Streamlining tool design and manufacturing process for balancing and function test equipment to a propeller hub assembly

Effektivisering av konstruktions- och tillverkningsprocess för balanserings- och provkörningsfläns till propellernav

Jimmy Vestlund
“The product development process is the tactical vehicle to convey the business strategy or strategic objectives of improving customer satisfaction, shorten lead-times, and reduce costs through the application of a product family.” (Lange & Imsdahl, 2014)
Acknowledgements

The overall goal of this master’s thesis is for the author to display the knowledge and capability required for independent work as a Master of Science in Mechanical Engineering, Karlstad University. The thesis work was carried out between January and June, 2014, at Rolls-Royce AB’s Manufacturing Engineering Department in Kristinehamn, Sweden.

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Abstract

Rolls-Royce AB in Kristinehamn, Sweden, part of Rolls-Royce Marine, is a leading developer and supplier of water jet and propeller based propulsion equipment. Its low volume production series and wide product variety offered to its customers along with an increasingly competitive market has entailed an increased demand on both delivery time and cost reductions. The on-site manufacturing engineering department is responsible for developing all tools and fixtures, and programming required to maintain the on-site production, assembling and quality testing. As part of the departments streamlining efforts this study aimed on evaluating streamlining possibilities related to the existing tool design used for static balancing and function testing controllable pitch propeller assemblies before packaging and shipping, along with the related tool development and manufacturing processes has been conducted.

The process evaluation started from the point when a hub assembly design was finalized until when a manufactured tool was delivered for use in production. Work focused on locating inefficient activities and product properties, with respect to tool cost and lead time, followed by setting up an amendment proposal, implementing it and producing an alternate tool design of which the effects on tool cost and manufacturing lead time would be evaluated. Post evaluating the current state of the process and product a set based front loaded product development methodology known as Modular Function Deployment was chosen to be the applied method. This application resulted in a modular tool design that avoided the determined most inefficient manufacturing operation combination of welding and annealing. Modularity increased manufacturing flexibility, enabling more concurrent manufacturing, to reduce the lead time. The tool design also applied integral properties by identifying the common components and features between tool sizes. This led to reducing manufacturing and material costs. Possible lead time reduction for manufacturing was determined to be 35-45%, 3-4 weeks, in comparison with the original tool design due to increased parallel manufacturing and avoiding inefficient manufacturing methods. The estimated cost reduction for combined development and manufacturing was determined to be 105K SEK the initial year followed by 175K SEK the second year assuming the current tool manufacturing rate. The combined effects of reduced cost and lead time would be beneficial to Rolls-Royce AB by contributing to an increase in delivery reliability and competitive prices on the market.

Keywords

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### Nomenclature

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1. Introduction
This chapter introduces the master’s thesis by providing a brief background of the Company’s business and the motivation behind why this project is carried out. This will be followed by the purpose, objectives and the research questions of the master’s thesis accompanied by the delimitations.

1.1 Background
Rolls-Royce is a global company focused on providing its customers with high quality and technologically advanced power solutions in a wide range of markets comprised of civil- and defense aerospace, energy and marine. Rolls-Royce Marine is a leading developer and supplier of propulsion equipment. The site in Kristinehamn, Sweden, is considered a center of excellence for both designing and manufacturing of propulsion systems. The site offers customers customized propulsion systems used in applications ranging between offshore, naval as well as merchant sectors. These systems include water jets, pods as well as fixed- and controllable pitch propellers.

Lean thinking throughout the organization entails there to be no prebuilt stocked items but rather the customized system design and manufacturing starts upon the finalizing of purchasing orders from the customers. The customizability of propulsion systems offered to Rolls-Royce clients results in a great variety in manufactured products and components. The size diversification of the sites product catalog along with the usually small series production entails large investment costs for tools and fixtures as well as ever-growing needs for inventory space for the increasing amount of unique tools obtained over time. One varying parameter for the controllable pitch propellers that are designed and manufactured on site is the hub size. During the manufacturing process of these hubs one of the final steps before packaging and shipping includes the static balancing and the hydraulic function testing of the full hub assembly. This function test involves using hydraulic pressure to maneuver the piston up and down, see indicators in the assembly in Figure 1, which in turn rotates the connected crank pin rings and propeller blades. For these tests to be possible a customized dummy flange, an example of which is shown in Figure 1, is required to be fixed to the hub, thereby enabling lift, rotation as well as pressurization of the hub assembly.

Current tool manufacturing of the balancing and function test flanges is estimated to consist of five unique tool setups each year, each of which has a lead time of 16 weeks from the start of design to final assembly. Hub diameters, based on the current product catalog, vary from 60cm to 132cm with a

Figure 1: Schematic representation of how the balance and function test flange is fitted and used. The two hydraulic systems used to change propeller blade pitch are colormarked.
manufacturing cost starting at 107K SEK.

A new generation of low cost controllable pitch propeller hubs, known as A1, along with its associated tools required for manufacturing has been introduced to the Manufacturing Engineering department. As such they’re scrutinizing the current static balancing and function testing tool design along with the tool development and manufacturing process. The purpose being to identify further streamlining possibilities in order to reduce cost and overall lead time for customer orders as well as reducing storage needs for manufactured tools. This is desired in order to meet future production needs and remain competitive in today’s market.

1.2 Purpose and Objectives
The purpose of the study is to evaluate the current tool design and produce a proposal for streamlining the tool design for the function test equipment for the A1-hub assembly. It will also evaluate and propose improvements for the general tool development and manufacturing process of tools used for static balancing and hydraulic function testing of hub assemblies. This will be done by an initial analysis of the current state processes, whereby identifying root causes for any wasteful processes during development and manufacturing. Any process amendments shall be derived from the gathered data. Thereafter the proposed process shall be implemented on the balancing and function test flange tool for the A1 hub assembly. Finally the resulting tool design and process will be evaluated against the current design and process taking into account to overall tool cost, lead time, as well as storage needs for the manufactured tools. Results from both the product and process evaluation shall be summarized in a future state proposal showing any proposed changes and what the anticipated effects are. The proposal shall strive towards reduced cost, lead time, and inventory requirements for tools without having a negative effect on production safety and delivery reliability.

Relevant questions to be answered within the study:

- Current state analysis of tool development and manufacturing of A1 hub balancing and function test flanges
  - Does the process currently contain any unnecessary, time consuming, costly, or in other ways wasteful activities?
  - Does the tool design currently contain any unnecessary, time consuming, costly, or in other ways wasteful activities?
- Product and process amendments
  - Can any process amendments be implemented to reduce overall cost and lead time?
  - How can tool design amendments on the A1 hub assembly balancing and function test flanges reduce tool cost, lead time, and tool based storage needs?
    - Design features, manufacturing method, and material selection shall be taken into account.

1.3 Delimitations
The scope of the paper focuses on tool design, tool development process and manufacturing process of the described test equipment. The parts of the organizational process that’s covered within the study’s evaluation stretches from the point where a hub design is developed, when it reaches the Manufacturing Engineering department whom starts the tool development process on to when the tool is manufactured, assembled and delivered for use in the production facilities. Within this specified part of the process the paper will be comprised of evaluating the information
transfer/management, the self-made manufacturing as well as the outsourced manufacturing process. The expected outcome shall be a new tool development and manufacturing process and a proposal for new tool design for the balance and function test flanges for the A1 hub assembly. This proposal shall contain a tool cost comparison and a comparison of lead time for manufacturing as well as storage needs.

2. Frame of Reference
The frame of reference starts by providing a summary of the lean thinking philosophy and the basic principles of it. Thereafter results from best practice as well as research related to concurrent engineering (CE) and set based concurrent engineering (SBCE) and their relation to lean product development (LPD) are summarized. The different phases of LPD are thereafter accounted for before a detailed process description of implementing the product development method known as Modular Function Deployment (MFD) is provided.

Despite more than 20 years of research focused on developing principles and practices aimed at increasing efficiency and effectiveness of product development there is still a lot of unanswered questions on the subject. What has been shown, drawing from years of best practice, is that a vital aspect for increasing engineering efficiency is concurrent engineering. A currently leading approach for product development, which incorporates this, is called Lean Product Development which has its initial inspiration from the works by Womack and Jones et al. *The Machine that Changed the World* (Womack, et al., 1991), and *Lean Thinking: Banish Waste and Create Wealth in Your Organization* (Womack & Jones, 1996). Their studies of the Toyota Production System, its values and principles initiated a revolution in manufacturing. Womack and Jones defined lean thinking from a manufacturing point of view by the five core principles; value, value stream, flow, pull, and perfection (Womack & Jones, 1996).

The first principle of lean, Value, is defined as the ability to fulfill the customer needs at the right time, in each case defined by him, for an appropriate cost. The second principle of lean, Value Stream, is defined as the set of required activities from the point of order and product design to delivering the end product to the customer. Depending on the type of work this includes everything between concept and launch, order to delivery, raw material to delivering a product into the hands of the customer. The authors continue to describe every value stream as consisting of three types of activities. The first defined type of activity is value adding, the second type of activity is non-value adding but is unavoidable with the company’s current assets, and the final type of activity doesn’t add any value and can be immediately avoided. Womack describes flow, the third principle of lean, as the “progressive achievement of tasks along the value stream so that a product proceeds from design to launch, order to delivery and raw material into the hands of the customer with no stoppages, scrap or backflows” (Womack & Jones, 1996). One may liken the principle by the preference of water traveling down a natural river rather than up a sluiced channel on the basis that it induces less stress on surroundings (i.e. machinery or personnel), the downstream river provides a comparably quicker way of travel (the flow of products or the “value”) and the state of which it arrives at the end destination is easier to manage (easier and quicker identification of deviations from the normal quality). The fourth lean principle defined is Pull, which the author describes as a “system of cascading production and delivery instructions from downstream to upstream in which nothing is produced by the upstream supplier until the downstream customer signals a need”
The fifth and final principle is Perfection which is defined as the “complete elimination of waste so that all activities along a value stream creates value” (Womack & Jones, 1996). One attempt to further reduce the explanation of lean concept down to its basics was done by Myles Walton who in one of his papers states:

*Lean is the search for perfection through the elimination of waste and insertion of practices that contribute to reduction in cost and schedule while improving performance of products.* (Walton, 1999)

Following the mentioned manufacturing revolution a wide range of research took off with the aim of implementing the same principles in areas other than manufacturing. While the basic concept of lean is easy to grasp it has proven harder and easily overwhelming from a research and implementation point of view to adapt and implement these onto other areas than manufacturing. As such, to this day, the philosophy is often well implemented on the factory floor whilst the level of education and implementation of it in other areas within the companies’ organization are often very low. One of these areas which have been of interest for continued research and implementation is LPD.

### 2.1 Concurrent Engineering

The term concurrent engineering is in itself a relatively new term that refers to the philosophy of using cross-functional cooperation to create better products both quicker and cheaper. In one of his papers R.P. Smith (Smith, 1997) describes concurrent engineering using the four principles:

- Manufacturing and functional design constraints need to be considered simultaneously.
- Combining people with different functional backgrounds into design teams is a useful way to combine the different knowledge bases.
- Engineering designers must bear in mind customer preferences during the design process
- Time to market is an important determinant of eventual success in the market.

The individual principles existed in the industry for many years before the coinage of the unifying term concurrent engineering. As such concurrent engineering is considered a summary of years of best practice in product development. As previously stated it is not considered a product of Toyotas lean philosophy however the concept is embraced by the flow principle within LPD, as one important aspect when reducing process door-to-door lead times. Cross-functional concurrent engineering teams contribute to creating a flow throughout the design process and the product development operations much like a single-piece flow in a manufacturing system, in comparison to having large batches. In this engineering process the new product design flows continuously from concept to production without stops, or backflow, when the project travels between separate departments.

A desire for this kind of product development process is commonly contradicted by the function oriented organizations which companies often tend to reorganize into as they grow in size and get a wider range of stable products. This often occurs naturally as a small company, which is usually based around a single core product, is often organized as one united collaborative multifunctional team. As the same company grows it more often gets more apparent separations with respect to engineering disciplines or functions, and is eventually split into separate functional teams. These teams tend to become increasingly isolated from each other and sub-optimize within itself. This can lead to miscommunication and lowered productivity which associates with an increased amount of required backflow and reworking as projects seesaw between departments. Enabling multiple engineering
specialties to work within the same team would therefore entail that a product design wouldn’t need to travel between multiple departments in the same fashion.

2.1.1 Set Based Concurrent Engineering
In his work Sobek defines set based concurrent engineering (SBCE) as engineers and product designers “reasoning, developing, and communicating about sets of solutions in parallel and relatively independently” (Sobek, 1997). SBCE is the result of the continued development and research of concurrent engineering, inspired by Toyota’s lean think regarding product development. It has and is the subject for continued research. The approach involves starting a development process by considering a broader range of designs and delaying certain decisions longer. The purpose of this is to gradually narrow design options, while working with multiple parts of the product in parallel, and thereby reducing the chance of picking and committing to a suboptimal design early on. This has been empirically proven that, while the approach prolongs the initial steps of defining a solution, it results in an overall quicker convergence of the different partial design steps and on to production.

In Figure 2 the illustration by Walton, illustrates the concept of this approach. It symbolizes a team consisting of three distinct specialties that initially brainstorm a wide range of design concepts. Thereafter they evaluate the individual concepts with regards to how well they fulfill their respective specialties demands. As the process progresses they gradually combine designs so they fulfill every given product demand, and gradually excludes faulty designs until there’s only one left.

Throughout a LPD process the use of SBCE is favorable during both the initial product definition phase as well as the following product architectural phase. Developing the larger set of solution options allows for people with differing expertise to more efficiently consider design problems from their perspective. By then combining and gradually excluding designs, until only one remains, a more beneficial design for the application is usually obtained.

2.2 Lean Product Development
Lean product development (LPD) is a leading approach of product development. When applying the lean principles to product development several different phrasings have appeared to define the implications on the process. There is to this date no one unifying definition within the scientific community on what the LPD process entails. Studies of the Toyota Product Development System have however summarized the company techniques down to 13 principles (Morgan & Liker, 2006):

1. Establish customer-defined value to separate value-added from waste.
2. Front-load the product development process to explore thoroughly alternative solutions while there is maximum design space.
3. Create an even product development process flow.
4. Utilize rigorous standardization to reduce variation, and create flexibility and predictable outcomes.
5. Develop a chief engineer system to integrate development from start to finish.
6. Organize to balance functional expertise and cross-functional integration.
7. Develop towering competence in all engineers.
8. Fully integrate suppliers into the product development system.
10. Build a culture to support excellence and relentless improvement.
11. Adapt technologies to fit employees and process.
12. Align the organization through simple visual communication.
13. Use powerful tools for standardization and organizational learning.

Another example of attempt to define LPD is when researchers, for the purpose of a review over current state LPD, formulate the broad definition:

Lean Product Development is viewed as the cross-functional design practices (techniques and tools) that are governed by the philosophical underpinnings of lean thinking – value, value stream, flow, pull, and perfection – and can be used (but are not limited) to maximize value and eliminate waste in Product Development (Martinez León & Farris, 2011).

Due to LPD being a relatively young approach in comparison to traditional product development, work has been done in order to find common ground between the two in order to correlate older and newer research, thereby providing a larger base on which to base continued studies on. This correlation has resulted with the categorizing of seven knowledge domains (Martinez León & Farris, 2011). These are Performance-based, Decision-based, Process-modelling, Strategy, Supplier/Partnership, Knowledge networks, and Lean manufacturing-based.

The Performance-based research focuses on developing methods for measuring effectiveness and the efficiency of lean product development practices. Decision-based research focuses on identifying and categorizing the major decisions made during a product development and how decision-making is ideally made in a lean product development process. Process-modelling related research focuses on the modelling and studying of the process architectures. The purpose of this specific type of studies is to improve overall process performance by identifying and maximizing values and information flow, while minimizing waste. Strategy-based research relates to project management, product platform development and multi-project management. Studies on Supplier/Partnership focus on companies’ abilities to effectively coordinate design and manufacturing activities involving their suppliers. The reason for this specific domain being of interest is the general assumption that a company’s ability to deliver new products with better quality faster strongly correlates with the organizations ability to coordinate both design and manufacturing activities with its suppliers. Therefore the primary research question within this domain is how a supplier relationship is best managed within different kinds of organizations. Works comprised within this area of interest include the master’s thesis Managing the Defense Industry Transition to Performance-Based Practices and Supply Chain Integration (Campbell, 1998), as well as the review article Supply Chain Integration
Research related to Knowledge-based networks covers how knowledge is created, transferred and updated throughout the product development system. The final domain, the Lean manufacturing-based, is focused on how the lean manufacturing principles translate/adapts, and is implemented in the product development setting. This application of lean principles on the product development process can be summarized within three identified phases. The first one of these is the Product Definition where customer needs and requirements are identified. The second phase is the Product Architecture Development where set based approaches of integrality and modularity is included. The third and final phase is the Product/Process Design phase which includes the detailed designs as well as prototype building and testing. (Walton, 1999)

2.2.1 Product Definition
The Product Definition, where the products needs and requirements are generated, is one of the most influential steps with regards to success for a project. As they require the most rework and generate the most waste problems that arise from a faulty requirement generation is the most expensive to fix if not caught early. A successful and effective requirement generation is often attributed to three main factors (Walton, 1999).

The first main factor for successful requirement generation is having competent people. For the best requirement generation trained and experienced personnel are needed. There’s a need to understand the customer, the end goal, as well as their own process. This phase is can be the most social phase cause of the need to gather and document inputs from people with varying perspectives while at the same time both having to securing the customers’ needs and convey information to them.

The second main factor for a successful requirement generation is having a well-structured process. A well-structured process does not in itself provide any direct results but acts more like a road map which aids with identifying requirements. Therefore having a standardized guideline for this process makes it more efficient and also acts as a quality assurance that different projects are measured equally. Note that while the process may be tailored and differ slightly between organizations the core structure is usually the same.

The third main factor for the requirements process is the managements support. Whilst requirement generation is a time consuming activity it doesn’t result in as physical results as that of design or manufacturing. Consequently it’s not uncommon for it to gain less management support. However in previous studies, based on industrial experience, the management support is suggested to be comprised of two parts. First part, as mentioned, is allowing the process the time needed to obtain the requirements and to validate what is feasible with respect to technology, cost, and time. The other key aspect for management support is getting the understanding how late changes to requirements influence the process, thereby knowing when they are to be accepted and when management simply needs to say no.

2.2.2 Product Architecture Development
During the Product Architecture Development phase the products functions are assigned to different elements and the interactions between these are defined. Architecture in products is defined by being either integral or modular. In integral architectures all components are customized and optimized for the product. A function may be spread over multiple elements and multiple functions
can be shared by the same components. Products with integral architectures usually provide better overall performance, contrary to products with modular architectures, but on the expense of sometimes more desirable strategic properties such as upgradability, product variety, and process flexibility. Modular architectures are characterized by using the same kind of components in all of the products sub-systems and that the modules have common interfaces to ease replacement (Cunningham, 1998). In this section the basics of modularity and modular product architecture will be explained.

Modularity combines components into blocks which each satisfy different needs of the product. Any components present in all variants of the product are defined as essential blocks. It’s this commonality across product variants that represent the benefits of modularity. As the initial development time and costs and can be split upon a greater number of products the increased volume contributes to an overall more efficient process. The tradeoff for the economic benefits through standardization is the reduced ability to customize the product for individual customer needs. This reduced customizability may sound contradictory when considering the aim of having easy replaceable modules. As a product is comprised of an increasing amount of modules, and thereby customizability, its architecture increases to resemble a handcrafted item. This increase in customizability entails that the economic benefit of higher production volumes is lost. Thus the main challenge with modularity is defining the desired amount of standard components that will satisfy the greatest amount of customers.

The six defined categories (Walton, 1999) of modularity are illustrated, illustrated in Figure 3. Component sharing, or commonality, involves using the same components on multiple products. Component swapping contributes to the products variety by pairing different components with the core product. An example of this would be car stereos. The Fabricate-to-fit category is utilized when a component is variable. As seen in the figure the fuselage of a plane is a prime example of this type of modularity. Mix modularity is categorized as the combining of components, for example paints, to create a new one. Bus modularity is defined by a common structure, a standardized interface, where many different components can be attached. Examples of these can be either computer racks on which a varying amount of components can be attached onto, or once again the fuselage of a plane on which different kinds of subsystems may be attached. The final type of modularity is sectional which is defined as when a collection of components may be arranged in any way as long as they are connected by a standardized interface. An apparent and illustrative example of category of modularity is Lego building blocks.

Benefits of having an established modular designed product include the ability to quickly replace modules containing components with rapidly changing technology thereby making it easier to keep pace with their respective development. Modular designs with well-defined sub-systems and interfaces also have the benefit of being able to borrow components, ideas and experience from previous designs or other product lines. That way it’s easier to utilize and learn from previous experience. By modularizing a problem into smaller parts with specified functions it may also become
more controllable for designers, thereby making it easier to solve. Other benefits of modularity are that designers can work on separate modules in parallel, entailing a reduced lead time for product development, and that that the designer can more easily focus on the specified function for his module, thereby often getting a more effective design solution. Lastly modular design of products may provide an organization with expertise and gained specialization in specific product areas (Walton, 1999).

When considering modularizing a design there are also disadvantages that need to be taken into account. Initial design steps of the product development will be more difficult if compared to a traditional stand-alone product system. The core difficulty is determining how to separate the system into modules and how to make them interconnect. Only after these questions have been answered can the remaining steps throughout the product development process be simplified. Another disadvantage, as mentioned in the previous paragraph, is that a modular design generally sacrifices some of the performance optimization. When modularizing products potentially shared functions can be overlooked and hence some methods or solutions may be overlooked. Modularity also usually makes a product more clunky then integral designs due to an increase in size and/or weight. Additionally if splitting a product into modules for separate teams to develop, and communication between groups is lacking, there may either occur redundancy in their work or the modules themselves may be difficult to optimize in order to make them work with each other (Walton, 1999).

2.2.3 Product/Process Design
The addition of lean thinking during the final development phase, when the detailed designs are produced, focuses mainly on increasing cost awareness in designs, assembly oriented designs, and data standardizing (Walton, 1999). Taking these kinds of product aspects into account, including but not exclusive to Designing For Manufacturing (DFM) as well as Designing For Assembly (DFA), and understanding how they affect the end cost is very important since designing “right first time” is the easiest way of obtaining low-cost products compared to having to redesign it later on.

2.3 Modular Function Deployment
Modular Function Deployment (MFD) is a product architecture method focused on the practical implementation of a modular product design. It is utilized by companies with the aim of being able to offer an increased product variety while also improving customer satisfaction, shorten lead-times, and reduce costs (Simpson, et al., 2006). The MFD method is the result of researchers’ effort to improve and an attempt to streamline and simplify the QFD (Quality Function Deployment) process. The coining of the method was first done in the doctorate thesis “Modular Function Deployment – A Method for Product Modularisation” (Erixon, 1998). The MFD concept follows the procedure set by its predecessor with the addition of a modularity concept. MFD is comprised of a five step process. These sequentially performed steps, along with available tools and techniques are (Value Driven Design Ltd, 2013):

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| Step 3 | Module concept generation         |
• Module Indication Matrix (MIM)

**Step 4**  Evaluate concepts
• Design For Manufacture and Assembly (DFMA), Activity Based Costing (ABC) & Design to Target Cost (DTC)

**Step 5**  Individual module improvements
• Rank Order Cluster (ROC)

Depending on the applied situation, and which steps are deemed required, the methodology can either be performed as a whole or using only selected steps. Gunnar Erixon, founder of the method, emphasizes that the design of products and processes is an iterative process and as such both the starting points and the amount of iterations may vary before the desired results are satisfied. It is also emphasized that the method has proven most successful when executed by a cross functional project team (Ericsson & Erixon, 1999).

### 2.3.1 Step 1: Defining the customer requirements

The initial “customer requirement” step of the QFD analysis serves to clarify and/or verify the current as well as the desired future product functionality. This step can be summarized as the translation of customer demands, needs and requests into technical design and manufacturing specifications.

The first action of this process is communicating and summarizing the customers own needs. This can be done in varying ways, ranging from an interview with a company representative to conducting a marketing survey directed to the general population, depending on who the targeted customers are. After summarizing customer needs the next step, if deemed required, is to analyze and benchmark the competition with respect to if or how they have fulfilled these customer needs. As this is finished all customer demands are translated into technical specifications and assigned target values that are to be met. A commonly used tool for this which, amongst others, visualizes how the technical specifications relate to each other and the set of demands is the House of Quality (HoQ). An example of how the HoQ can be seen in Appendix 1. A simplified version of this QFD method, illustrated in Appendix 2, has also proven to work well for this task. Note that unlike the original QFD matrix the simplified one is missing the correlation matrix (the roof), the fields for benchmarking, and has “Modularity” directly incorporated in the Design Requirements list.

### 2.3.2 Step 2: Select the technical solutions

This step is consists of two main parts, identifying the product functions and selecting a technical solution for each function. Firstly to be able to continue on with the product design from the previous step it is needed to evaluate the obtained specification list from a more technical point of view. This is done by doing a *functional decomposition*; analyzing the specification list from a functional view, breaking down the product into individual functions and sub-functions, and determining their corresponding technical solution, or “function carrier”. The purpose of this is getting a mutual understanding within a project group of how each part contributes to the whole. This is necessary since identifying functional independence is required when wanting to create an optimal modular design. When identifying functional independences these can be isolated, treated separately from each other, and a more robust modular design can be obtained with minimal interactions between modules.
During the functional decomposition multiple technical solutions will be found for the same function. These solutions are preferably evaluated against each other using Pugh matrixes, exemplified in Figure 4. This Pugh matrix is used by selecting one technical solution as a reference, followed by comparing each alternative against the criteria, usually gathered in step 1, and grading them using + if they’re considered better and – if they’re considered worse than the reference. The purpose of this exercise is making it easier to in an objective way gradually eliminate solution concepts until only the best ones remain. As both the function decomposition and Pugh matrixes are completed the end results are preferably visualized in a functions-and-means tree, as is exemplified in Figure 5.

2.3.3 Step 3: Module concept generation
After specifying technical solutions in the previous step of the MFD-method the next objective is evaluating what the reasons are for creating modules. This is done using the empirically established module drivers, “driving forces for modularization”, as criteria for weighting the different module options. These module drivers include, but are not limited to carryover, technology evolution, planned production changes, different specification, common unit, supplier availability, service and maintenance. More detailed information regarding module drivers is available in the literature (Ericsson & Erixon, 1999).

Each previously attained technical solution is assessed against module drivers by using a Module Indication Matrix (MIM), exemplified in Figure 6. The use of this matrix is emphasized as the core of the MFD method (Ericsson & Erixon, 1999). Similarly to the process previously described for the simplified QFD matrix, seen in Appendix 2, each technical specification is weighted against the module drivers. Note that one difference when comparing the QFD and MIM, which is implemented with the purpose of easing the identification of strong drivers, is the scaling of awarded points for the identified drivers. In the MIM a strong driver is awarded nine points, a medium driver is awarded three points, and a weak driver is awarded one point.
To know which function carriers would be the most beneficial module candidates you start with picking out the highest Module Driver-scoring technical solutions and continue with looking for any patterns within the matrix. When analyzing the MIM a technical solution that has few and/or low weighted module drivers indicate that it could be easy either to encapsulate or to group with other solutions. Provided that there is a matching module driver pattern or at least no contradictions, such as putting a carry-over together with a planned product change, integration of these functions should be considered. A technical solution that gets highly weighted, has many and/or unique module drivers does on the other hand indicate that it is likely to form a module by itself, due to its complicated requirement pattern, or that it at the least has be a basis for a module.

When looking to identify modules in a product the MFD literature proposes a rule of thumb stating that in order to reach the minimum lead time “the number of modules equals the square root of the number of assembly operations in the average product” (Ericsson & Erixon, 1999), see Equation 1. Note that this is based on desired balance between time required for assembling each separate module and the time required to assemble the modules to each other in a main flow of an ongoing production line. It assumes that, based on average “best practice” experience, that an assembly operation for parts takes about 10 seconds and that the average final assembly time between modules takes between 10 and 50 seconds.

Equation 1: The general rule of thumb used for finding the optimal amount of modularisation in an assembly line.

\[
Product_{modules} \approx \sqrt{Product_{Assembly \ Operations}}
\]

As the identification of what function carriers are best kept by themselves and which ones are preferably integrated into a single module is finished a set of concepts containing rough module designs, dimensioning and forms are developed through brainstorming. One, or a few, of these are then selected to be kept for continued evaluation.

2.3.4 Step 4: Evaluate concepts
As a modular concept has been generated it is evaluated if or how much better it is compared to either each other or an already existing design. Keeping in mind that the assembly order and the interfaces between modules are of vital importance determining how fast and simple the product is to assemble during production. A way of evaluating these interface relations is by using an Interface Matrix (Ericsson & Erixon, 1999), exemplified in Figure 7. This matrix works in a similar fashion as the correlation matrix (the roof) of a traditional House of Quality. In the interface matrix interfacial connections are split into three categories. If an interfacial connection is fixed, only transmitting forces, it is marked with a G for “geometry”. When an interface...
connection is moving, also enabling the transmittance of rotating or alternating energy, it is marked with an E for energy. Lastly an interface marked is marked with an M for media, when it transmits some kind of media such as fluids or electricity.

In order for a product to obtain a quick and easy assembly procedure the interface relations should preferably follow either the “hamburger” assembly or the base unit assembly line seen in Figure 7. When modular relationships divert from these sidelines it is worth evaluating further if they can be redesigned in order to ease the assembly process.

Other than module interface relations there are several aspects that should to be considered when evaluating a design. Estimating the cost for product is one of these aspects. While doing an activity-based cost (ABC) analysis it’s worth noting however that it may not always value the benefits and effects that a modular product entails unless the entire product assortment is taken into account during the assessment. Similarly more consideration to if and how well the benefits of modularity are represented when applying common tools and methods such as Design for Manufacturing and Assembly (DFMA). When doing these analyses beneficial representations may vary depending on whether they’re done on a single component, a module, a product, or on assortment level. Despite a lack of standardized methods and tools for fairly comparing different modular benefits and deciding on a final module concept empirics has shown that open discussions about specific design aspects within the cross functional project team are beneficial to have. Recommended topics based on the empirics are (Hjalmarsson & Jonsson, 2010) (Erixon, et al., 1994):

- Recommended number of modules in a product is the square root of the expected amount of components in the end product.
- Create modules that enable a wide product assortment.
- Design module interfaces for quick assembly. Target value, based on “best practice” <10seconds per interface.
- Develop modules that are individually testable.
- Minimize cross-modular relations by avoiding the same function being spread onto multiple modules.
- Maximize the proportion of carry-over modules.
- What modules could be bought from available manufacturing suppliers?
- Avoid multiple materials within the same module, due to environmental aspects (recycling).

To help making a final module design choice assigning appropriate design rules or measurable metrics may aid to rationalize and evaluate the effect of modularized concepts.

2.3.5 Step 5: Individual module improvements

After the evaluation of the module concept is finalized detailed specifications are established for each individual module. These specifications can include but are not limited to technical information, possible material requirements, module functions, descriptions of variants, planned development, and cost targets. As the information stated in the module specifications will come to represent the backbone of the continued product platform the specifications need to be both comprehensive and unambiguous. Establishing this enables continued independent design and development of the modules.
Since the MFD method has its focus on a product-module-level its process description doesn’t delve further into detail regarding the design development and improvement process other than commenting on the still significant work of “traditional” design improvements on component level in order to secure the resulting final product. At this point the previously established module indication matrix serves as a pointer of what aspects might be especially important to take into consideration for each module. An example of this could be a module with a high Technology Evolution driver which could be preferable to design with a layout that would require minimal design alterations in the future; or a module with a high Service and Maintenance driver being designed with additional focus on easing disassembly.

2.4 Project Aims
Based on the identified aspects within the development and manufacturing process of the A1 hub assembly function test flanges Module Function Deployment shall be utilized for implementing the proposed process and product development amendments. The effects of the amendments shall be accounted for by producing a comparison between the current development process and product design with the proposed process and product design, based upon the projects stated goal parameters. This comparison shall be comprised of activity based process and lead time requirements, personnel costs, and product material costs. To ensure fair representation of the amendment effects the comparison shall be produced for an initial tool, a subsequent tool, as well as a full series of tools.
3. Methodology
The study initiated with compiling existing product demands, characteristics and requirements with the aid of the on-site manufacturing engineers. Thereafter the following work was comprised of constructing and analyzing the current state value stream map and cross functional process map. The analysis was to identify any unnecessary steps or stops that would prolong the combined process as well as identifying costly or in other ways wasteful activities within the process. Results from the analysis were used to deduce what amended or alternate product architecture and development process was to be applied. Thereafter the proposed method for product development was applied on the balance and function test equipment for the A1-hub series. After developing the new tool design a comparison between the proposed and the existing product and process summarizing cost and lead times was produced.

3.1 Current State Report: Understanding the current situation
The current state analysis was comprised of a current state Value Stream Map/Analysis (VSM) and a Cross Functional Process Map (CFPM). When combined the two maps visualizes all activities and people involved throughout the tool development and manufacturing processes providing a more easily comprehensible understanding of the work process, and enabling identification of any costly or in other ways wasteful activities. The VSM was used to visualize the material flow throughout the process, outline and identify the critical path through the material value stream, and identifying the most wasteful manufacturing operations in the sense of value adding time set in relation to the process time it entails. Individual activities within the value stream maps critical path were therefore individually analyzed in order to review their effect on the overall process cost and induced lead time. The CFPM, also known as a Swimlane-diagram, was made in order to clarify informational dependencies throughout the process.

Initial study activity was comprised of interviews and a tour through the manufacturing facilities alongside the manufacturing engineering manager, manufacturing engineers, and production manager. Additional input gathering from the operators was done to ensure that a comprehensive understanding of the tool and how it was used during production.

The data gathering for the CFPM was done by conducting individual interviews with all the roles involved throughout the tool development and manufacturing process. These interviews includes the Production Planners who receives the initial work order and plans the in-house manufacturing, the Manufacturing Engineers who were responsible for tool design and drawings, the Buyer at the purchasing department who handles supplier contacts, and the Quotation Engineer at a supplier who receives and plans the received manufacturing orders. Following these initial interviews and the compiling of all gathered information into the CFPM follow-up discussions involving all previously involved parties as well as the Manufacturing Engineering Manager was done. These discussions served the dual purpose of both verifying the validity of the CFPM as well as giving the possibility for all involved parties to reflect and give feedback on any possible process amendments.

The VSM interviews and data gathering as well as follow-up discussions were conducted simultaneously as the CFPM. Compiling available process data from previously made equivalent tools as well as the verification of the compiled value stream map was done alongside the Production Planner and the suppliers Quotation Engineer. Final discussions regarding the VSM were thereafter conducted alongside the Production Planner, the Manufacturing Engineers and the Manufacturing
These final discussions focused on comparing and reflecting on the possibilities and limitations regarding manufacturing processes, including both the self-made and outsourced components. This analysis and the conclusions derived from it took into account component sizes effects on manufacturability, chosen manufacturing methods, and their relative wastefulness with regards to value adding time in relation to entailed added lead time the addition of the individual manufacturing operation implies.

After finalizing the VSM and the CFPM the identified issues and possible amendments regarding the current tool development process and product design was used for deciding the desired product architecture and the suitable product development process perceived to be the most time and cost efficient for the application. This choice was derived from surveying and setting up a framework based on prior research regarding product architectures and product development methods and practical approaches. The choice of what product development method was to be adapted and implemented was taken based on the gathered product demands, starting with deciding the appropriate product architecture. Thereafter the decision of what product development method was to be utilized was done focusing on light weight modelling and efficient tools, while still being able to take into accounts the determined product properties and layout. The focus on using lightweight and efficient methods and tools was considered important due to it being a major aspect on whether new methods are to be embraced and possibly replicated within existing organizations that are already occupied with everyday work.

Implementing the chosen, 5-step method, known as Module Function Deployment (MFD), on the A1-series function test equipment was done on the basis of starting from the existing design with the aim for the continued development to reduce the existing cost, lead time and tool based storage needs.

3.2 Streamlining product design through Module Function Deployment

The initial step of product development was setting up a What-How-matrix, of which a visual representation is shown in Appendix 2. As the project assumed an existing design this meant setting up what product aspects were to be improved and setting them in relation with what product properties would be considered within the study in order to fulfill these needs. The product properties listing how the improvement needs were to be fulfilled was gradually supplemented until the relations showed that no needs were being neglected. Simultaneously a summary of the existing product specifications was set up for the latter stages of development. Before continuing on to the latter stages of the MFD method the table of technical requirements and the What-How-matrix was discussed and approved by manufacturing engineers. This was done in order verify that no product requirements had been missed and that the product aspects were adequate to be able to fulfill the desired improvement needs.

The next step was using the technical specifications as a base to divide the product into functions and sub-functions in the function decomposition. Conceptual technical solutions were then individually developed for each of these functions and sub-functions through brainstorming sessions alongside manufacturing engineers. These were then evaluated individually for each function and the most beneficial solution or solutions for each function was selected, through the use of Pugh-matrixes based on the company’s improvement needs, for continued development. After selecting the functions technical concepts they, along with their respective functions and sub-functions were
summarized and visualized in a functions-and-means tree to enable easy review and feedback from the manufacturing engineers as well as the manufacturing engineering manager.

Following the selection of which technical solutions for the products functions that were to be kept for continued development they were all evaluated and mapped against the Module Drivers, explained in section 2.3.3, in a Module Indication Matrix. After mapping the technical solution’s relations to the drivers the matrix was used to find patterns and similarities that either indicated that different solutions would be best kept separate or that multiple solutions had integral properties with each other. Before finalizing the splitting of the technical solutions into modules the rule of thumb, seen in Equation 1, was taken into account as a preliminary guide on the appropriate amount of modularization for the product.

After deciding on a desired number of modules the functions were grouped into their preferred modules and an Interface Matrix, seen in Figure 7, was used to visualize and determine the preferred module assembly and disassembly order in order for ease the operators workload the most as the equipment would be used during regular production. After deciding on the assembly orders a series of interface concepts were developed through brainstorming sessions. Thereafter the interface concepts were evaluated against each other, in unison with the manufacturing engineers, using Pugh-matrixes based on predetermined product design properties. This process led to the decision regarding which single interface concept was to be kept for the continued development.

Following the interface concept decision the possible integrality within the flange plate module throughout the A1-hub series was done. The integrality was limited by two factors, wherein the first was the maximum allowed overhang from the edge of the hub to the flange plate’s edge. Its second limiting factor for integrality being the hole pattern diameters of the guide pins and shaft bolts which wasn’t allowed to overlap with the hub sealing of an integrated model size without it losing its function. The sizing and detailed specifications of module interface layouts as well as common joints between modules was calculated by considering the extreme cases that would occur and standardizing the results throughout the full product series. These results were thereafter compiled along with the description of module variants, technical specifications and design target and used to provide a module specific technical specification, thereby enabling separate detail designs to be developed for each desired module throughout the entire size range of the function test equipment.

Thereafter a detailed design model was developed for each module, using the produced module specifications as a base. The new design was developed while keeping in mind the result from the current state VSM in order to avoid the proven increasingly wasteful manufacturing processes with regards to its value adding process time in relation to the increase in lead time that the use of the process implied. Individual module designing started with considering alternate internal component designs and materials, followed by rough calculations of minimal material thickness required to maintain component function as well as the sizing of internal joints. This was followed by surveying and mapping available material dimensions from suppliers while doing minor amendments to component sizing in order to accommodate for available material dimensions and minimizing the amount of machining required.

After finishing the individual designs and 3D-model for each of the three modules they were assembled and reviewed as a finished product, alongside the manufacturing engineers, serving as a
final stage gate and quality assurance before declaring the design as final and initiating the final lead time, cost, and tool based storage need comparison.

3.3 Future State Report: Results and effects from process and product amendments

As the balance and function test equipment design was finalized a cost and time comparison between the new design and the current was conducted. This included the material-, manufacturing-, and product development cost as well as a brief storage space and cost comparison.

Material costs were to be estimated by doing an assumption of 2-5mm surplus material, depending on component size, on all component surfaces intended for machining. Thereafter volumetric calculations were made for each of the components. Thereafter averaged material purchasing costs from suppliers for standard structural steel (such as S355JR // SS-2172-00) and aluminum bronze (JM7-15 // SS-5716-15), were applied to acquire material costs.

The manufacturing time comparison was made by summarizing estimated manufacturing times for each individual tool component. These estimations were calculated by first listing the operation parameters required for manufacturing followed by applying basic formulas for calculating machining durations for turning, milling, drilling/boring, and threading correspondingly. All equations that were used are accounted for in Appendix 3. After the machine duration calculation estimated machine time efficiencies (for manual machine) were applied as well as adding machine setup times. These were then summarized into process times. At this point key components that had not been significantly altered compared to previous designs were used to benchmark and validate the convergence between calculated process times and empirical process times from similar previously manufactured components. Two variables, machine setup time and averaged machining efficiency, were used to calibrate the convergence between the model and reality. Note that the machining efficiency, which takes into account time between cuts, amongst others varies depending on manual or automated machines. The provision of this empirical data, as well as the verification of convergence between theory and reality, was carried out in cooperation with the production planners. After finalizing the process times the internal hourly rate for production personnel at the site was applied to obtain the final manufacturing cost. For the lead time comparison, initially, a single worker working sequentially with all tasks was assumed and the previously acquired overall “value adding” efficiency obtained from the initial value stream mapping, after removing the effects of the welding and annealing processes, was applied.

The process time for the product development phase was carried out in a similar fashion for both the current process as well as the proposed MFD process. Individual activities were identified and each respective activity times estimated. Post estimating the individual activity times a standardized work efficiency factor used when planning officials’ workload, 82%, provided by the manufacturing engineering manager, was applied. After verifying the resulting time estimates with the manufacturing engineers these were summarized to a total process time both for initial tool development as well as subsequent tool development within the tool series. As the final process times had been set the internal hourly rate for engineering officials at the site was applied to obtain the final product development cost. The calculation of lead time for the product development process was, where applicable, done assuming parallel work between the existing two manufacturing engineers currently working with tool and fixture development.
When summarizing the cost, process- and lead time for development, material, and manufacturing this was done for three different tool sets.

1. Initial tool set
2. Subsequent tool set
3. Full tool set

The estimating of space and cost reduction related to storage space was conducted without considering any overhead or maintenance costs for storage upkeep etc., and based solely on a standardized surface rent cost, \(72 \text{£}/(\text{m}^2 \cdot \text{year})=771 \text{SEK}/(\text{m}^2 \cdot \text{year})\), standardized E-pallet storage space size, and a standardized cost per storage space, 450 SEK/year. Everything was assumed to be placed on an E-pallet except for the modularized flange plates which was assumed to be stored standing upright on a rack.

Proposed process amendments, based on the results from the tool design evaluation, were visualized in a future value stream map and cross-functional process map. The future state value stream map was constructed while taking manufacturing lead time as the primary driver for improvement. As such the capabilities and limitations of the in-house machinery was taken into account and the manufacturing and assembly work was divided between the in-house toolmaker and the external supplier, with respect to the estimated lead times, so to maximize parallel work. The estimated lead times were based on assuming similar production efficiency as in the current value stream map, while taken into account the removal of welding and hard annealing processes. Amendments to the cross-functional process map were constructed in a similar fashion. Primary focus was set on minimizing the resulting lead times when receiving an order from the customer amendments focused on enabling proactive engineering prior to specific customer order reaching manufacturing.

4. Result

Results from the project were divided into three parts. The first part, the current state, focused on identifying product requirements as well as the initial mapping and analysis of the tool development and manufacturing process. This part consists of the identification of the less efficient aspects throughout the development process and the product design followed by a proposed alternate product development process chosen based on these identified inefficiencies. Post completing the process mapping the following part was comprised of the step by step implementation of the proposed module function deployment method. The final part, the Future State Proposal, consists of summarizing the possible amendment options that emerged from the study and their respective predicted effects.

4.1 Current State

The initial tool requirement compilation resulted in the specification accounted for in the list below.
At the current state the time required to design and manufacture a balancing and function test flange has been set to a standardized 16 weeks. This includes all activities from the point when the new tool design and its corresponding work order package arrives at the manufacturing engineering department and the tool is manufactured, assembled, and delivered to production. Out of this time the first 6 week period has been dedicated to tool design development, planning the self-made manufacturing, prepping tool and fixture manufacturing work orders, and placing purchasing orders. Following this the last 10 weeks have been dedicated to tool manufacturing.

The production planner explained the overall preparation phase. During this phase he designates what tools and fixtures are to be used during the manufacturing and testing, which of these already exist and which ones are brand new and needs to be designed and manufactured. The production planner provided process times for previously manufactured comparable to ones. He also explained the collaboration with the toolmaker as new components and assembly structures are received from the upstream design department, with regards estimating lead times for manufacturing and assembly.

The manufacturing engineers explained their process from receiving requests for design development for new tools and fixtures in their order stock. This generally started with a brief check if any previously manufactured components could be utilized followed by the production of any new components along with their associated detail and/or assembly drawings.

To understand the outsourcing process the appointed Rolls-Royce buyer in the purchasing department was also interviewed. He provided a step by step description of the purchasing process, the information he needed to be able to start the process as well as the general lead times for each step of the process.

Alongside the interviews carried out within the organization a study visit was also conducted at the most recurring and reliable supplier of outsourced manufacturing. This started with a brief tour of their manufacturing facilities, consisting of machining, welding, assembly, packaging and shipping areas. Thereafter the interview with their quotation engineer discussed manufacturing routines, estimated process and lead times of the sequential step in the manufacturing process. At this point a brief discussion was also had with regards to the possibilities for continued streamlining of the combined outsourced process in terms of reducing lead times. Foreseeing a potential need to reengineer flange design feedback from operators about previous flange designs concerning unpractical manufacturing geometries, and possible machine limitations, was also discussed.

Technical Specification

- All product joints shall be sealed.
- All major components shall be equipped with CE marked lifting devices (safety factor 4).
- Flange must be able to cope with pressures at 1.5 times safety valve pressure level during workshop pressure tests.
  - SP-system: 4.7Bar design pressure. 7Bar test pressure.
  - A-system: 80Bar design pressure. 120Bar test pressure.
  - B-system: 160Bar design pressure. 240Bar test pressure.
- Tap shall have the same diameter as their corresponding propeller shaft flanges.
- Tap shall have the same length as their corresponding propeller shaft flanges.
- Flanges shall have same guide pin and shaft bolt hole patterns as corresponding hubs.
- Product shall hold combined tool and hub assembly weight in radial force during static balancing.
- Assembled product shall have mass centre on centre axis.

SP-system: 4.7Bar design pressure. 7Bar test pressure.
A-system: 80Bar design pressure. 120Bar test pressure.
B-system: 160Bar design pressure. 240Bar test pressure.
The gathering of data from these interviews and facility tours throughout the different process steps resulted in the current state value stream map in Appendix 4 as well as the cross functional process map in Appendix 5.

4.1.1 Current State Value Stream Mapping

As visualized in the value stream map in Appendix 4 and the cross functional process map in Appendix 5 the general manufacturing process for tools and fixtures started when the production planners received an electronic work order from the, upstream, product design department. This work order is sent to signal that the products design, along with its related drawings, manufacturing lead times and deadlines as well as manuals, for a new hub assembly has been finalized. As an order arrived to the production planners his initial responsibility was to create work orders for manufacturing engineers to produce tool designs and associated drawings. Once these drawings were reviewed and finished the production planner categorized whether components were either "Purchased Items" or "Manufactured Items" depending on whether they were standard component, needed to be outsourced for manufacturing, or if it was to be self-made. Following this categorizing the production planner, accompanied by the toolmaker, estimated the process times for the items that would be self-made. Thereafter the production planner purchased standard components and raw materials needed for the self-made manufacturing while simultaneously prepping the work orders for the self-made components and final assembly before transferring accountability for these activities to the toolmaker. At the same time the production planner sent purchase requests for all outsourced components to the appointed buyer, at the on-site purchasing department, who initiated quotation and purchasing processes.

While awaiting the ordered materials intended for the self-made tool components the tool maker continued the process by planning the work order, taking into account the individual orders respective deadlines. When the raw materials arrived he carried out the self-made manufacturing as per given descriptions. Post finishing with the self-made manufacturing and receiving the purchased components, the toolmaker carried out the final assembly and quality inspection of the finished product before delivering the finished tool to production.

The buyer received the list of desired purchased items along with related drawings and the maximum allowed lead time through the use of the determined deadlines for delivery. At this point the buyer inherited the on-site accountability for components being delivered on time and started the purchasing process by sending out requests for quotations. A standard waiting time to receive quotations from suppliers was set to five days before evaluating the received quotations those that had been received and sending out purchasing orders.

When the manufacturing supplier receives the purchasing order he started by confirming the previously given price and lead time stated in the quotation, orders any materials needed and scheduled the manufacturing process for the component. As the raw materials arrived manufacturing started with the first stage of turning and welding. Thereafter the intermediate product was shipped to a second supplier for stress relief annealing. Once the product returned from annealing the second round of turning and boring was performed. Thereafter the finished flange was packaged and shipped back to the toolmaker at Rolls-Royce who would initiate the final tool assembly.
4.1.2 Cross Functional Process Map
As shown in the current state cross functional process map in Appendix 5 the flow of information throughout the tool development process started when the propulsion design department finalized a hub assembly, setting a deadline for when final assembly was to commence, and forwarding the electronic work order package to the production planner. The production planner then performed an initial review, checking if the tools and fixtures required for manufacturing already existed or if new equipment needs to be developed. Should new tools have been required the production planner would’ve forwarded the order to the manufacturing engineers assigned to tool and fixture development. In those cases they would’ve developed the required tools before sending manufacturing and assembly drawings as well as component lists back to the production planner. At this point the production planner set component specific deadlines, designated what was to be purchased or self-made, estimated the process times for the self-made components, and placed purchasing orders. All of these steps are described into more detail in the previous section, 4.1.1 Current State Value Stream Mapping.

Upon reaching the purchasing operation in the process the designated buyer sends out requests for quotation, containing drawings as well as deadlines for delivery, to surrounding suppliers. Once having received the quotations he chose the best supplier and he placed the final purchase order along with resending the updated drawings. When supplier’s quotation engineer received the purchase order he reviewed the new drawings, making sure that there were no major changes since the quotation which would reduce the validity of the previously quoted price or lead time. Once drawings were confirmed the quotation engineer sent out purchase orders for the required raw materials, scheduled the component for manufacturing, and forwards the order to production. As it receives the work order production along with the required raw material the manufacturing of the flanges is performed, as described in the previous section 4.1.1 Current State Value Stream Mapping, before having transferred the product onto shipping and returning it to Rolls-Royce for the final assembly is conducted.

4.1.3 Current State Analysis
The first point of interest visualized from the combined informational and value stream mapping was at the initiation of the work order notice to the production planner to evaluate tool and fixture needs. When developing a new generation of hub assemblies the appointed product development department develops a parameterization of vital and limiting design measurements for all hub sizes that will be available for development. This preliminary work was done prior to receiving any customer orders, and was done without creating the different sizes respective 3D model. The existing parameter document could have been used to analyze and produce a similar document for tools and fixtures throughout the same product series. In the existing process description however the manufacturing engineering department was notified of the need for tools and fixtures for a new hub assembly only after the 3D model of the hub for a customer order was finalized.

Similarly the next point of interest in the current process description that was discovered was at the handover of tool drawings from the manufacturing engineers to the production planner. The existing standardized process description implied that the production planner received the tool component list, along with manufacturing and assembly drawings, at the point where it’s completely finalized. This entails that any components that were to be manufactured in general had to wait 5-10 workdays before starting manufacturing due to having to wait for receiving the raw material. Introducing a
A parameterized design for a testing flange series would have eased the production planners’ work by enabling him to, instead of having to wait for finished drawings, purchase the required materials for components through the use of preliminary external dimensions obtained from the earlier preliminary work.

An additional identified point of interest was the seemingly unbalanced parallelized workload when comparing the predefined overall manufacturing lead time, 10 weeks, with the summarized process time for manufacturing the self-made components and the final assembly, which was 2-3 weeks in total. The longer set lead time showed to be greatly dependent on the manufacturing and delivery of the flange component which, after finalizing the outsourcing agreement between Rolls-Royce AB and the supplier, was given an average lead time of 8 weeks. This lead time was noted to be largely depending on logistics, which comprised ~25% of the total lead time. Other factors contributing to the flange components overall required lead time was the chosen manufacturing method and size-dependent geometrical difficulties during manufacturing. This entailed the continued tool design evaluation to focus largely on this flange component.

The value stream map showed the flange component to be the critical component, with respect to lead time, during manufacturing. Analyzing the value stream for the flange component showed a comparatively great amount of downtime caused by long waiting times between machines and operations. Continued focus on manufacturing operations involved to produce the flange component, showed the welding and stress relief annealing to be the single most wasteful operation throughout the value stream. This was concluded by comparing the process and value adding time with the lead time the combined manufacturing method entailed by requiring the component to be transported to and from an additional third party between operations.

4.2 MFD product assessment
The initial steps summary of customer demands resulted in the what/how-matrix shown in Figure 8.

![Figure 8: The resulting "What"/"How"-matrix showing what the customer demands are and how it will be met.](image-url)
Results show that all product design requirements (“how”) contribute to a lowered cost as well as lead time. It shows that the customer desired specification to lower occupied storage space is related to the chosen component assembly method as well as both the modular and integral aspects within the product family’s architecture. As seen by the summary the lead time and cost reduction will benefit the most from the MFD implementation, and that the products module/integral-architecture followed by designing for manufacturability will be the most important design aspects to accomplish this.

The relations between customer specification and the previously stated technical specification of the existing product design resulted in the functional decomposition seen in Appendix 7. At this point multiple concepts were identified for 1) Matching guide pin and shaft bolt hole patterns to the hub, 2) Sealing the tap to the inside of the piston, and 3) Prevent maximum pitch bypassing. Therefore they were weighted against the design requirements previously stated in Figure 8, to identify the best alternatives with respect to the set conditions. This was done by setting up individual Pugh-matrixes, seen in Appendix 8, for each group of function/sub function where multiple concepts had been identified. In the case of the sub function “Prevent piston from bypassing maximum pitch” two concepts were considered to be equal due to the small score margin between the concepts. Therefore both were kept on until further on in the MFD method. The resulting functions-and-means tree from the function decomposition can be seen in Appendix 9.

Entering the remaining technical solutions, from the functions-to-means tree above, into the MIM resulted and weighting them against the “standard” Module Drivers resulted with the relations seen in Appendix 10. Pattern analysis of the MIM primarily showed the technical solutions concerning varying diameter and length of taps to have identical Module Driver relations, indicating that the two could beneficially be incorporated into the same module. The alternative concept to using taps with varying lengths, using adapters to adjust length, indicated an increased difficulty to be successfully incorporated into any combined modules. Low scoring concepts, such as the lifting device, tap length adapter, and tap end bushing, with varying MD-relation patterns indicate that these may all be beneficial to incorporate into other modules. The concept concerning tap length preventing pipe adapter to bypass bushing, with its high score and unique pattern, indicates that it should be kept by itself.

When making the final decision on the degree of product modularity for the tool-series the amount of individual assembly operations in the current tool design was taken into account, following the mentioned rule of thumb, Equation 1, shown in chapter 3.2. The identified number of separate assembly operations in the current tool assembly was

![Figure 9: Rough visualization of how (a) three and (b) two module based function test flanges could be modularized.](image-url)
five which hinted on the appropriate amount of modularity would be either two or three. The resulting functional technical solution divide, when constructing two respectively three modules, is shown in Appendix 11. All concepts in the MIM were kept and reflected upon for further evaluation, one being composed of two modules and two composed of three. Rough sketches visualizing the modules relative dimensions and forms are shown in Figure 9. Note that there’s one tap-length-changing technical solution for the two module concept while the three module based concept still has two competing tap-length-changing technical function solutions. The adapter based tap-length-changing technical solution was excluded from the two module based concept since it was considered counterintuitive to plan for the requirement to manually alter “fixed” modules. Furthermore the adapter based tap-length-changing concept was eliminated for the three module concept as well during the following brainstorming session of possible module interface concepts that followed along with the manufacturing engineers. This was due to foreseen difficulties to incorporate it to tool designs while maintaining function as well as efficient disassembly and reassembly.

The resulting interface designs and their original rough drafts are accounted for in Appendix 12. The decision of interface design was done by first taking into account designing for repeated assembly and disassembly during production. Two module concepts only allow one assembly order, while using three modules increased the complexity slightly. At this point two main aspects, with respect to integrality, were taken into account.

1) The lower tap, module 2 in Figure 9(a), was always replaced when changing hub size. The flange, module 3 in Figure 9(a), was sometimes, but not always, replaced when changing hub size. Thereby module 2 should be possible to assemble/disassemble without disassembling the carryover module 1.

2) If needing to replace both the lower tap and the flange modules the carryover top tap module, 1 in Figure 9(a), should have been possible to assemble/disassemble without having to disassemble the remaining modules.

As a result of these factors, along with taking DFA into account, the interfacial relations and preferred assembly order of modules was determined to be a base unit assembly using the flange module as a base, as illustrated in the two interface matrixes in Figure 10.

The set of six interface designs, seen in Appendix 12, was evaluated using the set design criteria in a Pugh-matrix, see Appendix 13. This resulted with the highest evaluated concept being number two.

Following the choice of interface design the degree of possible integration for the flange module was decided through the mapping of shaft bolt and guide pin hole patterns, seen in Appendix 14, and thereafter limiting the integration by a maximum overhand between flange and hub of 150mm (≤300mm diameter difference). As visualized in the matrix in Figure 11 this resulted in the six unique
flanges for the product series: 60/86, 66/94, 72/102, 79/111, 121, 132.

Figure 11: Visualizing of possible integrality within the flange module when comparing shaft bolt and guide pin hole patterns with hub sealing placements and flange diameter differences between size models.

Module specific interface dimensions were thereafter calculated and summarized in Appendix 15. Standard MC6S 12.9 inex bolts were assumed for all bolted joints. The proposed bolt dimensions used to connect the different combinations of component are summarized in Table 1. General recommendation for sealing placements at module interfaces were, due to recommendations based on operator experience, during the continued module design sought to be placed radially where possible in order to ease assembly. The data in Appendix 15, Table 1, along with the supplementary specifications in Appendix 16 made up the module specifications used for the continued independent development of individual modules.

Table 1: Summary of calculated standardized bolt dimensions at inter-modular interface joints.

<table>
<thead>
<tr>
<th>Interface</th>
<th>Hole Pattern</th>
<th>Number of bolts per pattern</th>
<th>Minimum Clamp Length $L_k$</th>
<th>Bolt size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Tap // Flange</td>
<td>Ø235mm</td>
<td>12</td>
<td>≥48mm</td>
<td>M16x60</td>
</tr>
<tr>
<td>Flange // Bottom Tap</td>
<td>60/86: Ø315mm</td>
<td>12</td>
<td>≥24mm</td>
<td>M8x55</td>
</tr>
<tr>
<td></td>
<td>66/94: Ø340mm</td>
<td>12</td>
<td>≥29mm</td>
<td>&quot;&quot;</td>
</tr>
<tr>
<td></td>
<td>72/102: Ø375mm</td>
<td>12</td>
<td>≥39mm</td>
<td>&quot;&quot;</td>
</tr>
<tr>
<td></td>
<td>79/111: Ø415mm</td>
<td>12</td>
<td>≥30mm</td>
<td>&quot;&quot;</td>
</tr>
<tr>
<td></td>
<td>121: Ø455mm</td>
<td>12</td>
<td>≥40mm</td>
<td>M10x65</td>
</tr>
<tr>
<td></td>
<td>132: Ø495mm</td>
<td>12</td>
<td>≥60mm</td>
<td>&quot;&quot;</td>
</tr>
</tbody>
</table>

4.2.1 Module designs for A1 balancing and function testing tool series

The detailed designs of modules started with determining if component materials mechanical properties or bolted joint sizing were the dominant factor, with respect to product function and induced stress, when designing the components. As bolted joints were the dominant factor these were all sized simultaneously and the results compiled into Table 2.

Table 2: Summary of precalculated bolt sizes and patterns within modules throughout the full tool series.

<table>
<thead>
<tr>
<th>Module</th>
<th>Interface</th>
<th>Hole Pattern</th>
<th>Number of bolts per</th>
<th>Minimum Clamp Length</th>
<th>Bolt size</th>
</tr>
</thead>
</table>
Due to there being no specified need for more advanced materials to obtain the desired tool function the same type of regular structural steel as was used in previously manufactured tools was kept due to its low cost. Thereafter the design, sizing and assembly of 3D-model component were produced individually for each broken down module for the combined hub size 60/86 tool set, after having taken into account the availability of manufacturing methods and surveyed available standardized material dimensions at suppliers. The resulting model design for the top tap is visualized in Appendix 18, the flange plate with dual hub size integration in Appendix 19, and the size specific bottom tap for hub size 60 in Appendix 20. Note that the bottom tap for the larger hub size, 86, had the same design concept with the exception of not including the upper module interface plate. A schematic cross section of the fully assembled tool design, enabling easy comparison with existing tool design, is shown in Appendix 21. The semi-assembled cross section of the 60/86 modular tool is shown in Appendix 22, visualizing the minimal degree of possible preassembly and maximum required disassembly when switching between hub sizes.

The summary of the calculated process and lead times as well as cost comparison between the current and the proposed product architectures is shown in Appendix 23. Storage space comparison of a full set of tools resulted in ~3m² (~20%) reduced space, from 14.4m² to 11.5m². Storage cost comparison of a full set of tools resulted in ~800 SEK/year (~10%) cost reduction, from 6750 SEK/year to 5950 SEK/year.

### 4.3 Future State Proposal

Two options for the continued tool development and manufacturing process were included in the future state proposal.

1. Only implementing the amendments to the initiating product development process steps, as visualized in the future state cross functional process map shown in Appendix 24. This would
have led to reduced lead time when the customer order arrives for the initial tool within the product series from four to one week (~75%) for tool development but no cost reductions.

2. In addition to option 1, implement the proposed amendments related to changing product architecture. By making the tool series modular it would have enabled the changes visualized in the future state value stream map in Appendix 25. The results of this would’ve been an equivalent cost for the initial tool set, comprised of tools for two hub sizes, followed by an average cost reduction of ~35’000 SEK/tool (~25%) thereon due to combined material and manufacturing cost reductions. Lead time reductions due to the changes in product architecture would have been 3-4 weeks/tool (≥35% of manufacturing lead time) due to reduced amount of components required to be manufactured along with increased possible parallel manufacturing of the individual tool components.
5. Discussion
The initial value stream mapping started with scheduling a meeting with the external supplier’s quotation engineer, followed by a tour of their manufacturing facilities. During the meeting the manufacturing engineers responsible for tool and fixture development were also present. At the meet, even if disregarding the value of the intended data gathering for the papers value stream and cross functional process mapping, valuable experience was gained by the manufacturing engineers as well. An increased understanding of the possibilities and limitations of the supplier’s machinery entailed an enhanced potential for more efficient product designing with respect to manufacturing. Thusly similar contacts between engineers responsible for product development and companies frequently used manufacturing suppliers are seen as beneficial as it enables more efficient designs, in regards to DFM aspects, in developed products.

5.1 Process evaluation
What became apparent from the CFPM was that when developing a new balance and function testing flange there was no need for an entire 3D modelled assembly to be complete for the manufacturing engineers to initiate tool development. In order to be able to start designing the tool there is only a need for some vital measurements to be determined.

The initial product specifications for the tool showed relatively simple technical requirements, a relatively wide product variety due to differing hub sizes, and that maintained tool functionality wasn’t relying on an optimized high performance design. Meanwhile the current state value stream mapping visualized a lack of strategic product properties, such as enabling a more parallelized work process, in the current integral tool design. These were the two main factors when deciding on implementing the modularized product architecture. Rolls-Royce AB’s expressed desire to reduced tool based storage needs, particularly for bigger tool sets, was an additional contributing factor for modularization due to the apparent benefit to storage efficiency gained by being able to disassemble them.

The increased standardization within the product family, gained by taking the entire tool series into account during the MFD development process was considered to contribute to increased engineering efficiency, entailing reduced the overall time needed for development. Additionally the modular concept was thought to increase the possibility of parallel concurrent engineering during module design development, entailing further reduced lead time.

As the VSM visualized the outsourced flange component as the critical path for manufacturing lead time this became the main focus of the continued tool design evaluation. Modularization of this main component was motivated by wanting to enable better balanced parallel manufacturing in order to reduce its lead time.

Current manufacturing of tools and fixtures were split between in-house and external supplier manufacturing. Outsourcing manufacturing of low volume components had the benefit of reducing variation in production as well as reducing operational costs from machines, personnel and maintenance. From a suppliers point of view low component volumes did however result in comparably low manufacturing-value of the outsourced parts. Also noted was that the recurrences of outsourcing similar tools for manufacturing to the same supplier were somewhat irregular. The combination of these two factors entailed that when a new manufacturing order reached the
supplying manufacturer he couldn’t usually economically justify setting it as a high priority (thereby reducing lead time) order compared to other perhaps more regular and/or bigger manufacturing orders. As such outsourced tool components got longer lead times for delivery. Although not having been covered to any bigger extent within the study, except concluding that logistics were a significant issue, one possible way of reducing the lead time for these component could have been continued development of local supplier-partnerships focused on creating closer relations and the mutual benefits of increasing manufacturing efficiency and reducing the limitations on manufacturing lead time caused by, amongst others, logistics.

5.2 Tool design

Many produced product development processes in research originated from the notion of having a continuous large scale production. This had to be taken into account when adapting it to the existing small series manufacturing of in-house tools. During the use of the MFD process when designing the modules and their connecting interfaces the rule of thumb for the degree of modularization, Equation 1, was an obvious example of this. The rule of thumb was derived from wanting to create the optimal amount of parallel assembly with respect to the assembly times of modules alongside a primary assembly lane. Due to this, while still taking the rule into consideration, it wasn’t applied literary but rather interpreted so to design the interfaces in such a way to minimize the required disassembly and reassembly while moving the tool between hubs and to allow the most amount of possible preassembly of a tool to a hub without disrupting an ongoing function test.

Initially interface concepts were evaluated with respect to the most beneficial assembly order. This was done by considering the most extreme situation that could occur within the Balancing and Function testing operations during full capacity, and thereby identifying the most efficient and versatile (thereby most desirable) disassembly and assembly order. Interface concepts were thereafter compared with respect to their perceived relative manufacturability compared to each other, taking into account estimated manufacturing time requirements.

To ease assembly, possible future maintenance, as well as reduce the amount spare parts entailed to keep in storage to secure production bolted joints were, to an extent, standardized so that the same size bolts were usable throughout the entire tool series.

The avoidance of welding and its associated annealing process have been stated as a principal design aspect for the tool. Additionally the development of new components was done while striving for basic geometry in order to further ease the manufacturability. When considering the design of the top taps an alternate design, which would have increased material cost but simultaneously reduce labor cost, was manufacturing these in one piece through a single turning operation instead of drilling, threading and bolting the cylinder and flange plate together. This would plausibly reduce the amount of possible failure modes and lower the initial assembly time required by reducing the number of bolt and sealing elements however the availability of a standardized pipe with the required dimensions also showed to be limited.

Bushings fitted using bolted joints was also considered in order to ease material separation for future recycling. This assembly method was however disregarded due to the combined factors of the increased bronze material usage, which would affect both the economic and environmental impact, as well as an increase in manufacturing time. Using bolted joint fitted bushings also entailed an
increased number of sealing components relied upon for maintained tool function, thereby entailing an increased function failure plausibility.

When implementing modularized in-house tools transparency and communication between departments was considered to be key aspects for making it work long term. Even though having taken into account that assembly and disassembly was to be as easy and quick as possible during production it would inevitably entail a slightly increased work for the operator assigned to the task. Because of this having working continuous two-way feedback between the manufacturing engineers and operators were considered to be vital. The manufacturing engineers responsible for tool development would be required to communicate the implied savings, thereby clarifying the gained value despite the additional assembly operation when a reoccurring hub assembly would be received in the future. Simultaneously the operators would get to provide feedback to the engineer regarding working aspects of the tool design as well as, should something be causing more work than estimated, notify the engineer any neglected needs prior to the next tool size or tool generation would be manufactured so that it could be properly documented and wouldn’t be repeated.

5.3 Cost and lead time
When setting up time and cost comparisons the empiric process data gathered for the current tool development proved to be equally helpful and limiting. This was due to Rolls-Royce AB and the supplier using different logging methods and categorizing process data to different extents. The obtained empirical data had also been from differing tool sizes and tools from different generations. As such the provided process times were solely used to benchmark and calibrate the simulated model for calculating individual process times for both the old and the new components, rather than being used as absolute values when comparing with the model. While this ensured an equitable comparison between the different products designs it was emphasized that the resulting lead time and cost comparisons from this method would preferably be reviewed as relatively to each other rather than absolute savings. This was stated due to it in general always being possible to further refine and reduce deviations between reality and a theorized model, due to variable changes. By doing a relative comparison between designs these deviations would however, to a bigger extent, be negligible while still providing a fair assessment of the effects of proposed product amendments.

Note that the lead times in Appendix 23 differed from the lead time in the future state value stream map in Appendix 25. This was due to the comparison in Appendix 23 having the main purpose of showing the overall reduction of manufacturing time needed, as well as the related cost effects, caused by the tool design changes. As seen the tool design related manufacturing reduction was estimated to ~70 hours for the first tool set comprised of the sizes 60 and 86, and a ~195 hours lead time reduction for a sub-sequent tool set comprised of the sizes 66 and 94. Appendix 25 continues by utilizing the flexibility provided to the manufacturing process by the modular product architecture, which shows a continued reduction in lead time caused by the increase in parallelism of the manufacturing. This step assumed the continued outsourcing of the flange plate, which couldn’t be self-made without possibly disrupting normal production, along with the corresponding cover plates assembled to it before delivery. Simultaneously the initial manufacturing for the top tap and a bottom tap, applying an averaged manufacturing time, was assumed to be self-made. The resulting value stream for the outsourced component, which still had the longest time estimate, entailed a reduced lead time of ~35-45% compared to the original value stream. This variation depended on if assuming the same overall manufacturing process efficiency, ~45% reduction, or the same estimated
time the components spent in storage between machining processes, ~35%, as the current state value stream showed.

When adding all processes post tool development, thereby including the initial two week period dedicated to quotation and purchasing, the amendments entailed a potentially reduced manufacturing delivery of 26-37%, depending on supplier processing efficiency. This, along with the previously mentioned cost reduction, was considered to provide considerable benefits to Rolls-Royce AB’s competitiveness and delivery reliability on the market.

At the time of the study it was noted that the product development time wasn’t logged or in other ways documented towards specific customer orders or products in order to enable an objective comparison between products. As such the process comparison was based on making a work package breakdown of the processes, both the old and the new, and accompanying these with individual work package times based upon estimations done alongside the manufacturing engineers. In the case for the MFD development process the work package times were based on the times gained by the implementation of the process on the A1 hub series performed within the scope of the study. Due to the apparent subjectivity of the gathering of this product development time no greater emphasis was put on this comparison. No increase or decrease in efficiency with regards to overall tool development process time was made. The only deduction made was that the altered process enabled more work to be performed before a customer order was received, thereby assisting in the reduction in lead time for incoming orders in the future.

Note that the calculated cost reduction was solely based on personnel and material costs. Determining the internal value of a reduced delivery date for a customer order was not deemed relevant for the study, but was considered to further increase the economic benefits of the proposed development process and product amendments.
6. Conclusions
The implementation of both suggested amendments stated in the future state proposal would have been economically beneficial provided that at least two out of the ten developed hub sizes were going to be manufactured on the site at some point. The modularization would have enabled a 26-37% reduction in overall manufacturing lead time for the tools, reducing it from 10 weeks to 6-7 weeks depending on supplier manufacturing efficiency. This was largely thanks to the increased possibility of parallel manufacturing thanks to the modularity, as well as the reduction of manufacturing required for subsequent tool sets due to the tool integrality. Deriving from the initial statement of five tool sets being manufactured each year this would entail a cost reduction of ~105K SEK the initial year followed by up to ~175K SEK the following year assuming the remaining five tool sets would be manufactured. These savings were made possible due to material savings, enabled by the integrality within the tool series, and the corresponding cost reduction from reduced manufacturing needs.

Should solely the suggested minor process amendments be implemented; first part of the future state proposal be implemented, then the proactive engineering and parameterization of the balancing and function test equipment would not generate any cost reductions but would still reduce tool development lead time of the initial tool set when a new generation of hubs would be introduced.

Continued study is recommended to focus on potential supplier/partnership developments, its possibilities, limitations, and mutual benefits gained from it. If wanting to continue streamlining the product development process, for further lead time or cost reductions, some sort of activity based time logging would be recommended in order to enable objective evaluation of any process changes.

Should Rolls-Royce AB choose to adapt to the proposed method and modularized product architecture for the static balance and function test equipment, and its implementation proved successful, then the set based product development methodology would be easily applicable on other tools and fixtures. By having implemented this kind of approach for proactive engineering it could enable continued improvements and savings by enabling off-site outsourcing of the final repetitive engineering activities such as 3D-modelling and drawing development. This would thereby enable the on-site manufacturing engineers to focus more on continuous improvements and developing efficient solutions for new generations of tools and fixtures.
6. References


7. Appendixes

Appendix 1

Appendix 1: Visualizing of the different components included in a "House of Quality".
Appendix 2: Illustration visualizing a simplified QFD matrix showing the relations between customer wants ("what") and product properties ("how").
Appendix 3

Milling

\[ v_c = \frac{D_{\text{cap}} \times \pi \times n}{1000} \]

\[ v_f = f_z \times n \times z_c \leftrightarrow n = \frac{v_f}{f_z \times z_c} \]

\[ v_f = \frac{1000 \times v_c \times f_z \times z_c}{D_{\text{cap}} \times \pi} \]

Boring/Drilling

\[ T_c = \frac{L_{\text{m}}}{v_c \times f} \text{ [mm] / [rev/min] *[mm/rev]} \]

Turning machining:

\[ v_c = \frac{\pi \times D_m \times n}{1000} \]

\[ f = \frac{I}{n} \]

\[ T_c = \frac{L_{\text{m}}}{I} \]

\[ T_c = \frac{\pi \times D_m \times L_{\text{m}}}{1000 \times v_c \times f} \]

Turning threading process time

\[ T_c = \frac{L \times \sqrt{P^2 + \pi^2 \times d^2}}{P \times v_c \times 1000} \]

\[ \frac{1}{f_{M_{\text{min}}}} = \frac{\sqrt{P^2 + \pi^2 \times d^2}}{P \times v_c} \text{ [min/m]} \]

\[ f_{M_{\text{min}}} = \frac{P \times v_c \times 1000}{\sqrt{P^2 + \pi^2 \times d^2}} \text{ [mm/min]} \]

\[ T_c = \frac{L}{f_{M_{\text{min}}}} \]

\[ f_{M_6} = 8476,34 \text{ mm/min} \]

\[ f_{M_{10}} = 7630,74 \text{ mm/min} \]

\[ f_{M_{14}} = 7268,14 \text{ mm/min} \]

\[ f_{M_{18}} = 7066,65 \text{ mm/min} \]

\[ f_{M_{22}} = 5783,67 \text{ mm/min} \]

\[ f_{M_{30}} = 5937,69 \text{ mm/min} \]

\[ f_{M_{45}} = 5090,38 \text{ mm/min} \]

\[ f_{M_{52}} = 4894,78 \text{ mm/min} \]

Appendix 3: Summary of basic formulas utilized for calculating and estimating component manufacturing time.
Appendix 4

Appendix 4: Value Stream Map of the tool manufacturing process.
Appendix 5: Cross functional process map of the analyzed tool design and manufacturing process
Appendix 6: Cross section and 3D-model visualization of the current tool design for the A1-series controllable pitch propeller hub.
<table>
<thead>
<tr>
<th><strong>Functions</strong></th>
<th><strong>Sub-functions</strong></th>
<th><strong>Tech. solution</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fix/Seal the hub assembly to the test flange</td>
<td>Match flanges guide pins and shaft bolt pattern to hub</td>
<td>Replaceable plates with size-specific hole patterns</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Replaceable plate with multiple set of holes</td>
</tr>
<tr>
<td></td>
<td>Seal flange to hub</td>
<td>One plate with multiple sets of hole patterns</td>
</tr>
<tr>
<td>Lifting equipment for combined tool and hub assembly</td>
<td>Safe lifts of all major components</td>
<td>Certified lifting device on each major component/module</td>
</tr>
<tr>
<td>Delimit and seal hydraulic systems</td>
<td>Seal oil distribution pipe bushings</td>
<td>Exchangeable bushing with seal at tap endcaps for different pipe sizes</td>
</tr>
<tr>
<td></td>
<td>Prevent oil distribution pipe adapter from traveling past seal</td>
<td>One standardized bushing with seal for the entire product series</td>
</tr>
<tr>
<td></td>
<td>Seal inside of piston to tap</td>
<td>Exchangeable top taps with varying length</td>
</tr>
<tr>
<td></td>
<td>Prevent collision between piston and bottom tap during maximum pitch</td>
<td>Replaceable tap, varying length</td>
</tr>
<tr>
<td></td>
<td>Prevent piston travel beyond designed maximum pitch</td>
<td>One tap with adapters to adjust length</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Telescopic adjustable tap-length</td>
</tr>
<tr>
<td>Hold hub assembly during static balancing</td>
<td>Hold for induced radial forces</td>
<td>Continuous leveled surface between the top of the hub and the flange plate</td>
</tr>
<tr>
<td></td>
<td>Prevent tool design from affecting balancing results</td>
<td>Size tool to handle total hub assembly and tool weight</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tool must have axially centred mass centre</td>
</tr>
</tbody>
</table>
Appendix 8

**Match flanges guide pins and shaft bolt pattern to hub.**

<table>
<thead>
<tr>
<th>Technical Concepts and solutions</th>
<th>Evaluation Criteria</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modularity</td>
<td>Efficient component assembly</td>
</tr>
<tr>
<td>One plate with multiple sets of hole patterns</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Replaceable plate with multiple set of holes</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Replaceable plates with size-specific hole patterns</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Reference concept

**Seal tap to inside of piston**

<table>
<thead>
<tr>
<th>Technical Concepts and solutions</th>
<th>Evaluation Criteria</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modularity</td>
<td>Efficient component assembly</td>
</tr>
<tr>
<td>Replaceable tap with varying diameter</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Have one tap with split semicircular adaptable bushing for sealing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Reference concept

**Prevent collision between piston and bottom tap during maximum pitch**

<table>
<thead>
<tr>
<th>Technical Concepts and solutions</th>
<th>Evaluation Criteria</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modularity</td>
<td>Efficient component assembly</td>
</tr>
<tr>
<td>Replaceable tap, varying lengths</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>One tap with adapters to adjust length</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Telescopic adjustable tap-length</td>
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</tbody>
</table>

Reference concept

Appendix 8: Resulting Pugh-matrixes from step 2 of the MFD method where multiple technical concepts for functions were identified.
Appendix 9: Function and means tree of the balancing and function testing flange tool. Function and sub functions explained at the top of boxes while technical solutions are noted in their bottom half.

Balancing and Function Test Equipment

1. Fix and seal the hub assembly to the test flange
   - Exchangeable flange plate with multiple sets of holes and non-disrupted contact
2. Lifting / Logistics
   - CE-certified lifting device on each major component/module
3. Delimit and seal hydraulic systems
   - Exchangeable bottom taps and oil distr. pipe bushings. Leveled bottom surface on flange plate. Top tap length adjusted to prevent oil distr. pipe adapter from colliding with endcap.
4. Hold hub assembly during static balancing
   - Size tool to handle total hub assembly and tool weight and have axially centred mass centre

1.1 Match flange guide pins and shaft bolt pattern to hub
   - Replaceable plate with multiples set of holes
1.2 Seal flange to hub
   - Non-disrupted contact area towards hub seal
3.1 Seal inside of piston to tap
   - Replaceable tap with varying diameter
3.2 Prevent collision between piston and bottom tap during maximum pitch
   - Replaceable tap, varying length
3.3 Prevent piston travel beyond designed maximum pitch
   - Leveled surface between the top of the hub and the flange plate
3.5 Prevent oil distr. pipe adapter from traveling past seal
   - Exchangeable bushing with seal at tap endcaps for different pipe sizes
3.4 Seal oil distr. pipe bushings
   - Adjust top tap length to prevent adapter travel beyond seal
## Appendix 10

<table>
<thead>
<tr>
<th>Module Drivers</th>
<th>Technical Solution</th>
<th>CE-classed lifting device</th>
<th>Flange plate with multiple sets of hole patterns and seal surf.</th>
<th>Taps with varying diameter</th>
<th>Taps with varying length</th>
<th>Tap with adapters to adjust length</th>
<th>Leveled flange plate surface</th>
<th>Replaceable bushings at tap end caps</th>
<th>Tap length prevents pipe adapter from bypassing bushing</th>
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<tbody>
<tr>
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<td></td>
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</tbody>
</table>

*: Competing technical concepts

Appendix 10: Module Indication Matrix (MIM) of the balance and function test equipment. Each technical function concept is weighted against Module Drivers to evaluate possible beneficial modularization.
Appendix 11: Summary of how function related technical solutions were split onto three respectively two modules during the MFD process.

### 3 modules - alt. 1

- Tap length prevents pipe adapter from bypassing bushing
- CE-classed lifting device
- Bushings at tap end caps
- Taps with varying length
- Taps with varying diameter
- CE-classed lifting device
- Bushings at tap end caps
- Flange plate with multiple sets of hole patterns
- CE-classed lifting device

### 3 modules - alt. 2

- Tap length prevents pipe adapter from bypassing bushing
- CE-classed lifting device
- Bushings at tap end caps
- Tap with adapters to adjust length
- Taps with varying diameter
- CE-classed lifting device
- Bushings at tap end caps
- Flange plate with multiple sets of hole patterns
- CE-classed lifting device

### 2 modules

- Tap length prevents pipe adapter from bypassing bushing
- CE-classed lifting device
- Bushings at tap end caps
- Taps with varying length
- Taps with varying diameter
- CE-classed lifting device
- Bushings at tap end caps
- Flange plate with multiple sets of hole patterns
- CE-classed lifting device
Appendix 12

Appendix 12: Original sketches of the evaluated set of module interface designs. Designs 1-4 consists of 3 modules while 5-6 consists of 2 modules.
Appendix 13: The resulting Pugh-matrix from evaluating the set of module interface designs.

<table>
<thead>
<tr>
<th>Module concept</th>
<th>Design For Assembly</th>
<th>Design For Manufacturing</th>
<th>Product Family Integration</th>
<th>Force Transmittance between modules</th>
<th>Sum +</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td></td>
<td>1</td>
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<tr>
<td>4</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-1</td>
</tr>
<tr>
<td>5</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>++</td>
<td>-</td>
<td>-</td>
<td>1</td>
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</tbody>
</table>
Appendix 14

Appendix 14: Mapping of the A1 series hub seals and diameter ranges occupied by shaft bolts and guide pins depending on hub size.
### Appendix 15

<table>
<thead>
<tr>
<th>Interface parameter</th>
<th>Parameter value [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top tap inner diameter</td>
<td>135</td>
</tr>
<tr>
<td>Top tap total module length</td>
<td>350</td>
</tr>
<tr>
<td>Top tap // Flange plate interface diameter</td>
<td>260</td>
</tr>
<tr>
<td>Top tap interface plate thickness at bolted joints</td>
<td>30</td>
</tr>
<tr>
<td>Flange plate countersink at top tap interface</td>
<td>3</td>
</tr>
<tr>
<td>Flange plate countersink at bottom tap interface</td>
<td>20</td>
</tr>
<tr>
<td>Flange plate-60/86 // Bottom tap interface diameter</td>
<td>340</td>
</tr>
<tr>
<td>Flange plate-66/94 // Bottom tap interface diameter</td>
<td>365</td>
</tr>
<tr>
<td>Flange plate-72/102 // Bottom tap interface diameter</td>
<td>400</td>
</tr>
<tr>
<td>Flange plate-79/111 // Bottom tap interface diameter</td>
<td>440</td>
</tr>
<tr>
<td>Flange plate-121 // Bottom tap interface diameter</td>
<td>480</td>
</tr>
<tr>
<td>Flange plate-132 // Bottom tap interface diameter</td>
<td>520</td>
</tr>
</tbody>
</table>

Appendix 15: Summary of the intermodular interface parameters.
## Appendix 16

<table>
<thead>
<tr>
<th><strong>Top Tap</strong></th>
<th><strong>Flange Plate</strong></th>
<th><strong>Bottom Tap</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Replaceable oil distribution pipe bushing seal with varying diameters.*</td>
<td>Shaft bolt and guide pin hole patterns mimics hub.</td>
<td>Seal pipe bushing.</td>
</tr>
<tr>
<td>Tap long enough to accommodate for both longest oil distribution pipe and pitch stroke in product series, &gt;135mm internal protrusion, , and provide sufficient length for safe maneuverability during static balancing, &gt;300mm.</td>
<td>Withstand force transmitted from top tap induced by A-system.*</td>
<td>Provide seal towards flange plate.</td>
</tr>
<tr>
<td>Tap inner diameter accommodates widest oil distribution pipe in product series, &gt;=135mm internal tap diameter.</td>
<td>Withstand force transmitted from bottom tap induced by A-system.*</td>
<td>Withstand A-system exterior pressure, 120bar.</td>
</tr>
<tr>
<td>Withstand A-systems internal pressure, 120bar.</td>
<td>Withstand SP-system internal pressure, 5bar.</td>
<td>Non-through threaded hole pattern facing flange plate.</td>
</tr>
<tr>
<td>Through bolted joint hole pattern for flange plate.</td>
<td>Leveled bottom surface.</td>
<td>Tap length and outer diameter mimics shaft flange.*</td>
</tr>
<tr>
<td>Pipefitting for hydraulic fluid for SP-system.</td>
<td>Provide seal towards top tap.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Create seal for unused through holes.</td>
<td></td>
</tr>
</tbody>
</table>

*See Appendix 17 for size-specific data.
**See Appendix 14 for hole patterns and sealing overlaps.

*Appendix 16: Module specific technical specifications for the three module concept.*
## Appendix 17

Summary of the vital model size specific data referred to in module specifications.

<table>
<thead>
<tr>
<th>Model size</th>
<th>60</th>
<th>66</th>
<th>72</th>
<th>79</th>
<th>86</th>
<th>94</th>
<th>102</th>
<th>111</th>
<th>121</th>
<th>132</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil distriution pipe diameter</td>
<td>60 mm</td>
<td>60 mm</td>
<td>75 mm</td>
<td>75 mm</td>
<td>90 mm</td>
<td>90 mm</td>
<td>100 mm</td>
<td>100 mm</td>
<td>115 mm</td>
<td>115 mm</td>
</tr>
<tr>
<td>Shaftflange tap length</td>
<td>190 mm</td>
<td>202 mm</td>
<td>217 mm</td>
<td>240 mm</td>
<td>267 mm</td>
<td>283 mm</td>
<td>307 mm</td>
<td>325 mm</td>
<td>355 mm</td>
<td>384 mm</td>
</tr>
<tr>
<td>Shaftflange tap diameter</td>
<td>240 mm</td>
<td>260 mm</td>
<td>280 mm</td>
<td>305 mm</td>
<td>340 mm</td>
<td>365 mm</td>
<td>400 mm</td>
<td>440 mm</td>
<td>480 mm</td>
<td>520 mm</td>
</tr>
<tr>
<td>Induced axial force on top tap exposed to A-system pressure</td>
<td>150.80 kN</td>
<td>150.80 kN</td>
<td>131.71 kN</td>
<td>131.71 kN</td>
<td>108.38 kN</td>
<td>108.38 kN</td>
<td>90.48 kN</td>
<td>90.48 kN</td>
<td>60.08 kN</td>
<td>60.08 kN</td>
</tr>
<tr>
<td>Obs. Assumed inner tap diameter = 140 mm</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Induced axial force on bottom tap by A-system pressure</td>
<td>508.94 kN</td>
<td>603.19 kN</td>
<td>685.89 kN</td>
<td>823.73 kN</td>
<td>1013.16 kN</td>
<td>1179.28 kN</td>
<td>1413.72 kN</td>
<td>1730.39 kN</td>
<td>2046.83 kN</td>
<td>2423.82 kN</td>
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</table>
Appendix 18: Visualizing of the bolts and manufactured components included in the top tap module before and after assembly with bolts and O-ring seals.
Appendix 19: 3D visualization of manufactured components included in a flange plate module. The picture shows the standardized cover plates for the inner shaft bolt hole pattern and the integrated flange plate for hub size 60/86 before and after assembly with bolts and O-ring seals.
Appendix 20: 3D representation of bolts, seals, and manufactured components included in the bottom tap module for hub size 60 before and after assembly.
Appendix 21

Appendix 22: Compilation of components included in the size 60/86 tool. It shows the bolted replaceable top endcap, the bolted joint between the carry-over top tap and the flange plate, and the size specific bolted bottom taps for size 60 and 86.
Appendix 23

Initial Tool set: 60/86

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>Manufacturing</td>
<td>132.9 h</td>
<td>536.3 h</td>
<td>148 503.64 kr</td>
</tr>
<tr>
<td>Prod. Development</td>
<td>185.4 h</td>
<td>185.4 h</td>
<td>92 682.93 kr</td>
</tr>
<tr>
<td>Total:</td>
<td>318.3 h</td>
<td>721.7 h</td>
<td>241 186.57 kr</td>
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</tbody>
</table>

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Manufacturing</td>
<td>115.4 h</td>
<td>465.4 h</td>
<td>126 364.20 kr</td>
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<tr>
<td>Prod. Development</td>
<td>226.8 h</td>
<td>135.4 h</td>
<td>113 414.63 kr</td>
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<tr>
<td>Total:</td>
<td>342.2 h</td>
<td>600.8 h</td>
<td>239 778.83 kr</td>
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Results of process change: 23.9 h -120.9 h -1 407.74 kr

Subsequent Tool set: 66/94

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<tbody>
<tr>
<td>Manufacturing</td>
<td>137.3 h</td>
<td>553.8 h</td>
<td>154 387.34 kr</td>
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<tr>
<td>Prod. Development</td>
<td>82.9 h</td>
<td>41.5 h</td>
<td>41 463.41 kr</td>
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<tr>
<td>Total:</td>
<td>220.2 h</td>
<td>595.3 h</td>
<td>195 850.76 kr</td>
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<tr>
<td>Manufacturing</td>
<td>88.9 h</td>
<td>358.8 h</td>
<td>99 200.24 kr</td>
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<td>Prod. Development</td>
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<td>Total:</td>
<td>143.8 h</td>
<td>395.4 h</td>
<td>126 639.27 kr</td>
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Results of process change: -76.4 h -199.9 h -69 211.49 kr

Full Tool Series: 60-132

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<td>Manufacturing</td>
<td>724.4 h</td>
<td>2922.6 h</td>
<td>827 232.68 kr</td>
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<tr>
<td>Prod. Development</td>
<td>517.1 h</td>
<td>351.2 h</td>
<td>258 536.59 kr</td>
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<tr>
<td>Total:</td>
<td>1241.5 h</td>
<td>3273.8 h</td>
<td>1 085 769.26 kr</td>
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<tr>
<td>Manufacturing</td>
<td>501.0 h</td>
<td>2021.3 h</td>
<td>574 428.49 kr</td>
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<tr>
<td>Prod. Development</td>
<td>461.6 h</td>
<td>263.4 h</td>
<td>230 792.68 kr</td>
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<td>Total:</td>
<td>962.6 h</td>
<td>2284.7 h</td>
<td>805 221.17 kr</td>
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</table>

Results of process change: -278.9 h -989.1 h -280 548.09 kr

Appendix 23: Summary of calculated process times, lead times, and total cost estimates for manufacturing and product development for the current tool design as well as the modular concept. This is shown for an initial dual tool set, a subsequent tool set, and the full tool series. Calculations assumed employees work 40h/week, one operator doing the manufacturing, one engineer doing product development for the current design, and two engineers working parallel for the module concept design.
Appendix 24: Proposed future state cross-functional process map for tool development.

- Design parametrized hub assembly
- Produce documentation for ordered hub assembly
- Are all documents final and "released"?
  - Yes: Proceed to next step
  - No: Revise and finalize documents
- Designate what components are:
  - Manufactured Items
  - Std.comp./RawMaterial
  - Purchased Items
- Send purchase order for ordered hub assembly
- Estimate individual process and lead times for Manufactured Components
- Plan schedule for manufacturing the Manufactured Items
- Manufacture all Manufactured Items
- Final assembly of tool
- Is parametrized tool design final?
  - Yes: Proceed to next step
  - No: Revise and finalize tool design
- Is quotation satisfactory?
  - Yes: Proceed to next step
  - No: Request a new quotation
- Does the final drawings match the plan schedule for manufacturing the Purchased Items?
  - Yes: Proceed to next step
  - No: Revise the plan schedule
- Package and distribute raw materials
- Send Purchase order for raw materials
- Execute the manufacturing of Purchased Items
- Produce quotation for Purchased Items
- Send quotation requests for Purchased Items
- Is quotation satisfactory?
  - Yes: Proceed to next step
  - No: Request a new quotation
- Distribute ordered std.comp./raw materials
- Plan schedule for manufacturing the Purchased Items
- Send Purchase order for raw materials
Appendix 25: Proposed future state value stream map for static balancing and function test of A1 controllable pitch propeller hub assemblies.