TOOL DEVELOPMENT FOR HIGH RATE ADHESIVE BONDING OF AIRCRAFT CARGO DOORS

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**Abstract**

The project aimed to develop a new production tool for cargo doors to single aisle airplanes using adhesive bonding as the method to join the different parts of the structure of the door. The tooling is required to support the structure of the door and create an equal pressure distribution during the adhesive curing process in the autoclave. It was performed in close collaboration with SAAB’s efforts in Clean Sky 2 where a cargo door for tomorrow’s commercial airplane was designed and developed. The door is manufactured with chromate free adhesive bonding. The tool developed enabled the high production rate demanded if the door becomes a success. The tool is develop following the method presented in “Product Design and Development” written by Ulrich and Eppinger.

This project was done as a Master thesis and resulted in a manufactured test tool. A full scaled tool was designed in Catia V5, the manufacturing cost and production rate for the theoretical tool were also analysed. The tool surpasses the production rate target with 26% and the preparation time when using adhesive bonding is reduced with 76% comparing to not using a tool. To manufacture the number of tools needed, the total cost became 25% lower than the original budget.
Acknowledgment

This is the resulting report from my master thesis project at SAAB Aerostructures Tool design in Linköping. The final part of my education at Luleå University of Technology in mechanical engineering with a master in Machine Design.

I would like to take this opportunity to thank my mentor at SAAB Per Eliasson for giving guidance and practical support whenever needed. I would also want to give the project leader Thomas Murray a special thanks for tremendous commitment and support.

The Tool design section at SAAB should also have an award for their ability to welcome and supporting a temporary member in a very including and warm manner. A special thanks to Sebastian Jakolini for the opportunity to do this master thesis at SAAB.

At last I would like to thank Josefin Andersson for the help with the report formalities and apologise for any caused difficulties.

Linköping, June 2018

Fabian Borgede
Abbreviations used in this report translated to full form table

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
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<tbody>
<tr>
<td>AHP</td>
<td>Analytical Hierarchy Process</td>
</tr>
<tr>
<td>CS2</td>
<td>Clean Sky 2</td>
</tr>
<tr>
<td>DFA</td>
<td>Design for Assembly</td>
</tr>
<tr>
<td>DFAM</td>
<td>Design for Assembly and Manufacturing</td>
</tr>
<tr>
<td>DFE</td>
<td>Design for Environmental</td>
</tr>
<tr>
<td>DFM</td>
<td>Design for Manufacturing</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>MFD</td>
<td>Multifunctional Fuselage Demonstrator</td>
</tr>
<tr>
<td>OST</td>
<td>One Side Tacky</td>
</tr>
<tr>
<td>PDD</td>
<td>Product Design and Development</td>
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Variables and constant definition table

<table>
<thead>
<tr>
<th>Notation</th>
<th>Unit</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>$10^{-6}/(k \times m)$</td>
<td>Linear expansion coefficient</td>
</tr>
<tr>
<td>ΔT</td>
<td>K</td>
<td>Temperature difference</td>
</tr>
<tr>
<td>$L_0$</td>
<td>m</td>
<td>Original length of material</td>
</tr>
<tr>
<td>$L_{grow}$</td>
<td>m</td>
<td>Length of material after expansion</td>
</tr>
<tr>
<td>Δ$L$</td>
<td>m</td>
<td>Length difference</td>
</tr>
<tr>
<td>$E$</td>
<td>MPa</td>
<td>Modulus of elasticity</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>-</td>
<td>Strain</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>MPa</td>
<td>Stress</td>
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1 Introduction
The presented work in this report is the final result of a master thesis in Machine Design from Luleå University of Technology at SAAB in Linköping. The project aimed to develop a new tool for the production of cargo doors to airplanes using adhesive bonding to join the parts of the main structure.

1.1 Project background
SAAB is part of a project called Clean Sky 2 (CS2) funded by the European Union (EU) to create a more sustainable commercial air craft industry. One way to do this is to find new ways to assemble different components. A large part of the components on aircrafts are today mounted through screw joints. It is believed that by using adhesive bonding instead of screw joints the total weight of the aircraft can be decreased. The toxic material Chromates are currently used in the adhesive bonding processes and removing Chromates is one of the main challenges with today’s adhesive bonding technology.

To see if this is possible SAAB been working on a new cargo door to be demonstrated in the CS2 Multifunctional Fuselage Demonstrator (MFD). This is a task that SAAB has been working with since 2015. SAAB had tested strengths and weaknesses of different designs. They were closing in to the final design but before setting it they needed to know that it could be produced effectively if a demand should arise. Because of that adhesive bonding was a part of the concept the production method was stated, and the undefined question was, how this should be done effectively (SAAB’s earlier experience with adhesive bonding have been in low rate production).

To produce a door with adhesive bonding without a specialised tool is time demanding due to the complex profile of a door. First, a bonding film needs to be applied. This process is the same with or without a tool. The operator then has to manually place an inner sheet with demanded tolerances, inside the outer sheet of the door. Thereafter, the components and frames need to be correctly placed before they are bagged as in production of composite components. This process is time consuming and takes great amount of time due to the dimensions of the door and the complex geometry.

For a profitable production of a bonded door the bagging process needs to be simplified. To accomplish this, a tool is needed and the project goal is to fulfil that need. To ensure that SAAB when delivering the demonstrator to the MFD also can offer adhesive bonded doors to future single aisle airplanes.

Note that terms in manufacturing are referring to the manufacturing of the tool and terms in production are referring to the production and manufacturing of cargo doors to airplanes. This is set throughout the entire report.
1.2 Technical explanation of problem

Before going into deeper detail, a more specific explanation of the problem is needed. As explained above, the goal is to assemble a door with adhesive bonding. More specifically to bond the outer skin of the door together with a support sheet, where the support sheet is bonded to the main frame work of the door. A simplified illustration of this is presented in Figure 1.

![Figure 1](image1.jpg)

Figure 1, Illustration of bonding components.

The door is supported by a number of frames as the one shown in Figure 1, illustrated in blue. It should also be remembered that an airplane body is circular, so the door structure has a diameter. The diameter together with the frames is making the door complex to bond. During the bonding process all parts needs to be pressed together. An autoclave is typically used to apply this pressure. A simplified 3D model of the door layout is shown in Figure 2.

![Figure 2](image2.jpg)

Figure 2, Cargo door structural design.

As seen in Figure 2, larger upper and lower beams are supporting the door in the end of each vertical frame. The beams are not included in the term door frames that only are referring to the vertical frames.
1.3 Question of issue
The work is aimed to search for the most effective production tool within the assumptions and limitations (see below). The question is; does a tool solution exist within the solution space, which can produce a door with sufficiently less time than existing solution.

This was to be investigated. Hence, if SAAB’s new door is proven to be the future solution for a more sustainable aircraft industry, it should be one step closer to enter the commercial market.

1.4 Intent and objective
The intent with this project is to: “Develop a manufacturable concept tool for production of the new generation of cargo doors, produced with adhesive bonding”. The deliverables that was intended from this project is one concept that have support from technical investigation in following subjects:

1. Locate the most important tolerances for the drawings to ensure that the tool can be manufactured. This can be critical for the concept due to the size. In this work it is also included to investigate the tolerances needed to give the door a desirable quality.
2. Estimate manufacturing cost for the tool.
3. Estimate the production speed possible using the tool.
4. How the tool effect the position of components bonding and if this can be used in a production advantage.

1.5 Assumptions and limitations
To do the project achievable delimitations is needed. This project was not going to investigate subjects regarding the following areas:

- Heating needed during the bonding process.
- The adhesive bonding process and the mechanical properties of the door.
- The department at SAAB will perform strength analyses using the finite element method.
- The interaction between this part of the production and the remaining production line for the door.
- The bonding process.

It is also, important to achieve is a structured and strategical plan. The theory of this plan is presented in the next chapter.
2 Product development process

To accomplish the objective for this project a methodology in product development was chosen as guide. The product development process chosen is described more profound in Product Design and Development (PDD) (Ulrich & Eppinger, 2012). It is used to give a structured way of proceeding throughout the project. This to secure that the best potential solution is found.

2.1 Planning

Planning in Ulrich and Eppinger is aimed to articulate a market opportunity and define market segments. This information is then used to distribute and priorities resources between different projects. The design team should start considering product platforms, architecture and asses new technologies. The production organisation starts to identify production constrains and set supply chain strategy. Before starting a specific project, a mission statement is stated.

2.2 Concept development

Collecting customer needs, identify-lead users and competitive products starts the development phase. This is to create a complete target specification. It is important to have a strong connection between need and target to ensure an appealing solution. Furthermore, the targets and needs were to be internal weighted to give clear directive when prioritising. Thereafter concepts should be generated towards a solution, but first a search for external products to see if a commercial solution exists. Since it is often cheaper to buy existing solutions then design and manufacturing a new one.

Generation of a new solution is done in a creative aura and over a time period, long enough to present all team members ideas. To secure a good exploration of the solution space. Yet it is still important to remain structured and brake down the problem to be able to find smart solutions for all sub problems. When the search for solutions are done the concepts should be documented with the same level of detail, to give a fair selection of the concepts. If numerous concepts have been developed the first elimination should be done by a screening, before moving one to the more detailed elimination named scoring. Last step before leaving the concept development is concept testing, where the concept functions can be tested or data can be collected from potential customers as an early market analyse.

2.3 System level design

In this phase the concept/solution is reviewed in perspective of architecture and modularity. It will say how easy different sections of the solution can be customized, upgraded or changed. The goal is to have a product easily adopted to different costumer’s wishes. A good example of these options is the car industry where functions can be added by the customer after needs and budget. This is achieved by establishing the architecture which in Ulrich and Eppinger is done by the following steps 1-4 below:

1. Create a schematic of the product
2. Cluster the elements of the schematic
3. Create a rough geometric layout
4. Identify the fundamental and incidental interactions

Depending on how modular or integrated the different sections are relative to each other, different project management styles are needed. If a more integrated
architecture is desired very careful planning is required during the system-level design phase. To limit functions and interactions between each section. An integrated design may however not have the same need of planning during the system level design but will instead require more conflict resolutions and integration during the detail design level (Ulrich & Eppinger, 2012).

Platform planning is an important step aimed to plan how different options on respective section changes the product from the customer view. This is a section critical for some industries such as the car industry, but in the creation of a tool not as important. It should still be in mind that the tool may be adjusted to a similar door or changes in the door design and should as far as possible be designed in a flexible way. The method described in PDD of *Differential plan, Commonality plan and Trade-Off between Differentiation and Commonality* were however not used in this project.

2.4 Detail design

The detail design should deliver a complete theoretical product in form of drawings, production documentation, complete geometric and complete tools designed. Critical issues like material selection, production cost, and performance are also set in detail levels. How to accomplish this is however not as clearly described as the earlier phases in the PDD but are broken down to three sub-parts, *Design for environmental, Design for manufacturing*, and *Robust design*. How to combine these theories of design in an organized and structured way is complicated due to the many factors needed to be recognised and proceeded.

- **Design for Environmental (DFE)**
  DFE is a process developed to reduce the environmental footprint/impact by the product. The method described in the PDD is large and wide. It will say, more described out of a company perspective, therefore not followed during this project. Despite not working actively with DFE it was a resulting goal for this project due to that it is a part of Clean Sky 2, having reducing footprint as the main target.

