in the MBOM creation process. This feature can be especially useful if multiple MBOM structures must be created for similar products. When constructing the MBOM for the bearing assembly studied, similar amount of work was required in Delmia and in TeamCenter MPP. (**TeamCenter MPP 4**, **Delmia 4.5**)

Resource structure creation

In both tools different types of resources from work areas to workers and assembly equipment could be created and managed. Delmia had more different resource types available compared to TeamCenter MPP. In both tools the resources were assigned to operations in the process structure. In Delmia the resource balancing capabilities were better than in TeamCenter MPP. The possibilities with the resource structure and features were better in Delmia Compared to TeamCenter MPP. Both tools had necessary capabilities for the studied scope, but Delmia tool has more potential for more complicated resource management. (**TeamCenter MPP 3.5**, **Delmia 4**)

Process structure creation

The process structure creation was also similar between both tools. The main building blocks of the process structure in both tools were systems and operations. In TeamCenter MPP activities could be created to the operations for more detailed description of the operation. The process structure was linked to the MBOM structure and objects form the MBOM were assigned to the operations. In both Delmia and TeamCenter MPP different resources could be assigned to the operations of the process structure. Both tools had similar operation sequencing tools and Gantt chart views for analysing the systems. However, the sequencing was slightly more straightforward and user friendly in TeamCenter MPP. The visualization of the process structure was better in Delmia similarly to the MBOM creation visualization. The construction of the process structure for the bearing assembly studied was slightly easier and faster in TeamCenter MPP compared to Delmia. (**TeamCenter MPP 4.5**, **Delmia 4**)

Factory layout

In both tools the factory layout model could be used as a resource. The work areas for the operations could be determined from the layout model and the layout could be utilized in the work instruction 3D views. The 3D layout of the factory could be used for basic space inspections. In both tools it was hard to utilize the factory layout to full extent. Delmia had more options for simulations using the factory layout. However, simulating for example the product flow in the factory work areas was hard to perform and provided no valuable information. (**TeamCenter MPP 4**, **Delmia 4**)

Assembly evaluation

In this category there were quite big differences between the two tools. In Delmia the assembly evaluation possibilities were much more extensive. With both tools basic visual inspection of the 3D models could be performed. Also, both tools had ways to evaluate the MBOM and process structures. In Delmia the assembly process could be simulated by moving and assembling the parts according to the operation sequence. The created sequences could be recorded in to a video. In TeamCenter MPP some video recordings creation was also possible by manually moving components while recording. In Delmia Collision detection could be performed on the simulated assembly sequence. It was also possible in Delmia to simulate the product movement trough work stations or areas and to simulate other resource utilization as well. (**TeamCenter MPP 2.5**, **Delmia 4**)

Visualization

Both tools relied heavily on the 3D visualization in the planning of the manufacturing process. The biggest difference in the visualization was the file type of the 3D models. TeamCenter MPP used JT-file models in the graphics window and Delmia used PRT-file models for the visualization. The JT files are more lightweight than the normal CAD software PRT- files. The graphics in TeamCenter loaded quickly and run smoothly on the screen. In Delmia there was some jagging in the graphical views when working with large assemblies. The JT files were especially good for large assemblies with a lot of complicated model entities. The models in Delmia looked sharper and more detailed than in TeamCenter MPP when the graphics in both tools were turned to the maximum settings.

The utilization of the visualization was identical between the two tools. In both the graphics of the assemblies could be used when creating MBOM: s, process structures or work instructions. (**TeamCenter MPP 4**, **Delmia 4.5**)

Work instructions

In the work instructions category, the creating and viewing of the instructions were compared. Creation of the instructions should be as fast as possible and the quality of the instructions should be as high as possible. The work instruction creation process was timewise quite similar with both tools. TeamCenter MPP had better textual work instruction capabilities but the snapshots of the 3D models were easier to produce with Delmia. Delmia had more intuitive controls to produce different visualization effects on the 3D snapshots. The quality and overall look of the 3D model snapshots were also better in Delmia.

