Automatic drilling of holes for wing- and fin interface

– A theoretic idea of how the drilling could be automated

Automatisk borrning av hål för interface av vinge och fena

– En teoretisk idé för hur borrningen ska kunna automatiseras

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Examiner: Mats Björkman
Acknowledgements

This thesis has been conducted during the spring term of 2017 at Saab Aeronautics in Linköping. This is the final project in our Bachelor degree in mechanical engineering.

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Linn Krüger & Maja Will
Abstract

Year 2024 U.S. Air Force will replace their current Northrop T-38 Talon aircraft trainer for pilots, and therefore they have designed the T-X program where several aircraft manufactures competes about the first order of 350 aircrafts. Boeing and Saab AB have in cooperation produced a new aircraft trainer, Boeing T-X, where Saab AB produces the rear part of the fuselage. Today two prototypes have been produced and tested to fly, but if Boeing and Saab wins the order the production has to be more effective to manage the production volume.

The aircraft has two wings and two fins which are assembled via an interface with several larger holes which were partially drilled manually during the prototype manufacturing. The purpose with this thesis was to examine if the drilling of the interfaces could be automated in order to increase the production volume, regarding to economy and high tolerance - and flatness requirements. The purpose was also to determine how much of the drilling should be done in an earlier stage and how much should be done where the fuselage is assembled. To manage the time limit, delimitations were set to only make a pre-study and examine which path Saab should take when selecting a suitable solution, the time limit will not be enough for a ready solution.

Different drilling methods and different machines and robots suitable for drilling were examined. Concept selection matrices were used in the work process to reach a result, where different concepts were developed and compared with each other based on the requirements. The result was to develop the CNC gantry machine concept.
Sammanfattning


Flygplanet har två vingar och två fenor vilka fästs via ett interface med ett fåtal större hål vilka under prototyptillverkningen till viss del har borrats manuellt. Syftet med det här exjobbet var att undersöka om borrningen av interfacen gick att automatisera för att kunna öka produktionshastigheten, med avseende på ekonomi samt höga tolerans- och planhetskrav. Syftet var också att avgöra hur mycket av borrningen som skulle göras i ett tidigare skede och hur mycket som skulle göras där flygkroppen byggs samman. För att hinna under tio veckor gjordes avgränsningar till att endast göra en förstudie och ett vägval åt Saab, och inte ta fram en färdig lösning.

Olika borrningsmetoder samt maskiner och robotar lämpade för borrning undersöktes. För att komma fram till ett resultat användes under arbetet konceptutvecklingsmatriser, där olika koncept togs fram och jämfördes med varandra utifrån de krav som identifierats. Resultatet blev att utveckla CNC gantry maskin konceptet.
# Nomenclature

<table>
<thead>
<tr>
<th>ADU</th>
<th>Automatic drilling unit, a machine that is used for highly demanding drilling, counterboring and reaming</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials, a trusted source for technical standards for materials, products, systems, and services</td>
</tr>
<tr>
<td>Beam</td>
<td>The outer article for the wing interface</td>
</tr>
<tr>
<td>Boring</td>
<td>Boring is used to enlarge a hole made by a previous process</td>
</tr>
<tr>
<td>CMM</td>
<td>A Coordinate Measuring Machine is able to measure complex details and products</td>
</tr>
<tr>
<td>CNC machine</td>
<td>Computer Numerical Control machine</td>
</tr>
<tr>
<td>Counterboring</td>
<td>Enlarge the entrance of a hole</td>
</tr>
<tr>
<td>DT</td>
<td>The detail manufacturing, DT, is a separate place of the factory and manufactures some parts for the aircraft</td>
</tr>
<tr>
<td>Flatness</td>
<td>The surface with the flatness tolerance must be within a certain distance between two parallel planes</td>
</tr>
<tr>
<td>Frame</td>
<td>The part under the beam</td>
</tr>
<tr>
<td>Fuselage</td>
<td>The body of the aircraft</td>
</tr>
<tr>
<td>Gantry</td>
<td>A structure that bridges over an area</td>
</tr>
<tr>
<td>Interface</td>
<td>The surface where the wing and fin are assembled</td>
</tr>
<tr>
<td>Legacy product</td>
<td>Saab’s main product that is fully manufactured at Saab</td>
</tr>
<tr>
<td>PKM</td>
<td>Parallel Kinematic Machine</td>
</tr>
<tr>
<td>Plunge</td>
<td>A tool that is placed in one of the drilled holes to stabilize during the remaining drilling</td>
</tr>
<tr>
<td>Probe</td>
<td>A handheld device that reflects the laser from a laser tracker</td>
</tr>
<tr>
<td>Reaming</td>
<td>Making an existing hole dimensionally more accurate</td>
</tr>
<tr>
<td>SB</td>
<td>The final production and assembly are made in fuselage assembly, SB</td>
</tr>
<tr>
<td>Shim</td>
<td>A thin piece of material that is placed at the drilling mechanism to make sure the holes get the same depth</td>
</tr>
<tr>
<td>Top skin</td>
<td>The outer article for the fin interface</td>
</tr>
</tbody>
</table>
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1 Introduction

This chapter describes the background and the objective of the thesis, also the research questions and the delimitations. It follows by a short description of the company Saab Group.

1.1 Background

United States Air Force, U.S. Air Force, will purchase a new advanced two-seated aircraft trainer for pilots that will replace the current Northrop T-38 Talon. Several aircraft manufactures are participating in what is called the T-X program which is designed by U.S. Air Force, to compete about the first order on 350 training aircrafts which are calculated taking into operation and replace T-38 year 2024. Boeing is one of the aircraft manufactures that are participating in the T-X program and they have partnered with Saab which manufactures the rear part of the body. In the current situation two T-X prototypes has been built and the first flight with Boeing T-X was performed in December 2016 in St Louis, USA (Saabgroup AB, 2016).

![Figure 1. A picture of T-X Boeing. The red highlighting shows where the wing- and fin interface are placed on the left side. ©Boeing](image)

The aircraft has four interfaces where the two wings and two fins are attached. The wing- and fin interface are placed at the rear part of the fuselage, the body of the aircraft, see Figure 1. To attach the wing and fin with the fuselage, six holes are drilled at the wing interface and nine holes are drilled at the fin interface. The wing- and fin interface are made in aluminum. When the two prototypes were manufactured the holes for the wing interface were pre-drilled in the detail manufacturing, DT, in another part of the factory. DT has a lot of different manufacturing machines and measuring equipment, for example CNC machines and CMM machines in varying sizes. A Coordinate Measuring Machine (CMM), is able to measure complex details and products. The articles mentioned in this thesis were manufactured in CNC machines out of aluminum blocks.

The final production and assembly were made in the fuselage assembly, SB, where the holes were reamed and bushings were placed in the holes. All the holes for the fin interface were drilled in DT and the flatness was measured in a CMM. The surface with the flatness tolerance must be within a certain
distance between two parallel planes. Based on the results from the measuring, bushings were chosen that were adapted for the flatness.

The final drilling of the wing interface in SB for the two prototypes was made manually, however if Boeing wins the T-X program the production volume will increase directly and Saab will have to decrease the drilling time considerably. The manufacturing rate will be 48 aircrafts per year, therefore the drilling has to be more effective in order to fulfil the rate requirement.