- **Design for Manufacturing (DFM)**
  DFM is an iterative process to lower the production cost. This is done by first propose a design and thereafter identify the main parts of the manufacturing cost. The next step is to reduce the cost of one or all the three cost types: *components, assembly and supporting production*. A process reducing each of these cost types is presented and well described in the PPD (Ulrich & Eppinger, 2012).

- **Robust design**
  Robust design is the products ability to perform during different conditions and also when assembled within the variation generated from different manufacturing process. In the PDD robust design exploits nonlinear relations to identify set points where the product performance is less sensitive to variation (Ulrich & Eppinger, 2012). To develop a robust design the PDD present a seven-step process:
  1. Identify control factors, noise factors, and Performance metrics.
  2. Formulate an objective function
  3. Develop the experiment plan.
  4. Run the experiment.
  5. Conduct the analysis.
  6. Select and confirm factor set points.
  7. Reflect and repeat.
  This seven-step process was not followed due to time management, however risks and their effect on the product were reflected on.
3 Methodology and theory.

This section summarises the information collected during this paper. It presents historical knowledge of adhesive bonding, relevant research connected to the problem and theory of different methods as well as explaining the equations used.

3.1 Adhesive bonding history

Adhesive bonding early history is undocumented but not obscure. Neanderthal tools have been found in Koenigsaupe, German dating all the way to 80,000 years ago. Residues of an adhesive substance were found on the tools and have been proved to be processed birch pitch (Koller, Baumer, & Mania, 2001). Similar tools have also been found at Ummel Tlel, Syria dating to 40,000 years ago (Boëda, o.a., 1996) which strengthens the theory of a sophisticated use of adhesives in this time periods. The oldest found use of adhesive bonding by the modern human was made at the Nahal Hemar cave in Israel and is dated to at least 8,000 years old (Bar-Yosef & Schick, 1989). First known structural bonding of metal to metal is from 530 BC (Feldhaus, 1931).

Until 1920 virtually all adhesive used in structural applications such as aircraft and automobile were out of natural glue, but phenol-formaldehyde became commercially available around 1930 (Adams, 2005). The early use was restricted to application in need of waterproof plywood due to high prices. These needs were present in the aircraft and boat building industry (Adams, 2005). Adhesive bonding in aircraft structures is today mainly used to attach stringers to fuselage and wing to stiffen the structure. The Hexcel Composites Redux Film 775 has been in service for over 25 years without indicating loss of mechanical properties (Higgins, 2000). The reason for this rapid acceptance of adhesive bonding in the aerospace industry is according to Petrie the major advantage, comparing to mechanical solutions such as riveting. Petrie also make it clear that some disadvantages exist (Petrie, 2008), the advantages and disadvantages are shown in Table 1.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Provides large stress-bearing area.</td>
<td>- Surfaces must be carefully cleaned.</td>
</tr>
<tr>
<td>- Provides excellent fatigue strength.</td>
<td>- Long cure times may be needed.</td>
</tr>
<tr>
<td>- Damps vibration and absorbs shock.</td>
<td>- Limitation on upper continuous</td>
</tr>
<tr>
<td>- Minimizes or prevents galvanic corrosion between dissimilar metals.</td>
<td>- Operating temperature (generally 175-200°C).</td>
</tr>
<tr>
<td>- Joins all shapes and thicknesses.</td>
<td>- Heat and pressure may be required for cure.</td>
</tr>
<tr>
<td>- Provides smooth contours.</td>
<td>- Jigs and fixtures may be required.</td>
</tr>
<tr>
<td>- Seals joints.</td>
<td>- Rigid process control usually necessary.</td>
</tr>
<tr>
<td>- Joins any combination of dissimilar materials.</td>
<td>- Inspection of finished joints is difficult.</td>
</tr>
<tr>
<td>- Heat, if required, is too low to affect metal parts.</td>
<td>- Useful life depends on the service environment.</td>
</tr>
<tr>
<td>- Provides attractive strength-to-weight ratio.</td>
<td>- Environmental, health and safety considerations are necessary.</td>
</tr>
<tr>
<td>- Often less expensive and faster than mechanical finishing.</td>
<td>- Special training may be required.</td>
</tr>
</tbody>
</table>
SAAB have used adhesive bonding when manufacturing the SAAB 340. The adhesive named Cytec FM73 was used (Higgins, 2000), the adhesive though to be used for this new door is a One Side Tacky (OST). It is a film adhesive with nylon scrim to ensure right flow and glue thickness (Higgins, 2000). This adhesive also requires that the metal has been pre-treated with a primer before the adhesive is applied and cured. It is this primer that on existing solutions using chromates to gain the characteristics needed.

3.2 Composite state of the art

Many similarities exist between adhesive bonding and composite production, because both need heat and pressure. Research in composite production has hence some relative information when developing a new adhesive bonding process. Research done about composite has therefore been investigated and the most relevant is presented below:

Tooling with reinforced elastomeric materials

Musch and Bishop did present a paper 1992 on how to generate an even pressure in geometrical complex composite products. This was accomplished by using air pads with reinforced elastics especially carbon-epoxy prepreg because of its ability to reduce shrinkage in most cases to less than 0.1% (Musch & Bishop, 1992). With this technology reinforced zones can be built in to give better pressure distribution at female corners. Other unsupported zones with higher flexibility to enable partial collapse. The collapse is forced with vacuum to allow smoother extraction from the completed parts (Musch & Bishop, 1992). One limitation with this technique is the tool stiffness that removes the possibility for a larger collapse. Which imitates where and how this kind of tool can be mounted and dismounted.

To test the air pad solution two production experiments was done. One test was to produce a Nose section for the Sauber-Mercedes C 291-B car. The other was integrally stiffened shell structure representative of a section of aircraft fuselage. Illustration of the aircraft orientated production test is shown Figure 3.

Figure 3, Illustration of production layout by Musch & Bishop, 1992.

Musch & Bishop comments on the finished part was clearly positive “The finished integrated stiffened shell structure showed excellent consolidation in all areas with good control of composite laminate thickness, fibre/resin ratio and void content and the stringer elements were found to have very good straightness and thickness
control.”. This indicates that the air pad technic may be used successfully without a negative impact on the shape of the geometry while applying an even pressure.

Manufacture and performance evaluation of composite hat-stiffened panel

Geon-Hui with co-workers investigated different manufacture methods for a composite hat-stiffened panel 2010 (Geon-Hui, Jin-Ho, & Jin-Hwe, 2010). In this investigation different ways of applying pressure from inside a hat panel was tested and the resulting physical data was collected to compare the methods. When Co-curing panel and hat-stiffener three different methods were tested, rubber mold, metal mold and inflatable mold. The paper shows that all three methods gave a favourable pressure distribution due to good mechanical properties on the result (Geon-Hui, Jin-Ho, & Jin-Hwe, 2010).

3.3 Analytical Hierarchy Process (AHP)

AHP is a structured and recognised method to create internal weights, it is presented in The Analytical Hierarchy Process (Saaty, 1980). The weights are distributed by combining logic, intuition, and mathematical matrixes to give a foundation for decision making. In the method criterions are compared pairwise and resulting in relative weight of importance between all incoming criterions.

3.4 Screening

The scoring often called Pugh concept selection was introduced by Pugh in 1990 and is a method where concepts are compared in different “selection criteria’s” with the score possibility from -1 to +1 (Pugh, 1990). This comparison is done with one concept chosen as reference. The chosen reference or benchmark should be well understood by the whole team. The selection criteria is selected from the customer needs thru the target specification or directly from the need list. The criteria should be chosen carefully since they have the same weight and a need represented multiple times does get a higher relative importance in this method. After the comparison is complete the net score for each concept is calculated. The concept/concepts with highest score have the best potential.

3.5 Scoring

The scoring is a method used when a higher resolution then screening is wanted between the competing concepts. First the wanted selection criteria is needed to be identified. It is recommended to use the metric from the target specification. This because the selection criteria itself should have a clear relation to the need identified earlier in the process to secure an attractive product. Thereafter, the selection criteria should be weighted by the team (Ulrich & Eppinger, 2012). When the weight is set for all criteria’s a reference concept should be chosen for each criterion given the score 3. It is important to choose a mediocre concept for each criterion so not all other concepts get the same better or worse score, if so the score for that criteria do not give as much information. After selecting the reference for all criteria’s each concept should be scored against the reference concepts. This is done by giving a score between 1 and 5 according to the following scale; 1. Much worse than reference 2. Worse than reference 3. Same as reference 4. Better than reference 5. Much better than reference (Ulrich & Eppinger, 2012).
To find out which rank respective concept get their total score is compared, where higher is better. The total score is calculated by multiplying the criteria weight with the concept scores given (1-5) in that criteria. When this is done to all criteria’s these weighted scores are summed for each concept and it is the total score (Ulrich & Eppinger, 2012).

3.6 Pressure by thermal expansion
To investigate pressure given by thermal materials, the difference in thermal expansion needs to be examined. To simplify the problem, it is only solved in one dimension which will not give as good precision, but it will still show the possibilities of using thermal expansion. A materials length after/during thermal expansion can be described as

\[ L_{\text{grow}} = \alpha \times \Delta T \times L_0, \]  

where \( \alpha \) is the linear expansion coefficient which is a material property, \( \Delta T \) is the temperature differences that creates the expansion and \( L_0 \) is the material original length. To find the expansion differences between two materials the following trivial equation is used

\[ \Delta L = L_{\text{grow1}} - L_{\text{grow2}}. \]  

In Equation (2) \( L_{\text{grow1}} \) is the length expansion by the larger growing plastic tool and \( L_{\text{grow2}} \) is the beams expansion.

The pressure formed on the beam is the compression that occurs on the plastic tool when it expands more than the door parts. The door parts are then pressed together by stress gained through the compression of the plastic tool. This stress can be calculated with Hook’s law

\[ \sigma = E \times \varepsilon. \]  

In Equation (3) \( E \) is the material property Modulus of elasticity and \( \varepsilon \) is the strain in the plastic tool that is calculated by

\[ \varepsilon = \frac{\Delta L}{L_{\text{grow1}} + L_0}. \]  

To note in these series of equations are that no play is considered between the tool and door parts. If a play is existing Equation (2) needs to be adopted with a term that subtract the distance between the object before the process is started.

3.7 Design for Assembly (DFA)
DFA is a well-used term in industry and development. DFA do not have a chapter in DDP (Ulrich & Eppinger, 2012) but is mention and the cost is calculated during the DFM chapter. In this project no, recognised method is followed straight on, however Boothroyd principal presented in Product Design for Manufacture and Assembly, Third Edition (Boothroyd, 1994) is reflected on during the process. Of extra interest is the data provided by Boothroyd, that an approximate value gives a good representation of the manufacturing prices for a component (Boothroyd, 1994). Proving that exact drawings and simulations adding minimal precision to extent of considerable more work.
4 Planning

The project started in alignment with Ullrich and Eppinger process with a planning phase. Due to that most of activates presented in Ulrich and Eppinger is on cooperation level it was not used. The project planning phase started with creating a Gantt-schedule, define intent and limitations. Also, research to find the “State of art” in related subjects and relevant patent were done. Ulrich and Eppinger recommends that a mission statement is stated, and this was done to clarify the aim even further.

4.1 Mission statement

The following statement was set to lead and guide the project:

“The thesis aims to create an effective tool solution for the assembling of aircraft cargo doors when using adhesive bonding to bond frames and outer skin. This should be done with as high automation as possible to secure a profitable and high rate production. Hence increase SAAB competitiveness when competing to deliver the new generation of cargo doors after showing the new doors function in the MFD.”

