IMPROVING MANUFACTURING THROUGHPUT TIMES USING ASSEMBLE-TO-ORDER PRODUCTION MODEL

Lappeenranta–Lahti University of Technology LUT

Master’s programme in operations management, Master’s thesis

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Examiner: Associate professor Petri Niemi

ABSTRACT

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Improving manufacturing throughput times using Assemble-To-Order production model

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Keywords: Assemble-To-Order, ATO, Modularity, Lead time reduction, Order penetration point, Customer order decoupling point

Objective of this master's thesis is to study how Assemble-To-Order (ATO) production model can be utilized for improving production throughput times and productivity. Thesis includes literature review that is aimed to provide framework for utilization of ATO. Literature review includes theoretical background of production models and other topics related to study, such as production perspective in product development and product modularity. Case part of thesis investigates suitability of ATO principles for case company operating in heavy process vehicle machinery business. Current state of case company's production operations and conditions for utilizing ATO principles are clarified.

Results of the study suggest that product modularity and cooperation between production and product development are key factors affecting to the ability to utilize ATO principles effectively in production. To allow better suitability of ATO principles for case company, need is identified to develop cooperation and product development from modularity perspective. Based on literature review and current state analysis, possible ATO production models for case company are presented. Recommendations are presented about actions for allowing better utilization of ATO principles.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

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Valmistuksen läpimenoaikojen parantaminen Assemble-To-Order tuotantomallia hyödyntäen

Tuotantotalouden diplomityö

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Diplomityön tavoitteena on tutkia kuinka Assemble-To-Order (ATO) tuotantomallia voidaan hyödyntää tuotannon läpimenoaikojen ja tuottavuuden parantamiseen. Työ sisältää kirjallisuuskatsauksen, jonka tarkoituksena on tarjota viitekehys ATO:n hyödyntämisestä. Kirjallisuuskatsaus sisältää teoreettisen taustan tuotantomalleista ja muista tutkimukseen liittyvistä aihealueista, kuten tuotannon näkökulmasta tuotekehityksessä ja modulaarisuudesta. Työn soveltavassa osuudessa tutkitaan ATO-periaatteiden soveltuvuutta raskaiden prosessiajoneuvojen valmistuksessa case-yritykselle. Soveltavassa osuudessa selvitetään case-yrityksen tuotantotoiminnan nykytila ja lähtökohdat ATO:n hyödyntämiselle.

Tutkimuksen tuloksina tuli ilmi, että tuotteiden modulaarisuus sekä yhteistyö tuotannon ja tuotekehityksen välillä ovat avaintekijöitä vaikuttamassa kykyyn hyödyntää ATO:ta tuotannossa tehokkaasti. Mahdollistaakseen paremman soveltuvuuden ATO-periaatteiden hyödyntämiselle, case-yrityksen osalta tunnistettiin tarve kehittää yhteistyötä ja tuotesuunnittelua modulaarisuuden näkökulmasta. Kirjallisuuskatsauksen ja nykytila-analyysin pohjalta esitetään case-yritykselle mahdollisia ATO-periaatteisiin perustuvia tuotantomalleja. Case-yritykselle esitetään suosituksia toimenpiteistä mahdollistamaan paremmin ATO-periaatteiden hyödyntämistä.

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ABBREVIATIONS

ATO	Assemble-To-Order
BEV	Battery Electric Vehicle
CODP	Customer Order Decoupling Point
DFA	Design for Assembly
DFM	Design for Manufacturing
DFMA	Design for Manufacturing and Assembly
ETO	Engineer-To-Order
JIT	Just-In-Time
MRP	Material Requirements Planning
MTO	Make-To-Order
MTS	Make-To-Stock
OPP	Order Penetration Point
P/D Ratio	Production to Delivery Lead Time Ratio
PD	Product Development
RDV	Relative Demand Volatility
S&OP	Sales & Operations Planning
VE	Value Engineering
WIP	Work-in-Progress

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1. Introduction

Company's success or failure is largely determined by competition. Competition determines if company's acts in appropriate way to gain performance needed to succeed. Starting point is that company needs to satisfy customer needs to gain value to customer and succeed itself, but it has also to be able capture the value it creates. Competition can drive that value away to others, for example to customer in the form of lower prices. Competitive advantage allows firm to capture the value it creates, that is key point for company to succeed in competitive markets. One source of competitive advantage can be time management and lead times. Providing value to customer is integral part of competitiveness, that can be seen as overall ability of company to survive in competitive environment. Competitiveness is relative and it can be driven by competitive advantage and differentiation, for example by being able to offer shorter order-to-delivery lead times, if that is valuable to customer. If company performs such valuable factor worse than competitor, this can weaken company's relative competitiveness. (Feurer, Chaharbaghi, 1994; Porter , 1985, p. xv-xviii, 1-10, 120-124; Tersine, Hummingbird, 1995)

Reason behind this study is the willingness of case company to study the possibility to reduce order-to-delivery lead times and increase productivity by moving towards Assembly-to-Order (ATO) type production. Reduction in lead times and increase in production efficiency is needed to improve competitiveness in market. ATO and modularity, that are related together, are seen as potential principles for developing production. In case company modularity is driven forward in product development but it is not much utilized in production. It is not well understood what all the opportunities modularity can bring.

1.1 Research scope and objectives

Main interest of this thesis is to study how ATO principles can be utilized to reduce throughput times and gain other benefits in case company's machinery production. From product offering perspective focus is on product group consisting of battery electric vehicles, acting as a case example. It is a new product group and represents where the case company is aiming for the future.

Thesis consists of literature review, current state analysis and discussion part. Purpose of literature review is to acts as frame of reference and gain understanding about the previous study made regarding the subject. Literature is investigated to gather information about production models and factors relating to them. One major relating factor to be studied is cooperation of production and product development. This includes how product designs and modularity affect to production and to move towards Assembly-to-Order.

Objective of current state part is to support main objective of thesis by investigating current state of case company's production including related factors from production development perspective. In current state analysis is investigated what kind of production model is in use, what factors affect to production and what is the readiness for developing production towards Assembly-to-Order type production. Role of current state analysis is to offer view of current readiness and conditions for developing production towards Assembly-to-Order. Key questions regarding current state can be reduced to following:

1. What kind of production model is in use?
2. What are the main factors affecting to production model choice? (Business environment and market positioning)
3. What are the readiness and conditions for assembly-to-order based production from product development perspective?

Meaning of discussion part is to construct reasoned vision of how ATO principles can be utilized in case company based on literature review and current state analysis. Discussion part deals with the main question of the thesis:

4. What kind of ATO models can be taken in use, what are the benefits they can bring and what the utilization of ATO demands from the organization?

Discussion part consists of review of proposed ATO models for case company and recommendations from perspective of developing operation towards ATO.

1.2 Execution process

First phase of the thesis project is defining the topic and objectives. After defining phase, literature review, current state analysis and final analysis are carried out. Current state analysis is formed based on literature review and materials gathered from case company, including interviews. Final analysis answers the main question of thesis, and it is carried out based on findings made literature review and current state analysis. Work process includes regular meetings with key personnel from case company to review and steer work process during thesis execution. Thesis is further developed based on the feedback from these iterative meetings.

2. Supply chain

Supply chain is a constant flow of products and information that aims to fulfil end customer need and maximizing overall generated value. Supply chain links between companies and can also be seen inside companies' linking between their internal functions. Despite its name, supply chains are often better described as supply network, linking many parties of different stages in a web like structure as seen in Figure 1. For example, manufacture companies will most likely have multiple suppliers and distribution channels. (Copaṛā, Meindl, 2013, p. 13-15)

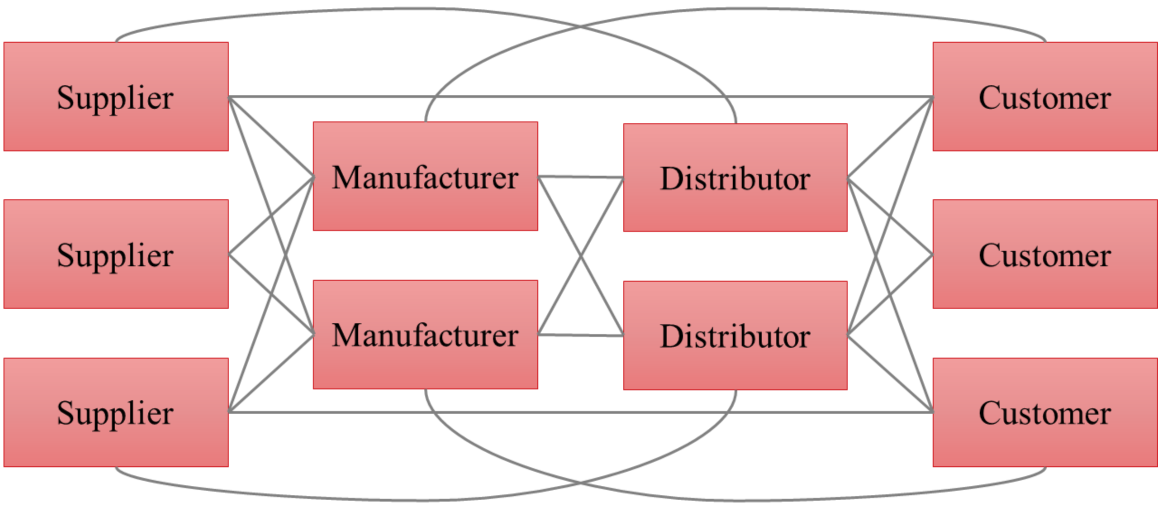

Figure 1. Example of web structure interconnecting supply chain parties (applied from Copaṛā, Meindl, 2013, p. 15).

Difference of product value to customer and product price is benefitting the customer as consumer surplus. Supply chain profitability can be defined as rest of supply chain surplus, that being the difference of product price and supply chain cost. Division of customer value and supply chain surplus can be seen in Figure 2. Focusing on profitability of individual stages in supply chain may lead to overall poor performance, hence total profitability of supply chain should be used to measure supply chain success. Growing overall supply chain surplus allows supply chain participants to benefit and share the increased profit. (Copaṛā, Meindl, 2013, p. 15-16) It can be seen from Figure 2 that supply chain profitability comes from product price customer is paying. Customer is the only source of revenue for any supply chain. (Copaṛā, Meindl, 2013, p. 16)

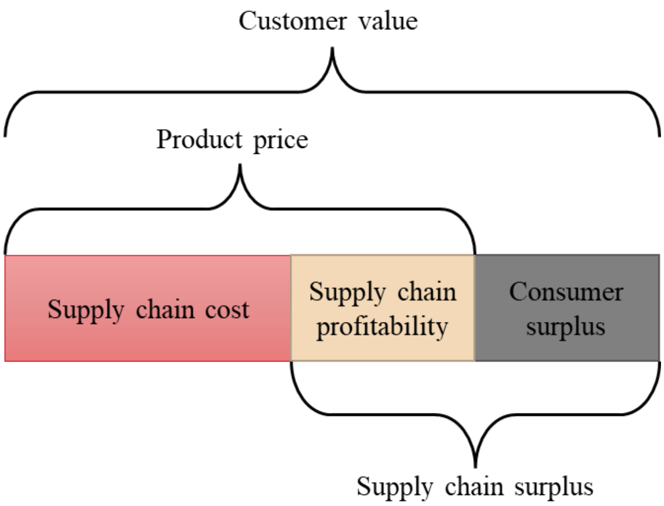

Figure 2. Division of customer value and supply chain surplus (based on Copaṛā and Meindl, 2013, p. 15-16)

2.1 Business environment

Business environment can be defined as external factors that influence company's operation, including macro environment (such as political, economic, social, technologic, ecologic and legal factors) and sectoral environment (market factors such as competition and customer needs). Globalization has made international interaction and competition more prominent, and it affects to business environment by continually broadening and changing it. Business environment factors are hard or impossible to control by individual companies, making them one of the determining factors of company strategy. Because of significant effect to company's operation, company should be able to react to changing business environment. Analysis of business environment factors is important part in guiding company's strategy and operations management (Eifert, Gelb, Ramachandran, 2005; Shtal, Buriak, Ukubassova, Amirbekuly, Toiboldinova, Tlegen, 2018; Yüksel , 2012)

2.2 Supply chain strategies

Design and management of supply chain flows are in close connection to supply chain success. Many notable and successful companies have driven their success from outperforming supply chain. In the other hand, failure to implement well performing supply chain and failure of adapting it to changing environment have led to poor results. Supply chain design, planning and operations are key elements for companies, contributing to their success or failure. Supply chain strategy and design is the foundation for supply chain. Strategy defines the big picture of how supply chain should look like. Decisions must be made in design, planning and operational fields in aim to maximize supply chain surplus. Supply chain strategy and design are effective in long run and changes are hard to make to action in short time period. Business environment is key factor in supply chain strategy guiding and constraining supply chain design. Decisions made in supply chain strategy must also consider expected changes and possible uncertainty in future business environment. (Copaṛā, Meindl, 2013, p. 16-19; Simchi-Levi, Kaminsky, Simchi-Levi, 2003, p. 9)