The T-X project will require a production line to be able to handle the capacity of 48 aircrafts a year. The wing- and fin interface are planned to be drilled at the same station in the future, the drilling station will be placed in the end of the production line. The reason for this is that the rear part of the body must be almost fully assembled in order to manage the high tolerance- and flatness requirements of the holes because of the stresses that occur. (Almé, L. 2017)

1.2 Objective
The objective with this thesis is to develop a drilling concept that fits Saab’s goals for a more effective drilling of the wing- and fin interface for Boeing T-X. The concept must be robust, effective, and economically justifiable but also fulfil the high tolerance- and flatness requirements. The purpose is also to examine how much of the drilling that should be done in detail manufacturing and how much that should be done in fuselage assembly.

1.3 Delimitations
The objective of the thesis is only to examine which path Saab should take when selecting a suitable drilling concept. Several different paths will be examined and since this thesis comprises 10 weeks the time will not be enough for a ready solution. Another delimitation is access of information. Because of the high security of handling out information to external people, people within Saab with expertise will be interviewed in first place to collect information about different concepts instead of manufactures and suppliers. The thesis also exclude mentioning dimensions because of the secrecy.

1.4 Research questions
The objective was broken down to the following Research Questions (RQs):

RQ1: How can the drilling of the wing- and fin interface be automated and more effective?
- Which concept is most suitable regarding to the requirements?

RQ2: How much of the manufacturing should be done in detail manufacturing and how much should be done in fuselage assembly?
- How will the fin interface avoid CMM measuring?
1.5 Company Description
Saab Group AB was founded in 1937 to secure production of military aircraft to maintain the security of the country. For decades Saab have been providing solutions from training- and command- and control systems, to military subsystems, weapons and next-generation aircraft. Saab has around 14,000 employees and operates in all continents, their main production is located in Linköping with about 5,000 employees. Today they operate in five business areas, see Table 1, to provide the global market with products, services and solutions, for both military and civilian markets. Saab’s legacy product is the military aircraft Gripen, which is one of the most advanced versatile fighters. (Saab Group, 2017)

Table 1. A description of Saab Group’s business areas (Saab Group AB, 2017)

<table>
<thead>
<tr>
<th>Business areas</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aeronautics</strong></td>
<td>Advanced development of military and civil aviation technology</td>
</tr>
<tr>
<td><strong>Dynamics</strong></td>
<td>Develops ground combat weapons, missile systems, torpedoes, underwater vehicles and signature management systems for the civil and defence market</td>
</tr>
<tr>
<td><strong>Surveillance</strong></td>
<td>Provides efficient solutions for safety and security, for surveillance and decision support, and for threat detection and protection</td>
</tr>
<tr>
<td><strong>Support and Services</strong></td>
<td>Offers reliable, cost efficient service and support for all of Saab’s markets</td>
</tr>
<tr>
<td><strong>Industrial Products and Services</strong></td>
<td>Comprises the business units Combitech, Avionics Systems, Aerostructures and Vricon and works with individual growth strategies for each business unit, as well as the development of product ideas that fall outside of Saab’s core business</td>
</tr>
</tbody>
</table>
Methodology and implementation
This chapter contains a description of the methods used and implementation to reach a result of the thesis.

2.1 Thesis work process
A process is defined as sequential steps of activities (Levy, Y & Ellis, T. 2006). The working process to reach a result of the thesis have been divided in four different steps as shown in Figure 2. The four steps will be explained further in this chapter.

2.2 Literature review
A literature review is a process defined as sequential steps to: collect, know, comprehend, apply, analyze, synthesize and evaluate literature in order to provide knowledge in a topic. A literature review can be divided in three steps: input, processing and output shown in Figure 3. (Levy, Y & Ellis, T. 2006)

Literature review have been included during the whole working process, especially in the first phase of the thesis. Planning on what keywords to use when researching have been decided before collecting literature. The importance with planning which keywords to use is to not search too wide. The keywords were for example different drilling methods.

The next step was to collect material to write about. Literature was collected from books, internet articles and websites from different manufactures. To find electronic books, internet articles and websites with drilling methods the databases Google, Google Scholar and UniSearch were used. A book about product design and development was recommended to use for concept selection by our advisor at Linköping’s University. The collected literature was further analyzed to collect relevant material and sort out irrelevant material. After planning, collecting and analyzing the literature, the writing process began. These steps have been done for all literature review during the thesis.
2.3 Semi-structured interviews
There are three different kind of interview techniques; unstructured, semi structured and structured. A semi-structured interview is a research method where the interviewer has an open interview with the person who is getting interviewed. The interviewer has prepared several questions before the interview, and during the interview the interviewer asks questions that are prepared but also depending on what ideas that is brought up during the interview. The interviewer generally has topics that will be discussed and examined. A structured interview is when the interviewer has prepared all questions and the questions never change during the interview. (Wilson, C. 2013)

The advantages with a semi-structured interview is that new issues that were previously unknown can be discovered, this will lead to new ideas and questions to ask. Complex topics can be clarified, for example if the interviewer does not know that much about the complex topic it is difficult to think of questions to ask before the interview. But if the person who is interviewed explains a difficult topic it will be easier to bring up new questions. Another advantage with semi-structured interviews is if the conversation digresses too far from the main topic the interviewer can easily redirect the conversation. It gives the interviewer a flexibility with supplementary questions, and it also require less training than an unstructured interview. The disadvantage with semi-structured interviews is the risk for misunderstanding and missing information. (Wilson, C. 2013)

In this thesis semi-structured interviews have been used, the purpose has been to gain knowledge and understanding for the thesis. Mostly people within Saab with special expertise have been interviewed, but also people at Linköping’s University and external people with drilling competence. During the interviews notes have been taken and afterwards a summary of the interviews have been written to assure that no facts are forgotten.

2.4 Benchmarking
Benchmarking is a method used to develop the organization by comparing to other organizations or units within the organization. It is considered to be one of the most effective methods to collect knowledge and innovation to organizations. Benchmarking starts with a deep understanding of the internal process, the next step is to compare with competitors, various organizations or different units within the same organization. It is a method for learning and improvement. Benchmarking is described as a structured process: plan (plan), collect (do), analyze (check) and adapt (act). (Emerald Group, 2006)

Benchmarking have been made within Saab Group’s business areas Aeronautics and Aerostructures. To see different drilling methods a visit to Aerostructures was made to see the aircraft part production for Airbus and Boeing. Aeronautics was visited as well to see the production of Saab’s legacy product to compare drilling methods with the method used on the two prototypes for Boeing T-X. The legacy product is Saab’s main product that is fully manufactured at Saab.
Concept selection process

A concept matrix is a two-stage process, concept screening and concept scoring, both stages are made using a matrix. The process for both stages are divided in six steps:

1. Prepare the selection matrix
2. Rate the concepts
3. Rank the concepts
4. Improve and combine concepts
5. Select one or more concept(s)
6. Reflect on the result and the process

(Ulrich, K. & Eppinger, S. 2008)

The solution selection process was done using the method below. The process began with listing and weighting the criteria for the solution. The criteria were discussed with advisors and managers at Saab. The criteria were also weighted to sort out the most important criteria. The potential solutions were listed and ranked after the criteria, however not all solutions could be ranked since a lot of information about the solutions are unknown. Finally, the best solution was selected and reflected based on the final weighted score.

2.5.1 Concept screening

Concept screening is based on a method developed by Stuart Pugh in the 1980s and is called Pugh concept selection (Pugh, 1990). This method is used to improve and develop concepts.