4.2 Gantt-schedule

To plane the project and to set up milestones for the project a Gantt-schedule was created. This was done by controlling the main tasks that is presented in Ulrich and Eppinger and list them as activities, thereafter approximate how much time each activity should be given compared to the others. By this process the period was filled out and the time range for each activity turned out to a plan that gave a convincing approach for the project. This gave a structure of when different tasks should have been done and ensured that the process itself was being followed. The Gantt-schedule is shown in Appendix A1.
5 Concept development

The concept development consists of Need finding, Target specification, Tool functions decomposition, External search, Concept generation and Concept selection. A Concept testing was not done, due to that the costumer (SAAB) was participating under the selection of every major decision during the project.

5.1 Need finding

To collect needs the description for the master thesis, statements done by the mentor at SAAB, and statement by the project leader (CS2) at SAAB was documented. These needs where then rewritten after the PDD guidelines to keep the solution space as large and general as possible. Thereafter it was discussed if any need was absent and the need search ended. No relative importance was set between the needs since it was decided to do an AHP on the metric in the target specification. The reason for this is the high concentration of information given in some of the needs, lowering the total number of needs. Ulrich and Eppinger also recommends organising the needs into a hierarchy and this was done according to their process (Ulrich & Eppinger, 2012). With the needs categorised in groups they are more easily navigated and processed. The levels make sure that no needs are over represented by being described multiple times and equal general/specific. The result from this work is presented in the need list shown in Figure 4.

<table>
<thead>
<tr>
<th>Need nr</th>
<th>Need</th>
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<tbody>
<tr>
<td>1</td>
<td>The tool is faster than the bagging method today</td>
</tr>
<tr>
<td>2</td>
<td>The tool manage the heating time</td>
</tr>
<tr>
<td>3</td>
<td>The tool enable lower assembly time than position the beams by hand</td>
</tr>
<tr>
<td>4</td>
<td>Desirable if the tool is able to do upper and lower beam in the same process</td>
</tr>
<tr>
<td>5</td>
<td>The tool is adapted for robots</td>
</tr>
<tr>
<td>6</td>
<td>The tool give a low cost per door</td>
</tr>
<tr>
<td>7</td>
<td>The tool lower the use of disposables</td>
</tr>
<tr>
<td>8</td>
<td>The tool is maintainable</td>
</tr>
<tr>
<td>9</td>
<td>The tool give right pressure distribution to all the areas being bonded</td>
</tr>
<tr>
<td>10</td>
<td>The tool can handle all incoming beams</td>
</tr>
<tr>
<td>11</td>
<td>The tool need to heat the adhesive under pressure</td>
</tr>
<tr>
<td>12</td>
<td>The tool give the right tolerances to the produced doors</td>
</tr>
<tr>
<td>13</td>
<td>The tool can handle the pressure</td>
</tr>
<tr>
<td>14</td>
<td>The tool has an attractive manufacturing price</td>
</tr>
<tr>
<td>15</td>
<td>The tool is possible to manufacture</td>
</tr>
</tbody>
</table>

Figure 4, Need list.
5.3 Target specification

The target specification was done according to Ulrich and Eppinger description. Each need was thoroughly processed and described by as many metrics as required. The needs were processed and converted by category, therefore the metrics were structured in same categories. Thereafter the metric was controlled and combined if they were describing the same mechanical properties. To ensure that the relation between need and metric not was affected by the translation a needs-metrics matrix was done shown in Figure 5.

<table>
<thead>
<tr>
<th>Need:</th>
<th>Metric:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The tool is faster than the bagging method today</td>
<td>Possible number of doors per day</td>
</tr>
<tr>
<td>2. The tool manage the heating time</td>
<td>Total time at packing-unpacking stations</td>
</tr>
<tr>
<td>3. The tool enable lower assembly time than position the beams by hand</td>
<td>Accurate time by operator</td>
</tr>
<tr>
<td>4. Desirable if the tool is able to do upper and lower beam in the same process</td>
<td>Possible products per door</td>
</tr>
<tr>
<td>5. The tool is adapted for robot</td>
<td>Handling temperature to 120°C</td>
</tr>
<tr>
<td>6. The tool give a low cost per door</td>
<td>Variable in cost per door</td>
</tr>
<tr>
<td>7. The tool lower the use of disposables</td>
<td>Number products per door</td>
</tr>
<tr>
<td>8. The tool is maintainable</td>
<td>Production cost per door</td>
</tr>
<tr>
<td>9. The tool give right pressure distribution to all the areas being bonded</td>
<td>Material cost of tool</td>
</tr>
<tr>
<td>10. The tool can handle all incoming beams</td>
<td>Possible to manufacture</td>
</tr>
<tr>
<td>11. The tool need to heat the adhesive under pressure</td>
<td>Total in area being bonded</td>
</tr>
<tr>
<td>12. The tool give the right tolerances to the produced doors</td>
<td>Number of critical components</td>
</tr>
<tr>
<td>13. The tool can handle the pressure</td>
<td>Bond lower beam in same process</td>
</tr>
<tr>
<td>14. The tool has an attractive manufacturing price</td>
<td>Bond lower beam in same process</td>
</tr>
<tr>
<td>15. The tool is possible to manufacture</td>
<td>Number of critical components</td>
</tr>
</tbody>
</table>

Figure 5, Need-metric matrix.

As shown Figure 5 metric 1 and 5 were related to a number of needs and this depends on that they are written in somewhat more general terms, due to their importance for the tool. In this way some of the other metric contribute to the same needs resulting in an “over” representing of this need in the metric. For that reason, only hand-picked metrics have been chosen to have ideal value in requests. This is to not get a stacking effect later in the screening and scoring. Finally, the target values were discussed with the thesis mentor and project leader at SAAB. The target specification is shown in Figure 6.
5.4 Tool functions decomposition

To analyse what functions that are needed by the tool and which problem that needs to be solved, a function decomposition was carried out. This was done by following the description in Business Analysis Body of Knowledge (LIBA, 2009). The result from this decomposition is shown in Figure 8.
Figure 7, Analytical Hierarchy Process on requests.

Figure 8, Function decomposition.
In the product development processes (Ulrich & Eppinger, 2012) it is suggested to do a concept combination table with the solutions identified from the function decomposition. To make it more visual that each sub-solution could be solved separately a concept combination table was set up. It was updated every time a new solution to solve one of the sub problem was discovered. A part of the documented sub-concepts is shown in the concept combination table in Table 2.

<table>
<thead>
<tr>
<th>System Nr.</th>
<th>Solutions: Nr 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Generate pressure/force</td>
<td>Pressurised air</td>
<td>Hydraulic pressure</td>
<td>Termo-elastic</td>
<td>Mass</td>
</tr>
<tr>
<td>2. Distribution of pressure</td>
<td>Metal tool with suspension</td>
<td>Soft plastic tool direct contact</td>
<td>Airbag</td>
<td>Use structure of the door</td>
</tr>
<tr>
<td>3. Heat system</td>
<td>Autoclave</td>
<td>Heating coils</td>
<td>Induction heating</td>
<td></td>
</tr>
<tr>
<td>4. Mange input of components</td>
<td>Possible to lift right in</td>
<td>Sliding</td>
<td>Assemble inside profile</td>
<td>Expand size</td>
</tr>
<tr>
<td>5. Mange output of tool components</td>
<td>Possible to lift right in</td>
<td>Sliding</td>
<td>Disassemble inside profile</td>
<td>Reduce size</td>
</tr>
</tbody>
</table>

5.5  External search

To identify that no commercial solution for any of the subsystem was available a search for existing patents and dialogs with different expert at SAAB were done. In this search both patents and some interesting existing products were identified and inspected. These existing technologies are in short terms explained below:

**Patent “METHOD FOR AUTOCLAVE-FREE ADHESIVE BONDING OF COMPONENTS FOR AIRCRAFT”**

The patent is claiming the processes of using adhesive bonding to bond stringers to skin panels in order to form a large-sized structural component for aircraft without autoclave (United States Patentnr 0021268 A1, 2010). The technical principal for the patent is to engage a successful bonding cure at a lower pressure than previous techniques. This allows the process to be done without pressure from an autoclave and can instead be done by pressure created by vacuum. By using vacuum less tension and load are applied to the structure and vacuum film due to this less preparation and after work are needed. When using an autoclave, much work is needed to prepare the structure with support materials, pressure equalising materials, adhesive tape, and etcetera. An illustration of the differences is shown in Figure 9.

Figure 9, Differences with/without autoclave bonding.
The main difference between the patent and the solution searched for in this project is the flexibility. SAAB is searching for an even more effective but specialised tool. This because of the limited door size and it even more complex geometry. The patent technical approach is however most interesting in other production processes at SAAB.

*Patent “PRESSURE EQUALIZING PAD FOR HEATED PLATE PRESSES”*

This patent is old and no longer valid but was claiming a pressure equalizing pad for presses with heated plates for production of compact laminates (United States Patentnr 4,612,081, 1986). The main claim was to use thin sheet metal as contact organ when pressing through support of enclosed oil on the other side. To give a more adoptive pressing surface and a better pressure distribution. The patent is designed for pressing flat surfaces but gives technical properties wanted in this project. The claimer states that this solution gives a good pressure distribution and on the same time increases the heat transfer. Abilities searched for in this project and therefore an interesting technology.

*Existing Air pad Product*

Air pads are commonly used in composite production today and several companies can today provide different solutions with air pads. Air pads are in composite production used to fill holes and spaces in the structure to be able to add the autoclave pressure during curing and avoid structure collapse. Thereafter the air pads are collapsed by draining them with vacuum so that they easily can be removed. Hence the air pads functions are very similar to what the project is searching for, due to their ability to apply pressure inside complex geometry.

5.6 Concept generation

Most of the idea generation was done alone. Mostly classic brainstorming was used during the generation but due to the quite complex problem Catia V5 was sometimes used as platform instead of pen and paper. The concept combination table was used as explained in PPD (Ulrich & Eppinger, 2012), where solutions from different sub-functions was combined and used to generate new solutions for the complete system.

The generation work has also been influenced by discussion with the thesis mentor, project at SAAB and head of door design throughout the whole concept generation period. To not influent my creativity by their thoughts they only answered on questions from the beginning to later give straighter opinions and viewpoints of the problem.

From the generation a large number of sketches for different sub-systems were accomplished. From these sketches a combination work for the difference sub-solutions was carried out and to give the different solutions the same level of detail all solutions main features were designed in Catia V5. Due to that many concepts were similar and combined, the effort resulted in a total of 11 complete concepts that is shown in Appendix A2.
5.8 Concept elimination

To ensure that the concept with the highest potential was chosen for future investigation a structured selection process was chosen as suggested in PPD (Ulrich & Eppinger, 2012). An Elimination matrix was used, to settle that all solution did accomplished the requirements and the result is shown in Figure 10.

![Figure 10, Elimination matrix.](image)

After the requirements were controlled, 9 concepts remained. It was decided to proceed with a screening to narrow down the number of concepts to a future scoring. The screening often called Pugh concept selection was chosen due to its efficiency with large number of concepts and still give a better resolution than the elimination matrix. The result from the screening is shown below in Figure 11. To ensure a good relation between the selection criteria and the needs, the criteria was taken from the request in target specification. Which contains information about ideal values of requirements and desired functions.