Competitive strategy defines to what customer needs company is aiming to respond and at what level, relative to competition. In the other hand, company's competitive strategy should be derived from customers' needs and prioritizations of price, delivery time, variety and quality. Competitive strategy can be derived down to functional strategies, that represent different functions of company, including supply chain strategy. Functional strategies should fit well together and align with competitive strategy. This means company should have similar goals and priorities between competitive and supply chain strategies to achieve strategic fit with supply chain. When competitive strategy is defining the customer needs and market segments that company aims to satisfy, supply chain must support to respond for these needs. (Copaṛā, Meindl, 2013, p. 31-32, 34; Simchi-Levi et al. , 2003, p. 238-240)

Processes in supply chain can be categorized into push or pull processes in relation of their execution to customer demand. In pull process, execution is actuated by customer order and push process is driven by anticipated demand. In push process uncertainty is present since customer demand is uncertain, in contrast to pull process where demand is known. First stages of supply chains are typically actuated by push type operation and later stages by pull type. Supply chain can be illustratively break up to push and pull processes where the breaking point is the timing of customer order (Figure 3). Defining suitable push-pull boundary for supply chain to meet supply and demand efficiently is major strategic decision. Postponement is a good example of strategy method applying push-pull frame of reference, where push-pull boundary is actively moved forward to gain benefits. Products and production processes are designed so that differentiation of products being manufactured can be postponed, enabling to extend push-pull boundary closer to customer. In practice, generic product is produced to as ready as possible when demand is uncertain and after demand is revealed, product is finalized by adding differentiating features. Aggregated undifferentiated demand is less uncertain that allows better forecast for push process operation. (Copaṛā, Meindl, 2013, p. 22-24; Simchi-Levi et al. , 2003, p. 122-123)

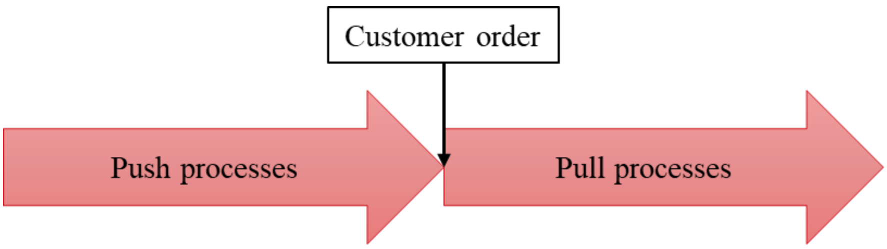

Figure 3. Breaking supply chain to push and pull processes

Ability to respond for experienced demand uncertainty is major requirement for supply chain. When actual demand being the same, experienced demand can vary depending on chosen competitive and supply chain strategies. Actual demand and variety of customer needs can affect to experienced demand uncertainty. For example, aiming to satisfy customer need for short lead time and large variety of products can increase experienced demand uncertainty. This is because there is less time to react for orders and demand will divide between large number of products. Other supply chain strategy aiming to satisfy customers accepting longer lead times and smaller variety of products will experience lower demand uncertainty. High innovation rate can increase experienced demand uncertainty because new products tend to have higher demand uncertainty. (Copaṛā and Meindl, 2013, p. 35-36; Simchi-Levi, Kaminsky and Simchi-Levi, p. 4-5, 240)

Supply uncertainty is other major uncertainty factor that supply chain must handle. Supply uncertainty tends to be higher for new innovations and product designs because designs and processes evolve and are not yet well defined. Over time and progress product maturity increases, decreasing supply uncertainty. Supply uncertainty can include uncertainty of company's own processes. Uncertainty can arise also from unexpected situations such as natural or man-made disasters that can have tremendous impact to both supply and demand. Experienced demand and supply uncertainties contribute to total uncertainty experienced by supply chain. (Copaṛā and Meindl, 2013, p. 36-37; Simchi-Levi, Kaminsky and Simchi-Levi, p. 5)

Supply chain uncertainty affects to supply chain strategy, whether company needs to design more responsive (better to handle uncertainty) or more efficient supply chain. Efficiency of supply chain means the ability of supply chain to perform on low cost. Supply chain responsiveness means ability to handle uncertainty and factors contributing to high uncertainty, such as short lead times, high new product development rate and high variability of products. Increasing supply chain responsiveness means often higher cost. This means that highly responsive supply chain strategy comes with lower supply chain efficiency and vice versa (Figure 4). Company must choose in supply chain strategy between this trade-off, what level of responsiveness and efficiency it aims to achieve. High uncertainty experienced by supply chain is best handled by high responsivity when flexibility and speed stress over cost efficiency. In less uncertain environment, responsivity can be lower and supply chain efficiency should be more emphasized. Supply chain can achieve strategic fit by different ways by assigning different roles to supply chain stages. Some stages can handle uncertainty and be responsible for total supply chain responsivity when other stages can be designed for highly efficient operation. Suitable allocation of roles depends on potential responsivity and efficiency in each stage. (Copaṛā and Meindl, 2013, p. 37-41; Simchi-Levi, Kaminsky and Simchi-Levi, p. 240)

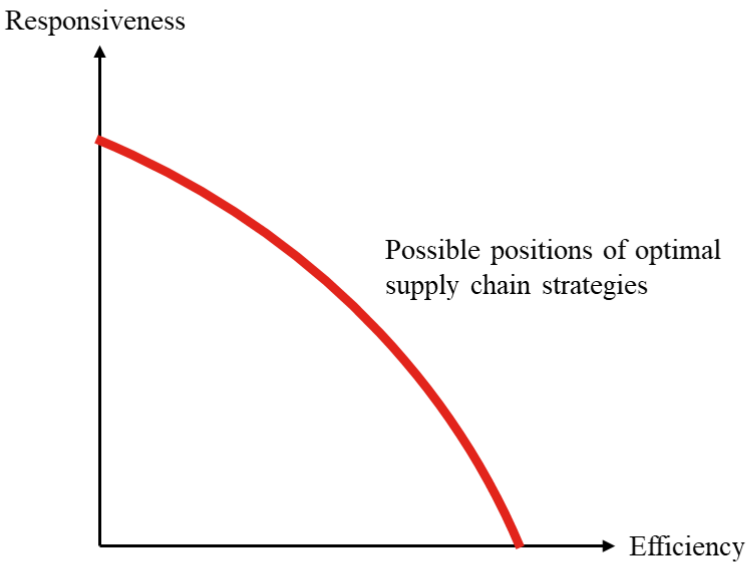

Figure 4. Trade-off relation between supply chain responsiveness and efficiency (applied from Copaŗā, Meindl, 2013, p. 38).

Different products and customer segments tend to have different uncertainty experienced by supply chain. To gain strategic fit in multiple different product types and customer segments, one type of supply chain is not enough, and supply chain has to be tailored for different purposes. In this case supply chain should be able to perform efficiently for low uncertainty segments and be responsive in case of high uncertainty. Needed tailoring can be achieved in some stages of supply chain by designing separate efficient or responsive options for them, while other stages can be common for all served demand. Tailoring tends to be needed when products move on their life cycle. In commonplace company should have responsive option for new and other uncertain products and more efficient solution for mature high-selling products. At the same time, as product variety affects to uncertainty, elimination of older products is often needed to limit product variety for what really adds enough value to the customer. (Copaŗā and Meindl, 2013, p. 42,46)

3. Product design for production

Cooperation between product development (PD) and production is important for company to succeed. This can be self-evident, but often the cooperation is not as good as it should be. To be able to design successful products, product development must take account comprehensive view of related factors, including production. (Lapinleimu, Kauppinen, Torvinen, 1997, p. 275-277)

3.1 Value in product development

Value in product development can be seen through concept of Value engineering (VE). Pessôa & Trabasso (2017, p. 60) defines value in product development as the ratio of function to cost. Therefore, value can be increased by reducing the cost or improving the function. From customer perspective, function to cost definition can be perceived as ratio of benefit to price. Because cost is easily measurable, cost reduction is often main driver in VE. Instead of this, increasing overall value should be the main goal of VE even when initial cost is higher. In VE, cost adding elements such as parts, products, equipment processes and service are looked through their contribution of value adding functions. Elements that contribute significantly to cost should be modified or eliminated if they are not adding enough value to function. (Pessôa, Trabasso, 2017, p. 60)

Value identification in product development project means determining the value that stakeholders expect to receive through product lifecycle. Developed function or characteristic adds value only if stakeholders experience it that way. Value identification is important part of PD, because providing incorrect or unneeded functionality adds no value and can be considered as waste. Errors in value identification tend to be hardest and most expensive to resolve, because they significantly add waste and needed rework. There is risk of pushing on to product needs felt by some participants, but in reality, may be non-value adding. These can include such as:

- Preconceived solutions that have worked before and since have become unquestionable
- Influential participant who has personal interest to drive for specific solution
- Underestimated difficulty to develop new technology that include risk of budget overruns and failure to meet customer desires.

Current practices often suppress recognizing of true value, therefore abandoning current practices are often needed. Previous problem can occur, and recognition of true value can hinder, if short term benefits of current practices are highlighted and long-term results overlooked. Even though value for customer is most important factor, also value for all other key stakeholders should be considered and negotiate trade-offs between them. Leaving off key stakeholders can lead to incorrect result and failure of development project to achieve its targets. Stakeholders include those who are involved in development or whose interests can be affected by it. Stakeholders' identification is important because they are those who demand the value and can have influence on development success, positive or negative. (Pessôa, Trabasso, 2017, p. 61-63)

3.2 Design for manufacturing and assembly

Journey from concept generation to ready and finished state takes end product through two major processes, designing and manufacturing. Interrelationship of designing and manufacturing processes is important for all production operation and key factor for product design. Smaller companies tend to handle this better, as people are naturally more interacted. As company size gets larger, natural interaction between departments tend to decrease. Utilization of design for manufacturing and assembly (DFMA) concepts improves design effectiveness and integration of designing and manufacturing processes. (Mynott , 2012, p. 219; Prakash, Sridhar, Annamalai, 2014) Eskelinen & Karsikas (2013, p. 7) describes that basis of DFMA is to break the "invisible wall" between product designers and production department. According to Prakash, Sridhar et. al (2014) the main principles of DFMA include:

- Fewer parts through standardization and simplification

- Enhancing manufacturability
- Alternative designs evaluation
- Using of design tools to create manufacturing ready designs before release to production

On the other hand, Eskelinen & Karsikas (2013, p. 9) notes that the main goals of DFMA are:

- Better integration between PD and production
- Saving time and money spent in PD
- Improving product quality and reliability
- Reducing throughput times
- Improving productivity
- Faster responsivity for customer requirements

Prakash & Sridhar et al. (2014) noticed that DFMA principles proved good investment in ensuring of optimal quality, reduced number of parts, reliability, time to market, lifecycle, and customer satisfaction. Also taking manufacturing issues in consideration in early phase of designing reduces product development time, minimizes costs and helps in smooth and fast transitioning of design to production and market. According to Lempiäinen & Savolainen (2003, p. 49) 60-85 % of production costs are determined by product development and design. Interaction between design and production has been low in history. Driver behind poor interaction has been the fact that it gives flexibility for departments to do their own things and more independence in achieving their nominal objectives. (Prakash et al. , 2014) One major problem is that product designer tries to utilize modular and standardized solutions from only products functional perspective without taking account production perspective and productional modules (Eskelinen, Karsikas, 2013, p. 9).

DFMA can be seen to consist of two different approaches, Design for manufacturing (DFM) and Design for assembly (DFA). DFM means all methods that simplify product manufacturing and reduce production costs, in the other words, meaning how to design product so that it is easier to manufacture. This will be achieved by co-operation of product designers and production staff. Product designer should be aware of manufacturability and assemblability and must learn to incorporate manufacturing methods to product design. (Lempiäinen, Savolainen, 2003, p. 13, 16)

DFA is concept of simplifying product structure to ease of assembly. It often includes at least combining functionality of parts and reducing parts number. DFA also helps in customer specific customization with modular design, allowing conditions for ATO production. Co-operation of product designers and production staff is equally important in DFA as in DFM. Every time when optimizing assembly or part manufacturing, good results are not achieved by chance, instead of that, tools and determination are needed helping to achieve good level of manufacturability and assemblability. (Lempiäinen, Savolainen, 2003, p. 13, 69) DFM and DFA are in many ways overlapping areas of DFMA. Lempiäinen & Savolainen (2003, p. 69-70) suggests that in general assemblability is more important than manufacturability, because assembly is often more labour intensive than part manufacturing, and because part number reduction has widespread cost reduction effects. DFA can support the reduction of product manufacturing costs and it provides much greater benefits than a simply reduction in assembly time (De Fazio, Rhee, Whitney, 1999; Favi, Germani, Mandolini, 2016). De Fazio, Rhee et al. (1999) notes that DFA usage and goal of enhancing product assembly ease is same for both simple and complex products and adds that for complex products ease of assembly favors sequential assembly lines. Directives about DFA by Lempiäinen & Savolainen (2003, p. 164-165) are presented in Table 1.