The work instructions created with Delmia and TeamCenter MPP were evaluated by presenting them to the assembly workers. The overall feedback was positive as currently most of the work instructions were in printed maps. The printed instructions, manufacturing drawings and part lists could cause the documentation to be outdated. Also, the accessibility and the inconvenience of finding the correct instructions meant that the work was usually done without the instruction material. With Delmia and TeamCenter MPP all the work instruction types were closer to each other and in electric form which according to the assembly workers significantly raises the threshold of finding all the necessary instructions for the operation. The interface for viewing the work instructions was better in TeamCenter MPP compared to Delmia. In TeamCenter MPP more information was presented in the work instruction view as drawings, part lists, textual instructions and 3D snapshot views could be viewed side by side. In Delmia the information was presented in linear fashion and different information was hard to view simultaneously. Also, in Delmia a lot of opening of individual information and backtracking to the main view was required. (**TeamCenter MPP 4**, **Delmia 2.5**)

Integration to the current tools in the company

The integration to the current tools was an important factor when comparing software tools. Good integration of tools reduces the amount of non-value adding work needed and the change management of the data is better. In this category TeamCenter MPP was clearly ahead of Delmia. The reason was that TeamCenter has been used in ABB Pitäjänmäki as the PLM software for many years. The TeamCenter MPP tool integrates to that much more easily than Delmia. (**TeamCenter MPP 4**, **Delmia 1.5**)

4 Results

In this chapter the results of the literature review, the bearing assembly case study and the manufacturing process planning tools comparison are presented.

4.1 Literature review results

In the literature review the basics of production planning and traditional tools of production planning were presented. Manufacturing process planning and factory modelling basics and state of the art was introduced. Current design methods for the product and the production in ABB Pitäjänmäki were studied. The final assembly process of the machines in Pitäjänmäki factory was presented. The concept of virtual reality and virtual reality tools in manufacturing planning were also introduced.

4.1.1 Production planning

Based on the literature review it can be said that the basic methodology and tools in production planning have not changed much. The main change over the years has been the implementation of more powerful computers and more complex production planning software tools. PERT and Gantt charts were found to be the very useful graphical tools for production planning. These graphical representations are used in the modern manufacturing planning tools as well. According to the literature review the main task in production planning is to reduce costs by optimizing the production. In the optimization different strategies are used. The most basic strategy was identified to be the balancing between warehouse stock and production according to demand. Lean principle of removing all non-value adding from the process can be applied in the production planning as well. The cost reduction however cannot affect the quality of the produced product. Better production planning tools can be used to reduce manufacturing costs and maintain or even improve the quality of the product.

4.1.2 Manufacturing process planning and final assembly process

In literature, the term manufacturing was distinguished from the term production by the level of detail of the processes. Manufacturing planning was considered to be more detailed planning compared to production planning. In manufacturing planning literature review, many categories that should be taken into account in the planning were identified. The production quantity, variance of the product, production capabilities, production facilities and the types of manufacturing processes affect the manufacturing planning.

ABB Pitäjänmäki production facilities were studied to identify the production quantity, variance of the product, production capabilities, production facilities and the types of manufacturing processes. The production in ABB Pitäjänmäki factory was identified as low volume and medium to high variety. The products are large and complex which causes the factory floor space to be one of the limiting factors in production capability. The production facilities consisted of work areas where the large machines were assembled in job shop type of environment.

4.1.3 Current product design and production design

The product design and production design processes in ABB Pitäjänmäki were studied. The main tool for the designers of the electric machines was the CAD tools integrated to the PDM tool. The documentation produced by the designers to the assembly workers were 2D manufacturing drawings and part lists. Only printed documents were used in the assembly area. In the worst-case scenario this could cause the drawing and part lists in the assembly area to be outdated. For the production planning the main tool was SAP ERP which was used for broad scheduling of the machines production. The manufacturing planning used documents produced by the designers to evaluate and plan the manufacturability of the machines. It was found that no visual manufacturing process planning tools were used in the product design or in the production design. The manufacturability planning of the machines was limited and some problems were not noticed until in the final assembly. A need for better tool for the manufacturing planning was identified.