![Figure 11, Screening matrix.](image)

After the screening only 6 concepts were remaining, and it was decided to move on to the final scoring. To be able to follow the scoring and understand the concepts strengths and weaknesses they are explained in shortness below:

- **Concept 1: Spring-upwards**

The concept **Spring-upwards** is shown in Figure 12. The concept was using disk springs to increase the pressure distribution. To be able to handle a larger shape tolerance on the incoming door frames. To give this flexibility a more easily deform sheet is located between the main body (transparent) and a rubber cover in contact with the door components. This construction forces the door frames to be slide in and out from the tool, which lowers the precision that can be given to the frames due to the play needed. When bonding upper or lower beam a force is needed to press the beam and profile together. This force is applied in the horizontal direction in Figure
12. To bond upper or lower beam in the same process, a solution giving this pressure needs to be added.

Figure 12, Illustration of Spring.

- **Concept 2: Drop**

*Drop* is somewhat similar to *Spring* but has no support for the profile, allowing much faster insertion and extraction of components. The frame itself transfers the force to the contact area between the skin and frame. This gives a risk of plastic deformation on the profile. Which in that case has to be solved by an additional solution. To bond upper or lower beam in the same process, a solution giving pressure between the lower/upper and the frames need to be added.

- **Concept 3: Hydra**

*Hydra* is a concept that is using hydraulics to solve the problem, shown in Figure 13. *Hydra* has hydraulic or pneumatic cylinders to do one horizontal and one vertical moment on each arm to give the ability to put in the door frames from above. After the frames are placed the arm position them horizontal before applying vertical pressure to give support to the frame profile. This concept demands a high number of cylinders which gives a higher failure risk but the ability to bond upper or lower beam is however quite good because of the movement capability.

Figure 13, Illustration of Hydra
- Concept 4: Solid.

*Solid* is similar to *Spring* and the tool has the same profile but without the springs. In this concept the springs are removed and replaced by only a rubber cover acting as a pressure distributor, the shape tolerance of the door frames is in this system more critical and a tighter tolerance on the frames may be needed. Upper and lower beams are as in *Spring* complicated to add.

- Concept 5: Autobag

*Autobag* is inspired by the air pads currently used in the composite manufacturing. The idea is that pads of this kind are mounted on a tool base and the door frames are placed in its right position before the pad is inflated. This pad could have two possible structures, it could either be reinforced to gain the frame shape naturally or unshaped and be inflated and formed after the nearby structures. Either way this type of solution gives a good pressure distribution. A challenge for this solution is how well the frames can be positioned and how to design the pad to successfully include upper or lower beam. A concept inspired by the research presented in “Tooling with reinforced elastomeric material” (Musch & Bishop, 1992).

- Concept 6: Plastic

This concept as shown in Figure 14 uses the high thermos-elastic properties of rubber to establish the needed pressure. This is done by applying a rubber profile in the door frame profile. The placement of the plastic is to be done by using air pressure, either vacuum or pressure from the autoclave. Upper and lower structure were not planned to be included in this solution.

![Figure 14, Illustration of Plastic.](image)

5.9 Concept scoring.

With the information gathered above a scoring was done to narrow down the number of concepts even further and ranking the concepts using a systematic method. The final scoring was done following the description given in PDD (Ulrich & Eppinger, 2012), where different reference concepts are set to different selection criterions. The criterions were taken from the target specification, to ensure a strong correlation to the consumer needs. Which is desired to secure that an attractive tool is developed for SAAB. The scoring as a process is demanding weights on every selecting criteria. The
PDD is accepting a subjective weighting of these criterions. In this project they were acquired from the AHP. This method was chosen to minimise the subjective effect given by favouring one concept and setting the selection conditions thereafter. The result from the scoring is shown in Figure 15.

**Figure 15, Target specification.**

As can be seen in Figure 15 concept *Drop* got the highest score before *Hydra* close together with *Plastic* and *Spring* on a shared third place. To see if this reflected the opinion from the personal at SAAB, with many years of experience in similar problems and earlier projects. A survey was done where four individuals rank the concepts (exclusive the reference concept) after given a presentation about them. The result from this can be seen in Table 3.

**Table 3, Result from survey.**

<table>
<thead>
<tr>
<th>5 highest - 1 lowest</th>
<th>Spring</th>
<th>Solid</th>
<th>Drop</th>
<th>Autobag</th>
<th>Plastic</th>
<th>Hydra</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual 1</td>
<td>X</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Individual 2</td>
<td>X</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Individual 3</td>
<td>X</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Individual 4</td>
<td>X</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Total score (higher better)</td>
<td>3,00</td>
<td>3,75</td>
<td>2,75</td>
<td>3,25</td>
<td>2,25</td>
<td></td>
</tr>
</tbody>
</table>

When comparing Figure 15 with Table 3 it is shown that *Drop* had the highest score during both the methods. Unlike *Hydra* that did not get the same support from the engineers at SAAB. *Plastic* did get the second most support from the engineers.
5.11 Concept selection

Drop’s high score in the scoring reflects well on the team thoughts about the solution capacity for an effective production solution, given by the possibility to lift the door right up and down in the tool. As a result of this Drop was chosen as the main concept for continues work. Due to the high score and the large automation possibilities Hydra was not eliminated. Third place was shared between Spring and Plastic. Due to Spring’s similarity to Drop this concept was eliminated. Plastic on the other hand was a new innovative way for adhesive bonding and through discussion with the thesis mentor it was decided not to eliminate Plastic directly. Solid’s similarity to both Spring and Drop did that the concept not provided any unique details and was therefore eliminated. At last Autobag was eliminated because of the failure risks and challenge to give an accepted tolerance position for the component to be bonded. This gave three concepts remaining Drop, Hydra and Spring.

5.12 Concept investigation

Before choosing concept, a brief investigation was done to ensure their potential.

Drop

The concern about the Drop concept was related to how the I-profile should withstand the pressure during the bonding process. The profile itself must withstand the pressure created from the autoclave. To secure that this key point could be achieved by the profile a Finite Element Method (FEM) analysis was done on a section of the solution. This analysis was done at a section cut including one I-profile and nearby geometry, shown in Figure 16. The boundary conditions for the analysis were decided, thereafter the information was carried over to the FEM department at SAAB that setup and run the analysis in Hypermech using the Nastran solver.

As shown in Figure 16 grey and blue represent the two outer sheets on the door and are in the material aluminium. Purple and dark yellow represent the Silicone cover separating the tool profile and bonding components aimed to increase the pressure distribution. The silicone selected was Mosites 1453 because of earlier experience and existing standards at SAAB. Red represents the I-profiled frame that is bonded to the door and is in aluminium. Last colour is the light yellow representing the tool body. It was chosen to cancel out thermal expansion otherwise occurring due to the heating in the Autoclave. The result from the analysis is shown in Figure 17 below.
Figure 16, FEM setup.

Figure 17, Result from the analysis.
In Figure 17a is the parts shown with same colour code as in Figure 16. The deformations are scaled 20 times in all sub-Figures. In Figure 17b the deformation in Z-led is presented, it is shown that the max deformation is -0.0613 mm. This deformation is small in contrast to the wave tolerance for the door. In Figure 17c the stresses in the beam are presented and it is shown that the max stress is 2.52MPa, far below tensile yield strength for any aluminium materials. In Figure 17d the stress scale is lowered and any stress above 5MPa is presented in grey, it is shown that no pressure is set to the end of the I-profile. This occurs due to that the profile has been bent downwards and has no physical contact with the doubler skin at the tip. This was discussed and assumed to be of no problem, due to the adhesive thickness and flexibility.

Through the higher pressure in the centre of the frame-profile adhesives are expected to be pressed outwards and therefore press eventual air out of the bonding. Giving an overall safer bonding.

Following result gave a promising view of Drop. Both low deformations, giving a small impact on the bonded door shape and a good pressure distribution. Giving a good potential for the bonding process. Combine this ability with the favourable mounting time achieved since the frames can be placed directly from above and the concept has large advantages.

Hydra and Plastic

Because of the good result from the study of Drop, proving that no support was needed on the profile. The other solution that implementing this support did no longer have any advantages compering to Drop and was therefore eliminated. With this argument Drop was chosen as the final concept.
6 System-level design

To manage and gain control of all the parts needed in the Drop solution the system-level design presented in PDD was followed for more detail see Section 2.3.

6.1 Product architecture

To localise different sections of the solution a product architecture was created following the 4 steps presented in 2.3 System level design.

1. Create a schematic of the product

The schematic was created from the understanding of the concept at the time, the element was chosen to visualize which abilities needed by the tool to produce one door.

Figure 18, Schematic of the concept Drop.

The schematic of the tool is shown in Figure 18. This level of the schematics was chosen due to that it shows every main step needed but not how it is solved. Which not limiting the creativity when solving these problems in the detail design.

2. Cluster the elements of the schematic

To track how the different sections of the solution exchange information, energy, or material the element in the schematic was clustered into chunks.
Figure 19 shows the result from the element clustering and how they interact with each other.

3. Create a rough geometric layout

To illustrate how these different chunks are physically connected, a two-dimensional geometrical layout was drawn. This defines the positions of the mayor parts, hence setting which parts should have interfaces or dimensional relations between each other. This layout is shown in Figure 20.

Figure 20 shows the support system is distanced from the tool but will still interact through delivering material, etc. This makes the interface in this interaction harder to design. This support system has multiple relations to the other systems and movements which adds many dimensions to the challenge.

4. Identify the fundamental and incidental interactions

When working in detail design, it is important to have specified conditions for each separate section being designed. How the section/chunk is interacting with one and each other is one of these conditions, but the interaction can be divided. The
interaction can be either a fundamental interaction or an incidental interaction. The fundamental interactions are the ones identified in Figure 19, and they are needed for the solution to function properly. On the other hand, incidental interactions are the interaction between chunks that are not intended, as example vibration from one chunk to another. These interactions are equally important to localise as they also affect the functionality.

![Figure 21, Incidental interactions.](image)

The interdental interactions shown in Figure 21, were created as described in the PDD (Ulrich & Eppinger, 2012).

6.2 Platform plan

Due to that the project aimed to develop a tool thought to only be manufactured limited times, a larger effort in platform planning should not be beneficial and it was decided to not proceed in this activity. Although future similar tools may be used to produce doors with this method. It was not possibly to design the tool modular because of the large impacts in tool parameters and design are given by small differences in the door design.

6.3 Subsystem

From the process done in the system-level design it was clear that the tool have three main components/chunks, excluding the bonding process and support system that both are outside the main focus of this project. The three main chunks were Tool frame and skin, Tool upper beam and chassis. It was decided to go in to detail design seeing them as independent system that can be solved separately. This tactic was chosen to keep the solution for each chunk as simple as possible, which gives more time to solve each subsystem effective and to come up with an attractive solution.
7 Detail Design

To accomplish the best result from the detail design a carefully shaped strategy was developed. First, the base principal of the concept was designed as a base to work from. Thereafter, a more trivial concept development from the DDP was done at the three main parts from the level-system design. Tool skin and Frame placement did get separated out of tool frame and skin to acquire a more specific task during the development. The four systems are developed and designed separately below.