Table 1. Directives about DFA according to Lempiäinen & Savolainen (2003, p. 164-165)

Aim for simplicity	Minimize number of different parts and part features, simplify handling and assembly of parts.
Standardize	Standardize materials and components. Use standard parts as much as possible to gain benefits in inventory management, less needed tools and utilization of mass production in smaller production numbers.
Rationalize product design	Use standardization over product group. Modularize product group so that customer specific customization can be postponed after assembly of basic product and Just-In-Time production can be simplified.
Use wide tolerance spectrum	Reduce tolerance in non-critical parts
Select suitable materials for manufacturing process	Materials should not be selected only by their functional properties, instead material choice should also favour selected manufacturing process.
Planning assembly work	Utilize material properties. Avoid unnecessary restrictions for production processes to allow flexibility in production process design.
Minimize unproductive actions	
Emphasize teamwork	

One notable thing relating to DFMA is production automation. One way of improving productivity is to present automation in production processes. Disadvantage of automation in production is that it often requires massive investments and causes loss of flexibility. Designing products in terms of manufacturability requires less investments than production automation. With optimization of product design, labour and other production costs can be driven down, making production automation more often unnecessary. In some cases, investments to automation have reduced up to 90 % when manufacturability have been taken better to consideration in designing. Despite of that, design for automation is good practice even if premises are not yet fulfilled for production automation, because it tends to simplify assembly and gives benefits also in manual assembly. It should be kept in mind that product design improvements should be done before design of production automation. (Lempiäinen, Savolainen, 2003, p. 14-15, 155)

3.3 Modularity

Modularization is used in industrial companies to increase competitiveness. It takes advantage of the benefits of standardization and rationalization combined to flexibility and customization. Idea of modularization has evolved over time, driven by need of variety, use of similarities and reduction of complexities. Terms or ideas in connect to modularity are *module,* a functional unit part of modular system or structure, and *modularization*, that being the action where modular structuring happens. Modularity is the main concept, a system attribute, as we can speak about modular system. (Miller, Elgard, 1998) According to Frandsen (2017) modularity is "*a method of designing a structure to reduce its complexity*". Langlois (2002) also describes modularity in connection to complexity as modularity being "*a very general set of principles for managing complexity*". Ethiraj & Levinthal (2004) adds that modular design can be seen from two broad aspects, as useful means of managing complexity and as "power of modularity" meaning advantages of modular design over integrated one. Complexity is handled by breaking complex system to clearly defined pieces that interact through standard interfaces (Frandsen , 2017; Langlois , 2002). Standard interfaces define how subsystems (modules) are fitted together to form whole product. interfaces separate design groups (components grouped together to form modules) that characterize whole modular design. Modular design process can increase knowledge about interactions between components. (Schaefer , 1999)

Product modularity is in close connection with product configuration strategies (Frandsen , 2017; Hsuan Mikkola, Skjøtt-Larsen, 2004). Interfaces allows company to "mix and match" various versions of product properties (or in physical level components and modules) (Schaefer , 1999). Producing customized products with low cost and delaying product customization have their basis in modular product architecture design (Frandsen , 2017; Hsuan Mikkola, Skjøtt-Larsen, 2004).

Degree of modularity in product architecture depends on use of standard components, standardization and specification of interfaces, characteristics of system coupling (loose or tight) and possibility for replacement and interchange of building blocks (Mikkola , 2006). Schilling & Steensma (2001) describes systems to have high modularity when their relatively independent components can be disaggregated and recombined in different ways to form new configurations, often for different functions, allowing greater system flexibility.

Miller & Elgard (1998) presents drivers behind modularization:

- Create variety
    - Customer wanted (external) variety to provide well-fitting product for customer need
- Utilize similarities
    - Avoid rework by reuse
    - Faster and better working by accumulating knowledge
    - Using previous well-proven and tested solutions to reduce risk
    - Reduce (internal) variation (such as variation of parts and processes) that creates cost but do not generate value
- Reduce complexity
    - Better control and understanding by breaking down to less complex sets
    - Task distribution
    - Parallel work
    - Separate testing

Miller & Elgard (1998) presents two attributes to identify modularity, those being “*ability to create variety by combination and interchange of different modules*” and “*modules contain essential and self-contained functionality*”. First describes modular system and latter describes properties of modules that are needed in modular system. Both attributes should be present in modularity. Requirement for interchange demands compatible interaction and standardized interfaces.

There has been confusion in companies what module exactly means, or in other words, what constitutes a module (Doran , 2003). Miller and Elgard (1998) presents that functionality point of view distinguishes modules from components. Individual components that are not modules, does not contain enough functionality to create wanted variety itself, in relation to product it is part of. Ability to contribute essentially to product variety is key attribute of modules that are part of modular system. System point of view is important when thinking of modularity. Modules containing essential and self-contained functionality are not contributing to modularity if they are not part of modular system e.g., when there is no option to interchange module. Actually, these kinds of “modules” are really not modules until they are part of modular structure. Definition of module is flexible in terms of viewpoint or scale. Same unit can be seen as component, module or whole product, depending on viewpoint. (Miller, Elgard, 1998)

Role of sourcing is significant in modular strategy. Outsourcing modular structures requires collaboration and integration between supplier and buyer. Modularization leads to more collaborative supplier relationships. (Howard, Squire, 2007) Opportunity for outsourcing is seen to increase by modularity (Frandsen , 2017; Schilling, Steensma, 2001). Sako & Murray (1999) presents that modular strategy can have different approaches from supplier point of view, where buyer acts as “integrator” or “modularizer”. In integrator approach buyer retains control over whole product design, including module level, whereas modularizer relies on suppliers’ ability to design and provide needed modules. (Sako, Murray, 1999)

By dividing product development efforts with partitioning product design to subsystems (or design groups), product development organization can manage complexity and realize specialization economies. Negative effect is that this dividing tends to reduce coordination across subsystems. Ability to communicate and coordinate between design groups is itself a factor affecting to product design partitioning thus cost and benefits of available communication technology can affect to level of module design partitions (meaning what components are grouped together to form modules and how fine this grouping is). (Schaefer , 1999)

It has been noted that product structures can design organizations, meaning that modular product structures are best handled by modular organizations, and vice versa, nonmodular product structures match best with nonmodular organizations (Langlois , 2002; Sanchez, Mahoney, 1996). In addition, Sanchez & Mahoney (1996) argue that modular product architecture can help in organizational coordination. Standardized interfaces and modules in product architecture can be extended to organizational level, as standardized interfaces inside organization. This can lead to effective and adaptive organizational coordination and increases strategic flexibility that helps company to adapt in changing business environment. (Sanchez, Mahoney, 1996)

Ability to combine old and new versions of modules together to form distinct products increases PD productivity and reduces cost of variety creation. New PD projects (or parts of them) can be unsuccessful and can be found worse than old versions. Modular system allows to use new improved modules with good old ones when unsuccessful new subsystem designs do not halt whole improvement of product design. (Schaefer , 1999) On the other hand, developing standard interfaces for modular system can be costly, which can halt modular system improvement. Need to redesign interfaces when improving modular system adds to the cost of remodularization. Remodularization cost outweighing benefits of improved modular system can lead to getting stuck in existing but inferior modular system and halting innovation. This way cost of interface development can lead to path dependency in modularity. Although modularity gives flexibility and ability to handle changing business environment by possibility of module recombination, at some point modular system may need to be redesigned, or remodularized, that can bring significant cost and will render old modules obsolete. (Langlois , 2002; Schaefer , 1999)

Modularity has many clear advantages, but it has also its downsides. Modular systems are not as easy to design as comparable non-modular integrated (monolithic) systems. Designers need to have wide knowledge of system functions to get modules working as a whole. Problems in modular design are easy to be unnoticed when design is ongoing in module level and possible problems tend to emerge only when modules are integrated together, eating up the speed and efficiency gains of modularity by using more time in integration and testing. (Baldwin, Clark, 1997; Ethiraj, Levinthal, 2004; Langlois , 2002) High costs in testing can lead to choosing monolithic design strategy instead of modular one (Schaefer , 1999). As modularity has its advantages and disadvantages, modularity should be seen as tradeoff between its effects. Over eager modularity can bring more downsides than benefits, hence intermediate level of modularity is often most useful. (Ethiraj, Levinthal, 2004; Frandsen , 2017)

Achieving appropriate modular design to complex product can sometimes be exceedingly hard (Ethiraj, Levinthal, 2004). In this regard, Schaefer (1999) notes that "*it would seem unlikely that a firm could ever hope to uncover an optimal modular design partition for a complex product*" and says that this problem arises from the comprehensive information requirements of modular design, where modular design itself is uncovering the needed information. Modular design will likely be difficult even when needed parameters for modular design are well known (Schaefer , 1999).

4. Production types

Value perceived by customer is based on variety of criteria fulfilled by company's capabilities. Many of those capabilities relates to production. Production strategy can be viewed from aspects of competitive priorities (how manufacturing should perform to be competitive in market) and decision categories (how to design manufacturing operations). Competitive priorities related to production include price, quality, delivery speed, reliability, and flexibility. Production strategy defines policies regarding to areas of decision categories, including process, capacity, facilities, vertical integration, quality, organization, production planning, control, and performance measurement. (Olhager , 2003) Regarding to competitive priorities, Hill (1994, p. 30-35) presents concept of order winner and market qualifier criteria. Qualifier criteria are those that must be fulfilled for company and its products being even relevant and possible choice for customers, bringing company to the same line with competitors. Order winners are those criteria that make company to stand out to win order, meaning that company has to perform better than competitor in these criteria. Importance of order winners and qualifiers are specific to certain market and their importance also changes over time with changing market environment.

4.1 Assembly production

Assembly production can be arranged as station assembly or line assembly. Station assembly is suitable for individual and small batch production, while line production is suitable for larger batches and mass production. In station assembly one person or team in one station performs assembly of product. In station assembly similar work is performed in all assembly stations. In line assembly work is divided in phases, where each phase is handled by specialized teams and workstations. Line assembly can also be arranged so that one team is responsible for product from start to finish by moving with product through workstations in assembly line. When assembly is ready, team can move back to start of assembly line and start assembling next product unit. (Tekes, 2001, p. 8-9; Lapinleimu et al. , 1997, p. 112-114)

Station assembly can be very flexible and allows high product variation, where line assembly is not as good. However, disciplined modularity allows line assembly to handle high product variation better. Assembly must be able to be performed smoothly in assembly line, as it is prone to disturbances and errors can stop whole assembly line. Station assembly often leads to long lead times, while line assembly can achieve shorter lead times. As one team performs whole assembly process, all team members should master multiple assembly tasks in station assembly. Other possibility is that team has specialized team members for different tasks, but this can affect negatively to working flexibility and productivity. In line assembly different workstations can be focused on their special competences. Dividing work in phases is more efficient way for assembly than performing assembly from start to finish by single team in one station. One problem with dividing work in phases can be less meaningful work from production staff point of view, that can be corrected by rotating workforce in different work phases. (Tekes, 2001, p. 8-10, 69)

Dividing assembly work with module-based assembly by assembling separate subassemblies for ready state before bringing them to final assembly (also known as preassembly) can be used to reduce final assembly lead times. Related option is to source preassembled subassemblies straight from suppliers. Short final assembly lead time also reduces working capital tied-up for work-in-progress. Preassembly reduces unexpected material shortages and quality errors in final assembly, as these are often detected beforehand in preassembly, thus causing less troubles. Preassembly tends to improve material control as number of items need to direct for final assembly is reduced. Competence level with each subassembly tend to increase significantly when they are assembled is dedicated production cells. (Tekes, 2001, p. 11-12, 69) In Figure 5 is presented example of combining line- and module-based assembly. This example distinguishes larger module preassemblies performed separately, and smaller subassemblies performed near final assembly line.

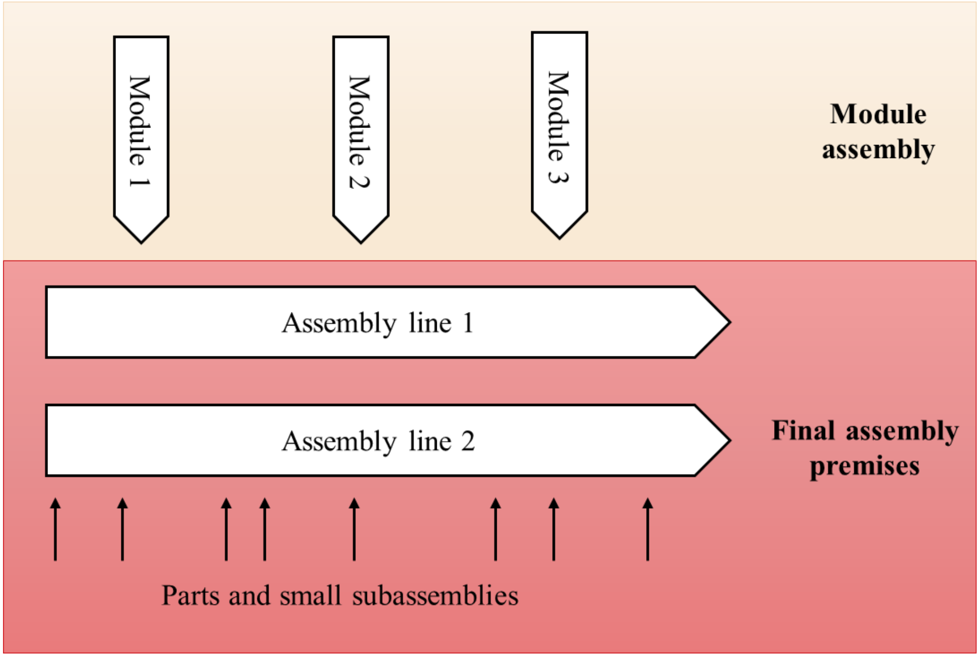

Figure 5. Example of combining line- and module-based assembly (based on Tekes, 2001, p. 10)

4.2 OPP and production types

Order penetration point (OPP), also known as *customer order decoupling point* (CODP), is a stage in products value chain where product is linked to specific customer order (Olhager , 2003; Olhager , 2010; Sharman , 1984). Product specification is often frozen at OPP, and it is often the last and most important stock point in value chain where inventory is held (Olhager , 2010; Sharman , 1984). Delivery capability depends on stock availability at the OPP and capacity availability downstream of it (Olhager , 2010). Driving forces of material flow before OPP (upstream) are plans and forecasts, switching to customer order driven material flow after OPP (downstream). Optimal OPP position for each product depends on balance of competitive pressure, cost and complexity, hence optimum OPP often moves with changing business environment. Competitive pressure gives incentive to move OPP downstream towards customer for better customer serviceability, on the other hand, increasing cost and complexity gives incentive to move OPP upstream away from customer. (Sharman , 1984) In entire interconnecting supply chain there is typically one dominant OPP.