4.1.4 Virtual factory and virtual manufacturing tools

According to the literature review virtual factory approaches could be roughly divided to 3D visualization of the factory layout and modelling and simulation of the whole factory system. The 3D model of the factory layout was used in VR as training environment for workers or as a customer tour platform. The 3D layout can also be used when designing new production facilities or when improving the current production methods. The simulation of the whole factory system enables the testing and evaluating in virtual environment before implementing the changes to the real factory. From the literature review key benefits of virtual factory were identified as:

- 3D model of the factory - advanced visualization.
- Integration of multiple organizations.
- Test bed for the real factory.
- Factory as a whole is considered - sub models and sub systems.
- Accurate prediction of factory performance.
- Support continuous improvement.

All the benefits above can improve the electric machines manufacturing process planning. The 3D model of the Pitäjänmäki factory layout can be used to plan the production. From the factory 3D model the space needed for the assembly of large machines can be seen and for example new production tools can be verified in the virtual environment before large investments. The advanced visualization can improve the communication between different organizations, for example the communication between the designers and the manufacturing planners could be easier. If the factory model is simulated accurately it can be used for testing and predicting the real factory performance. The benefits of simulating everything from the factory including for example the communications network were according to the author small compared to the complexity of the required model of the factory system. This approach would suit better for example production line type of production with high volume and low product variation. In ABB Pitäjänmäki factory the products are large and varied, which makes the modelling of every aspect difficult and unproductive according to the author.

The virtual manufacturing tools such as basic CAD tools or VR environments can be utilized in product and production design. The literature review for virtual reality and virtual manufacturing tools showed that especially automotive and aerospace industries were already utilizing VR environments in product design and in production design. The advantages and possibilities of using VR in product design and in production design according to the literature review were identified as:

- Higher product quality.
- Better manufacturability.
- Lower production cost.
- Faster time to market.
- Faster change management loop.
- Better visualization.
- Improved communication between different organizations.

The author's opinion is that using virtual manufacturing tools can lead to above improvements in ABB Pitäjänmäki. One of the main causes for this study was the long assembly times in the final assembly phase of the machine. With virtual manufacturing tools the assembly times can be lowered. According to the author the communication between different organizations and the better manufacturability planning are the most important areas where virtual manufacturing tools could be useful in ABB Pitäjänmäki. In ABB Pitäjänmäki VM technology is a new tool and it is in continuous developed and tailored to the factory's specific needs.

4.2 Delmia and TeamCenter MPP results

In this section the results for the bearing assembly case study done with Delmia and TeamCenter MPP tools are presented. The results of the comparison of the tools are presented as well. The studied bearing assembly was evaluated with both manufacturing process planning tools.

4.2.1 Bearing assembly case study

Bearing assembly of the pump motor was used as a case study in order to find ways to utilize the production planning tools in electric machines manufacturing planning. Two production planning tools Delmia and TeamCenter MPP were studied.

The following tasks were successfully performed on the bearing assembly with both Delmia and TeamCenter MPP tools:

- Importing the engineering structure.
- Creating the manufacturing structure.
- Creating the resource structure.
- Creating the process structure.
- Allocating and balancing resources.
- Evaluating the assembly.
- Creating the work instructions.

In the case study the product data of the bearing assembly was successfully imported to the production planning tool environments. Some problems in the 3D models arose from the importing but the structures remained similar to the original product structure.

MBOM creation from the imported engineering structure of the studied bearing assembly was possible with both tools. The MBOM created represents the structure of how the studied bearing assembly is assembled in the factory floor.

Resource structure creation and resource allocation could be performed with both tools tested. The resource structure consisted of the factory layout 3D model where different work areas and tools were created. Operators and assembly tools assigning was tested to be possible. Also, resource balancing tools were inspected and verified to be able to be used when planning the studied bearing assembly manufacturing process.

The process structure creation was done with both tools tested. Systems and operations were created to describe the manufacturing process of the studied bearing assembly in both tools. Parts from the MBOM structure of the bearing assembly and different resources were assigned to the operations according to the manufacturing process in the final assembly of electric machines.

Work instructions of the assembly operations of the studied bearing assembly were created with both manufacturing process planning tools. The work instructions were validated by presenting them to the assembly workers in ABB Pitäjänmäki factory. The feedback from the assembly workers was mainly positive. The electrical form of 2D manufacturing drawings, part lists and other documents was complimented by the workers. The assembly workers found the gathering of individual documents to the same work instruction layout useful. The electrical document instead of printed documents was a welcoming improvement to the assembly workers. The 3D snapshots created with Delmia and TeamCenter MPP were also complimented but in order to present useful information in the 3D snapshots, more refining and consulting of the assembly workers is required. The assembly workers also stated that being able to inspect the actual 3D model would be more useful compared to the 3D snapshots of the models.