7.1 Upper beam

The challenge in the design regarding upper beam is to give a solid support to the surrounding parts and still allowing an easy insertion and extraction of the door components. In combination with the need to apply a force between the frames and upper beam (perpendicular to the frame direction, shown in Figure 2), required for the bonding process. These two difficulties make the upper beam section challenging, when the bonded door is desired to be lifted right up. The upward lifting is challenging because the tool needs to be retracted to give space for the I-profile frame. Demanding the tool to move around 25mm before and after applying the force needed during the bonding process.

The bonding section between door frame and upper beam is going to be reinforced with screw joints but it is still necessary to bond. This to remove the demand to deburr the holes, a common requirement in the aircraft industry.

When the design work regarding Upper beam started it was one important boundary condition that was discussed. Does the beam need support from the inside of the U-shaped area or not. If it only needs support from outside the U-shape a new set of subsolutions should be possible. An illustration of the U-shape is shown in Figure 22.

![Figure 22, Illustration of upper beam profile through section view.](image)

In Figure 22, the profile of the upper beam is shown. In Figure 22, no tool is supporting the inside of the U-shape section. The darker tool does however support to the upper beam outside of the U-profile and the idea of less support was examined in a FEM analysis.

A linear FEM analysis was done by the FEM department at SAAB aerostructures, using Hypermesh software with the Abaqus solver. Tetrahedrons with ten nodes were used (Tetra 10 in Abaqus). The geometry analysis was done at one section cut out from the upper beam, this was possible due to the symmetrical layout of the beam.
Fix constrains (all three directions) were set on the dark red surfaces presented in Figure 23a, to simulate the support given by the tool. The surface in Figure 23b, marked in green is the area where pressure was applied equal the pressure thought to be applied in the autoclave.

![Figure 23](image)

**Figure 23, Concepts of forces during upper beam analyses.**

In Figure 23 the right side of the upper beam cannot be seen but no constrains or loads are set to that side, to give a conservative perspective of the reality. In the final tool upper beam is getting support alongside the right side of the beam, due to that upper beam position is against the tool on that side, as shown in Figure 22. Results from the FEM analysis is shown in Figure 24.

![Figure 24](image)

**Figure 24, Analysis result from FEM on upper beam.**

Figure 24a and b, shows the displacement and stresses given from the FEM. The absolute displacement is 0,2mm in Figure 24a, and the stresses reaching a top of 10 MPa in Figure 24b. Both values higher then previous results from the FEM analysis on *Drop*. Never the less this result is within the target set in the specification (Metric 11). It should also be in mind that both the doubler and outer skin are in reality placed between the autoclave presser and upper beam taking up some of the stresses. They were chosen to not be included to simplify, reduce the time, reduce error risks, and secure a more conservative result. With the given result it was shown that no support was needed inside the U-shape of the upper beam.
**Concept generation**

With the result from the FEM analysis and 3D-models created in concept generation, all boundaries were set and the concept generation could begin. During this generation discussion and brainstorming was used, but also old concept generated to the overall solution was looked through. To see if any potential customisations of old concepts were possible. The concepts developed are presented below:

- **Hydsta**

Similar to the concept *Hydra* generated in the overall generation, it uses hydraulic cylinders to apply the force needed between door frame and upper beam. To give the support outside of the U-shape the same silicone cover used in the overall solution was chosen.

To investigate the possibility of a hydraulic solution TEMEC was contacted to see if they had any cylinder fulfilling a demands. To see if an existing solution was available on the market. The demands listed to the retailer are shown in Table 4.

<table>
<thead>
<tr>
<th>Demand for hydraulically cylinders.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manage 150 degrees Celsius</td>
</tr>
<tr>
<td>Deliver a pressure of 600N</td>
</tr>
<tr>
<td>Cross section dimension 35 x 35 mm</td>
</tr>
<tr>
<td>Max length 140mm</td>
</tr>
<tr>
<td>Stoke length of 30mm</td>
</tr>
</tbody>
</table>

In Table 4, the dimension was taken from the 3D model with a small margin to give as many thinkable cylinders as possible. The force was calculated by taking the connecting area between the frame and upper beam divided by the pressure needed by the bonding process as stated in the trivial rewriting of the pressure equation \( F = \frac{p}{A} \).

TEMEC recommended a MERKLE cylinder named BZ 500.16/10.01.201.30.V (A.nr 013287) fulfilling all the requirements except the cross section dimension. This cylinder has instead a rectangular section with the dimensions 60 x 35mm, due to that one side still was 35 mm it was still possible to fit the cylinder in to the solution. To give an illustration of this concept, a simplified CAD model was done, shown in Figure 25.
As seen in Figure 25, the pressure applied between the frames and upper beam do not cover all the overlying area. This because of the ability to lift the completed door right up was wanted, and the bottom of the upper beam therefor needed space to move pass the pressure plate.

- Plasto

*Plasto* was similar to the concept *plastic* created in the overall generation. The idea was to place a plastic part in the upper beam before it is mounted, and let it grow by thermal expansion during the bonding process. Giving the correct sideways force when reaching the final temperature. This kind of pressure generation has been proven successful by Geon-Hui with co-workers describe in Section 3.2. To investigate what materials and relations needed to successfully use this method a simplified one-dimension calculation was done. To start with reliable data, the material data of SH0040U (from KCC Co.) Silicone rubber presented in the paper “Manufacture and performance evaluation of the composite hat-stiffened panel” (Geon-Hui, Jin-Ho, & Jin-Hwe, 2010) was first tested. Material properties needed to calculate the pressure are summarised in Table 5.

**Table 5. Properties for SH0040U Silicone to calculate thermal expansion pressure.**

<table>
<thead>
<tr>
<th>Source</th>
<th>Index</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive elastic modulus (Geon-Hui, et al.,2010)</td>
<td>$E$</td>
<td>2,15</td>
<td>MPa</td>
</tr>
<tr>
<td>Coefficient of thermal expansion SH0040U (Geon-Hui, et al.,2010)</td>
<td>$\alpha_1$</td>
<td>315</td>
<td>$10^{-6}$ $K \times m$</td>
</tr>
<tr>
<td>Coefficient of thermal expansion aluminium AA 7075-T6 (Sundström, o.a., 2013)</td>
<td>$\alpha_1$</td>
<td>23,6</td>
<td>$10^{-6}$ $K \times m$</td>
</tr>
<tr>
<td>Temperature differences</td>
<td>$\Delta T$</td>
<td>100</td>
<td>$K$</td>
</tr>
<tr>
<td>Length of material before expansion</td>
<td>$L_0$</td>
<td>0,1575</td>
<td>$m$</td>
</tr>
</tbody>
</table>
With the data from Table 5 compiled into Equation 1 to 4 the theoretical pressure against the bonding surfaces reached 90% of the wanted pressure. This appears to be somehow low when comparing to the previous mentioned paper where they need to make the plastic tool hollow to lower the pressure.

With even more work localising a plastic material with good properties and the fact that the quality was not of same importance in this bonding. The Plasto concept was seen as a possible solution regardless of the limited pressure generated.

- Spring arm

Spring arm was a generated concept, where a spring is moved in position by a manual arm or an electrical motor. The core idea of the concept was to pre-set the spring to give it a high force delivery, but still a relative low torque when moving it in position. An illustration of this concept is shown Figure 26.

![Spring Arm Illustration](image)

Figure 26, Concept illustration of the Spring arm.

As seen in Figure 26, a circle and beam/rectangle is interacting by a link representing the spring package. When applying pressure as in Figure 26a, the spring package has been forced above the centrum of the circle to be self-looked in that position. To validate that springs of these sizes can deliver the needed force, a market check was done and a spring from LESJÖFORS was found with a diameter of 20mm and a reacting fore of 483N when compressed to 19,4mm (6745: CSS 3,2X20X34). One disadvantage when doing the moment manual by an arm is the challenge to seal off the outside pressure applied by the autoclave. To give a wider understanding of the idea a model of the spring section was done without a spring, shown in Figure 27.
If these concepts were to be chosen the automations possibilities are of high interest, because of this a market analysis was done regrinding the rotation movement. Multiple online product catalogues were analysed, and no complete solution was found, however on Maxon motor AG website (Maxon motor, 2018) electrical motors made for repeated use in autoclave could be found. This electrical motor did not have the torque needed and was not offered in combination with planter gears. On the other hand, planetary gears that should give the wanted torque were possible to combine with other motors. This information lead to the conclusion that potential automation, with an electrical motor was available possible with products on the market.

**Concept selection**

In the upper beam section, it was hard to identify which concept that was the most competitive, because of this it was decided to do a scoring matrix. The same metric as used in earlier scoring matrixes was chosen, except from metric number 18 and 19 requesting bonding of lower and upper beam not relevant in this scoring. This change affected the internal weight on the selection criteria and the AHP needed an update to give internal weights without metric 18 and 19. After the removal of metric 18 and 19 and updating of the AHP a new scoring for the sub-system of upper beam was done and is shown in Figure 28.
As seen in Figure 28 Plasto was deducted against the remaining two concepts. Between Hydsta and Spring arm the score was closer, and a discussion was held. It was decided to move on with Spring arm due to that the changes only affected the tool itself. Hydsta on the other hand requires a major modification on the autoclave to install access to a hydraulic system under the bonding cycle.

**Design**

Before starting to model details on the Spring arm concept the layout sketch (see Figure 26) was used to identify and lock dimensions on the major parts. This to provide a wider understanding of the wanted lengths, and how much compression that was needed to be mange by the spring. With most dimensions locked a rough estimation was done to find out the maximum momentum and the spring flexibility needed from the design. The result is shown in Table 6.

**Table 6, Values regarding spring movement and forces.**

<table>
<thead>
<tr>
<th>Ind.</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Force</td>
<td>400</td>
<td>N</td>
</tr>
<tr>
<td>b</td>
<td>Max angle, when engaged</td>
<td>30</td>
<td>Degrees</td>
</tr>
<tr>
<td>c</td>
<td>Arm length</td>
<td>35</td>
<td>mm</td>
</tr>
<tr>
<td>d</td>
<td>Spring length</td>
<td>44</td>
<td>mm</td>
</tr>
<tr>
<td>e</td>
<td>Max momentum needed to drive the solution: sin(b)<em>a</em>(c/1000)</td>
<td>7</td>
<td>Nm</td>
</tr>
<tr>
<td>f</td>
<td>Total length of punching device</td>
<td>159</td>
<td>mm</td>
</tr>
<tr>
<td>g</td>
<td>Total length from rotation centre to frame</td>
<td>156,75</td>
<td>mm</td>
</tr>
<tr>
<td>h</td>
<td>Minimum spring distance needed: f-g</td>
<td>2,25</td>
<td>mm</td>
</tr>
<tr>
<td>i</td>
<td>Extra margin for minimum (when passing 0 degrees)</td>
<td>1</td>
<td>mm</td>
</tr>
<tr>
<td>j</td>
<td>Extra margin for spring not to go to end (loaded under process)</td>
<td>0,75</td>
<td>mm</td>
</tr>
<tr>
<td>k</td>
<td>Total length of spring movement</td>
<td>4</td>
<td>mm</td>
</tr>
</tbody>
</table>

Figure 28, Scoring of sub-system upper beam.
With the information from the trivial calculations in Table 6, a 3D model of the solution was built. To secure that the different parts should fit properly, the sketch seen in Figure 27 was used as a master geometry, and all parts were built with that sketch as reference. This CAD approach is widely known as Top Down Design. After the spring arm concept was designed, it needed to be integrated into the tool body otherwise occupying that area. To accomplish this, the spring arm was first positioned inside the tool body and the tool body was then hided. Rough solid bodies were built up around the spring arm and thereafter subtracted from the main body. The result from this design phase is shown in Figure 29.