From company perspective, OPP can be positioned inside company's own operations, within suppliers or even customers, or somewhere in between. (Olhager , 2010)

Different manufacturing strategies are related to positioning of OPP. From this point of view, production strategies can be divided to Engineer-To-Order (ETO), Make-To-Order (MTO), Assemble-To-Order (ATO), and Make-To-Stock (MTS) (Haug, Ladeby, Edwards, 2009; Olhager , 2010). Relationship of these manufacturing strategies to OPP positioning is illustrated in Figure 6. In ETO, engineering and design work is carried individually for each order, while other types do not include design work after OPP. In extreme form of ETO, whole design is done based on order. In MTO engineering is already done before customer order but the production itself starts after OPP. ATO extends OPP to production operations as production is already started (components or subassemblies are made to stock) but not finished when order arrives. In MTS products are made and sold from end product inventory. At the extremes, ETO is purest form of customization while MTS is the mass production approach. MTO and ATO lie in between, being the approaches for mass customization. (Haug et al. , 2009; Sharman , 1984)

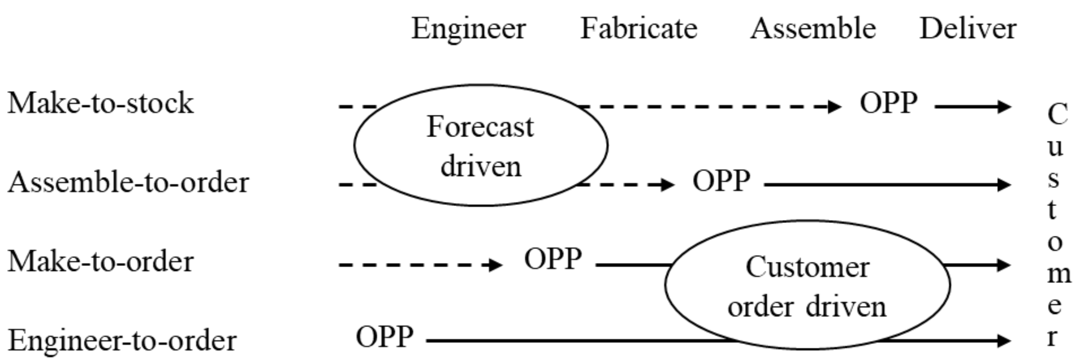

Figure 6. Different order penetration points and related manufacturing strategies (applied from Sharman 1984 and Olhager 2010)

According to Jenssen et al. (2012) production types can include also Configure-to-order and Modify-to-order strategies that lie between pure ETO and MTO, as Configure-to-order strategy relies standard parts and modules that are configured to whole product based on customer requirements, while Modify-to-order strategy relies in generic “technical platform” that that can be modified on customer preferences. Configure-to-order is almost like MTO but with small extend to ETO, as almost all design work is done before order. In Modify-to-order more design work must be done based on order, while still large part of design work is done in advance.

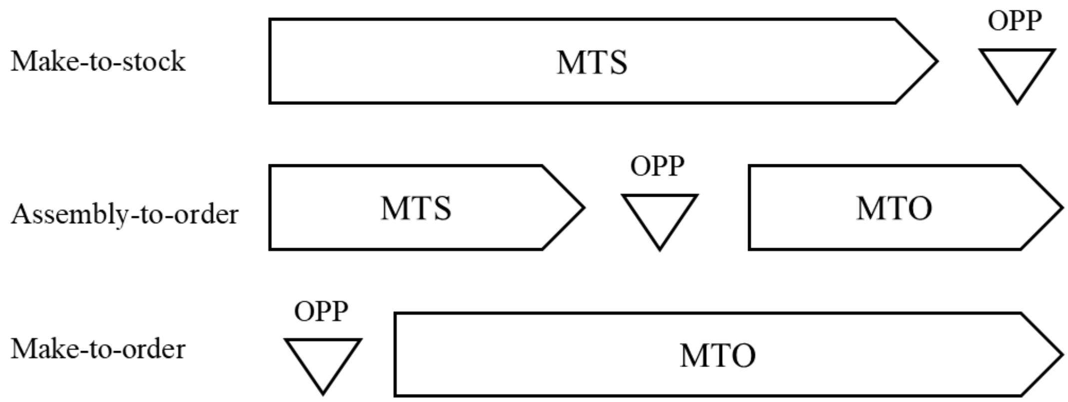

Figure 7. OPP relation to MTS and MTO policies from production material flow point of view (Olhager , 2012)

MTO and MTS are the fundamental types of production from material flow point of view, where MTO includes ETO situations, while ATO is combination of both MTS and MTO, separated by OPP (Olhager , 2012). This is illustrated above in Figure 7. OPP can also be seen as breaking point of lean (i.e. efficient) and agile (i.e. responsive) supply chain approaches, where lean supply chain fits better in upstream of OPP (or MTS) and agile supply chain being suitable for operations downstream of OPP (or MTO). Production process flexibility is needed to handle MTO situation. In MTS aggregate level planning (also known as sales & operations planning or S&OP) is typically based on level strategy, where capacity loading is kept in steady and high utilization state without much flexibility, while fluctuations in demand are absorbed by other measures, such as keeping inventory. This is related to lagging capacity in relation to demand. Typical MTO aggregate planning strategy is chasing (trying to meet) demand with production capacity flexibility. In MTO production capacity typically leads demand and has buffer to effectively respond for fluctuating demand. (Jamalnia, Yang, Xu, Feili, 2017; Olhager , 2003; Olhager , 2010).

Some common attributes relating to upstream and downstream of OPP are presented in Table 2.

Table 2. Common attributes relating to up- and downstream of OPP (Olhager , 2003; Olhager , 2010; Olhager , 2012)

	Upstream of OPP (MTS)	Downstream of OPP (MTO)
Supply chain design	Efficient Lean	Responsive Agile
Demand	Predictable	Unpredictable
Product characteristics	Standard High volume	Customized High variety
Key performance focus	Productivity Cost reduction	Flexibility Lead time reduction
Production process	Line production	Job shop
Capacity	Lagging demand High utilization	Leading demand Buffer capacity
Aggregate planning (S&OP)	Level planning	Chasing demand
Demand fulfilment	Based on stock availability	Based on lead time together with capacity and material availability
Master planning	Replenishing inventory at the OPP	Delivery planning of orders with respect to capacity

In MTS and MTO related situations value is typically perceived differently by customer, meaning that order winners and qualifiers are typically different in MTS and MTO situations. In MTS price is typically the main order winner, while quality, delivery speed and delivery reliability are often market qualifiers. In MTS flexibility criteria does not often have much weigh. In MTO order winners are often related to flexibility, qualifiers often being delivery and quality. Price often has not much weigh but can also be qualifier. With some MTO products price is not real criteria at all. (Olhager , 2012) Typical competitive priorities related to MTS and MTO are presented in Table 3.

Table 3. Typical competitive priorities related to MTS and MTO (based on Olhager 2012)

	MTS	MTO
Order winners	Price	Flexibility
Market qualifiers	Quality Delivery	Quality Delivery Price (sometimes)

4.3 Factors affecting to production strategy

Olhager (2003) presents impact model of factors affecting to production strategy, illustrated in Figure 8. Impact model reflects how affecting factors flow towards production type and OPP selection, starting from market characteristics. Market characteristics influence product and production characteristics. Product offering with market expectations determines delivery lead time requirements, whereas production lead time is determined on product and production attributes. All these interact together to determine production type and OPP selection. It is noted that relationship of delivery and production lead times is major determinant of OPP position.

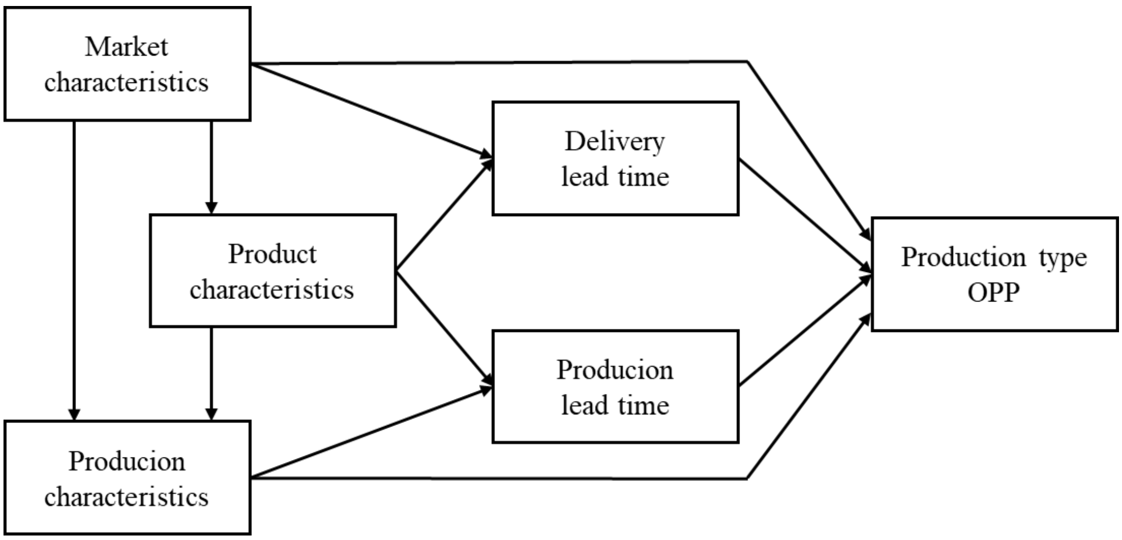

Figure 8. Production strategy impact factor model (Olhager , 2003)

4.3.1 Volatility and differentiation

Demand volatility (that is often highly correlated with demand volume) affects positioning of OPP, as low volatility allows to drive production based on forecast. Products with high demand volatility are more difficult to forecast, making them more reasonable to be produced to order. Demand volatility tend to be high in initial stages of product life cycle when volume is low, and volatility coming down as volume increases. Customer order sizes and order frequency affect demand volatility as large order sizes and low frequency tend to increase volatility. With wide variety of products and customization requirements, it might not be feasible to keep OPP near customer, especially when differentiation affect in early phase of production, when MTO strategy might be necessary. Differentiation entering to products in late production phase can make ATO better choice, this being often related to modular product design. With narrow variety products and customer choices even MTS strategy can be feasible. (Olhager , 2003)

4.3.2 Lead times

Market requirements of order to delivery lead time restricts how far away from customer OPP can be positioned, where production lead time have major role. Delivery lead time and production lead time relationship plays important role in OPP positioning. Product structure complexity and depth can lead to long lead time in production. Lead times of various manufacturing paths of complex product structure should be analysed relative to delivery lead time requirements to determine where OPP and in-process inventories should be held. If production lead time is the major factor that can constrain OPP positioning, reducing production lead time can wider the range of potential OPP alternatives. Order delivery time being order winner, OPP should be positioned closer to customer than competitors do, to gain advantage in order winning criteria. Customers expecting rapid delivery times can even force company to use MTS strategy. (Olhager , 2003)

4.3.3 Bottleneck

Positioning of OPP relative to production bottleneck have contradictory propositions. Need to deal with volatile demand and high product variety undermines the use of scarce bottleneck resources, suggesting that OPP being downstream of bottleneck (meaning volatility and variety are handled after the bottleneck) is advantageous from resource optimisation point of view. Tight capacity downstream of OPP means also that volatile customer demand will transfer to volatile delivery lead times. From Just-In-Time (JIT) point of view, that focuses on elimination of waste, bottleneck should work based on real demand (customer orders) to eliminate unnecessary work and stock. This suggests that OPP should be upstream of bottleneck to allow bottleneck with straight contact to customer orders. Bottleneck is good reference point for positioning OPP near it, especially if bottleneck resource is expensive and significant part of the production process. (Olhager , 2003)

4.4 Positioning Order Penetration Point

Positions of OPP in production are restricted by planning points of production process, where planning points are single entities of production resources from capacity planning point of view. Appropriate positions of OPP are before or after each production resource (can be seen also as production phase). In line production the production line can be regarded as single resource that offers OPP positions only before or after the production line process. In contrast, there are more possible OPP positions in job shop type of production, that includes more individually planned resources. (Olhager , 2003)

Changes in market and thereby competitive priorities, should be reflected in OPP positioning, where decision to change OPP positioning should be strategically motivated and strengthen competitive priorities. For changes in delivery lead time preferences this is especially relevant. For example, if delivery lead times gain more weight as order wining criteria, this knowledge can be utilized to shift OPP downstream to reduce delivery lead times, the other option to gain the same result being production lead time reduction. Overall, lead time reduction is one of the best ways to make progress in competitive priorities. Giving more opportunities to OPP positioning, reduced lead times can be utilized by moving OPP upstream, while able to keep delivery lead times the same, or keeping OPP position the same and gaining advantage from reduced delivery lead times. (Olhager , 2003)