With the case study it was demonstrated that Delmia and TeamCenter MPP tools can be used for manufacturing process planning of electric machines. Overall, the work instructions created were found to be the most important benefit of the manufacturing process planning tools. The work instructions were the concrete result of the work done with the manufacturing process planning tools and they can offer actual aid in the manufacturing of electric machines.

4.2.2 Comparison of the tools

In table 4 the results of the functionalities comparison are presented. The scores for Delmia and TeamCenter MPP were calculated without weighing coefficients of the categories and with the weighting coefficients. From table 4 it can be seen that TeamCenter MPP scored higher with and without the weighting coefficients. The difference to Delmia was highlighted when the weighting coefficients were applied.

Strengths of TeamCenter MPP compared to Delmia were the work instructions and the integration to the current tools in ABB Pitäjänmäki. TeamCenter MPP had also slightly better process structure creation capabilities. Strength of Delmia compared to TeamCenter MPP was the assembly evaluation. Delmia had also slightly better visualization and MBOM creation capabilities. The resource structure creation, allocation and balancing was also slightly better in Delmia compared to TeamCenter MPP.

Table 4. Delmia and TeamCenter MPP comparison results.

FUNCTIONALITIES	TeamCenter MPP	Delmia	Weighting coefficients	TeamCenter MPP (Weighted)	Delmia (Weighted)
MBOM creation	4	4,5	1	4	4,5
Resource structure creation	3,5	4	1	3,5	4
Process structure creation	4,5	4	1	4,5	4
Assembly evaluation	2,5	4	0,6	1,5	2,4
Factory layout	4	4	0,6	2,4	2,4
Visualization	4	4,5	1,5	6	6,75
Work instructions	4,5	2,5	2	9	5
Integration to current tools	4	1,5	2	8	3
TOTAL	**3,88**	**3,63**		**4,01**	**3,30**

ABB is a global company and the tools used today may not be the same in a few years. Therefore it is important to also compare the two tools without taking into account the integration to the current tools category. In table 5 the numerical comparison results are presented without the integration to the current tools category. It can be seen that without the weighting coefficients Delmia actually scored slightly higher than TeamCenter MPP. When the weighting coefficients were applied, TeamCenter MPP performed better than Delmia although the difference was not as big as it was when the integration to current tools was taken into account.

Table 5. Delmia and TeamCenter MPP comparison results without integration to the current tools.

FUNCTIONALITIES	TeamCenter MPP	Delmia	Weighting coefficients	TeamCenter MPP (Weighted)	Delmia (Weighted)
MBOM creation	4	4,5	1	4	4,5
Resource structure creation	3,5	4	1	3,5	4
Process structure creation	4,5	4	1	4,5	4
Assembly evaluation	2,5	4	0,6	1,5	2,4
Factory layout	4	4	0,6	2,4	2,4
Visualization	4	4,5	1,5	6	6,75
Work instructions	4,5	2,5	2	9	5
TOTAL	**3,86**	**3,93**		**4,01**	**3,77**

The slight superiority of TeamCenter MPP was also evident when testing and working on the two tools. The overall usability of the TeamCenter MPP tool was better than Delmia tool. Delmia was sometimes quite difficult to use because of crashes and inconsistent running of the tool. These problems were probably caused by the test environment of the tool running in the cloud.

TeamCenter MPP performed well in technical functionality categories that were determined the most important. Delmia had the biggest advantage in technical functionality categories that were determined not as important. From the numerical scores it can be deducted that TeamCenter MPP is more suitable tool for manufacturing process planning for electric machines in ABB Pitäjänmäki compared to Delmia.

5 Discussion

In this chapter the results of the study are discussed. The objectives of the study are reviewed and the fulfillment of the objectives based on the results are discussed. The methods used in the study are analysed and discussed. Key conclusions, recommendations and possible future research are presented.

5.1 Methods and results review

In this section the bearing assembly case study method is discussed. The comparison method is also discussed.

5.1.1 Bearing assembly case study

The case study was performed by testing Delmia and TeamCenter MPP tools with the bearing assembly structure. The bearing assembly was chosen because it was used in a challenging vertical pump motor project as a sub-assembly. The studied sub-assembly of the whole machine was intentionally chosen because studying the whole machine structure would have caused too much extra work and testing the manufacturing process planning tools functionalities would not have been as thorough. In hindsight maybe an even smaller assembly of the machine could have been used in the case study. The reasoning for choosing the bearing assembly structure for the study was that the assembly contained a good variety of different parts. The assembly consisted of larger parts such as the bearing shield, smaller subassemblies such as terminal box, piping and some cabling.

The steps of the case study were carefully planned to include all the main functions of the manufacturing process planning tools. The steps were executed chronologically and normal operating procedure of the tools was mimicked.

5.1.2 Comparison method

In the comparison of the manufacturing process planning tools technical functionality categories were defined. These functionalities were analysed separately and scores from 1 to 5 for each category were determined to both Delmia and TeamCenter MPP tools. Weighting coefficients were determined for each functionality based on their importance. The scores and the weighting coefficients were determined by the author. The scores and weighting coefficients were discussed with ABB employees who had experience with both tools compared and based on the discussion the final scores and weighting coefficients were determined. Ideally a wider sampling of people contributing to the scores and especially to the weighting coefficient would have been better for the comparison. The method used was still the best possible one because involving people with no experience of Delmia of TeamCenter MPP probably would not have given valuable input to the decision making considering the comparison.

Detailed measuring of the time used for the manufacturing planning process and different functionalities was not included in the comparison. The main reason was that the results would have been distorted because of the bigger learning curve when testing the first tool before the other. Also, the structure of the studied bearing assembly would have become more familiar which would have sped up the manufacturing planning steps in the latter tool tested.

5.1.3 Fulfilment of the objectives

Two main objectives for the study were defined. One objective was to find ways to utilize production planning tools in manufacturing planning of electric machines. The other objective was to compare and determine which of the two production planning tools Delmia or TeamCenter manufacturing was better for ABB Pitäjänmäki manufacturing planning.

Both main objectives of the study were achieved. It was found that production planning tools can be utilized in electric motor manufacturing planning. The main use is the describing of the manufacturing process by sequenced operations with parts and resourced assigned to them. The other main use is the work instruction creation of the operations for the assembly workers. TeamCenter MPP was determined to be the more suitable option for ABB Pitäjänmäki production planning compared to Delmia.

5.1.4 Objectivity of the study

The research and the results in this study can be considered objective. The study method did not favour either of the two manufacturing process planning tools tested. Approximately equal amount of studying and testing was done with the tools. Both tools were tested by using the same bearing assembly structure and the same functions were studied with both tools. The comparison method used did not favour either tool tested.

5.2 Key findings and conclusions

Based on the research done in this study the most important functionality from manufacturing process planning tools to electric machines manufacturing were the work instructions that could be created for individual operations. The work instructions can provide concrete benefits to the manufacturing of the machines by easing the assembly workers tasks. The interface for the work instruction viewing created in TeamCenter MPP was especially good. It presented different types of information such as 2D manufacturing drawings, part lists, written operation instructions and 3D snapshots from the assembly models in one location. The electrical instructions format compared to the current printed instructions would be a great improvement for the assembly workers. The non-value adding work of searching for the specific instructions would be removed and performing the assembly operations could be faster. The electrical work instructions would also always be up to date. The work instructions could also possibly aid in the training of new unexperienced assembly workers.

Alongside the work instructions the integration to the current tools used in ABB was found to be one of the most important properties when evaluating the manufacturing process planning tools usefulness. Without proper integration to the current tools used in product design and production design, a lot of additional work would have to be done. The KPIs presented in figure 32 describe the quality of the product data and the better the integration between different tools is the better are the KPIs. Without the integration the data would be duplicated and change control of the data would be required to be performed separately in different systems. This means that every time changes would occur in the design structure of the machine, the same changes would have to be manually implemented to the product structure in the manufacturing process planning tool as well. If all the tools were integrated and shared the same product data, the changes would automatically appear in all tools.

When conducting the study on the manufacturing planning tools the current machines design structure in ABB Pitäjänmäki turned out to be a partial hindrance. The structure of the manufactured machine in TeamCenter PDM tool does not fully correspond with the 3D model of the machine created in NX CAD tool. For example, some entities of the machines structure in TeamCenter are different items with different properties compared to the 3D model items of the entities that are used to create the manufacturing drawings for the machine. The 3D models are also usually not perfect representations of the physical product. Fastening parts such as screws and washers are often missing from the assembly models. This is problematic because the manufacturing process planning tools rely heavily on the 3D visualization of the structures. If the 3D model items are not used in the actual machine structure or if some parts are missing from the 3D model, the work instructions cannot be made as detailed as required. Also, for example allocating 3D items to operations in the process structure is pointless if the same item code is not actually ordered and used in the physical assembly.

5.3 Recommendations and future research

One future research possibility that arose when conducting this study was studying the current design structure of electric machines. The objective of the study could be how the structure in TeamCenter and in NX would correlate better. Another possible future research topic could be improving the 3D models of the machines. Currently the 3D models are not perfect representations of the physical product. Also, more standardized modelling practices, fastener libraries, tool libraries and parametrization of the 3D models could improve the design of electric machines and also improve the manufacturing process planning.

For the manufacturing process planning tools more in-depth studying of the work instructions could be beneficial. The work instruction studying could include the creation of more detailed work instructions by consulting the assembly workers. Possible approach with the work instructions would be to create common work instructions for the basic operations for electric machines. These common instructions could then be used as a template to create more specific instruction for specific difficult assembly operations for a machine if necessary. Also, creation and evaluation of some training material with manufacturing process planning tools for assembly workers could be beneficial.

One possible future study subject could be the implementation of VR to the work instructions or to the training material. Also, creation of a virtual factory tour or presentation of the assembly process to for example customers could be one research topic.

Based on the results of this study continuing the implementation of TeamCenter manufacturing process planning tool to the current design tools in ABB Oy Pitäjänmäki is recommended.

6 Summary

The objective of this study was to examine how production planning tools can be utilized in manufacturing planning of electric machines. The other main objective of the study was to compare two production planning tools, Delmia and TeamCenter MPP. The goal was to determine which of the two tools studied was better suited for manufacturing planning of electric machines in ABB Oy Pitäjänmäki.

A literature review was conducted where the basics of production planning and traditional tools of production planning were introduced. Manufacturing process planning basics and factory modelling state of the art was introduced. The concept of virtual reality and virtual reality tools state of the art in manufacturing planning were also introduced. Current internal product design, production design and assembly processes in ABB Pitäjänmäki were also studied. Bearing assembly of a vertical pump motor was used as a case study in order to find ways to utilize the production planning tools in electric machines manufacturing planning. In the study basic technical functionalities of the manufacturing planning tools were tested and evaluated. The two tools were compared by rating the technical functionalities numerically. Weighting coefficients were determined for the functionalities of the tools based on their importance to manufacturing planning of electric machines. The weighting coefficients were applied to the numerical scores to get the final results of the numerical evaluation of the tools comparison.

The main result from the literature review was that better manufacturing planning tools can improve the current production planning and final assembly process of electric machines in ABB Oy Pitäjänmäki. It was found that for example automotive and aerospace industries were already utilizing virtual manufacturing planning tools in product and production design. With the case study it was demonstrated that Delmia and TeamCenter MPP tools can be utilized in manufacturing process planning of electric machines. Overall, the work instructions created were found to be the most important benefit of the manufacturing process planning tools. The work instructions were the concrete result of the work done with the manufacturing process planning tools and they can offer actual aid in the manufacturing of electric machines. From the numerical results it was deducted that TeamCenter MPP is a more suitable tool for manufacturing process planning of electric machines in ABB Pitäjänmäki compared to Delmia.

The key findings of the study were the importance of the work instructions and importance of the integration of the manufacturing process planning tool to the current tools used in ABB Pitäjänmäki. Based on the results of this study continuing the implementation of TeamCenter manufacturing process planning tool to the current design tools in ABB Pitäjänmäki was recommended.

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