![Figure 29, Design of “Spring arm”]{a) Spring arm in contact b) Spring arm withdrawn}

To enable the assembly of the spring arm the bottom of the main tool was removed and replaced by a plate mounted afterwards. To lower the failure risk when withdrawing the pressure plate a chamfer was added to the plate (dark grey seen in Figure 29) and the main tool body.

It was decided to use a manual solution as moment input, due to that the electrical motor should class the tool as a machine, complicating the registration process of the tool. The manual idea had an axel going through the tools bottom sheet, and this passage need to be sealed. It was believed that the best sealing option was an O-ring. A retailer named Apple rubber products was found. The axel and hole were therefore, designed after there O-ring (AS-568-107) with a rod gland diameter of 9.68mm, rod diameter of 5.51mm and a maximum pressure of 10MPa, which is far above the pressure given by the autoclave.

7.2 Tool skin

Tool skin placement is referring to how the outer skins are guided to the right position and thereafter how the area between the skin and tool are sealed. This area needs to be sealed so that the pressurised air from the autoclave does not enter the tool.

Concept generation

The concept generation was done by brainstorming, it resulted in three concepts presented below:
- **Bager**

*Bager* was a concept using a reusable vacuum bag to seal between outer skin and tool. To position the skin an immersion in the tool was done. It also removed the height differences between tool and skin, making it easier to use the vacuum bag. An illustration of this immersion is shown in Figure 30.

![Figure 30, Illustration of immersion for outer skin in tool.](image)

In Figure 30, no vacuum bag is included but the flat surface between the tool and skin is shown. The play between the skin and tool should be so small that a vacuum bag without extra support resists the autoclave pressure.

- **Boxer and Flater**

*Boxer and Flater* should use the same immersion technique to position the skin, but a different method for sealing the area. Instead of a vacuum bag a softer plastic such as rubber or silicone is mounted on an aluminium profile screwed towards the tool to seal. This means that a number of screws are needed to be tightened during mounting and released when dismounting, which clearly costing time. In Figure 31, is the two solutions illustrated.

![Figure 31, Illustration of the two concepts without vacuum bag.](image)

As shown in Figure 31, both concepts are based on the similar idea and none of them have screws illustrated. The sealing between skin and tool are then needed around the whole door and to ensure a complete sealing, therefore are screws needed periodically throughout the skin contour. The advantage of these concepts is the reducing of
disposable products used per door, saving money and environment. On the other hand, is the time demanding handling of each screw during mounting and demounting costing time.

**Concept selection**

After all three concepts were documented and understood a scoring was proceeded to find the concept with the highest potential. The scoring was once again done according to the PPD and with the same selection criteria used during Section 7.1. The result from this scoring is shown in Figure 32.

<table>
<thead>
<tr>
<th>M.nr</th>
<th>Weights</th>
<th>Selection criteria</th>
<th>Concept Flater</th>
<th>Concept Boxer</th>
<th>Concept Bager</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0,077</td>
<td>Critical and exposed components</td>
<td>3 0,232143</td>
<td>3 0,232143</td>
<td>2 0,154762</td>
</tr>
<tr>
<td>21</td>
<td>0,137</td>
<td>Disposable products per door</td>
<td>3 0,410714</td>
<td>3 0,410714</td>
<td>2 0,27381</td>
</tr>
<tr>
<td>22</td>
<td>0,185</td>
<td>Time needed by operator(s)</td>
<td>2 0,369048</td>
<td>2 0,369048</td>
<td>3 0,553571</td>
</tr>
<tr>
<td>23</td>
<td>0,089</td>
<td>Maintenance</td>
<td>3 0,267857</td>
<td>3 0,267857</td>
<td>2 0,178571</td>
</tr>
<tr>
<td>24</td>
<td>0,101</td>
<td>Investment for automation needed</td>
<td>3 0,303571</td>
<td>3 0,303571</td>
<td>1 0,10119</td>
</tr>
<tr>
<td>25</td>
<td>0,054</td>
<td>Manufacturing cost (tool)</td>
<td>3 0,160714</td>
<td>2 0,107143</td>
<td>5 0,267857</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>Possible number of doors per day</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>0,196</td>
<td>Total Time at packing-unpacking station</td>
<td>3 0,589286</td>
<td>3 0,589286</td>
<td>4 0,785714</td>
</tr>
<tr>
<td>27</td>
<td>0,161</td>
<td>Heating and cooling time to 120 C</td>
<td>3 0,482143</td>
<td>2 0,321429</td>
<td>4 0,642857</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Net score</th>
<th>Rank</th>
<th>Continue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flater</td>
<td>2,81547619</td>
<td>2</td>
<td>No</td>
</tr>
<tr>
<td>Boxer</td>
<td>2,601190476</td>
<td>3</td>
<td>No</td>
</tr>
<tr>
<td>Bager</td>
<td>2,958333333</td>
<td>1</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Figure 32, Scoring of sub-system skin placements.

As shown in Figure 32 **Flater** and **Bager** are close in score. The biggest score differences are found at M.nr 22 and 26 both regarding time efficiency during production. These two alone give a point overweight to **Bager** of 0,38, it will say more than the score difference between the two concepts. The time demanded to screw and unscrew **Flater** appears to be vital for the scoring outcome and is therefore important to reflect on. **Bager** is harder to automate due to the challenge to control a thinner vacuum film with a robot. On the other hand, when the automation level increases it should be possible to go from **Bager** to **Flater** without major reconstructions of the tool. It should also be taken into account that vacuum bags are an existing technology on the market, well known and functional. Therefore, it was decided move forward with **Bager** and if later required, an upgrade to **Flater** is possible.
Design

To accomplish bag support all around the skin, a frame structure was designed. Thereafter the immersion was trimmed, and the concept designed emerged. The tool frame was then set on a thick sheet, joined together they were named Main tool structure. The structure needs to be air tight to separate the autoclave pressure from the vacuum inside the tool. Between the sheet and frame structure an O-ring cord was chosen. Because of their good performance assurance and ease to mount on a contact surface of this size. A sealing solution between the difference frame parts was also needed and provided a more challenging problem. It was chosen to seal these sections with silicone Result from the design phase for the tool skin solution is shown in Figure 33.

![Image of Main tool structure midway project]

Figure 33, Main tool structure midway project.

![Image of Illustration of concept Guider]

Figure 34, Illustration of concept Guider.
7.3 Door frame placement of the tool

Frame placement refers to how it can be ensured that the components of the door are guaranteed a position within the tolerances. To place a beam or line in space two points needs to be fixated (not considering rotation). The placement of the frames in relation with upper beam was solved in Section 7.1, when the frames are pressed against upper beam positioning the door frames in one point. Leaving one point left to fixate the frames in space. It was easiest to do this positioning where the lower beam later should be mounted. The reason for that is the available space and the flanges from the profiles simplify the geometric problem.

Concept generation

The generation of ideas of lower beam positioner started by a discussion with the Thesis mentor. Thereafter, ideas were organised and worked into concepts that are presented below:

- **Lower supporter**

  This concept was an idea of pairing each door together with a specific lower beam during the bonding process. This by placing a lower beam inside the tool and use an applied force to position the frames alongside each flange on the lower beam similar to how the upper beam *Spring* solution. How this force should be applied was not certain but it did not seem impossible due to the space available in the lower beam. The largest challenge was if the lower beams structure should manage to support the outer skin from the pressure applied and if not how to increase this support. The main advantage of the concept was the extreme precision between lower beam and frames, also the possibility of bonding the lower beam in the process was a function highly wanted. On the other hand, the high insecurity of structure strength, cost, production time, and complexity to apply the force contributed to a high risk for the concept.

- **Guider**

  *Guider* was a concept using a positioning block with tracks where the door frames could be placed and given the right position. This concept is fast to mount and dismount in cost of precision given to the frames. The precision limit came from concepts need of play, allowing frames with tolerance variation to be mounted in the track without difficulty. Concept *Guider* is shown in Figure 34.

- **Steady sider**

  *Steady sider* used a similar block as *Guider* but instead of giving a passive support on both sides *Steady sider* only provides support on one side. Instead an active support was found on the other side, after the frame is placed some kind of force pressed the frames against the passive support. This concept gave a higher precision on the placement of the frames in cost of manufacturing cost, failure risk and production time.
Concept selection

To find the concept with the best potential a scoring was done. Due to that all concept was assumed to give a rightful precision no extra selection criteria were added. The scoring is shown in Figure 35.

<table>
<thead>
<tr>
<th>M.nr</th>
<th>Weights</th>
<th>Selection criteria</th>
<th>Lower support</th>
<th>Guider</th>
<th>Steady sider</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.077</td>
<td>Critical and exposed components</td>
<td>2</td>
<td>0.154762</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Production cost per door</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>0.137</td>
<td>Disposable products per door</td>
<td>3</td>
<td>0.410714</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time needed by operator(s)</td>
<td>1</td>
<td>0.184524</td>
<td>5</td>
</tr>
<tr>
<td>22</td>
<td>0.089</td>
<td>Maintenance</td>
<td>3</td>
<td>0.267857</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Possible number of doors per day</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>0.196</td>
<td>Total time at packing-unpacking station</td>
<td>2</td>
<td>0.392857</td>
<td>4</td>
</tr>
<tr>
<td>27</td>
<td>0.161</td>
<td>Heating and cooling time to 120°C</td>
<td>3</td>
<td>0.482143</td>
<td>3</td>
</tr>
</tbody>
</table>

| Net score | 2.410714286 | 3.922619048 | 3.160714286 |
| Rank      | 3           | 1           | 2            |
| Continue  | No          | Yes         | No           |

Figure 35, Scoring of solutions for lower placement

The result from the scoring is shown in Figure 35, where it is clear that Guider won without any close competitor. With that result Guider was chosen, hence the score reflected the increased time efficiency gained by Guider comparing to the other two concepts.

Design

The design of Guider shown in Figure 34 was mainly done in the generation phase and no larger changes were done to the final design. Some screw holes and adjustments were however made, to get the concept to connect properly with the Main tool structure.

7.4 Chassis

The chassis are the supporting structures for the tool. During concept generation no wheels or way of moving the tool is installed or investigated.

Concept generation

The concept generation was done on a wide level because the tool design not was completely done, hence not all boundaries was set.

- Short side

A simple sketch was done to illustrate how beams alongside the short side should support the structure. This simplified illustration of the concept is shown in Figure 36.
Figure 36, Beam support along the short side.

Figure 36 shows the down side of the tool with support beams going along the short side of the tool.

- **Long side**

An equal simple sketch was done over the long side. To illustrate the beams in this concept is along the longer side instead. An illustration of the concept is shown in Figure 37.

Figure 37, Beam support along the long side.

Figure 37, shows the illustration of the concept *Long side*.

**Concept selection**

Out from manufacture possibilities the concept *Long side* was chosen. Because, the production method of water cutting was not possible for *Short side*, due to that *Short side* demanded curved cross section to fit directly against the bended tool sheet. Giving a lower manufacturing cost for *Long side* for a similar function.
Design

A foundation was introduced to make it easier to put the tool on tool wagons or autoclave wagons. As the height of the long going beams grow during the design phase, stiffness was needed. Resulting in extra perpendicular support beam, giving a combination of the two original concepts. The perpendicular beam was however not directly mounted in the tool structure but only screwed to the long going beams. This new design is shown in Figure 38.