Table 2. An example of a concept screening. (+ for better than, 0 for same as, - for worse). (Adapted from Ulrich, K. & Eppinger, S. 2008)

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>Concept 1</th>
<th>Concept 2</th>
<th>Concept 3 (reference)</th>
<th>Concept 4</th>
<th>Concept 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easy to handle</td>
<td>+</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Robust</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Effective</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Durability</td>
<td>-</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Sum +’s</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Sum 0’s</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Sum –’s</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Net score</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>-2</td>
<td>1</td>
</tr>
<tr>
<td>Rank</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Continue?</td>
<td>yes</td>
<td>combine</td>
<td>combine</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

As shown in Table 2 concepts are compared with the reference concept using a simple code (+ for “better than”, 0 for “same as”, - for “worse”) for the criteria. The reference concept is generally an industry standard or a concept with which the team members are very familiar, however the matrix does not require a reference. Concept screening is the first step of the concept matrix. With concept screening the user can easily see which concepts to continue with and which to not continue with. If two concepts get the same net score the team can consider combining the concepts if they believe combining them will remove several “worse than”. (Ulrich, K. & Eppinger, S. 2008)
2.5.2 Concept scoring

Concept scoring is the next step, however it is not always necessary if the concept screening produces a dominant concept. This method is used to improve the comparisons to each criterion. In this stage a finer rating scale is used:

Much worse than reference 1
Worse than reference 2
Same as reference 3
Better than reference 4
Much better than reference 5

(Ulrich, K. & Eppinger, S. 2008)

The concept scoring can use a single reference concept, as in the screening stage, however this is not always appropriate in scoring stage. The reason for this is if the reference concept happens to be the best concept, all the other concepts will be rated with 1, 2, and 3. Therefore it is recommended to use different reference points, see bold numbers in Table 3, in this stage to avoid the reference concept receiving a neutral score. (Ulrich, K. & Eppinger, S. 2008)

Table 3. An example of a concept scoring. (Adapted from Ulrich, K. & Eppinger, S. 2008).

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>Weighting</th>
<th>Rating</th>
<th>Weighted score</th>
<th>Rating</th>
<th>Weighted score</th>
<th>Rating</th>
<th>Weighted score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easy to handle</td>
<td>15%</td>
<td>3</td>
<td>0.45</td>
<td>3</td>
<td>0.45</td>
<td>5</td>
<td>0.75</td>
</tr>
<tr>
<td>Robust</td>
<td>25%</td>
<td>2</td>
<td>0.5</td>
<td>3</td>
<td>0.75</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>Effective</td>
<td>45%</td>
<td>3</td>
<td>1.35</td>
<td>4</td>
<td>1.8</td>
<td>2</td>
<td>0.9</td>
</tr>
<tr>
<td>Durability</td>
<td>15%</td>
<td>2</td>
<td>0.3</td>
<td>4</td>
<td>0.6</td>
<td>3</td>
<td>0.45</td>
</tr>
<tr>
<td>Tot score</td>
<td></td>
<td>2.6</td>
<td>3.6</td>
<td>2.35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rank</td>
<td></td>
<td>2</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continue?</td>
<td>No</td>
<td>Develop</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Table 3](attachment://table3.png)
3 Theoretical background

This chapter contains theory that will be used for a result.

3.1 Hole making

One of the most important operations in manufacturing is hole making. The common use for holes are either for assembly with fasteners or to provide access to the inside of a part. The most accurate holes are produced by the following sequence of operations:

1. Centering
2. Drilling
3. Boring
4. Reaming

Round holes of various sizes and depths can be made by drilling, but for a higher accuracy the hole requires boring and reaming as well. Boring is used to enlarge a hole made by a previous process, by producing circular internal profiles. Reaming is used to make an existing hole dimensionally more accurate than can be obtained by drilling alone. A reamer is a tool with fluted edges that removes very little material.

Another method for hole making is high-speed machining. In high-speed machining the approximate range of the cutting speed is 600-1800 m/min. High cutting speeds are recommended when drilling in aluminum because of its high thermal coefficient of expansion and relatively low elastic modulus which otherwise can cause a problem with the dimensional tolerance control. With high-speed machining, the tool and the workpiece remain close to ambient temperature because most of the heat generated in cutting is removed by the chip. This is beneficial because there is no thermal expansion or warping of the workpiece that can affect the tolerances during machining. (Kalpakjian, S & Schmid, S. 2001)

3.2 Orbital drilling

Orbital drilling is another drilling method. In orbital drilling three motions are combined - feed, spindle rotations and orbital rotation. The cutting tool is always smaller than the diameter of the hole. The drilling movements are eccentric along with the outer edge of the hole. The cutting tool has a high speed around its own axis and the spindle rotation has a low speed around the central axis of the hole, see Figure 4. (Manufacturing guide, 2017) By use of a traditional drilling machine, chips and cracks can emerge by the edge of the hole, and a high pressure is needed to drill through the material. With orbital drilling it is possible to drill through carbon fiber and other composites, also through stacks of several hard materials, without pressing with high force through the material. In orbital drilling coolant is not needed since the cutting forces are relatively low. (Ståhl, F. 2014) With a traditional drilling machine the hole is often drilled in several operations, with a predrilled hole that later is reamed and counterbored. However orbital drilling does not require a predrilled hole. With orbital drilling the hole can be made in one step, with the same tool and higher quality of the hole. (Mellgren, E. 2002)
Novator AB is a Swedish company that has patented orbital drilling since it was the founder of the company, Dr. Ingvar Eriksson, who invented the drilling method. Novator AB manufactures orbital drilling machines, see Figure 4, which are used by for example Boeing, Airbus and Bombardier Aerospace. Saab Aerospace and the Royal Institute of Technology were involved in a project which purpose was to find out what effect the quality of drilled holes had on the strength and durability of fiber composites. For this project, a reference hole without delamination and burrs was required, which resulted in the first patent related to orbital drilling. (Novator AB, 2017)

The disadvantage with orbital drilling is that it does not occur tensions in the material which it does with traditional drilling, because of the lower force that is used to drill through the material. To test the strength of a hole so-called open-hole tests are made. If a fastener is inserted into the hole it is called filled-hole tests. The test methods were developed to compare toughness in new composite materials. (Adams, D. 2016)

For the open-hole test there are ASTM-standards, American Society for Testing and Materials, of how the test will be performed, which is relatively cheap and easy to follow. The method means that a hole is drilled in a coupon made of a specific material, in this case aluminum. The coupon is placed in a machine that pulls the coupon until failure. There are no standards for the filled-hole test which makes it more difficult to perform. Novator AB is involved in a project where they perform filled-hole tests, to investigate how the strength in the material is affected when there is a fastener placed in the hole. The project has been going on for two years and is expected to be done in the end of 2017. (Andersson, H-P. 2017)

3.3 Gantry
A gantry is a structure that bridges over an area. It is either placed on the ground or on parallel rails that makes the structure movable. The rails works as one axis and the gantry bridge forms the other axis. The rails are strong enough to carry the weight of the machine and the equipment that is mounted on it. They are also designed to provide accurate motion for the machine. By coordinating the motion of the two axes simultaneously, it can move in any pattern necessary for example cut shapes out of steel plate. That is why a gantry design lends itself to CNC shape cutting. Gantries are available in a wide variety of sizes that can handle a lot of different areas and weights. (ESAB, 2013)
Güdel is a Swiss company which manufactures for instance gantries and Gantry robots. The gantries consist of several components that can be combined for linear movements. They are very precisely and can handle weights from a few kilos up to several tons. Güdels Gantry robots can handle components weighing up to several tons as well, with extreme accuracy, speed and repeatability. (Güdel, 2017)