Besides reducing delivery lead time, other main driving force for moving OPP downstream, is intention to improve production efficiency. Shifting OPP downstream requires prefabrication of components or subassemblies, often by implementing modular product design, leading to ATO type production policy. (Olhager , 2003)

Driving force for moving OPP upstream is often associated with intentions to gain better insights of real demand at the time of production, better allowing variety and customization and reducing work-in-progress (WIP) inventories. As said, reducing downstream lead times can be used as means to gain ability to move OPP upstream. This allows keeping delivery lead time preferences and same time being able to perform greater production activities during delivery lead time. (Olhager , 2003)

With varying demand, especially with seasonal demand, it can sometimes be reasonable to alter production strategy according to current demand, making products to stock when demand is low, if peak demand is anticipated in near future. This way production volume can be levelled, and capacity utilization rate increased. Similar strategy can be applied to produce parts or subassemblies of end products when demand is low and assemble them to end products when demand peaks hits, allowing shorter lead times for customer orders. In this strategy parts and subassemblies made to stock should have high work content and long manufacturing time relative to material content, to get sufficient time savings in customer order delivery. (Olhager , 2003)

4.5 Selecting Production type

Selecting appropriate production type can be compacted as relationship between two main factors in 2x2 matrix to four basic situations, seen in Figure 9. Main factors presented include ratio of production and delivery lead times (P/D ratio) and relative demand volatility (RDV). In P/D ratio production lead time (P) indicates what the lead time ability actually is, while delivery lead time (D) indicates what are the market preferences and desire for lead time. P/D ratio indicates if production can be completed inside desired delivery lead time. P/D ratio being over 1, production takes more time than desired delivery lead time indicates, meaning that at least some production phases should be done based on forecast upstream of OPP. P/D ratio being less than 1, all production phases can be done in desired lead time scope, meaning that production can be customer order driven. Other main factor is RDV, indicating demand volatility (standard deviation) relative to average demand. Both factors can have high or low value, P/D ratio having the critical value of 1, while RDV value is more relative, where definitions of high and low RDV values differ by context. (Olhager , 2003)

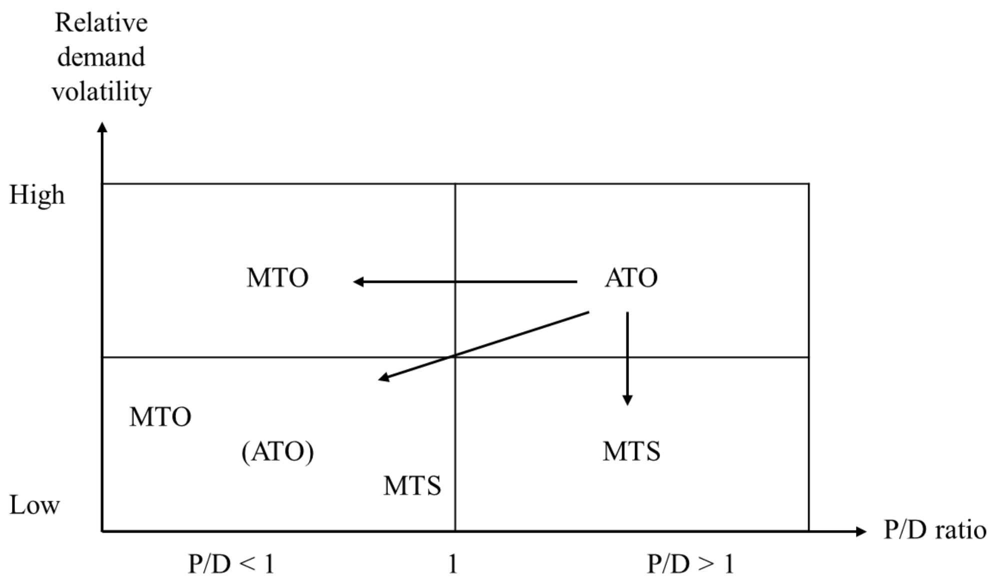

Figure 9. Production type selection dependence on volatility and production to delivery lead time ratio. Decoupling and repositioning of individual production operations in ATO situation is illustrated by arrows. (Based on Olhager 2003)

P/D ratio being under 1, MTO policy is possible. If demand volatility is also high, MTO is preferable choice (upper left corner of matrix). Low demand volatility however allows more options, making possible to utilize economics of scale with more efficient production types (lower left corner). Even MTS policy can be used if RDV is low and high productivity is needed. Other option is that MTO and MTS policies can be mixed, producing some items to stock and some items based on orders, resembling ATO. (Olhager , 2003)

P/D ratio being over 1, MTO policy cannot achieve desired result, meaning that production must start before customer order arrives and at least some items must be produced to stock (or WIP inventory), based on forecast. If demand volatility is low, MTS policy is preferable choice (lower right corner). (Olhager , 2003)

Demand volatility being high, MTS policy would lead to excessive inventories. Restriction is that items made to order must have P/D ratio less than 1 (their production must fit in delivery schedule). Items for which this is not the case, and RDV also being high, are problematic because they add up excessive inventories if made to stock. In this situation ATO is best choice (upper right corner), being able to deal with both high demand volatility and strict delivery lead time preferences. (Olhager , 2003)

MTO and MTS policies are mixed in production material flow of ATO. This is good when it is important to find good balance between excessive inventories and economics of scale. Inventory must be kept in some point, indicating that fine tuning of OPP is important part of ATO. Optimum point for inventories (and OPP) would be point where variation is relatively small, lower volatility often coinciding with higher volumes. Individual item volumes tend to decrease when going product structure up towards ready end product, meaning that MTS policy becomes more feasible in upstream production operations. When splitting ATO with OPP, MTO policy is used downstream, and MTS policy upstream of OPP. With good positioning of OPP, MTO part of operations can be fitted in delivery time scope. MTS and MTO policy relation to OPP, and partitioning ATO by OPP to MTS and MTO is illustrated in Figure 7. As ATO can be seen as combination of MTS and MTO, it can be thought that in ATO situation production phases are decoupled and repositioned from upper right corner (high volatility and P/D ratio over 1) to more reasonable positions in Figure 9 matrix (illustrated by arrows). Then individual production phases can be handled with MTS or MTO principles. (Olhager , 2003; Olhager , 2012)

5. Current state

Current state of case company's operations from production development perspective was examined to allow further exploring of development opportunities. Key questions regarding current state were the following:

1. What kind of production model is in use?
2. What are the main factors affecting to production model choice? (Business environment and market positioning)
3. What are the readiness and conditions for assembly-to-order based production from product development perspective?

Current state was examined through interviews and material found from case company. Discussion and interviews covered case company's personnel from production and product development functions.

5.1 Case company and scope

Case company is machinery enterprise operating in Business-to-Business markets aiming to offer complete solutions for specified customer processes including equipment, services and other related products. Case company's revenue magnitude is 300-400 million euros. It has specialized to few selected product lines, representing offering to specific customer processes. Equipment manufacturing consists mostly of heavy process vehicles. Case study focuses on new equipment manufacturing of heavy process vehicles in specific product group having battery electric driveline (illustrated in Figure 10). The other and more traditional option being diesel driveline. The battery electric vehicle (BEV) product group acts as an example, from where applicable study results can possibly be extended to other product offering. Case company has few equipment manufacturing facilities globally. In this case study, production operations current state focus is on main production facility, accounting to most of company's total throughput of new equipment manufacturing and all manufacturing of BEV product group under consideration.

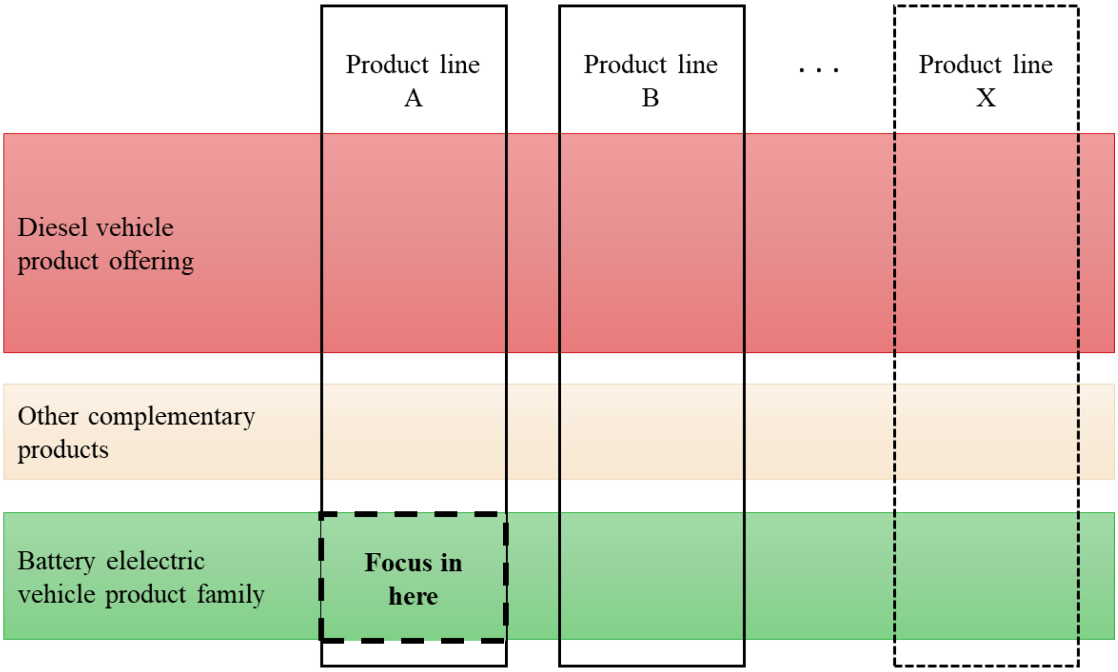

Figure 10. Case company's equipment product offering and scope in case study.

5.2 Business environment and market positioning

Case company's equipment product offering has wide variety of standard products and individual products are highly customizable. This leads to high variation in products. Case company has production volume of few hundred units annually, despite still being big player in its field. Price range for equipment offering is roughly 100k € - 1000k €. Differentiation among end products is driven from standard product selection and from vast variety of customer selectable standard options and their variations (illustrated in Figure 11). In addition, there is also possibility to non-standard options and customizations.

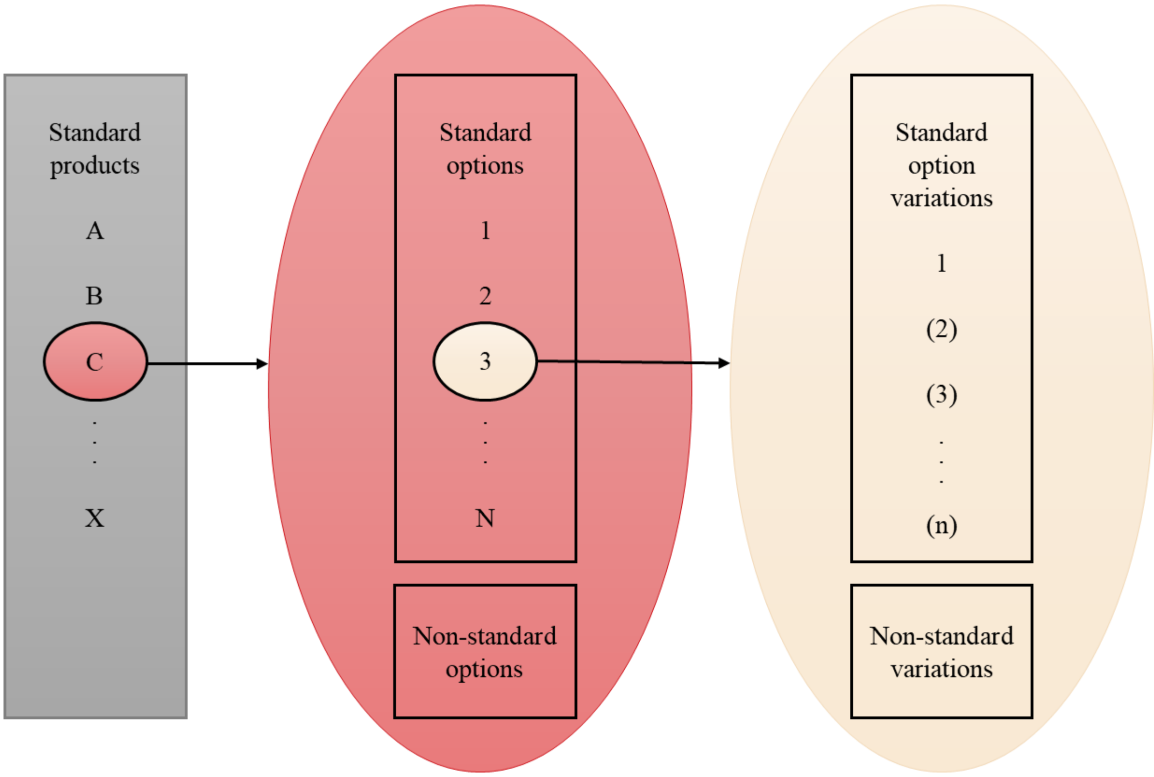

Figure 11. Levels of differentiation among end products

Case company's market environment has high demand volatility. Main competitive factors are quality (including support and technical capabilities of product), flexibility in terms of customization, delivery lead time and price, while weight of these factors varies depending on customer segment and specific customer need. In high demand situations when equipment manufacturers have had difficulties in responding to demand, lead times and availability have become more important order winning criteria. Company positions in higher price end of market as technological forerunner.

5.3 Production operations

Production operations inside company are focused to product assembly. In-house part manufacturing operations mainly includes the frame manufacturing. Production phases include frame manufacturing, preassembly, final assembly, and finishing & testing. Final assembly has been organized to one assembly line and multiple station assembly stations. For each product, final assembly is performed in line assembly or in one of the assembly stations. After frame manufacturing is ready, components and subassemblies for final assembly comes either straight from suppliers or through preassembly. The planned bottleneck of production is situated in final assembly capacity. Bottleneck can sometimes be formed in finishing and testing phase. As final assembly is defined as main production bottleneck, factory loading is planned based final assembly capacity. Capacity of final assembly line and stations are managed individually by queue control. Production phase arrangement is illustrated in Figure 12.

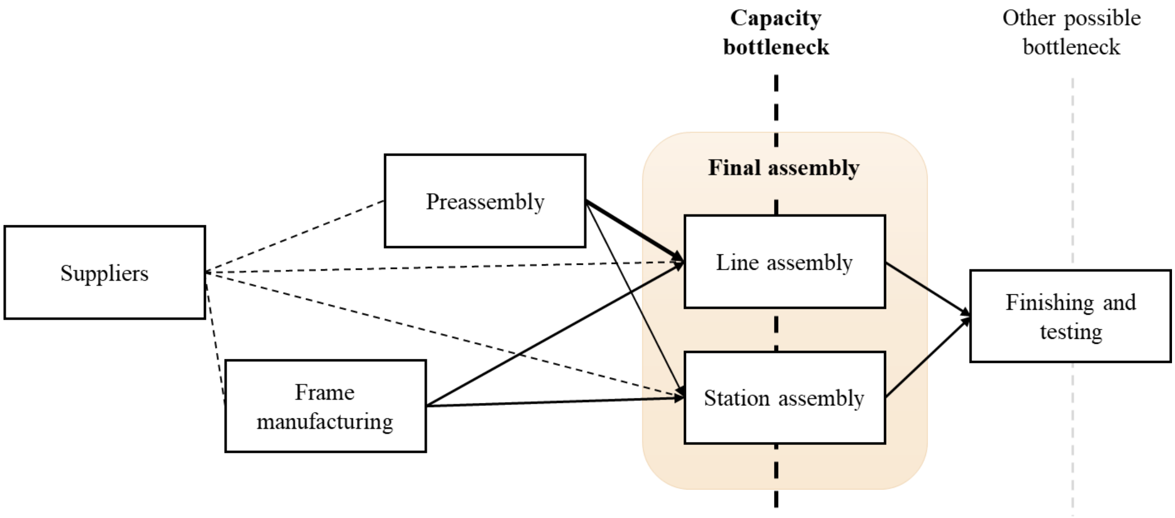

Figure 12. Arrangement of production phases

In addition to internal assembly work, company has also subcontractors conducting end product assembly. Subcontracting handles the whole assembly work that is equivalent to work conducted in-house by pre- and final assemblies. Components are sent to subcontractors through case company’s perimeter (roughly 95 % of components) or straight from suppliers (5 %). In assembly subcontracting arrangement frames are manufactured and final testing is made in-house. Assembly subcontracting arrangement is illustrated in Figure 13.

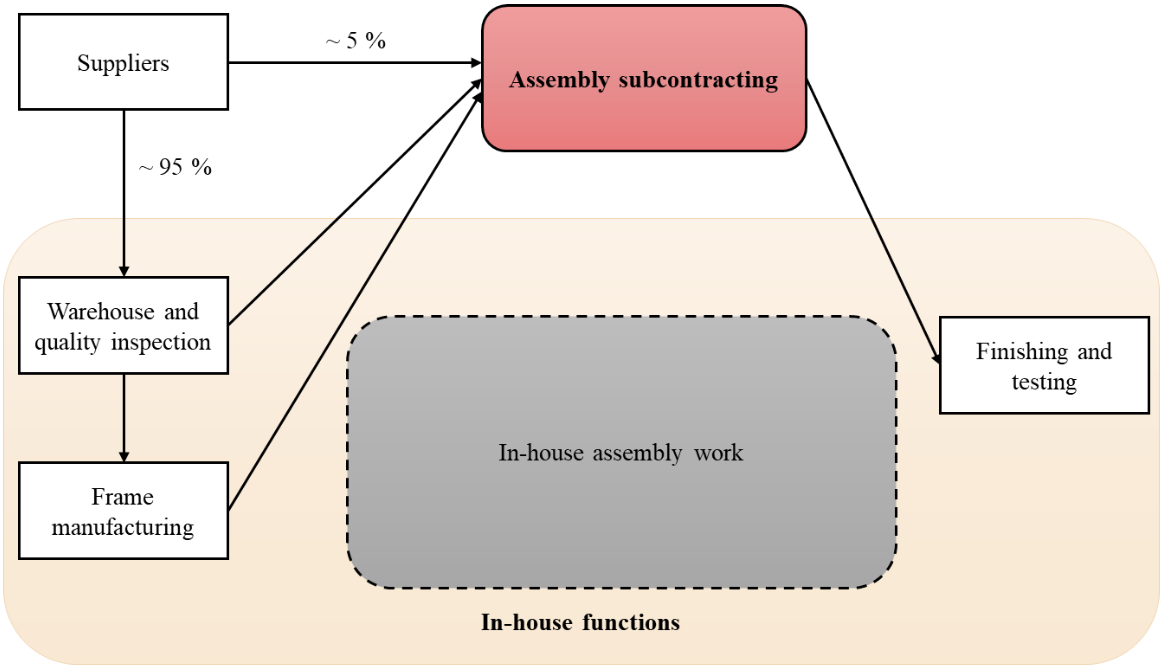

Figure 13. Arrangement of assembly subcontracting

5.3.1 Final assembly

Final assembly elements have different properties and roles. Line assembly is the most rigid element, whereas subcontracting is important flexibility element in overall assembly capacity. Station assembly has more capacity flexibility than line assembly, as number of assembly stations can be more easily increased or reduced. This is still relatively slow process and station assembly has much more limited ability to add for capacity flexibility than subcontracting. Both line assembly and subcontracting work best when loading them with machines having high similarity, and that are simple to assemble, meaning that these capacity elements can handle only part of whole product offering. Bringing new type of product to subcontractor's competence portfolio always takes extra time and effort. Station assembly is the most flexible element in terms of competence and product differentiation, being able to handle the whole product offering. Station assembly loading emphasizes complex and highly customized products, solely handling unforeseen special and development phase products. From productivity and efficiency point of view line assembly have been proved to best and has the shortest assembly lead time. Station assembly can at is best to same assembly lead times as line assembly. This depends significantly on assembly teams’ competence, but overall station assembly is less productive than line assembly. Subcontracting is most expensive and time-consuming assembly capacity element. Summary of final assembly elements and their main properties is presented in Table 4.

Table 4. Properties and roles of different final assembly capacity elements

	Station assembly	**Line assembly**	**Assembly subcontracting**
Capacity flexibility	Moderate but limited	Low	Main element
Flexibility on variety and disruptions	High, adaptable to changes	Low, best with simple and standard products, vulnerable to disruptions	Low, best with simple and standard products
Product range	Whole product range, handles complex and special products	Few selected product types	Many of standard products
Efficiency and assembly speed	Moderate to high	Highest	Lowest

Station assembly has been the traditional method for final assembly in case company, whereas line assembly is relatively new. Idea for line assembly was to ramp up productivity for basic and simple end products. It was first designed to handle one single product group with relatively high volume and simple products. Problem still raised was that line assembly did not have enough volume, and for now line assembly is used also for other products that are relatively simple and fast to assemble. Product scope expansion has still led to variation in simplicity and assembly time of products loaded to line assembly. Line assembly is now planned so that it should always have enough load from suitable customer orders, but sometimes it still needs to be loaded with non-optimal (more uncertain and longer assembly time) products. These factors affect so that line assembly has often disruptions caused by problematic products and line slows down due to longer assembly time needed for some products. Despite line assembly is the most rigid element of assembly capacity, it also needs some flexibility to handle variation and disruptions. Problem for loading line assembly and subcontracting is that both of them are best loaded with simple and standard machines, meaning that line assembly and subcontracting kind of compete for the same production load. This leads to situation where both line assembly and subcontracting must be loaded with non-optimal end products for them, leading to disruptions, lower productivity and longer assembly lead times. Line assembly is still relatively small part of whole assembly capacity, accounting roughly ¼ of in-house final assembly throughput, and less for whole capacity including subcontractors. Few interviewees mentioned that another assembly line is seen as most realistic opportunity to expand line assembly. Another line would be fine-tuned for product with one degree longer and more complex assembly work as the original line would continue to serve fastest assembly products.

5.3.2 Preassembly

Preassembly is important way to reduce the amount of work in final assembly, thereby increasing final assembly throughput capacity and reducing final assembly lead times. By this, it has effect to production bottleneck in final assembly. In preassembly, components are assembled to subassemblies in dedicated preassembly stations, and are then delivered to final assembly. In-house preassembly is not included for end products made in subcontracting and subcontractors plan their own set-up to carry out assembly. Preassembly is tightly integrated to line assembly, balancing and supporting efficient operation of line assembly. Line assembly capacity adjustment mostly relies on preassembly, as line production throughput can be increased by increasing preassembly contribution, and respectively decreased by the opposite. Preassembly work management has not systematic planning and it is mainly managed by ad hoc measures. Preassembly is used more with line assembly than with station assembly. One main reason for that is steadier need for preassembly in assembly line, making capacity management for preassembly easier. Station assembly can have huge variations in need for preassembly, which can easily lead to capacity shortage and overcapacity situations in preassembly. One opinion emerged in interviews was that from capacity management perspective preassembly work is in many cases better to manage by final assembly stations, rather than using dedicated preassembly capacity, in situation when volatility for preassembly need is high. As more flexible component, station assembly can manage continually changing amounts of preassembly contribution.

During high demand, preassembly becomes other bottleneck factor by limiting final assembly throughput. In high demand preassembly work is maximized within line assembly and preassembly might not have enough capacity to make all subassemblies possible for station assembly, thus station assembly cannot achieve its best possible throughput. Increasing preassembly capacity would be straightforward solution, but in production this is felt problematic. There comes the problem with managing capacity in volatile demand, and overcapacity if demand plummets. Overall, preassembly and its management are seen with lots of development potential and possible unutilized benefits.

5.3.3 OPP positioning

Most common production type for standard products with standard customizations can be classified as MTO or Configure-to-order. Company’s own production normally starts many weeks after customer order is received. After order is received, it is configured for end product structure, and bill of materials is gathered, which is fast and straightforward process for basic products. Often most of the time between received order and moment when production can possibly start, must be reserved for sourcing needed materials. Some basic components are held in buffer stock, but components and subassemblies are mainly purchased from suppliers based on customer orders. This means that OPP is positioned within suppliers, upstream of company’s own production operations. Some long lead time components must be purchased based on forecast even if they are in other ways non-optimal for keeping in stock. There is the risk of needlessly adding up costly components in stock, probably sitting there for long time. Cooperation is done with suppliers to secure needed materials and enhance suppliers’ delivery ability. Normal procedure is that material forecasts are sent to suppliers. Material forecast has been obtained through material requirements planning (MRP), that itself is based on sales forecast and supply plan of end products.

Sometimes products are made to stock. There are some guidelines for stock making policy, but MTS production cases are mainly individual decisions based on current assumptions of demand and view of production capabilities. For MTS produced end products often happens that they are sold before they are ready from production. Number of products sold from end product inventory is small.

Production has some aspects of utilizing modularity, as gaining higher productivity by using preassembly to assemble smaller modules or subassemblies before they are joined together in final assembly. There is still not modular thinking combining design and production, as possible subassemblies are determined after structures are brought to production and design work is already done. There is no experience in case company of utilizing modularity for ATO type production.

Special customization cases require engineering work and in these cases OPP positioning represents ETO (or more exactly Modify-to-order). Overall, production can be classified mostly MTO, with some cases of ETO and MTS production. OPP positioning in case company is illustrated in Figure 14.

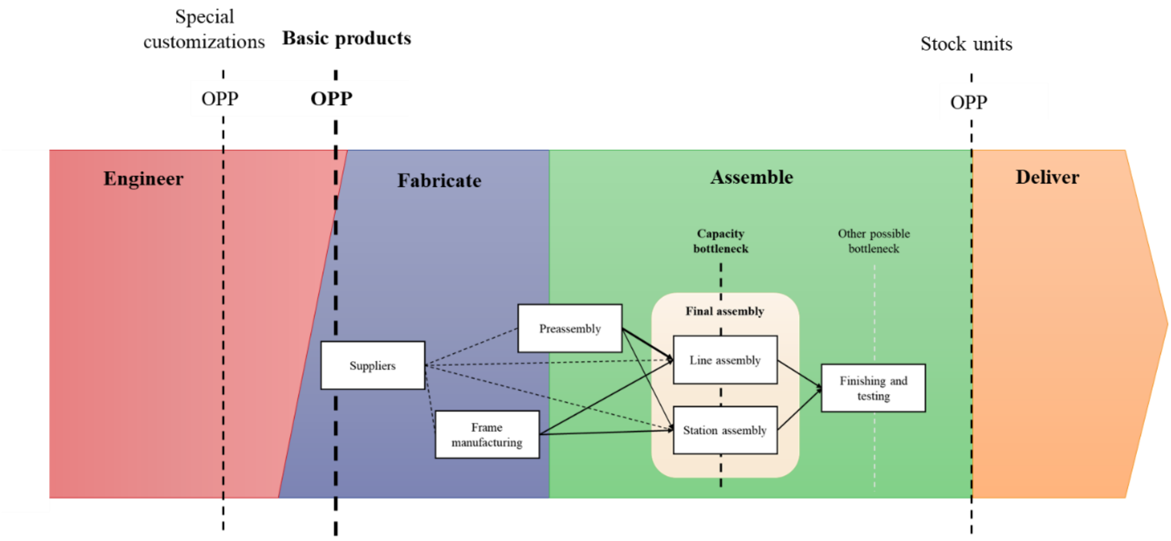

Figure 14. Rough categorization of OPP positioning in case company

5.4 State of product development and modular design

In case company modular thinking in product development started to properly show up over decade ago, as new product generation was developed. Old generation machines were highly unique, engineered by customer requirements. New generation machines had more standard parts and standard interfaces and these structures have since improved further during their life cycle. This have made customization options more standard and have allowed the change from mostly ETO type production to more MTO like production. Despite the standardization and modularization effort for new product generation, product customization and differentiation come into play in early phase of production. In addition to standard products and customization options, special customizations are still widely offered for customers.

During last few years in PD, one of the biggest efforts have been development of brand-new BEV product family. It is said that modular thinking has been included from the beginning in development of BEV product family.

Despite modularization idea has clearly been present in company for a while, it still seems that there is not common clear picture what modularity means, what it aims for and what are the benefits. Because of this and the fact that modular design work is in many cases more laborious, designer do not have good incentives to do proper modular designs. When product design lacks consensus and common policy for modularity, designers in PD make their decisions based on their own view, that might be conflicting.

In discussions with many persons in production and PD emerges the opinion that cooperation with production and PD is superficial. Cooperation tends to concentrate to improvement of structures already launched to production, while cooperation is weak in early design phase. As production point of view is poorly involved in early design phase, modules might bring real modularity only from designing perspective. From production point of view, intended modules can lack modularity i.e., they can include structures that couple modules too tightly together in production to allow separate manufacturing and other benefits of modularity in production. DFMA approaches used in PD seems to rely on individual designers' knowledge of production and reviewing of 3D models. Overall, it seems that DFMA principles are not widely used in practice.

One problem noted in PD is that there are different owners in PD for common development entities, meaning that they are not handled uniformly. This leads to multiple separate solutions while one uniform solution could be possible, bringing more unnecessary structural variation to product range. Finishing of new BEV products are often done individually in hurry based on first customer orders i.e., designs are finished only after first customer order arrives. In this situation time pressure is often more determinant than achieving modular common solution for multiple products.

5.4.1 Ongoing improvement plans in product development

During last 2-3 years product development processes and organization have faced major reorganization and replanning. Product development organization has been reorganized to have responsible persons and groups for keeping overlook of modularity and product architecture. Aim of reorganization is also to gain uniform handling and ownership of interconnected development projects.

Replanning of processes have included development of product development gate model, being a great effort for standardizing and improving PD processes. Gate model defines what tasks must be done and how related functions of organization (such as production, sourcing or marketing) have to be taken in account in each phase of product development project. Related organizational functions have been involved in gate model development as defining how, what and when issues relating to their own fields must be taken in account in product development project. This means that production staff is involved in every phase of gate model and production point of view is constantly taken in account from very start of product development project. Modularity and architectural aspects are also covered in gate model. Product development gate model is illustrated in Figure 15.

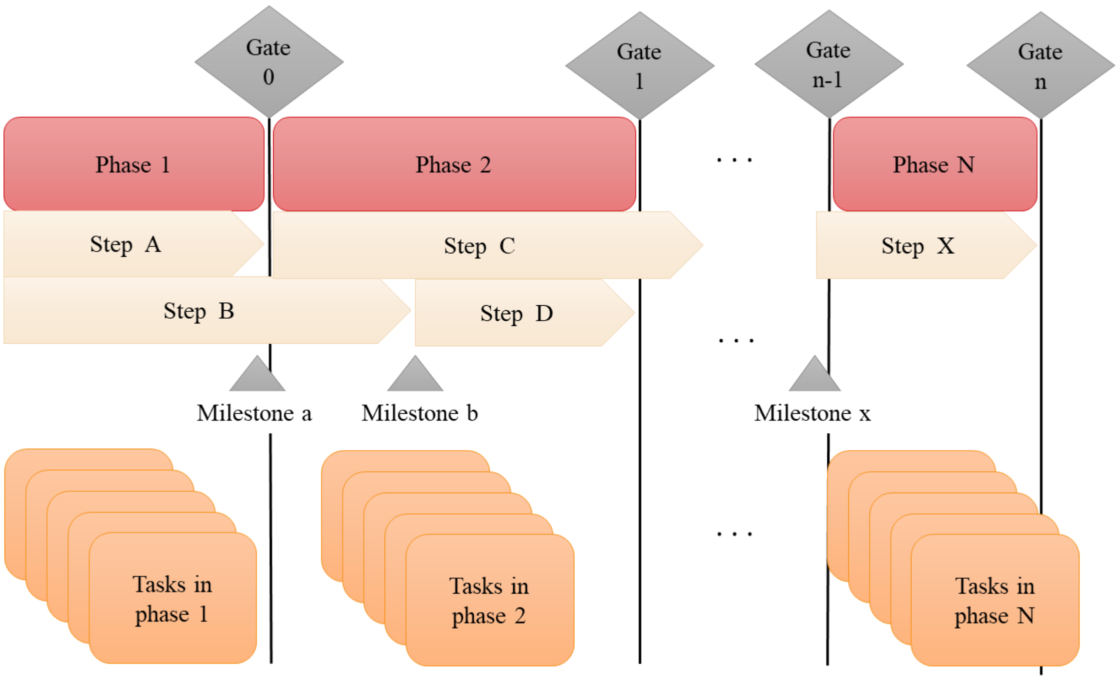

Figure 15. Mock-up illustration of product development gate model

Product development gate mode and organizational changes seem to be capable to tackle many of previously described weaknesses in product development, mainly to improve cooperation between production and PD, and improve the management of modular and architectural design. However, as previously described observations indicate, problems are not yet solved in practice level. This means that PD development plans are not yet widely implemented, or their benefits have not yet been clearly demonstrated in practice level. Development plans include major changes in organizational practises and have been ongoing only short period of time. Gate model has just brought to action and only few first projects are yet launched in accordance with it. It is clear that full implementation of development plans require time.

5.4.2 Modularity level in product group

In case product group, product structure has three main parts in high product structure level: cabin, middle section (front axle and battery pack including high voltage electrics and front drive motor) and rear section (back frame including rear drive motor and machine specific process application). These are higher-level modules i.e., module sets, that itself can include lower-level modules (Figure 16). Lower-level modules can have many different variations.

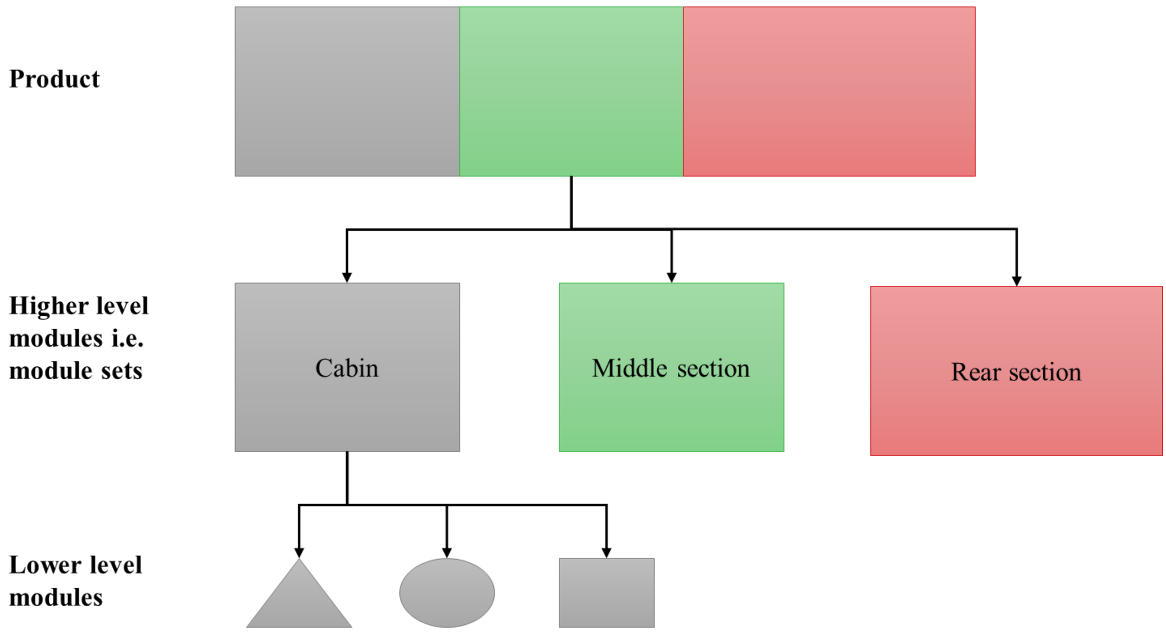

Figure 16. Module levels in product group.

Cabin and middle section are intended to be modular, having common basic structures and more ideal modular structure. Rear section has high variation and less ideal structure from standardization and modularity perspective and may need significant redesign to reach good modularity design level. Cabin and middle section module sets also include many customer specific options that adds up differentiation and brings differentiation to play in very early phase of production. Overall, cabin and middle section modules have more variation than intend was in original design plans. Still, cabin and middle section module sets have potential for ATO type production principles with minor changes in product structures.

6. Discussion

In this part of thesis, possible ATO models and recommendations for case company are presented. Possible ATO models are compared to current production model. Presented ATO models and recommendations are based on observations made in current state analysis.

6.1 Proposed models

Possible models to utilize ATO principles include three models, later referenced as “components in stock”, “assembly in stock” and “final customization”. The first and the second are two different basic ATO situations from OPP perspective. The third model is more comprehensive proposal for assembly process arrangement, in which first two models can be applied.

First option for ATO is to source and store components based on forecast and start assembly when customer order arrives (“components in stock”). Keeping components in inventory means higher working capital relative to current practice, where most of components are purchased based on customer order. If all components are in stock, time taken by component manufacturing and sourcing can be eliminated from order lead time. In ideal situation assembly can possibly be started right away when customer order arrives. In reality assembly capacity availability can greatly affect to when assembly can be started. High order backlog can postpone assembly start longer than component sourcing time would be. In this situation there would be no benefit in terms of lead time from keeping components in stock.

Postponing OPP after start of assembly work is other option (“assembly in stock”). In this model subassemblies and modules are assembled to stock, to wait for customer order. This method can reduce part of assembly time from total order lead time. This lead time reduction comes in addition to lead time reduction by components storage. Ideal “components in stock” and “assembly in stock” models are illustrated in Figure 17.

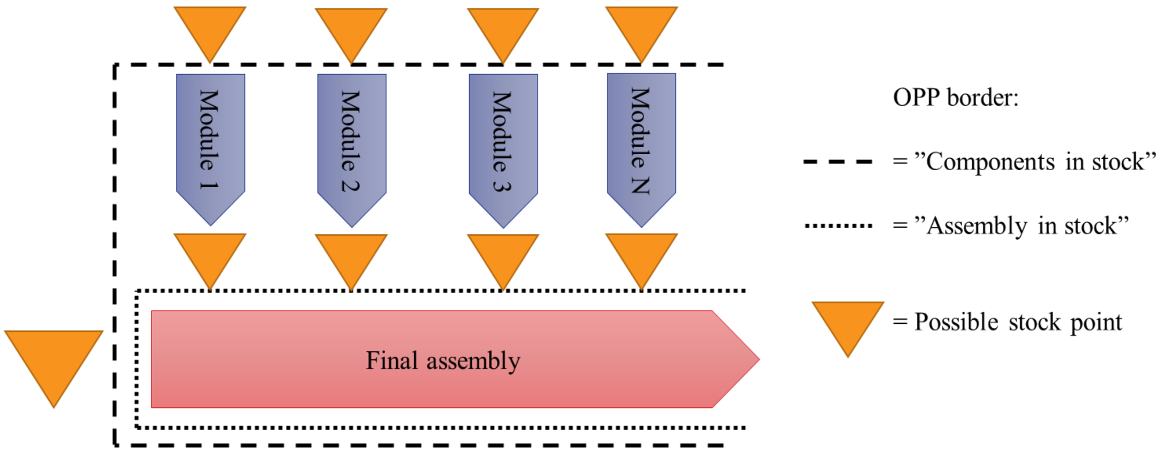

Figure 17. Illustration of ideal “components in stock” and “assembly in stock” models.

Both of presented ATO model variants can be used to achieve more efficient production. In production actions before OPP there is no direct contact for customer orders and less flexibility is needed. In practice assembly in stock model can mean that only some of subassemblies are feasible to be made to stock. This leads to combination of “components in stock” and “assembly in stock” models, where there are stocks of both subassemblies and basic components at the OPP, illustrated in Figure 18. In this situation subassemblies made to stock should be the limiting ones from lead time perspective e.g., those subassemblies that affect the most for lead time. By this way the total lead time can really be reduced. If the limiting subassemblies (from lead time perspective) are not made to stock, there is no lead time benefit from making other subassemblies to stock.

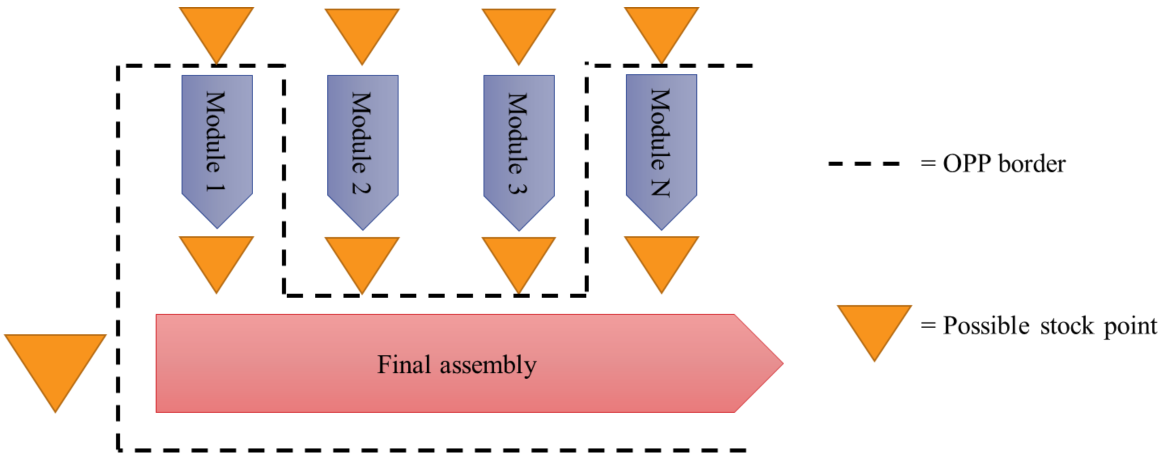

Figure 18. Combination of “components in stock” and “assembly in stock”

As line- and station assembly methods have different strengths and weaknesses, it can be useful to combine these methods. Combining good features of line- and station assembly and minimizing the effect of bad features can possibly be achieved by using combination of both methods. Line assembly can’t handle variation well but is efficient when working correctly. On the other hand, station assembly is good for handling variation but is less efficient assembly method. One solution to combining is to divide final assembly for line assembly phase and final customization phase made in station assembly. This “final customization” model is illustrated in Figure 19. Basic low variation assembly can be done in line assembly, and after that product is moved for final customization, for which station assembly is suitable.

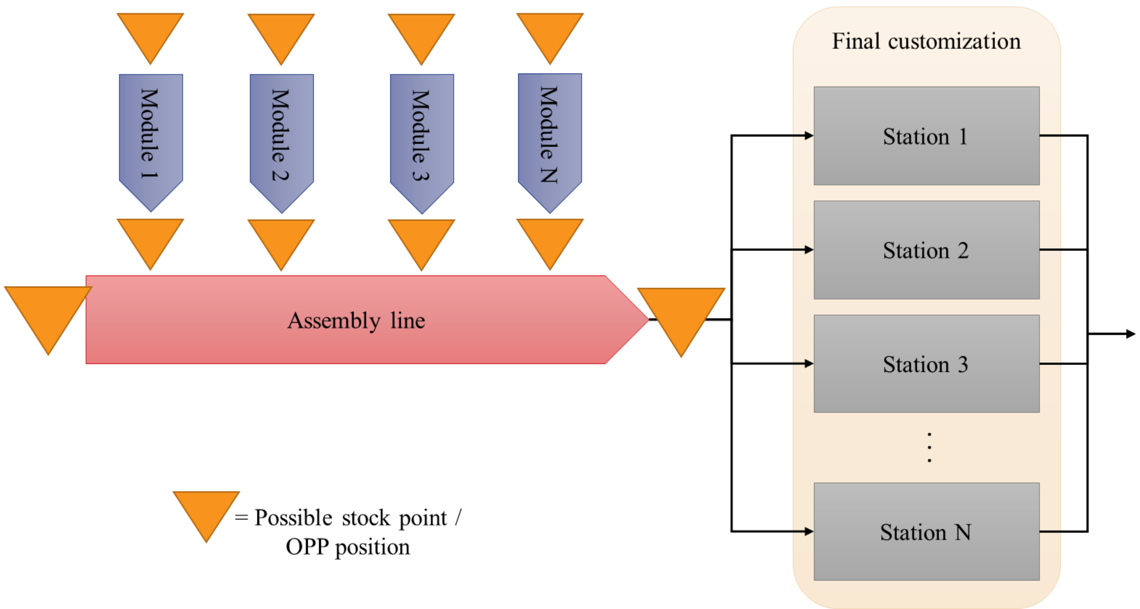

Figure 19. Illustration of “final customization” model. OPP positioning has multiple ATO-type options in stock points illustrated by orange triangles.

Station assembly can be used to handle both whole final assembly and final customizations. Current final assembly stations can be loaded with mix of present style final assembly tasks and smaller final customization tasks. This can make capacity management complicated, as capacity compatibility between assembly line and assembly stations must be taken in account. Mismatch in capacity management or work pace in either assembly line or stations can cause disruptions in station assembly. For example, this can cause waiting time and postpone assembly of other products in station assembly if product coming to final customization is not yet ready from assembly line when it was planned to be. Other option is to make final customizations in dedicated assembly stations that follows work pace of assembly line. This makes capacity management less complicated. In addition to dedicated assembly stations, also other assembly stations can be used to balance capacity in final customizations when suitable.

From ATO perspective the point between line final assembly and final customization is suitable stock point and OPP position. Product inventory can be kept in this point. Product can be quickly finished in final customization if needed components for customization are kept in stock or they are otherwise quickly available. Quickly available capacity is also needed in final customization. This can be achieved by accounting some capacity buffer. Moving unfinished products between different areas inside production facilities can possibly be problematic because products are large and possibly not suitable for moving when unfinished.

6.2 Recommendations

Observations indicate that case company's current mode of operation do not well support move towards ATO. Actions are needed to make move towards ATO more feasible. Some of those actions are also worthwhile in general even without ATO perspective.

First recommendation is to improve cooperation between production and product development and take production perspective better in account in product development. First part of this is to develop DFMA principles further. This can reduce the needed work to be done in production and should be one of the first steps in effort to reduce production lead time. Cooperation development process has already good start with R&D gate model. Its development should be continued with full commitment. Cooperation also means that product development perspective needs to be understanded in production. With suitable understanding of other perspectives, the needed information can flow easier.

Case company should determine what it really wants to offer in basic product offering and what products and options are excluded. Those excluded can be offered in future as the same way as special customizations already are. Cost of complexity and real market and customer needs should be taken in account when defining basic product offering. Real customer need is not always to offer all the options that customer might want, but better solution might often be to offer less customized product with lower price tag and faster delivery.

Based on strictly defined basic product offering, a comprehensive plan for product modularity over the whole product range should be developed. This plan must be clear to everyone in organization in touch with product modularity. With well-defined plan there is clear objectives regarding modularity in every product development project. Future plans should also be taken in account when defining plan for future modular product system. Making the plan consist of assessing what product structures have enough commonality to be designed as standard modules, which are suitable to use over different products and product groups.

Good level of cooperation is a base for move towards ATO. Defining basic product offering and modular product system are based on good cooperation and mutual understanding between production and product development. Because of this, continued development and implementation of R&D gate model is the first step in roadmap towards ATO. This step is worthwhile even without intention to utilize ATO principles, as in any case, good cooperation enables to design product structures better suited to production and gain productivity benefits. Defining basic product offering should be the second step. After basic product offering is defined, based on that should be done the plan for modular product system. Implementing the whole plan of modular product system can be time consuming and costly. Because of this, implementation of modularity plan might be feasible to carry out one product group or other suitable entity at a time. Despite this, modularity plan can be good to make at once for whole product offering to allow best possible overall plan. Implementing modularity plan to actual designs will lead to product structures in basic product offering that are suitable for ATO. Proposed roadmap towards ATO is presented in Figure 20.

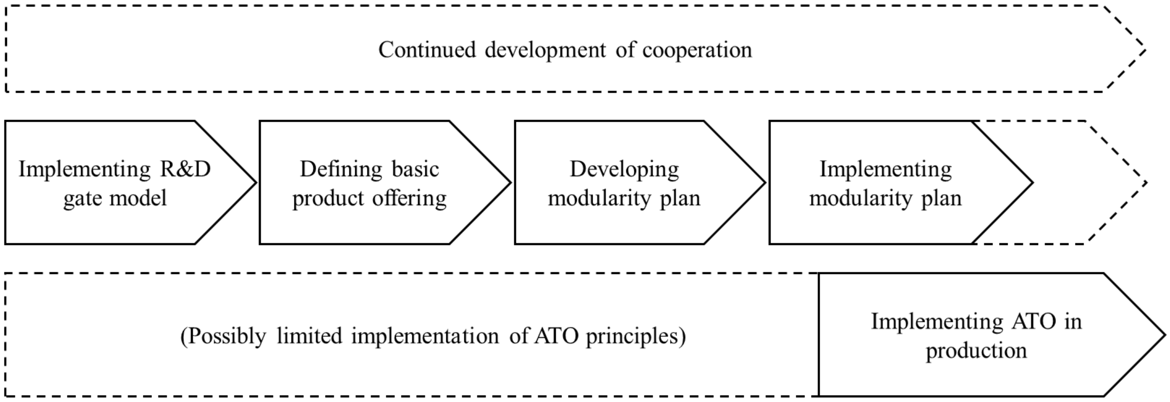

Figure 20. Proposed roadmap towards ATO.

7. Conclusions

Product design is in key position from production development perspective. Product design is a major factor defining how production can be performed and how it can be developed. DFMA principles can be used to enhance cooperation between product development and production, that leads to taking production related issues better in account in product design. Enhancing assembly ease by DFMA principles should be the first step to streamline assembly and reduce assembly lead times before making more comprehensive development efforts, such as assembly automation.

Product modularity is one of main aspects for designing products that suit well to production. Comprehensively designed modular product structures opens more possibilities in production design and planning. Modular product structure allows to use Assembly-to-Order based production type, where OPP is positioned inside production process. Positioning of OPP should be based on business needs, that depends on business environment and company strategy. Design of modular product structures should also follow business needs and allow appropriate OPP positioning. Modular partition of product structures should reflect suitable OPP positioning in production. Moving OPP upstream or downstream have their own effects, affecting to how efficient or agile the supply chain and production can be. One main benefit from postponing OPP is the reduced order-to-delivery lead time. With enough modular product structure system, OPP can be postponed for making change from MTO to ATO, leading to reduced lead times.

In case company was investigated what kind of production model is in use, what factors affect to production and what is the readiness for developing production towards ATO based production. ATO type production is not in use in case company at the moment. Most of production represents MTO or ETO type, with also small amount of producing end products to stock. Production operations of case company focuses on end product assembly. Company’s own operations utilizes line assembly and station assembly methods and assembly capacity is supplemented with use of outsourced assembly subcontracting.

Dominant factors affecting to production are high product variety and need for customization, added by low volume of individual products. Order-to-delivery lead times are long, but they are also seen as major competitive factors. Assembly methods include preassembly. It reduces the amount of work in final assembly, where production bottleneck is located. Preassembly utilizes the ability to partition product structure to smaller subassemblies, representing modular assembly. Preassembly is not systematically managed and suitability to preassembly is not well taken in account in product development.

As previous studies have shown, there is often need to develop cooperation inside organizations, including cooperation between product development and production. This need can also be seen in case company. Cooperation between product development and production have not been well managed, but just recently many actions have been made to improve production development processes. Problem have been that production perspective and needs have not been taken well in account in early product development phase. This has led to situation where product structures are often not near optimal when they are brought to production. Modularity and standardization are themes that have been strongly involved in product development, but still there are not clear wide scale plan about desirable modular product system. Overall product development is more focused on individual design projects than looking product development projects as a whole. This has partly led to unnecessary variation in product structures and poor modularity. To allow well OPP positioning inside case company's production process, production perspective and modularity has to be taken better in account in product design and changes has to be made in product structures. Still there are identified possibilities to move towards ATO type production from product structure perspective.

Case company's new battery electric vehicle product group was in focus from product structure perspective. Despite this the results can be also expanded to other product offering when thinking future actions. ATO type production can be already possible but not especially suitable for current situation. Possible models were presented to show how ATO can work in case company. Recommendations and action plan was presented for case company to reach better suitability for utilizing ATO in production. Recent improvement actions in product development can better the situation and do its part to allow move towards ATO type production. Knowing the potential benefits of modular product structures can also guide decision making in product development.

Role of sourcing was not in focus in this study, but it was identified that sourcing has also significant role when thinking about modularity and ATO. The role of sourcing and suppliers as enabler of ATO type production is one point for future study. Other shortcoming of this study is not clarifying the methods how to determine suitable basic product offering and level of modularity for case company. In relation to these topics there is the need for calculating cost of complexity. That would require information of what are the real amounts of comparable benefits and downsides for case company from delimiting basic product offering, making modular designs, and moving towards ATO. Methods to respond for these issues should be addressed in future work.

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