![Figure 38, Chassis design.](image)

As shown in Figure 38 the chassis is resting on Aluminium profiles, downloaded from Aluflex website, with 8mm profile groove and 120mm x 120mm in dimension. All chassis parts are assembled with L-profiles and screws.

7.5 Material

When most of the design was settled the material was chosen. The materials have been discussed with the thesis mentor and project leader throughout the project, but no final decisions have been made.

All metal components in the tool are the same material as the door frames, due to the large temperature change during the curing process. Because of that reason the same aluminium alloy was chosen. The Mosites #1453 was chosen for the silicone cover because SAAB has used it before and the expensive test process needed new silicon’s is not necessary.
Design for Assembly

DFA was used to increase the possible numbers of doors produced per day. As known the door design was already set, which made the optimisation harder due to that classic DFA often is focusing on the product itself. Traditionally part minimisation, part function, and how to fasten different parts are examined (Boothroyd, 1994), an approach that not was possible with a fixed design.

To be able to estimate the production time of one door and optimise that time, a production layout was needed. A rough layout sketch was made in PowerPoint. Because of the possibilities of easy adjustment and having a correct scale. The production layout was iterated by doing several time studies, giving small adjustments in the layout until no more optimisations were found.

The time studies did not follow any proven concept, but to get understanding of how to think, the Boothroyd method was reviewed (Boothroyd, 1994). It was there learned to look for how challenging different parts were to position, grip, or lift. It was also learned to look for difficulties, as example; number of way to put a part incorrectly, can it be mounted upside down, inside out, or at the wrong place? During the time studies this approach resulted in improvements on the details were found. One example on an improvement found was setting a large chamfer on the tool main body to give an easier insertion and extraction of door frames.

The time analysis was done by listing all necessary production steps to produce one door. Thereafter, a time estimation was done for each production step, the estimated time was created by clocking one person doing the specific motion in that production step. The motion was done without any tool and should not be seen as precision time, instead as an approximated time. This method gives an overview of which assembly activity that consumes the most time and should be examined for optimisation possibilities. A part of this list is shown in Table 7 below.

<table>
<thead>
<tr>
<th>A.No</th>
<th>Time [s]</th>
<th>Number of occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,1</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>1,2</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>2,1</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>2,2</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>2,3</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>2,4</td>
<td>20</td>
<td>7</td>
</tr>
</tbody>
</table>

To gain the total production time from Table 7, each rows time and number of occurrence needs to be multiplied. Thereafter, the result from each row needs to be summed and the total production time is given. A percentage of the total time for each major stage (As A.No 1 and 2) was also settled, to see which production step giving the biggest impact. When using the designed tool, it was clear that the majority (around 80% depending on production configuration) of the production time now was related to the autoclave cycle and not to pre-assembling of the product. Because of this, the most important improvement was to reduce the tool mass, to decrease the extra heating time needed when using the tool. Observe that no heating analyses were
done, but the larger tool mass demands more energy for heating. A lighter tool is hence more environment friendly. The mass optimisation work is summarised in Table 8.

The time analyse did also compare a manual versus an automated assembling line. The result shows that the assemble time was halved but due to the autoclave cycle time, a faster time did not generate any specific advantages. It was also calculated what an automation could cost to breakeven. The Excel sheet used for this can be seen in Appendix A3.

<table>
<thead>
<tr>
<th>Table 8, Mass optimisation result</th>
<th>Before [kg]</th>
<th>After [kg]</th>
<th>Difference [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main tool structure</td>
<td>236</td>
<td>178</td>
<td>75,4</td>
</tr>
<tr>
<td>The main tool bodies</td>
<td>480</td>
<td>235</td>
<td>49,0</td>
</tr>
<tr>
<td>Chassis</td>
<td>254</td>
<td>254</td>
<td>0,0</td>
</tr>
<tr>
<td>Spring solution</td>
<td>90</td>
<td>90</td>
<td>0,0</td>
</tr>
<tr>
<td>Total</td>
<td>1060</td>
<td>757</td>
<td>71,4</td>
</tr>
</tbody>
</table>

As shown in Table 8, a considerable amount of mass is remaining. The reducing of material given by the optimisation is going to affect the tool manufacturing cost negative, but as proven in the AHP (Figure 7) is not of the same importance as the production rate and disposable products (which heating energy is equivalent to).

The key contribution of the mass reduce was the hollowing of the main tool bodies, increasing the machining needed for the component. Furthermore, it creates numbers of joints, increasing the risk of pressurised air leaking in to the tool, a critical error. These joints were sealed with the same O-ring chosen to seal part of the main tool structure, due to that the method is well verified. The result from the optimisation is shown in Figure 39.

One other improvement contracting the mass optimisation considering the heat optimisation was the vacuum created by the frame placement solution Guider. As presented in Figure 34, the Guider solution creates air pockets that are put in vacuum during the bonding process and is therefore isolating the area from heating. Instead of removing material it was needed to increase the material and mass to minimise the amount of vacuum in the tool. Which reduces the heating time. The reason for this is that aluminium have better specific heat conductivity than vacuum. The result of the vacuum minimisation is shown in Figure 40.
Figure 39, Result from mass optimisation.

Figure 40, Lower beam positioner with less vacuum space
7.8 Design for Manufacturing

The DFM was done iterative towards the end of the design phase. A picture of each part and the most important dimension was printed. In the next step, the printings were reviewed of an experience tool engineer. In the review manufacturing approach, functions, and possible improvements was discussed, resulting in several small and large changes of the design.

It was noted, that the beam going along the short side of the chassis, could provide a lot more support if connected smarter with the long going beams. This resulted in a major change during the DFM, due to that the redesign also affected the longer beams connecting points. It was also chosen to split the support from the short going beam to two beams, to increases resistance against twisting motions on the structure.

The other major redesign was done to the spring solution. As the solution was designed after concept selection (shown in Figure 29), the plate delivering pressure to the frame goes outside the remaining tool body. Hence leaving the track in the tool body, risking jamming to the edge of the tool body on the way back. To prevent this jamming a chamfer was added to both the plate and tool body in the first design. Despite this the risk was not eliminated, in a scenario were the screw holding the plate in position start to loosen, a failure is unavoidable if not detected. If it instead is re-designed so that the plate never leaves the tool body the failure risk is removed. Also, giving an opportunity to remove both chamfers added in previous design, allowing a change in production method for the plate to water cutting. Doing it cheaper than the original machining approach despite that a critical risk has been eliminated.

A minor manufacturing improvement was found on the guiding track of Lower beam positioner illustrated in Figure 40, where the guiding track positioning the frames flanges. These guiding tracks were to be machined but with their large deep and small width, it should have been an advance and uncertain operation. During the DFM it was questioned if the track could not be all the way through the part, and with some small design changes it was possible. A track going all the way through do not need to be machined in classic manor and could instead be processed with a disc allowing a much safer manufacturing.

The assembling of the tool was also discussed, and it was agreed that the assembling accuracy gives consequences of the tools function. To increase the accuracy it were decided to add location pins to the design. A retailer named Halder, was found which could provide location pins in the appropriate size with article number 22630.0224 and 22630.0244. With a mounting diameter of 6mm and mounting height of 9mm, and a fitting diameter of 10mm and a fitting height of 10mm (Halder, 2018).

At last, when no more improvements could be found, updated prints were given to the machine workshop at SAAB, to be reviewed for feedback and for a manufacturing cost approximation.

7.9 Concept test

During a meeting midway the development process a risk aspect arose. When producing adhesive bonding with the classic production technique a plastic film is in direct contact against the side of the two components to be bonded. Illustrated earlier in Figure 9a where 14 and 21 are components to be bonded and 16 is the adhesive. The plastic film is then pressed against the components by the autoclave to give a bonding pressure, but it also holds the adhesive in position during the curing. The
pressure given to the adhesive during the curing gives a circular fillet to the adhesive between the two materials.

A concern was raised of how the adhesive should behave when no plastic film was there to hold it back. The behaviour of the adhesive during the curing is depending on a number of unknown variables such as the adhesives local temperature, viscosity, surface tension, and local pressure. Due to the numbers of parameters and desire of a physical guarantee of the concept, it was decided to build a small test rig for the concept.

The aim with the test rig was to verify the principal idea of the concept, having no support for the frame and no direct contact between the plastic and adhesive film. On the same time a low price for the rig was of importance, therefore a cross section of two profiles was chosen as test section. To simplify production and lower the price of the test tool, the section was represented with a straight body.

To lower the price further it was built after a standard profile available at SAAB. The dimensions of the available profile were marginally thicker and had one flange considerably larger. Nonetheless overall the profile was similar to the thought one. Due to that one larger flange it was decided to make an extra test with that side. To lower the price for this extra test, the design of the test tool was made possible to turn around, making it possible to test both flange dimensions with the same tool. The result of this test tool design is shown in Figure 41.

Figure 41, The manufactured test tool.

After the design was fixed, a more thoroughly test plan was set up and is shown in APPENDIX A4. No test was done during the project period due to time limitations.
8 Results

The final result from this master thesis is the conceptual tool approach for solving the challenges to bond larger structures effectively and a CAD drawing of the solution, resulting in a designed tool approach for the new generation of adhesive bonded cargo doors on commercial aircrafts. The CAD drawing is presented in Figure 42.

Below is difference aspect of the result presented. At first the tool process is explained. Afterwards, are the targets set in the specification during the PDD process presented. Thereafter, is the production capacity and related numbers presented. At last, are general results about the concept and tool. The intent and objective are presented in the discussion.

8.1 Tool process

The production process with the tool starts with the upper structure of the door being placed in the tool, followed by the frames. Thereafter the support skin and outer skin is placed on top. Before applying vacuum, the tool needs to be sealed. A reusable vacuum bag accomplishes this by sealing the doors outer skin and tool from the autoclave pressure.

8.2 Result relative target specification

Out of the 17 targets stated in the target specification 10 had been controlled and all of them have achieved their target values. Of the two requirements that were set up with a target value, both had been controlled and one was fulfilled with the current design.

8.3 Production capacity

The most important value for SAAB was the number of doors possible to produce per day. Their target value was surpassed with 26%. Time needed for preparation before the autoclave has been reduced with 76% comparing to not using any tool, at the same time reducing the number of operators from two to one. For the total number of tools needed the manufacturing cost is estimated to 75% of the original budget.

8.4 General results

The concept tool designs is made of 26 unique articles, used repetitively giving a tool with 173 components in total. Effectively giving a total tool weight of 750kg. To breakeven during a 5 years period, the investment for an automation robot cannot cost more than 9 million Skr. In Figure 43 is a chart presented, showing the correlation between investment cost and total cost for the autoclave and number of tools.
Figure 42, Final tool design.

Figure 43, Chart of investment effect on total cost.
9 Discussion

The discussion is divided by process reflections and reflections done on the tool concept.

9.1 Administration and working process

Below the reflection and discussion regarding the PPD process and how well the paper accomplished the intent and objective are presented.

Reflection of intent and objective

The main intent stated in Section 1.4 regarding “develop a manufacturing concept tool...” has been accomplished. A concept has been developed and confirmed manufacturable by the machine workshop at SAAB. Each subject in Section 1.4 are separately answered below:

1. The most important tolerance has not been located but other critical interaction has been identified.
2. The manufacturing cost of the door has been estimated.
3. An estimation of the tool productions capability has been done.
4. Due to the tool design the tool does give position to all door components and is therefore responsible for the position quality of all door components.