3.4 Laser tracker
A laser tracker is a portable measurement system that consists of a laser beam and something that can reflect the laser, which is either held or mounted on the object to be measured. A reflector, which is a small mirrored sphere, is an example of a thing that is mounted on the object. When using a bushing, the reflector can be placed in a hole, or if the material is magnetic it can be placed right on a surface. A handheld device that can reflect the laser is called probe, see Figure 5. The operator can move the probe to the desired location as the laser tracker follows with the laser beam. When the reflector or the probe are placed the laser beam reenters the tracker at the same position from which it left and the distance is recorded. (Meagher, H. 2014)

A laser tracker is sensitive for air flows, temperature changes and vibrations. The measuring should be done in a temperature controlled room and not close to machines that can cause vibrations. To reach points that is difficult for an operator to reach, a laser tracker can be combined with a robot, for example an UR robot that can work beside a human. The laser tracker can also be used for measuring the T-X aircraft in SM. An advantage with a laser tracker is that it is moveable/portable and can be used both in SB and SM. (Cristalli, G. 2017)

Leica Geosystems is a company that manufactures measuring systems for several industries such as aerospace, defence, security, construction and manufacturing. Their laser tracker systems can handle high accuracy probing, scanning and reflector measurement for large parts in industrial applications. Leica AT960, see Figure 5, is a portable model that is used for large volume measurement by probing, scanning, reflector measurements and automated inspection. (Hexagon, 2017) The accuracy, the measuring time and the purchase cost of Leica AT960 are approximately equal to a CMM machine, the difference is that Leica AT960 is portable. (Cristalli, G. 2017)

Figure 5. To the left a Leica Laser tracker A960. To the right a T-probe from Leica.
3.5 Automatic Drilling Unit

An Automatic Drilling Unit, ADU, is a device that can perform various types of drilling operations, including counterboring and reaming. The motor is generally electric and the feed system can be pneumatic, hydraulic, electric or mechanical. (Direct industry, 2017) ADU machines are dedicated to the aerospace industry and used by major aircraft manufactures like Boeing and Airbus. In aircraft industry it is often necessary to drill through diverse material components, the components are often in lightweight materials such as aluminum and titanium. It is often complex to drill through these kind of materials with the most precise drilling results, this claim technically highest requirements. (Lübbering, 2017)

An ADU is semi-automated and can drill holes in varying diameters. An ADU machine requires a drill jig fixed to the workpiece, see Figure 5, in order to stabilize itself before drilling. The machine is clamped to a drill jig by expanding its concentric collet which is co-axial with the cutting tool. (Apex Tool Group, 2016) However Lübbering has another locking system as well, called twist lock which is designed like a bayonet that can be locked by a quarter turning in the locking bushing. This locking system allows larger drilling holes. (Lübbering, 2017)

![Figure 6. To the left an example of how the ADU machine is clamped to the drill jig. To the right an ADU machine from Seti-Tec. ©Desoutter](image)

Lübbering and Seti-Tec are two manufactures of ADU machines to aerospace industry. Both Lübbering’s and Seti-Tec’s ADU, see Figure 5, builds on modular solutions where the machines are built after the customers’ requirements. Seti-Tec’s ADU machines are used within Saab and Saab is very familiar with this product. However there is no ADU machine at Saab that drills these hole dimensions. Lübbering in the other hand are more familiar with drilling larger hole dimensions. Both Lübbering and Seti-Tec can handle specific requirements. (Wikström, T. 2017)

3.6 Industrial robot with end effector

As defined by ISO 8373, an industrial robot is “an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications”. Industrial robots are used for many different applications, for example welding, painting, assembling and packaging. They are often used to perform tasks that are dangerous or unsuitable for humans. The industrial robot improves the productivity and quality, with its high speed, accuracy and repeatability. (Ribeiro, L. 2015)

A robotic end effector is an object that is attached to the end of a robotic arm, for example grippers, tools for screw fastening, material removal tools and force-torque sensors. (Bouchard, S. 2014)
3.7 Parallel Kinematic Machine

The first Parallel Kinematic Machine, PKM, was developed by Karl-Erik Neumann and was called Tricept, this machine was used in industry already in 1994. Then in 2004 Exechon technology was invented and the PKM was further developed. With a PKM the flexibility is maintained and the accuracy and stiffness is outstanding, in this technology the motions in X, Y, Z are performed by three or more parallel axes. (Exechon World, 2008) The links of the machine are acting in parallel and in cooperation with each other and have a large load carrying capability. The axes can be pushed in and out from their attachment which means it does not need any ball joints. This makes it as stiff as a conventional machine tool. (Mellgren, E. 2011)

A PKM can easily carry a probe, which is a handheld device that reflects the laser from a laser tracker. In combination with a 5-axis machine it can measure and adjust relevant programming data before machining. For example, a frame for a car or a plane can be measured in production and adjusted before the final machining if needed. Boeing is using this technology in their production. (Exechon World, 2008)

Exechon Enterprises L.L.C. is a joint venture in the United Arab Emirates focused on advanced machining technology, owned by Lockheed Martin, Tecgrant AB (formerly Exechon AB), a Sweden-based technology company and Abu Dhabi-based Injaz National. Exechon will establish a manufacturing and engineering center of excellence for PKM in the aerospace area and other industrial areas. (Exechon, 2016)

One of their products is called XMini, made of carbon fiber, it has the capability to make a 50mm diameter hole in titanium with a 5-axis machine tool. The XMini is produced in cooperation with Boeing and Airbus. The product is as flexible as a robot and can easily be moved around in the factory to different working stations. The positioning accuracy is +/- 10 micron and it can be applied with a tool force of 7kN. It takes only 72 hours to integrate the XMini into production and it can be adapted to any existing jig or fixture since it has a flexible frame system called XFrame. (Exechon, 2016). Güdel is a company manufacturing gantry robots and they have a license for producing the XMini. (Engström, M. 2017)

A gantry Tau robot is another PKM, but in contrast with other PKM a Tau-robot has a larger working range. The robot has three linear actuators with arm links, working in parallel, connected to the end of the robot arm using a Tau-structure. Today there is a desire to find an efficient way to assist human workers. This would require a much stiffer robot in the sense of motion compliance compared to traditional industrial robots, it would also require a much more flexible robot to use. A gantry Tau robot can offer high stiffness, accuracy and speed. ABB has the patent of this robot, however it is so far only manufactured as prototypes and is still in research stage. At Lund’s University there are four prototypes of gantry Tau robots, these are combined with Güdel’s gantries. (Nilsson, K. 2017)

3.8 CNC machine

The multi-axis computer numerical controlled (CNC) is a programmable machine with a cutting tool that is movable relative to a workpiece. Modern CNC machines are used in almost all industry production today with varying sizes. The machine tools are versatile and capable of milling, drilling and boring. CNC machines can also do 3D printing, plasma cutting and laser welding and it can process a lot of different materials depending on requirements, for example it can process steel, aluminum, plastic etc. The accuracy of a CNC machine is of a very high level, the positioning and the repeatability are measured with an incremental coder to manage the accuracy. The CNC machine could be programmed with modern CAD/CAM systems, this is the most efficient and common system to use. (Isel Germany AG, 2017)
A CNC machine can be combined with a gantry, see Figure 7, to be able to handle large parts. Zimmermann is a company which manufactures conventionally CNC machines and 5- and 6 axis CNC gantry machines. They cover all possible machining capabilities with top-quality workpieces, short throughput times and optimized surface quality. The gantry construction has a stable clamping table and side walls filled with special concrete which leads to a reliable structure. (Zimmermann, 2017)

Figure 7. A CNC gantry from Zimmermann.
4 Empirics

This chapter contains a description of how the drilling at the wing- and fin interface of the two prototypes were manufactured at Saab, and also a description of the benchmarking visits within Saab.

The wing- and fin interface is related to a datum reference which is placed where the rear part and the front part of the fuselage are attached. The position of the datum reference is shown in Figure 8. It is high positioning tolerances between the holes and the datum reference, and between the holes in each interface.

4.1 Wing interface

The wing interface has six counterbored holes that is used to attach the wing with the fuselage, see Figure 9. Counterboring is a method used to enlarge the entrance of a hole. The positioning tolerance between the holes in Figure 9 is very high.

Figure 8. The highlighting shows where the wing- and fin interface is placed in relation to the datum reference. ©Boeing

Figure 9. A principal sketch of the hole pattern for the wing interface in relation to the datum reference. The figure shows the dimensions that are allowed to be showed.
The holes are drilled through the beam and the frame and both articles are made in aluminum. The beam is the skin on the wing interface and the frame is the part under the beam, see Figure 10. The fuselage and the wing are attached with bolts and nuts via the holes at the wing interface. All holes were predrilled in DT, both for the frame and the beam, and drilled (reamed and fine machined) in SB when the frame and beam were assembled. The drilling in SB was performed manually, with three different cutting tools, with a drilling mechanism, see Figure 11. A fixture held the fuselage in the right place and a drill jig was clamped at both sides for the interfaces, see Figure 13. The drill jig and the fuselage were attached via a small hole and three screws that held the jig in the right place.

\[ T = 4 - \frac{\text{MAX} + \text{MIN}}{2} \]  

Figure 10. A principal sketch of the frame and the beam of the wing interface. The upper article is called beam and the lower is the aircraft’s frame.

Figure 11. To the left a picture of the three cutting tools used for the prototypes, and above them the shaft where the cutting tool and the shim are assembled before drilling, see the right picture of how it is assembled.
The first step was to measure where the drill jig is in relation to the fuselage. This was made in all the holes with a gauge, see Figure 12. A max- and minimum value were read and with the equation (1) a value was calculated that decided which shim that should be used for the drilling of all holes at one interface, the shims could vary on the two interfaces. The shim is a thin piece of metal that was assembled on the drilling shaft, see Figure 11, to make sure the holes got the same depth. Max is the largest noted value and min is the smallest. T is the thickness of the shims that shall be used. The drilling shaft was clamped in the first hole and then it was drilled with three different cutting tools, see Figure 11. The first cutting tool was for boring which is a method to enlarge a hole. The second cutting tool was used for planning the bottom of the hole, and the last was for reaming the diameter. When the first hole was drilled it was measured with a go/no go gauge to check the diameter. Then a plunge was placed in the hole to add stabilization during the drilling of the remaining holes. The procedure was repeated in hole number 6, 3, 4, and then also in hole number 2 and 5, see Figure 13, but without placing the plunge. When all holes were drilled they were measured with a gauge to check that they got the right tolerances.
As shown in Figure 14 there are two different diameters, \( D_1 \) and \( D_2 \), of the wing hole. \( t \) is the thickness and \( D_2 \) is the inner diameter of the bushing. The lower hole was drilled in DT and upper hole was only predrilled in DT, this was made in a CNC machine. The arrow indicates the surface that has a high requirement on the flatness for all the holes after drilling, the hole pattern has to be in a certain distance between two parallel planes. However the flatness of the bushings surface is the final requirement. All the dimensions shown in Figure 14 have high tolerances.

![Figure 14](image1.png)

**Figure 14. To the left a principal sectional view of the wing hole with the bushing. To the right a principal 3D view of the hole with the bushing**

### 4.2 Fin interface

Boeing T-X has two fins on the fuselage. The holes of the fin interfaces are drilled through the top skin. As shown in Figure 15, one fin interface has three pin holes placed in the middle row of the hole pattern, which takes up the load and helps to steer in when assembling the fin. Then there are six holes for the bolts and nuts placed in the first and third row of the hole pattern. These holes were made in DT in a CNC machine and afterwards the flatness was measured in a CMM machine with nominal bushings placed in the holes. The arrow in Figure 16 indicates the surface that has very high flatness tolerances on the final requirement. Afterwards bushings for the holes were selected depending on the result from the measurement of the flatness. Since the CMM machine is very expensive and not always available it would be an advantage if this could be done in the SB-line. For the two prototypes all the holes got the same result in the CMM machine and the same bushings were used for all holes, but since only two aircrafts have been manufactured it is too early to say if this was just a coincidence or not.

![Figure 15](image2.png)

**Figure 15. A principal sketch of the hole pattern for the fin interface in relation to the datum reference. The figure shows the dimensions that are allowed to be showed.**
4.3 Bushings

The bushings, see Figure 17, that are pressed using a tool in the holes after reaming are made of steel. The reason for using bushings is that steel takes up load better than aluminum. The process for placing the bushings is difficult because of the time limit. It is interference fit between the bushings and the holes, therefore the bushings are cooled down to shrink in liquid nitrogen to a temperature of -200°C. After picking up the bushings from the liquid nitrogen, the bushings must be placed in the hole in the time limit of 20 seconds. The cause for the time limit is that aluminum shrink faster than steel, and since metal conducts cold the aluminum hole will shrink in contact with the steel bushings. After reaming the holes and after machining the surface by the holes the bushings must be placed in 30-60 minutes to avoid surface treatment. (Almé, L. 2017)

4.4 Benchmarking Aeronautics

A visit to Aeronautics was made to see the production of Gripen. The whole production line was visited, from detail manufacturing to fuselage assembly. In fuselage assembly there was a fuselage where the wing was not attached yet. The interface was studied which led to increased understanding for the attachment of the wing at Boeing T-X, since the interface of Gripen is similar to Boeing T-X.

Further a second visit was made to Aeronautics to learn more about how the drilling are performed at Gripen. The drilling method at the wing- and fin interface at the prototypes of Boeing T-X are similar to the drilling method at the wing- and fin interface at Gripen. The fuselage was clamped in a fixture and the holes for the wing interface were drilled with a traditional drilling mechanism. The holes were measured with several gauges. Karolina Gustafsson, an operator at Gripen, was interviewed about the drilling station for the wing interface.
4.5 Benchmarking Aerostructures
Two visits were made to Aerostructures to see different drilling methods. The first visit was at the production of flap support structures for Airbus A350-1000. Holes in different sizes are drilled with very high precision in a large CNC machine from DMG Mori. The reason for this visit was especially to see a method for drilling of large holes with high accuracy. After the drilling, the parts are measured in a CMM machine that is placed in the same part of the factory. The CNC machine is placed at a concrete foundation to avoid vibrations that can affect the accuracy.

The second visit to Aerostructures was made where the purpose was to look at a drilling machine called “the phone box”, which is used for drilling at the leading edge for Airbus A380. The drilling machine is moved along the 32 meter long part which is clamped in a fixture. The operator fixes the machine at different places where it performs the drilling with very high precision. A lot of holes at this structure are also drilled with ADU machines which can be made at the same time as the “the phone box” drills.

4.6 Conclusion benchmarking
The benchmarking studies were especially very helpful for increased understanding for how the production of an aircraft can be designed and how the drilling was performed at both Gripen and the prototypes of Boeing T-X. Also helpful to gain knowledge in different machines that can be used for drilling. This knowledge have been used during the working process to develop the different concepts.
5 Concepts

This chapter contains information about the different concepts for the fin hole and for the drilling concepts that will be compared in the concept selection process.

5.1 Concept for fin holes

The fin holes have a very high flatness tolerance, and as mentioned earlier the fin holes for the two prototypes have been measured in CMM-equipment after detail manufacturing to select the right bushing for the holes. Since this method takes too much time, because the part needs to be moved to another location and the CMM is not always available, another more effective solution for the fin holes is necessary if Boeing and Saab wins the order. Different ideas have been discussed on how to solve this problem.

5.1.1 Counterbored holes

This idea builds on the method used for the wing interface, it is simply described as a counterbored hole with the same diameter as the bushing’s outer diameter. The inner hole would be drilled in DT, and the counterbored hole would be predrilled in DT like the wing interface. Then in SB the hole would be reamed and planed. The advantage with this is that both wing- and fin interface could be drilled with the same method. However, with this idea it removes material from the fuselage and that is not an option since it could have an impact on the strengths of the aircraft even though it is just a removal of a couple of millimeters. It is not certain it would have an impact on the aircraft, but even if it would not, a lot of strengths calculations would have to be remade. Another disadvantage with this method is that other bushings must be used since the flange of the bushing needs to be thicker.

5.1.2 A “cuts”

A “cuts” is when leaving material above the surface in DT where the hole will be drilled, see Figure 18. The idea of a cuts is to get control of the surface after DT by making a counterbored hole in the cuts, when the top skin is assembled to the fuselage in SB. The counterbored hole will be drilled to the same height of the surface where arrow B points at in Figure 19. Therefore, the same bushings used for the prototypes can be used, see arrow A in Figure 19 on how the bushing is placed. With a cuts the surface is controlled and the same method could be used for both the wing- and fin interface. The advantage is that this method does not differ from the prototypes, since it only removes material from the cuts.

Figure 18. On the left a principal sketch of how the cuts looks like from the side. On the right a principal 3D sectional view of the cuts when counterbored.

Figure 19. To the left a principal sectional view when bushing placed in counterbored hole. To the right a principal 3D view of how the fin hole looks like when a bushing is placed.
5.1.3 Measuring with other equipment
The final idea is simply explained by finishing the holes of the fin interface in DT and when assembled in SB use a laser tracker, model 960 from Leica, to assess which bushings to use. A laser tracker will most likely be purchased for other uses if Boeing and Saab wins the order, and therefore it could be economically justifiable to use this method for the fin interface. A laser tracker can measure in the same time limit as a CMM machine, the advantage is that the article that needs to be measured does not have to be moved to another part of the factory. The only disadvantage is that the laser tracker requires regulated environment, for example regulated temperature. (Cristalli, G. 2017)

5.2 Concepts for drilling
Six different concepts have been compared, by using concept screening and concept scoring matrices, on how to automate and make the drilling station for the wing- and fin interface more effective. The concepts below are described by adding a cuts for each fin hole.

5.2.1 Concept A – ADU machine
The first concept is to use ADU machines from for example Lübbering or Seti-Tec. These machines require drill jigs for all four interfaces to achieve stability and manage the high tolerances. A fixture holds the fuselage in the right place and the drill jigs are clamped in the fixture. The machines are clamped in the drill jig and placed by an operator. ADU machines require predrilled holes from DT at both wing- and fin interface, for a more effective and economic production. Otherwise more machines would need to be purchased for predrilling operations. However, ADU machines are relatively low in purchase cost, and since they are relatively difficult to adjust, different ADU machines will be used for the different drilling operations and hole diameters. For example the drilling for the wing interface is made in three steps, and the fin interface’s holes would be predrilled in DT, and in SB use one or two ADU machines for reaming and fine machining the counterbored holes in the added material. Most likely two or more sets of ADU machines will be purchased to increase the reliability for the machine, to avoid stop in production if the machine break or when it needs repairability. This concept is similar to the method used for wing interface of the prototypes, only this concept is semi-automated apart from the old method that is manual.

5.2.2 Concept B – Gantry with Xmini
This concept builds on combining a gantry from Güdel with an Xmini from Exechon. The gantry can move in three axes (X, Y, Z) and combined with the Xmini it can reach both the wing- and fin interface. The fuselage will be placed in a fixture. This concept requires an automatic change of tools in order to manage drilling at both wing- and fin interface. The advantages with this is that an Xmini has high accuracy and is easy to integrate into production. However this concept does not fulfil the budget or the dimensions.

5.2.3 Concept C – Gantry with Tau robot
Concept C builds on the same idea as concept B, but with a Tau robot instead of the Xmini. However, the Tau robot is still under research progress and for now only manufactured as prototypes.

5.2.4 Concept D – CNC gantry machine
This concept is to use a CNC gantry machine, for example from Zimmermann. The spindle can reach all the interfaces, the machine has an automatic change of tools and a very high accuracy. The fuselage will be placed in a fixture. An advantage with a CNC gantry machine is that it is fully automated, however it requires a CNC-operator with special education. The purchase cost for the machine does not fulfil the budget, however it might be profitable if the production volume will increase and if more operations could be done in the CNC machine.
5.2.5 Concept E – Orbital drilling machine

Concept E is to use an Orbital drilling machine. Today there is no machine that fulfil the dimensions for the wing interface, but according to the CEO of Novator AB it should be possible. The disadvantage with orbital drilling is that it does not occur tensions in the material which it does with traditional drilling, because of the lower force that is used to drill through the material. Novator AB is involved in a project where they perform filled-hole tests, to investigate how the strength in the material is affected when there is a fastener placed in the hole. The project has been going on for two years and is expected to be done in the end of 2017. An orbital machine would be used in similar way as concept A, the advantage with orbital drilling compared to traditional drilling is that it does not have to be drilled in several operations to manage the high tolerances, it could be made in one step.

5.2.6 Concept F – Industrial robot with end effector

This concept is to combine an industrial robot from for example KUKA with an end effector for drilling. The fuselage will be placed in a fixture, and the robot would be placed on for example rails or under the fuselage. This would require the fuselage to be able to rotate in order to reach all the interfaces. The disadvantage with this method is that turning the fuselage may affect the accuracy because it is difficult to stabilize the fuselage completely. Another disadvantage with this concept is that it does not fulfil the budget.
6 Concept selection process

This chapter contains the concept selection process.

6.1 Concept screening

For the concept screening matrix, see Table 4, no reference was used because none of the concepts are an industry standard. Therefore all the concepts were compared to each other for every requirement. The matrix was discussed with people within Saab with special expertise for a more accurate result. The concept screening matrix resulted in continuing with concept A and concept D in a concept scoring matrix. The matrix is further explained in the subheadings, 6.1.1 – 6.1.6. Below the different concepts are listed:

Concept A ADU machine
Concept B Gantry with Xmini
Concept C Gantry with TAU robot
Concept D CNC gantry machine
Concept E Orbital drilling machine
Concept F Industrial robot with end effector

Table 4. Concept screening for wing- and fin interface. See chapter 5.2 for concept description.
6.1.1 Functionality
The functionality describes the requirements with functions that the concepts needs for operating. With strength requirements the concept needs to fulfil the strength in the fin- and wing holes, orbital drilling does not fulfil this requirement since in traditional drilling tensions occur in the holes which does not occur in the same way in orbital drilled holes. All the concepts will avoid CMM measuring. The concept must fulfil the dimensions, the hole diameter and the tolerances, concepts B, C, E and F technology does not fulfil the dimension requirements. An ADU machine can manage the dimensions and a CNC gantry machine can manage the requirements with higher tolerances. When drilling in metal it is important that the metal chips that occur does not affect the quality of the hole with scratches. ADU machines can affect the quality of the hole with metal chips when the cutting tool is retracted from the hole, the other concepts does not have the same problem. Another requirement is the capacity/production volume, the concept must manage the cycle time of 48 aircrafts per year. All the concepts manage the capacity, however concepts B, C, D and F could handle larger capacity.

6.1.2 Convenience
Convenience is the state of being able to proceed with little effort or difficulty. It is a convenience if the concept is easy to use in form of education, for example a CNC machine require a special educated CNC operator. ADU machines and orbital drilling machines are relatively easy to use compared to Concepts B, C, D and F. However these concepts are better if the production volume will increase to, for example 60 aircrafts per year. If the production volume would increase more ADU machines and orbital drilling machines would have to be purchased.

Another convenience is the ability to place bushings within 30-60 minutes to avoid surface treatment, this is a problem for all the concepts. However concepts B, C, D and F might be able to drill one hole pattern in less than an hour and therefore be able to place the bushings within the time limit. The difficulty with ADU and Orbital drilling is the time for drilling a hole pattern and also the drill jigs that are in the way of placing bushings. An automatic concept would ease the production, concepts A and E are semi-automated and the rest are fully automated. The last convenience is if the drilling of the fin- and wing interface could be done at the same station, all the concepts fulfil this.

6.1.3 Ergonomics
Environmental requirements compares if the concepts fulfils laws concerning the environment. All machines needs to fulfil this to be approved to be used. Safety for operator compares how safe it is for an operator to labor in the working environment. Some concepts may need light beams and safety fences. However all the machines needs to fulfil the safety laws to be approved to be used.

6.1.4 Durability
The durability describes how reliable the machine and the cutting tool is, for how long time it can operate before it breaks. It also describes how easy it is to repair and serve, and how long time it takes. The repairability/reliability for the ADU machine is better in comparison to the other concepts since it is possible to have several sets because the ADU machine has a low purchase cost. This means that the production does not need to stop while an ADU machine is on reparation.

6.1.5 Other
Finished solution/Delivery is a comparison of the delivery time and if there exists a finished solution of the concept or if it needs to be developed. ADU machines and CNC gantry machines are concepts that already exists and could be purchased and delivered directly for this task. A gantry Xmini, an Orbital drilling machine or an industrial robot could be used, but today they do not fulfil the requirements, therefore they have to be developed first. The gantry TAU is still in research stage. Machine size shows how much space each machine needs. An ADU machine and an Orbital drilling machine does not require much space in comparison to a CNC gantry machine that is very large.
6.1.6 Costs
Purchase machine, installation and fixtures are fixed costs for the concepts. Gantry Xmini, gantry TAU, CNC gantry machine and industrial robot are quite expensive compared to the Orbital drilling machine and the ADU machine. The ADU machine is the cheapest alternative. Variable costs changes depending to the operating volume, for example operating- and service costs. The ADU machine and the Orbital drilling machine has low variable costs and the CNC gantry machine has higher costs.

6.2 Concept scoring
For the concept scoring matrix, see Table 6, concept A was used as reference because it is easier to have a reference when just comparing two concepts, in this case concept A and D were compared. The same criteria were used in the concept scoring matrix as in the concept screening matrix, the difference is that this matrix is more accurate, partly because it has a more accurate scale but also because all the criteria are weighted. The weightings are based on an importance score from 1 to 5, where 5 is the most important, that all the criteria got before weighting them, see Table 6. The importance scores were discussed with advisors at Saab and afterwards the weighting for each criterion was calculated from equation (2) and (3).

\[
weighting\ for\ one\ importance\ score = \frac{100}{\sum importance\ score} \quad (2)
\]

\[
weighting = importance\ score \times \text{weighting for one importance score} \quad (3)
\]

Table 5. An earlier stage matrix to show the importance score that was used to calculate the weighting.
The concept scoring matrix resulted in a very even result between concept A and D. The concept scoring matrix is further explained in the subheadings. The concepts compared in this matrix are listed below:

Concept A  ADU machine  
Concept D  CNC gantry machine

Table 6. Concept scoring for wing- and fin interface

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>Concept A (ref)</th>
<th>Concept D (CNC gantry)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weighting [%]</td>
<td>Rating</td>
</tr>
<tr>
<td><strong>Functionality</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength requirements</td>
<td>7.042</td>
<td>3</td>
</tr>
<tr>
<td>Avoid CMM measuring</td>
<td>7.042</td>
<td>3</td>
</tr>
<tr>
<td>Dimensions</td>
<td>7.042</td>
<td>3</td>
</tr>
<tr>
<td>Metal chips</td>
<td>7.042</td>
<td>3</td>
</tr>
<tr>
<td>Capacity</td>
<td>7.042</td>
<td>3</td>
</tr>
<tr>
<td><strong>Convenience</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Easy to use</td>
<td>2.817</td>
<td>3</td>
</tr>
<tr>
<td>Adjustable production volume</td>
<td>4.225</td>
<td>3</td>
</tr>
<tr>
<td>Ability to place bushings directly</td>
<td>2.817</td>
<td>3</td>
</tr>
<tr>
<td>Automatic</td>
<td>2.817</td>
<td>3</td>
</tr>
<tr>
<td>Same drilling station for wing- and fin interface</td>
<td>5.634</td>
<td>3</td>
</tr>
<tr>
<td><strong>Ergonomics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental requirements</td>
<td>7.042</td>
<td>3</td>
</tr>
<tr>
<td>Safety for operator</td>
<td>7.042</td>
<td>3</td>
</tr>
<tr>
<td><strong>Durability</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repairability/reliability machine</td>
<td>5.634</td>
<td>3</td>
</tr>
<tr>
<td>Repairability cutting tool</td>
<td>5.634</td>
<td>3</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finished solution/Delivery</td>
<td>7.042</td>
<td>3</td>
</tr>
<tr>
<td>Machine size</td>
<td>2.817</td>
<td>3</td>
</tr>
<tr>
<td><strong>Costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purchase machine, installation, fixtures (fixed costs)</td>
<td>5.634</td>
<td>3</td>
</tr>
<tr>
<td>Variable costs</td>
<td>5.634</td>
<td>3</td>
</tr>
</tbody>
</table>

6.2.1 Weighting the criteria

All the criteria under functionality are weighted high because these are requirements that have to be fulfilled, there are requirements under ergonomics and under other that also have to be fulfilled. The criteria under convenience does not have to be fulfilled, however same drilling for the wing- and fin interface is weighted higher because this would ease the production. Some criteria are not that important, for example machine size since the drilling station will be built after the concept if Boeing and Saab wins the order. The biggest difference between ADU and CNC gantry is the purchase cost.
7 Discussion and conclusion

This chapter contains discussions, ethics, conclusions and future recommendations for Saab.

7.1 Discussion connected to research questions

To find a possible concept for the drilling of the wing- and fin interface that is automated and that is more effective regarding to the requirements, different concepts have been compared by using concept selection matrices. Six concepts were developed and compared with each other in the matrices. Over a group meeting with people within Saab with special expertise the concept screening matrix was discussed, it resulted in continuing with two concepts for the concept scoring matrix.

In the concept scoring matrix the total score proved to be very even between ADU machines and a CNC gantry machine. However, concept D, CNC gantry machine, got a higher total score. With a CNC gantry machine the wing- and fin interface can be automated and more effective but also manage the high tolerances and dimensions. Concept D manages most of the requirements with margin, the difficulty is the purchase cost for the CNC gantry machine compared to several ADU machines, and this is a criterion that needs to be considered. Another difficulty with concept D is the criterion easy to use, a CNC gantry machine requires an educated CNC operator.

To examine how much of the drilling that should be done in DT and how much that should be done in SB three different ideas were discussed on how to solve avoiding CMM measuring for the fin holes. It resulted in two ideas that could work. One included leaving material in DT on the fin hole, called cuts, and then drill a counterbored hole in SB. The second idea was to use a laser tracker in SB to measure which bushings to use. The concepts were described by using the cuts idea for the fin interface, because when purchasing one of the concepts you want to assume it can be used for all interfaces. If there is a cuts on the fin interface, all the holes at all interfaces could be counterbored. This probably saves time compared to using a laser tracker. Also when comparing the concepts they need to be equal for the purpose of use. Therefore the result for how to solve avoiding CMM measuring for the fin holes, can be changed after the result of drilling concept. For example, if the result would be ADU machines, then it could be considered to purchase ADU machines only for the wing interface and then drill the fin holes in DT and use a laser tracker instead of purchasing more ADU machines for the fin interface.

The drilling for the interfaces are today predrilled and drilled in DT before SB, one of the research questions was to examine how much of the drilling should be done in DT and how much should be done in SB. Since the interfaces in DT are made in CNC machines it is worth looking into if the drilling of the interfaces made in DT could be done in the CNC gantry machine in SB. The advantage with a CNC gantry machine is that the fin interface does not have to be measured in a CMM machine since concept D can implement different machining operations and therefore manage the high tolerances, by for example milling to fine machine the surface of the fin interface to manage the flatness requirement.
### 7.2 Discussion methodology

A problem with literature review is to know how reliable the source is, especially if the literature is from an internet article. The articles may be written by unprofessional people who are not completely familiar with the topic, which can be difficult to decide. However, there are articles that have been peer reviewed, which are more reliable sources since several knowledgeable persons have previewed the articles before publishing. Another issue with electronic references is to use information from a manufacturer’s website. It is a reliable source but the information are written to the advantage of the company so it can be difficult to find disadvantages with the product.

The disadvantage with collecting information from books is that books can be many years old without the ability to be updated with new information. The book *Manufacturing engineering and technology* (Kalpakjian, Serope & Schmid, Steven R.) which is used in this thesis was written 2001 which may be considered too old. However one step in literature review is to analyze the collected material which is a way to decide if the information is still valid, which has been made in this case.

A lot of interviews have been made during these ten weeks. Interviews are a good method to collect information that can be difficult to find in books, for example how the drilling operations were made. A disadvantage is that it can be difficult to remember the conversation just by writing key words from the interview, which can lead to misunderstandings. A better way would have been to record the interviews, however this could not be done because of the secrecy.

One of the delimitations is access of information. A lot of information in this thesis is collected from people within Saab, instead of manufactures, because of the secrecy. The disadvantage with this is that some of the information used in the thesis might not be facts. For example, the group meeting when discussing the concept screening matrix, not all the invited could show up. This could have led to an inaccurate result since the people who did not show up could not contribute in the discussions and “defend” the machine they have knowledge about. Another disadvantage with not being able to contact manufactures is that the information is used in Saab’s perspective and not from an angle outside Saab. However, the advantage with not contacting manufactures is that they cannot try to sell in their product by only telling the advantages with their products.

The benchmarking was only made internal at Saab. It was a useful way to get a clearer picture of Saab and how drilling operations were made in other places of the company. There were very rewarding discussions with a lot of people during the benchmarking which led to new ideas. It would have been very interesting to visit other companies to see their solutions but ten weeks was not enough for that.

In the concept selection process two matrices were used to reach a result. The advantage with matrices is that it is an easy way to present the procedure and the result. A person that is not familiar with the thesis can still understand which alternatives to proceed with from the first matrix and which alternative to develop in the second matrix. Another advantage is that the concept selection process occurs in two steps. In the concept screening matrix the alternatives are compared in relation to each other and the alternatives that does not fulfil enough requirements are excluded. In the concept scoring matrix the alternatives get their score from how important the requirements are. In this way the most suitable concept can be selected from the concept scoring matrix. A disadvantage with the matrices is that it is difficult to rank the concepts in comparison to each other without talking to the manufacturers of the machines in the concepts. Also the weighting was an issue because of the difficulty to know which requirement that is more or less important. Since the result between CNC gantry machine and ADU machine is very equal it is difficult to decide if the result is correct. Only by changing one ranking the result can be changed to the opposite. However both concepts seems to be suitable solutions for Saab.
7.3 Ethics
Since Saab Group are manufacturers of military defence and security products, services and solutions there is an ethic aspect to consider when working for Saab. Saab Aeronautics are for example manufacturers of the military aircraft Gripen, and T-X Boeing is also included in the business area Aeronautics. However, T-X Boeing is an aircraft trainer for pilots and will not be used as a military aircraft. Also Saab are constantly working with building and maintaining trust of customers, authorities, owners and partners which is important for a defence and security company. Saab Group's vision is that it is every human right to feel safe, and that their work contributes to increased safety. For example they also produce security systems for prisons, protection against Chemical, Biological, Radioactive or Nuclear weapons.

This thesis is about automating the drilling station of the wing- and fin interface, which means that the working process done by an operator for the prototypes will be automated by using a machine. A lot of operators are replaced by machines and robots in industries because of today's technology. This is an ethic aspect to consider when automating industries. However, in this case the machine will most likely require an operator anyway and since there is no production today it will only create working opportunities, not replacing.

7.4 Conclusion

RQ1: How can the drilling of the wing- and fin interface be automated and more effective?

- Which concept is most suitable regarding to the requirements?

The most suitable concept is to use a CNC gantry machine for the drilling at the wing- and fin interface. With this concept the drilling can be automated and more effective. A CNC gantry machine can handle large parts and is capable of milling, drilling and boring, which means that it can be used for more operations except from the drilling at the wing- and fin interface. It is fully automated with high speed and extremely high accuracy and fulfills most of the requirements.

RQ2: How much of the manufacturing should be done in detail manufacturing and how much should be done in fuselage assembly?

- How will the fin interface avoid CMM measuring?

The CNC gantry concept is described by leaving a cuts on the fin holes in DT. The drilling and predrilling in DT will be the same as for the prototype manufacturing. The difference is that the CNC gantry machine in SB performs the counterboring at the wing- and fin interface, which leads to that no measuring needs to be made in a CMM after the drilling. However, if investing in a CNC gantry machine it could be an advantage to perform more operations in SB. If all drilling steps are made in SB the cuts for the fin holes is no longer needed.
7.5 Future work and recommendations

The thesis was delimited to find a concept for Saab to move forward with and examine which concepts to exclude for Saab’s future work. Therefore we recommend Saab to further studies in the subject. Our recommendation is not to exclude ADU machines, these fulfil the requirements and above all the budget. A CNC gantry machine on the other hand is an investment, especially if the production volume would increase. This is something that needs to be considered. It is considerably easier to increase the production volume in a CNC machine compared to ADU machines.

Another recommendation is to consider if more steps and operations could be done if a CNC gantry machine is invested. For example if the drilling made in DT could be done completely in SB, or if there are other parts on the fuselage that can be machined in the same CNC gantry machine. If Saab decides to continue with ADU machines instead it is also worth to further study measuring the fin interface with a laser tracker in SB. A laser tracker will after all be purchased for other uses in the fuselage assembly.
8 References

This chapter reports the references used for the thesis.

8.1 Electronic references


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