So overall the main objectives were completed, with a details giving SAAB valuable information of the tool concept cost and performance. As well which main risks exist and are needed to be settled before a future production.

Reflection on the PDD process

The use of Ulrich and Eppinger’s PPD process has provided the project with structure and a rational way of solving problems. The outcome of the modification, how to give weights to the requirements and requests were found most pleasing. It felt like a clear separation of requirements and request were favourable during the elimination phase. On the other hand, if collected weighted data from the customers, it had been challenging to keep the correlation. If all needs were weighted and converted to metrics it should also have been hard to keep the weight correlation, if not all metrics were weighted.

During the translation from need to target some requirements generated become tough to prove. As example M.nr 13 in the target specification, is referring to the door wave tolerance of a produced door. A property that alone could take the time frame of this project to prove, due to the many variables as: adhesive behaviour, thermal expansion, tolerance of components, and tool. This uncertainty resulting in that the target does not contribute during the concept selection. Worth reflecting carefully on when creating a target specification, so it can embrace as much information as possible.

No risk analyse was done during the planning of the project, something that may has been profitable. Reflecting on how one lost week or design challenge could affect the project can gain a faster reacting time when a problem occurs.
Limitations

During the project work limitations is of grave importance, to focus the time and effort more effective and on the most critical challenges. Regardless this limitation has an impact of the result and afterwards, the limitation to not learn the FEM program /working process at SAAB may have been a mistake. The time learning their working process should probably have been rewarding for the project.

More generally the limitations for the tool space have affected the result of the concept tool. It did also make the concept generation possible during the given timeframe. After doing this work regarding adhesive bonding in the autoclave I personal believe that, remarkable more time and resource effective solutions can be found for bonding outside of the autoclave. It need a great amount if investment costs and probably only profitable for large quantities. In that kind of solution, it is believed that some kind of reinforced airbags will give a good result.

9.2 Tool performance and design

The two most critical risks for the tool concept are the leakage and weakening fillets. The leakage risks have been mentioned in some part of the paper, but it is critical that all joints successfully get sealed.

The most insecure joints are the once connecting the frames mounted on the Main tool structure. The sealing between the sheet and frame is done by an O-ring cord that is trusted by experience. Between the frames silicone is used and it is not as trusted, and a more secure method should be preferred. The challenge is that on top of the frame the vacuum bag is to be connected and below the sheet sealed with the O-ring. Giving few options due to the need to correlate with the other sealing methods.

The O-ring sealing on the input axel to the Spring solution is going to have an increased wear, due to that the axel is rotated regularly. Something that needs to be in mind when doing service scheduled for the tool.

The Testing tool has been manufactured to settle the concerns regarding the fillets. If a negative result should appear, a weaker support film is suggested to help holding the adhesive in position. It may require some minor re-design if not giving a proper fillet, but it should not have any major affect on the concept principle.

Worth reflecting on in the fillet concerns is that if the I-profile is to be change to asymmetrical. It completely changes the possibility for supporting the adhesive, allowing the tool body to support the encirclement of the adhesive.
10 Future Work

Before manufacturing the tool, several things need to be established. At first, the test should be completed and analysed. If not an acceptable result is sustained during testing, the tool needs to be improved to the result is acceptable. Secondly, complete 2D drawings are needed, including setting the tolerances, which should be done carefully to not compromise the function of the tool or the produced door.

Before ordering the tool, tool-wagons should be designed or bought so it can be secure that the two parts fit together. Furthermore, the equipment needed around the tool such as an adhesive cutting machine, lifting tools, tool-wagons, and working tables should be decided and put into the economical calculations over the total cost. With the costs of surrounding equipment, tool-wagon design, and complete drawings of the tool, an order of the equipment should be in mandated.

Thereafter, a service schedule carefully describing how and when different services are needed should be given to the responsible technician.
11 References


Appendix A

A1. Project plan.
A2. Concept presentation.

1. SPRING - UP

- Frame structure where the t-beam slides in
- Pressure applied at outer skin
- Green part removed during on-off loading
- Springs to compensate for beam tolerance
- Autoclav

1. SPRING

- Disk springs
- Pro
  - Can reposition tool body
  - Good probability upper beam
  - Independent upper beam pressure
  - Compensate for beam shape tolerance
- Con
  - Need to slide beam in and out of tool
  - Good low and precision (slide play needed)

2. SPRING DOWN

- Disk springs
- Tools removed through other end (red circle)
- Pro
  - Tool and beam can be assembled from above
- Con
  - Tool needs to be side out
3. DROP

- Similar to SPRING but no direct support for the I profile
- Allows mounting from above
- Pros
  - Can handle shape differences on I profile
  - Fast on/off loading
- Cons
  - Risk for weak bonding on I profile outer slots

4. HYDRAULIC - UP

- Hydraulic control rail to I-beam pressure
- Autoclave
- Pros
  - Beam and door can be mounted dismounted from above
  - Green part can be flat
  - Good probability for upper and lower beam
  - Should give good position quality
  - Adjustable tool position
- Cons
  - Weak pressure section close to I profile
  - Lengthways

5. HYDRA - UP

- Hydraulic system control rail sideways and vertical
- Autoclave
- Pros
  - Beam and door can be mounted dismounted from above
  - Adjustable tool position
  - Green part can be flat
  - Good probability for upper and lower beam
  - Should give good position quality
  - Compensation for beam shape tolerance
- Cons
  - Complex system gives higher failure risk

6. SOLID - UP

- Similar to SPRING
- Pros
  - Low failure risk
  - Adjustable tool position
- Cons
  - To integrate upper beam hydraulic, springs, or other solutions are needed to apply the sideways forces
  - High demands on beam shape tolerance
  - Position quality limited due to play needed to slide in and out beam and door
7. SOLID-DOWN

- Same as 5 but upside-down
- **Pro**
  - Low failure rate
- **Con**
  - Harsher to integrate upper than in 5
due to more isolated bolt inside door
  - High demands on beam shape tolerance
  - Position quality limited due to play
  - High number of steps for rabbot per door

9. AIRBAG – NO AUTOKLAV

- Creating the pressure with an airpad
- Springs to maintain reaction force and applying pre force to I-beam
- Can be possible to have the pad give the position, proven on T profile.
- **Pro**
  - For underwater, possible to more effective heating/cooling, no heating time.
  - Good conditions for upper beam and lower
  - Pressure distribution quality
- **Con**
  - Positioning of I-beam a challenge
  - Expanding and shrink with curved profile

10. AUTOBAG (AUTOKLAV)

- Using the same airbag but pressurised by ventilation to autoclave pressure
- Door structure is supporting in Autoclave
- Two options with profile pad and unshaped pad
- **Pro**
  - Low extra mass to heat
- **Con**
  - Position quality

11. PLASTIC

- Similar to hydraulic but with thermoelastic rails
- Fixed sheets give position to beam
- Mounted and dismounted from above
- Experiment on composite have proven the thermoelastic method as pressure creator.
- **Pro**
  - Composite experiment
- **Con**
  - No pressure area between plastic and solid part of beam
  - Play between profile and plastic was 0.4mm in experiment, but shape tolerance is 0.2mm.
Cost calculation.

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<th>General Variables</th>
<th>Value</th>
<th>Unit</th>
<th>Comment</th>
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<tr>
<td>Autoclave heating rate</td>
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<td>C/min</td>
<td>Given by process Test_6240. (karin)</td>
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<td>Industrial efficacy</td>
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<td></td>
<td>* From Panel to assembly Cost.Excel</td>
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<tr>
<td>Effiacy rate for autoclave</td>
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<td></td>
<td>* Need statement, industrial efficacy used</td>
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<tr>
<td>Cost of one tool</td>
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<td>Kr</td>
<td>Given on Exjobb design 2018-05-30 (FOT440-2-QO-0002)</td>
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<td>Baserad på medeltimkostnad för autoclav 2018</td>
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<tr>
<td>Operator cost for per hour</td>
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<td>Kr/h</td>
<td>Baserad på medeltimkostnad för verkstad 2018</td>
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<td>h/day</td>
<td>2-shifts</td>
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<tr>
<td>Doors per day</td>
<td></td>
<td>st/day</td>
<td>Counted on 20 work day per month (average per year)</td>
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<tr>
<td>Doors per month</td>
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<td>doors/m</td>
<td>CARE: Togheter with doors per day in gives work day per month</td>
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<tr>
<td>Number of resver tools</td>
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<td>St</td>
<td>For maintenance rotation</td>
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<tr>
<td>Number of years calculating</td>
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<tr>
<td>Packing cost over 5 years for manual bagging</td>
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<td></td>
<td></td>
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<tr>
<td>Packing cost over 5 years for automated bagging</td>
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<tr>
<td>Cost per door</td>
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<td>Kr</td>
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Differens in price. positive = cheaper (MKr)

Regular maintenance are not included in any of the cases calculated below.

Automated process

Manual process
A4. Test plan.

Koncept test “Drop” Clean Sky 2 TD-4

Dokument skapat av: Fabian Borgede

Beskrivning av verktyget och de två olika sidorna

Verktyget består av två liknande sidor som båda kan monteras uppfåt. Nedan syns en bild med sida 1 monterad uppfåt.

För att byta sida uppfåt skruvas samtliga 8 skruvar bort infästa på undersidan av den grå plåten. Därefter vänds de tre mittersta kropparna och skruvarna fästs igen.

Efter att verktyget har monterats med skruvarna ska 3,18mm tjock gummi läggas på de över ytorna. Över skarpa kanter skarvas gummit men över mjuka kanter kläs gummit över kanten.

Under testet ska följande lim och ytbehandling gälla.

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<th>Behandlingsbeteckning:</th>
<th>Komponenter:</th>
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<td>-</td>
<td>Skin, dubbler 1 &amp; 2, profil</td>
</tr>
<tr>
<td>Primer</td>
<td>-</td>
<td>Skin, dubbler 1 &amp; 2, profil</td>
</tr>
<tr>
<td>Lim</td>
<td>-</td>
<td>Skin, dubbler 1 &amp; 2, profil</td>
</tr>
</tbody>
</table>
Komponenterna placeras som illustreras nedan med lim emellan Skin och dubbler samt dubbler och profil. OBS att bubblaren har två olika storlekar beroende på om sida 1 eller 2 är uppåt, den större bubblern ska användas när sida 2 är uppåt.

Information om defekter
Defekter är tänkta att läggas in under testerna för att testa kontrollutrustning (OFP). För mer information kontakta xxx.

Testordning


   Lägg släpfilm över alla gummi ytor. Anteckna hur och var defekterna är placerade.
   Anteckningar:

   __________________________________________________________________________________

   __________________________________________________________________________________

   __________________________________________________________________________________


   Lägg släpfilm över alla gummi ytor. Anteckna hur och var defekterna är placerade.
   Anteckningar:

Lägg släpfilm över alla gummi ytor. Anteckna hur och var defekterna är placerade.
Anteckningar:


Lägg släpfilm över alla gummi ytor. Anteckna hur och var defekterna är placerade.
Anteckningar:


Släp filmen ska i det här testet ha 1-2cm överhäng över gummit längsgående profilen. Det här för att se om släpfilmen kan ge städ Lägg släp film över alla gummi ytor. Anteckna hur och var defekterna är placerade.
Anteckningar: