

New Flexible Tooling For Carbon Fiber Components In Aircraft Assembly

Master's Thesis in the Master Degree Program, Production Engineering

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Department of Product and Production Development

Division of Production System

CHALMERS UNIVERSITY OF
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Cover:

The picture on the cover is the tooling design with Boxjoint
and new Dflex 201.

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ABSTRACT

Assembly tooling design is a significant process in aircraft assembly production, meanwhile it is a bottleneck strongly affects production set-up time and capacity increasing. In some degree, problems existing in assembly tooling constrains the performance of aircraft manufacturing industry. Along with the trend of applying composite and hybrid material in aircraft manufacturing, new requirements are challenging the conventional of designing assembly tooling.

To meet today's challenges in aerospace industry, an EU project called LOCOMACHS (LOW COst Manufacturing and Assembly of Composite and Hybrid) is ongoing. One of the work packages for the project is focusing on new tooling solutions. Delfoi, as one of the participants in LOCOMACHS, takes responsibility of tooling hardware design.

This thesis, as a sub-project of LOCOMACHS, starts with testing existing solutions in Delfoi by creating 3D models. Results are compared with the requirements in LOCOMACHS to see how well Delfoi tooling kit can fulfill the requirements. Improvements to the Delfoi tooling kit are given in this thesis by improving the design of products and searching potential standard components. With several tooling concepts, a concept selection matrix is provided in order to evaluate each concept from various aspects. At last, the application of tooling design principles in aircraft assembly is discussed.

Key words:

Tooling design, Aerospace, Standard components, Concept selection

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Gothenburg March 2013

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1. Introduction

This thesis, completed at Delfoi, Gothenburg, focuses on assembly tooling development in Aerospace Industry. As a participant of the project Low Cost Manufacturing and Assembly of Composite and Hybrid (LOCOMACHS), Delfoi designs new tooling hardware and engineering tools, test and evaluate assembly tool prototypes, among other work packages. Delfoi has many years of experience in aircraft wing assembly tooling design, both on hardware and engineering tools in CATIA V5. This thesis is a sub-project on one of the LOCOMACHS work packages, using the Delfoi tooling kit.

The author first introduces the general context. In the Introduction chapter, the industry, project background, Delfoi tooling kit, objectives and delimitation are described in detail. The structure and method of the project are described in the following Methodology chapter. The Theoretical Framework chapter reviews the theory that the results of this thesis is based on. The results, discussions and conclusion are given in the end.

1.1 Background

The necessity of assembly tooling development is becoming more apparent as the Aerospace Industry is growing up. Innovative improvement in assembly tooling plays significant role in increasing quality and capacity of aircraft production. Assembly tooling is widely used in aircraft assembly process. The main function of assembly tooling is to hold and fasten aircraft part at certain point, to ensure the parts in the right position of each other. Assembly tooling is one of the key factors for fulfilling the extremely small tolerance.

Since the thesis have a heavy aerospace influence, the way of working in aircraft production is introduced to make the thesis more readable to the unfamiliar reader. The necessity of the thesis can also be approved by the current situation of assembly tooling. Readers will get a general picture on aircraft structure, the utilization of assembly tooling in aircraft production. Then current limitations of conventional assembly tooling are introduced, and the gap between conventional tooling and utilization of composite or hybrid material is revealed.

1.1.1 Aircraft Structure

In general, aircraft structure can be divided into several subsections, called product families (Kihlman 2005). One product family contains different subparts. From different rules, one product family, as the figure 1-1 presents, can be divided into smaller product family. The definition of each product family can be based on an

assembly tooling point of view or a machine point of view (Kihlman 2005).

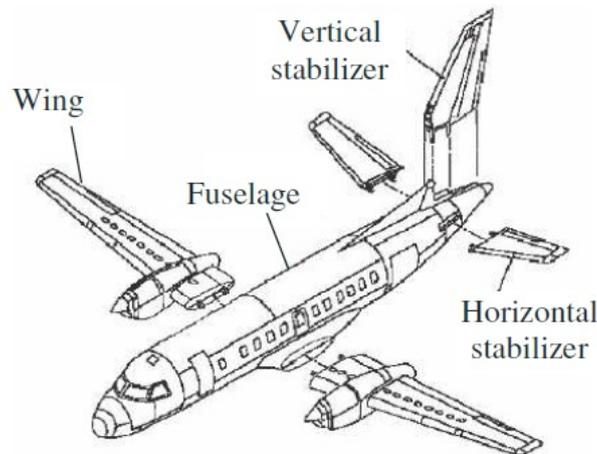


Figure 1-1. Theoretical fuselage layout and sections

In this thesis, assembly tooling design is mainly carried out in the model of Delmia Wing and wing box structure from Bombardier. Because the wing and box structure assembly process is mainly considerate when building 3D model of assembly tooling. Figure 1-2 shows the cutaway drawing of the wing box structure product family and its position in the general airframe.

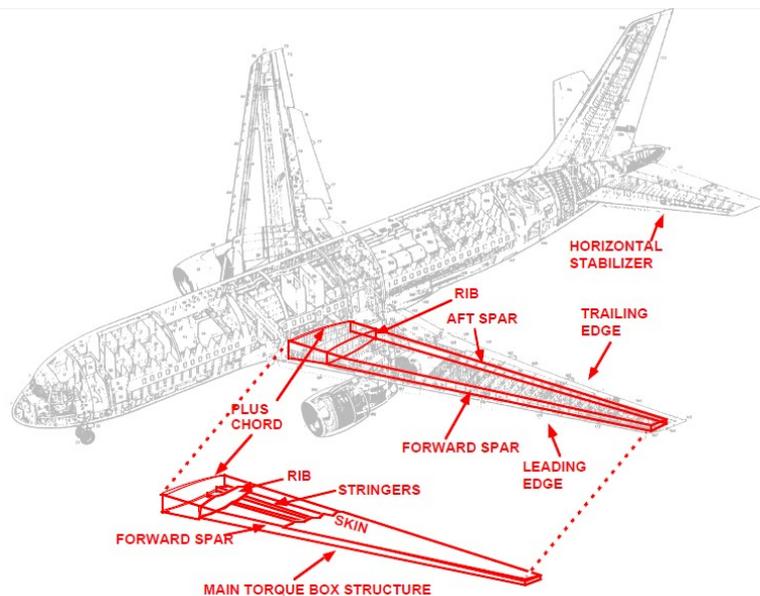


Figure 1-2. Cutaway drawing of the Boeing 767 aircraft

The wing of aircraft can be 20 to 30 meters long, contains forward spar, after spar, rib and stringers. Ribs are located along the length direction of the wing, which naturally separate wing into small sections. For assembly convenience, the wing is often divided into two to four wing boxes (the number of wing boxes depends on the length and engineering requirement.). Each box contains several sections. The typical structure of a wing box is presented in figure 1-3.

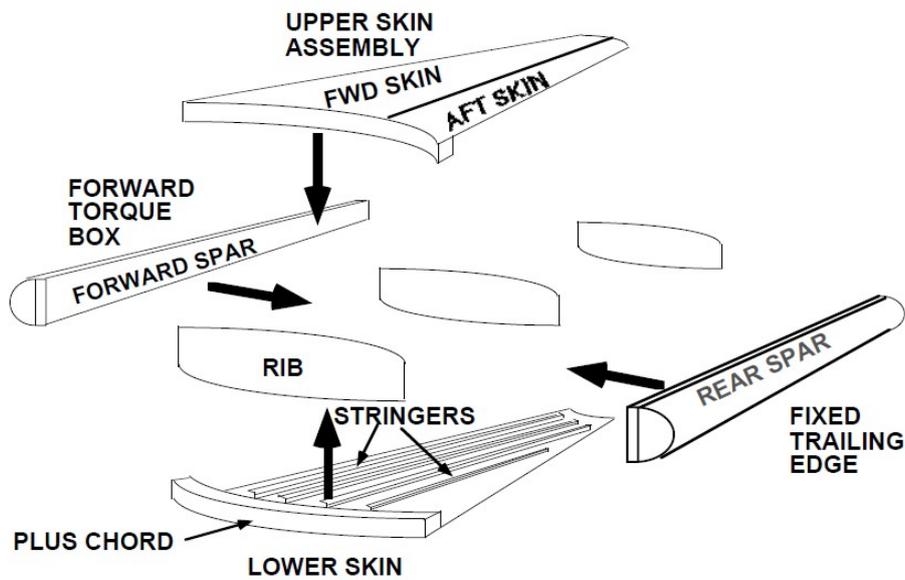


Figure 1-3. Wing box structure

1.1.2 Aircraft Assembly

The Assembly sequence is decided based on parts designs and engineering requirements. Aircraft parts require extremely high quality in dimension and surface, which leads to high demands in the assembly process (Kihlman 2005). The assembly process is complicated due to large numbers of parts and tolerance. In order to give a simplified picture, Dr. Kihlman has divided the aircraft assembly stages into four different levels:

1. First level: Stringers and stiffeners are assembled to panels
2. Second level: Inner structures are assembled and combined with the first panel
3. Third level: Inner structures and the first panel are further combined with the second panel that closes the structure
4. Fourth level: The substructures are combined into the complete fuselage section that finally constitutes the complete fuselage



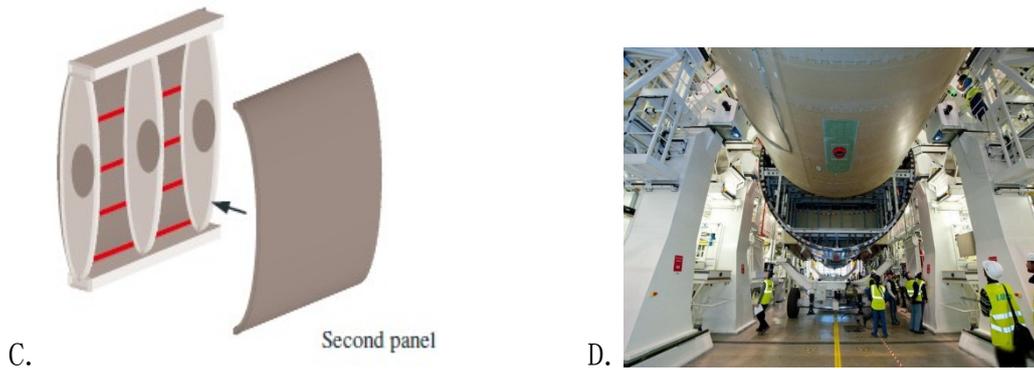


Figure 1-4. Four levels in aircraft assembly. Picture A is the first assembly level. Picture B is the second level. Picture C is the third level. Picture D is the fourth level

In reality, the sequence of skin-stringer assembly and spar-rib assembly is not unchangeable. Top skin first, down skin first, front spar first or back spar first is chosen in assembly engineering phase as a result of balancing process technique, machine and tooling. Sub-process can be taken parallelized as shown in figure 1-5.

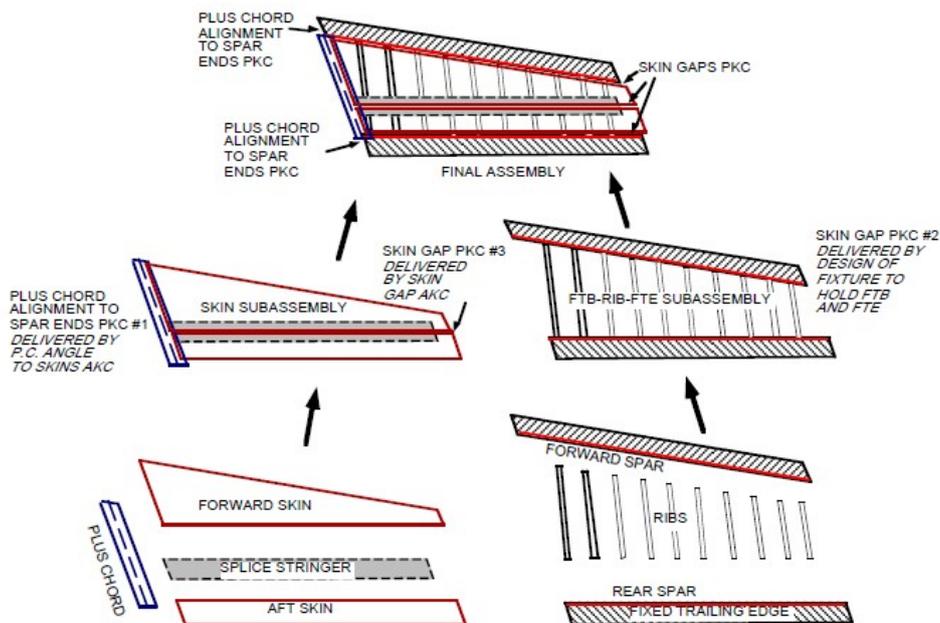


Figure 1-5. Parallelized sub-process method for Boeing 767 horizontal stabilizer

Different assembly strategy may lead to various tooling design, yet the aim remains the same: to hold and fasten aircraft part at certain point, to ensure the parts in the right position relevant to each other.

1.1.3 Conventional Assembly Tooling and Limitations

Tooling is a wide definition of manufacturing aids in industry, such as cutting tools, dies, fixture and jigs. Within the aerospace industry, assembly tooling mainly takes

the responsibility of fixture, thus in production assembly tooling is also called assembly fixture. Fixture means a ‘work holding’ device used for positioning and holding parts during assembly (Airbus 2010). Other tooling such as jigs is sometimes used to guide tools in drilling operations, yet fixtures are more commonly being used than jigs. In this thesis, fixture design is the objective. Jigs, dies and cutting tools are not taken into consideration.

Conventional tooling or dedicated fixtures is commonly used in aircraft assembly process. Known from its name, conventional tooling is designed for a specific product or product family. This kind of tailor-made concept makes the fixture very expensive because of the different components that have to be individually designed and manufactured. This leads to long lead time, up to 24 months, account for around 10~24% of the total manufacturing cost (Airbus 2010). When aircraft design changes happen, tooling design has to be changed as well, which may double the lead time. Conventional tooling is not set-for-permanent, when the production plan changes to another airplane, parts of tooling have to be re-bolted into new positions to fulfill the change or the whole tooling have to be redesigned. Thus there is huge waste in using conventional tooling; there is huge potential of improvement as well.



Figure 1-6. Conventional tooling used at SAAB

Conventional tooling consists of three sub function units.

- Structure or surrounding system: The main framework of tooling, constructed to connect the fixture as one stiff part. Structure holds flags and pick-ups in the same frame and keeps their position. For assembly of big parts the structure serves a second purpose, it support the tooling on the shop floor as well.

- Flag or distance support: In order to support pick-up in different geometrical positions, flag is in between of pick-up and structure. Flags are always custom made and made out of steel, then bolted or welded together with the structure. It takes up large geometrical tolerances after the tooling set up.
- Pick-up: The part that holds the component to its datum points and surfaces tolerances. To be able to hold the component in a stiff and accurate position, the pick-up needs to be spread all over the component, often locating the component in six degree of freedom.

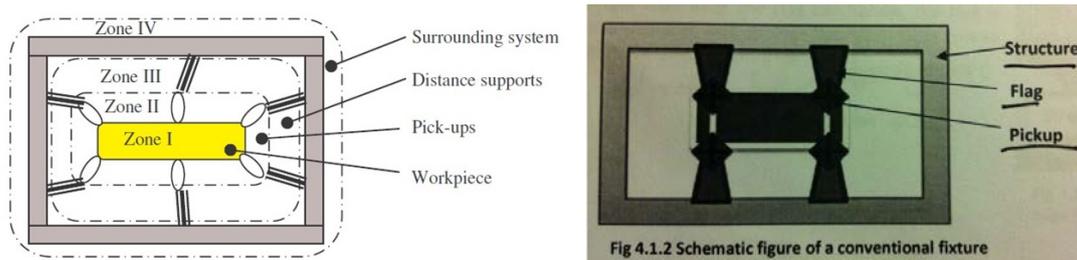


Figure 1-7. Conventional tooling structure

There are five main limitation of today's fixture as Airbus reported:

- Concurrent Engineering: Aircraft designers may change the design of the components, which will require the tooling designers change the fixture as well.
- Ramp up: When there is a demand on increasing aircraft capacity, new conventional tooling needs to be built from the start, which leads to long set-up time. Any problem with the fixture requires down time of manufacture and expensive fixture modification.
- Expensive to Manufacture a Fixture: Due to assembly tooling is custom made and manufactured, it is extremely costly and time consuming to produce new fixtures. If wing design changes or the production of a certain aircraft stops, then tooling parts becomes useless and will be thrown away.
- Product Changes: A change made late in a design process has a great cost and time impact rather than a change made early in the design phase. After the final fixture is manufactured and the aircraft goes into production, the design of the aircraft will likely be changed, causing delays in production because of the lead-time to configure the fixtures.
- Fixture Movement during product lifecycle: After the fixture finally is being used in production and set to reach the high accuracy target for the product, the fixtures may tend to deform or move slightly during its life time due to thermal

expansion, creep deformation, wear of the tooling and also the fact that the fixture foundation movements.

Above, five limitations are provided by Airbus, which shows the track of main aspects to improve assembly tooling. Limitations of conventional tools guide a way to figure out requirements for new tooling design. They are represented in the design process, and strongly influence criteria decision in the concept selection phase (see chapter 4). There is another aspect of demand that considerate in this thesis, the utilization of new material in aircraft manufacturing.

1.1.4 Composite and hybrid material in wing manufacturing

Composite structures typically consist of laminates stacked from layers with different fiber orientation angles. The layer thickness is most often fixed, and fiber orientation angles are often limited to a discrete set such as 0° , $\pm 45^\circ$, and 90° (Liu 2001). Fiber in the same layer is aligned according to one certain direction, which provides high strength and stiffness in that direction, yet low strength in the vertical across direction (Campbell 2010). To meet the strength performance requirement in aircraft manufacturing, layers in different directions are glued together in order to achieve isotropic structure as figure 1-8 presents.

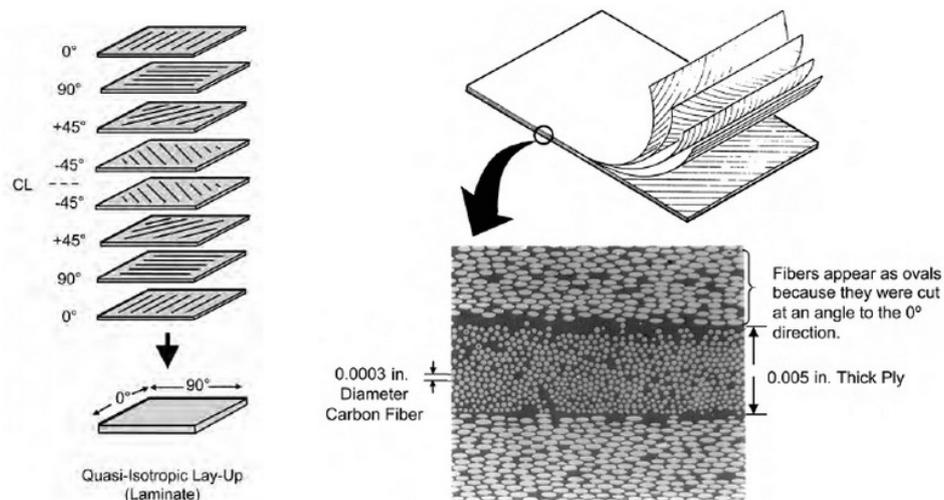


Figure 1-8. Composite layer are consequently glued together

Today's aerospace industry has a requirement that demands higher performance in light-weight designs, high reliability and passenger safety than before. In military aircraft, there are more demands in aerodynamic performance and invisible technology. The following characteristics can composite and hybrid materials bring to the aerospace industry (Mangalgiri, 1999):

- Light-weight due to high specific strength and stiffness;
- Fatigue-resistance and corrosion resistance;
- Capability for high-degree of optimization: Tailoring the directional strength and

stiffness;

- Capability to mould large complex shapes in small cycle time reducing part count and assembly times. Good for thin-walled or generously curved construction;
- Capability to maintain dimensional and alignment stability in space environment;
- Possibility of low dielectric loss in radar transparency;
- Possibility of achieving low radar cross section.

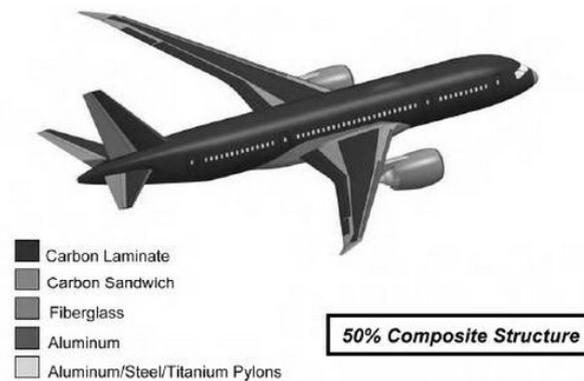


Figure 1-9. Composite material used in Boeing 787 Dream liner

Meanwhile the utilization of composite and hybrid material leads technical problems in manufacturing and production. Geometrical variation and surface quality are two difficulties that are reinforced by composite material. The geometrical variation is adding throughout the assembly production, which means the variation keeps increasing during the process. Therefore every sub assembly process is one section in a chain, and the chain would be easy to break by a weakness in any section. The geometrical variation in wing assembly is up to 7mm (Saadat & Cretin 2002). The surface tolerance is another shortage of composite material structure. The up surface or outside surface is always accuracy however the inner surface is 'rough' around 1cm tolerance compared with aerospace industry requirement. The rough surface will not influence aerodynamic performance but leads that the flag and pick-up has to adapt to large variation. Since the dimension is unique from product to product, the tooling must be adjusted to reach datum point within 1cm level variation. Shimming method is commonly used in conventional tooling, which needs a lot of time and well trained operators. In conclusion, as composite material becomes more popular used in aircraft frame, requirement of handling large variation is important for assembly tooling design (Liu 2001).

1.2 LOWCOMACHS

1.2.1 Introduction of LOWCOMACHS

The purpose of the thesis is to test and demonstrate tooling solutions under the frame of BoxJoint technology and to contribute to the EU project LOCOMACHS. This

project involves SAAB Sweden, AI-UK and other companies from aerospace background, such as Chalmers Tekniska Hoegskola AB and Delfoi. LOCOMACHS focuses on significantly reducing or totally eliminating the most time-consuming and expensive non-added value operations. The aim of LOCOMACHS is to improve the design conditions which today strongly dictate the way part manufacture and assembly is performed. Important changes will be made by dramatically improving the use of tolerance and geometrical variation management. LOCOMACHS will integrate existing technologies with missing breakthrough technologies developed and matured within LOCOMACHS.

Since the thesis is carried out as a sub-project of LOCOMACHS. The new tooling design must put an effort to meet the requirements of LOCOMACHS, both general and specific work package requirements. The following section will introduce what LOCOMACHS demands, which also reflect the voice from market.

1.2.2 Requirement of LOWCOMACHS

This thesis work will mainly contribute to the work package (WP) 34.2---New Solutions for assembly tooling, as a sub-work package of LOWCOMACHS's WP 34--- Assembly tooling solutions. The thesis is using the LOWCOMACHS frame and strive to meet both higher level requirements of WP 34 and specific requirements of WP 34.2. See below:

Requirements of WP 34:

- The tooling shall be able to adapt for geometrical variations in airframe parts in up to six degrees of freedom in less than 3 minutes per tooling locating point.
- The tooling shall require 30% less engineering work and 30% less lead time for manufacturing of the tooling compared to conventional tooling.

Requirements of WP 34.2:

- Survey of potential standard components and support for tooling engineering in other industries relevant for use in aerospace industry.
- With reference to defined requirements for new assembly tooling generate concepts for new tooling solutions (tooling hardware, set-up equipment, engineering tools and tooling design methodology) using obtained knowledge from other industries and projects. These concept will be developed further and for example include the following detailed solutions.
- Design, test and evaluation of the use of robot solutions for positioning parts while assembly operations takes place manually or automatically.

- Design, test and evaluation of reconfigurable tooling with different level of automation in setting equipment depending on production rate using standard components.
- Design, test and evaluation of thermally stable fixtures (through mechanical compensation, etc.), self-locating fixturing and tooling for rapid location, clamping and removal of components.

1.3 Purpose and aim

This thesis starts up with searching for new potential standard components. By applying BoxJoint tooling kit with modular tooling system, Dflex and Flexapods, the purpose of the thesis project is to test BoxJoint tool kit's performance under LOCOMACHS frame work and the future market demands, to improve the existing technique instead of invent new modularized assembly tolling. A systematic frame is given to assist selecting best tooling design concept based on customer need.

1.4 Delimitation

The thesis is done by one student, collaborated with Delfoi LOCOMACHS team. The author contributed to the scaled D-flex 201, standard components searching and tooling design with scaled D-flex 201, composed the thesis alone. Ideas and concepts were inspired and supported by team members (Henrik Kihlman and Torbjörn Jakobsson). Other tooling designs used in concept selections is done by Henrik and Torbjörn. Conclusions of new D-flex 201 and electronic linear actuator are in the concept design phase. The thesis in based on BoxJoint Tool Kit, other flexible tooling test is not included. Some of the results in student project work are not presented in thesis due to intellectual property issue.

2. Methodology and tools

In this chapter, the structure of the thesis project is provided. Readers will get the information on general research methodology and tools used in this thesis. The framework of how the author gets the conclusion is also introduced.

2.1 Thesis research methods

2.1.1 General methodology

The student put efforts in tooling design engineering work from begin till middle and later periods in the thesis project. From the improvement engineering point of view, PDCA work cycle (Liker & Meier 2006) is used to guide the general methodology:

- **Plan: Develop an Action Plan**
The development of an action plan follows the rules that method or tool is not as important as the thought process and the skill of the user. Planning is the first assurance of project success. Resources will surely be wasted and results minimized if the plan is unclear or if everyone is not aligned to the task.
- **Do: Implement Solutions**
Plan is implemented in this phase. Performance and data are also collected for charting and analysis in the following "CHECK" and "ACT" steps.
- **Check: Verify Results**
Analyze the results and compare against the expected targets set in plan phase. Look for deviation in implementation from the plan and also look for the appropriateness and completeness of the plan to enable the execution. Gathering information on what you need for the next step.
- **Act: Make Necessary Adjustments to Solutions and to the Action Plan.**
Since the problem-solving process is a continuous progression, improvement work should be back to the start point of the cycle and carry out again. Only with continued practice, skills are improved and the first-time success rate will be increased.

This thesis follows the direction of PDCA cycle and adapts it into engineering work. Implement of PDCA cycle is presented in figure 2-1.

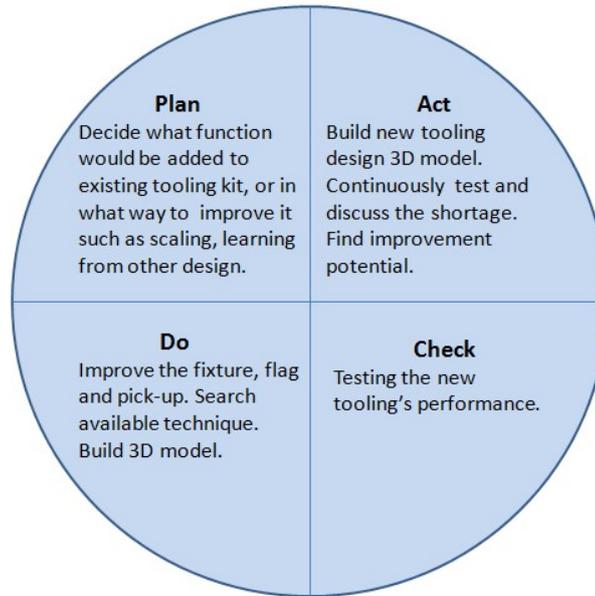


Figure 2-1. PDCA cycle in this thesis

2.1.2 Literature Study

The purpose of literature study in this thesis is revealing current situation of aircraft production, learn existing solutions and to search for potential techniques which can improve existing solutions. Literature study is along with every tasks and phases of this thesis. In each phase of this project, literature is the first step to start with.

2.1.3 Data gathering

The choice and collection of data requires an overall consideration about the type of data, in order to serve specific problem solving process (Ghuri & Gronhaug, 2005). If incorrect or misleading data are collected, not even the most sophisticated approaches will be of help in the analysis (Bergman & Klefj , 2010). Having a substantial basis for decision-making is vital.

In this project, definition of requirements from market and searching for potential standard component are the two information gathering activities. For requirements definition, the author applies LOCOMACHS team seminars and internal document study as data collection methods. Seminars are held in the beginning of the project, assuring team member get common understanding on the LOCOMACHS requirements and setting same goals. Quantitative and qualitative data searching are used in standard component searching. Company website searching, product searching engine, quote asking and product catalog searching are approaches in order to get information about the overall engineering requirement.

2.1.4 Project structure

This project starts with learning about aircraft production and assembly tooling and software training on CATIA V5, meanwhile practicing BoxJoint engineering tools. Each time project moves to next stage, literatures study and company document reading is along with, see figure 2-2.

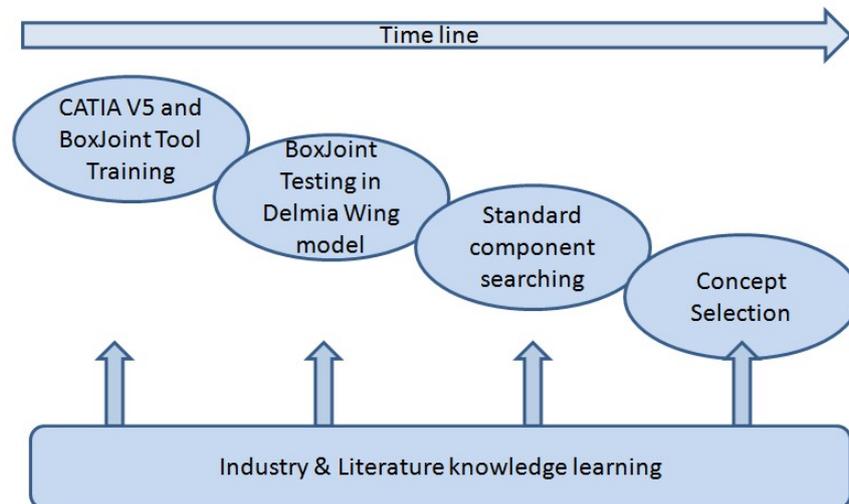


Figure 2-2. Project Structure

2.2 Tools

2.2.1 CATIA V5

CATIA (Computer Aided Three-dimensional Interactive Application) is a multi-platform CAD/CAM/CAE commercial software suite developed by the French company Dassault Systemes. CATIA is widely used in car and aircraft industry. CATIA offers a product life cycle management solution with various workbench and function unit. Functions used in this thesis are part design, product assembly and kinematics. BoxJoint engineering tool is also designed in CATIA environment. Tooling design is saved together with wing 3D model as CATIA product file.

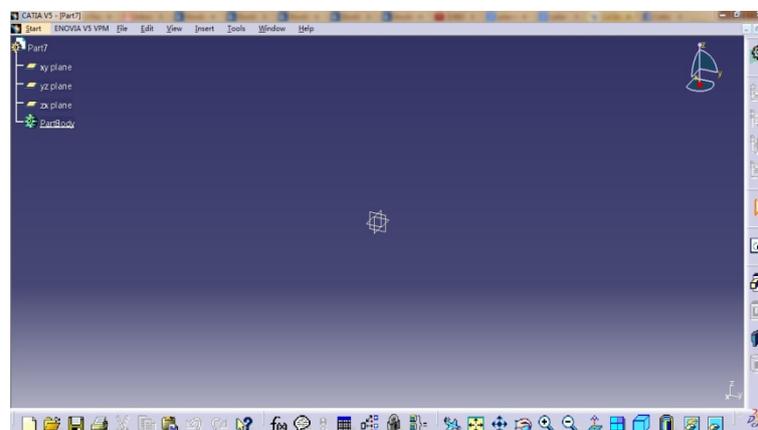


Figure 2-3. Part design workbench in CATIA V5

2.2.2 Delfoi Tooling Kit

Delfoi has plenty of experience in aircraft tooling design both in hardware and software. Its tooling kit consists of BoxJoint, BoxJoint software and flexible pick-ups. Design work in this thesis is mainly supported by Delfoi Tooling Kit. Testing how well Delfoi Tooling Kit can fulfill LOCOMACHS's requirements is the purpose of the project. In this section, reader is provided with detail information on Delfoi Tooling Kit.

BoxJoint

Flexible tooling is the trend today for new assembly tooling design, however there is no accurate definition of flexible tooling. Flexible tooling is more like a general idea reflecting aerospace industrial demands. Assembly tooling design companies have their own understanding of it and use it as guide to design in their products. From an industrial requirements point of view, flexibility refers to configurability, re-configurability, changeability and modularization. Possible flexible structure solutions using in industry are:

- Aluminum Profile Framework
- Building Block Framework
- Pipe Framework
- BoxJoint Framework
- Tetra Fix Framework
- Phase-Change Assembly

(Airbus 2010)

Among those tooling system, BoxJoint is leading in simple mounting, cheaper parts, short parts lead time and quick design software. BoxJoint is modularized tooling fixture technology. The solution is to join steel beams in a construction with standard plates, bolts and nuts instead of welding process. The bolts are pulled with high torque to give a rigid friction joint, which is equal in stiffness to a welded joint (see figure 2-4).

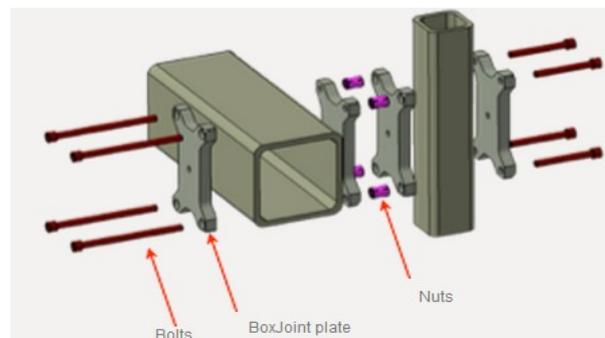


Figure 2-4. BoxJoint beam constructed method.

Beams and plates in various sizes are constructed in different way. BoxJoint catalog provides commonly used sub-structure. Beams and boxes can be mounted in single box structure, double box structure, squeeze box structure, truss box structure, triple joint structure and turn-joint structure. See in figure 2-5.

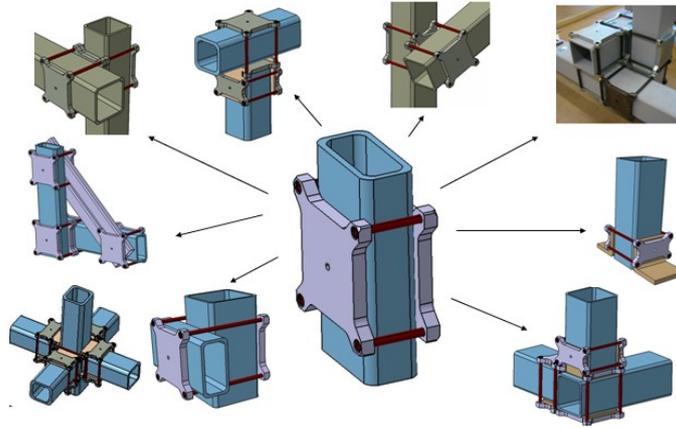


Figure 2-5. Basic sub-structures of BoxJoint



Figure 2-6. BoxJoint Fixture used in aircraft assembly (BoxJoint application by Dr Henrik Kihlman, 2010)

BoxJoint flexible flag

Delfoi offers various flexible flag solutions integrated in BoxJoint fixture with different size, movement range and limited load:

- D-flex 601: D-flex 601 is one of the flexapods series products, used for holding parts during assembly. D-Flex 601 is designed in parallel-mecanical structure which consists of one base plate, six legs and a top plate. 6 Degree of Freedom (DOF) is achieved by adjusting the length of each leg. On the top plate is mounted a tool changing unit to attach pick-ups. The D-Flex 601 units are manually configured with the D-Flex 601 manipulators.

- D-flex 201: D-Flex 201 Clamp is a manual 6DOF modular unit that can serve a multiple range of pickup needs either for measuring or assembly fixtures. Bolt-joint head makes D-flex 201 easily mounted with various pick-ups. 6 DOF movements and the long arm give D-flex 201 large range that can reach datum point in large variation.
- Mini-flex: Mini-flex is a new innovation, bolted on BoxJoint plates. Four springs are used to connect mini-flex and plates with available angle movement range. The angle of mini-flex can be changed by lose or tighten screws around it. The advantage of mini-flex is small size, easy attachment and small range adjustment.

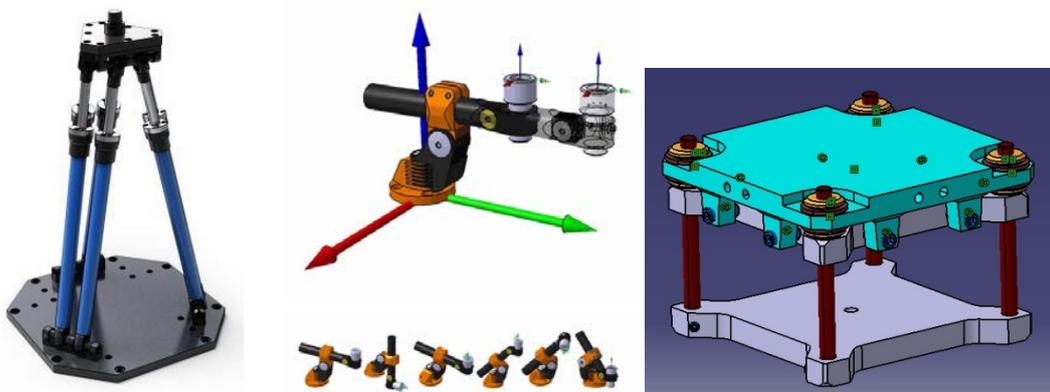


Figure 2-7. Dflex 601, Dflex 201 and Mini-flex

BoxJoint Engineering Tool

The greatest advantage of BoxJoint is that it offers quick development tool in CATIA environment to simplify the engineering work. Engineers can use BoxJoint tool in the same interface of product 3D model, directly adding beams, boxes and flexible flags. In this tool, beams in different standard size and customized length are easily inserted as standard components in CATIA. Boxes are intellectually added along beams. Basic BoxJoint sub-structures are achieved by adjusting relative position of beams and boxes. Flexible flags are attached on boxes with base-fasten kinematic movement, which make flag reach datum point without disconnected with BoxJoint structure. Once the draft design finished, it is easy to modify when if product design changes. The author can use BoxJoint tool to build simple fixtures after two hours training (figure 2-8).

In aim of testing BoxJoint tooling kit performance, first step is to get a general picture on how BoxJoint works in reality. The author was trained in CATIA V5 and BoxJoint. After training, two wing models are used to test: Delmia Wing and LaWIB. BoxJoint

fixture performs well in quick build and adaptable in various situation, successfully support flags and pick-ups to reach the datum point range. BoxJoint fixture is competent in different product size due to various standardized size.

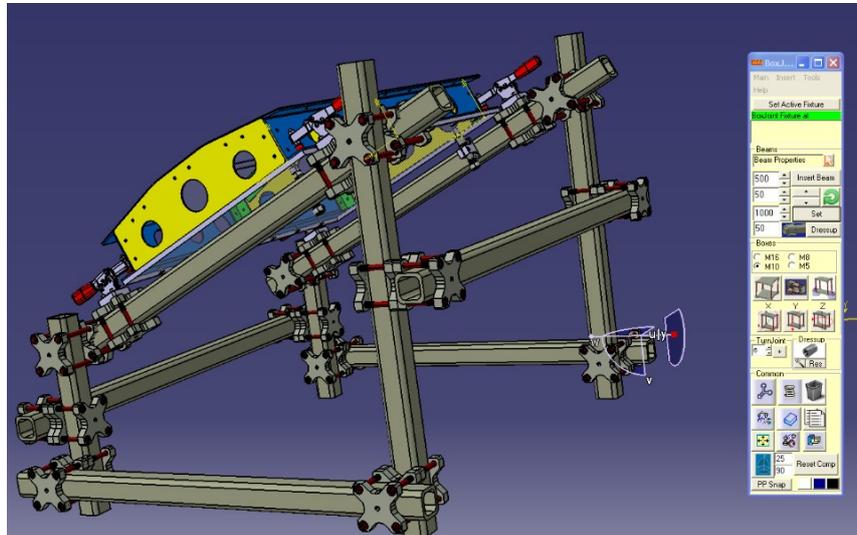


Figure 2-8. BoxJoint engineering tool and exercise

3. Theoretical Framework

3.1 Lean thinking

Lean is not only production management tools started to use in Toyota Production System, but also a philosophy guiding continuous improvement. Beside lean tool box which widely used in manufacturing industry, the way of lean thinking has a great influence on project work also. In the theme of LOCOMACHS, it is concerns 'integrated approach and demonstration to lean manufacturing of metal, composite and hybrid aircraft/engine structures'. Following the director of LOCOMACHS, lean thinking guides this project in a general level from three aspects:

Reducing waste

Eliminating waste is the core activity in lean improvement. Seven-plus-one types of waste (overproduction, waiting, unnecessary transport, over processing, excess inventory, unnecessary movement, defects and unused employee creativity) are introduced by Toyota production system (Liker 2004). Waiting and non-value adding process such as shimming is two main wastes that costs huge time and money. Therefore idea of reducing tooling set-up time, design time, reconfiguration time is reflected through each phase of tooling design.

Focusing on customer needs

Focusing on customers need is one of the corner stone to ensure high quality (Bergman & Klefjö, 2010). Focusing on customer needs implies finding out what they want and need, then to systematically try to fulfill these needs and expectations when developing and manufacturing the product. Processes that don't satisfy customer can be treated as waste. For assembly tooling, the first tier customer is aircraft manufacturing company and LOCOMACHS project team, this means that tooling design should meet industry and LOCOMACHS requirements.

Continuous Improvement

Continuous improvement is core philosophy of Lean improvement. Result of improvement cannot last permanently unless continuous modifying to meet higher target. After an improvement, the team should reflect the result and discover new ideas to make it better. PDCA cycle is carried out in this project as implementation of continuous improvement.

3.2 Tooling design philosophy

Tooling design philosophy guides the design work by introducing basic rules to maintain a workpiece at certain position. A workpiece or product has six degrees of freedom or twelve degrees of freedom by consider the + / - movements in each

category (Nee, Tao and etc., 2004). Point supports is commonly methods in fixture building because surface of parts are not always plates, point supports reduce the geometrical variation for example hemi-spherical surface.

3-2-1 Method

3-2-1 principle represents the minimum requirements for locating elements (Henriksen 1973). Six points is used to fix six degrees of freedom by three fixed the first surface, two fixed the second surface and on for the last surface. The base plate is equivalent to three points or two strips, one strip is equivalent to two points. Thus 3-2-1 principle is also explained as surface-strip-point method.

4-2-1 Method

By the addition fourth locator in the first face, the shape of the supporting area can be changed from triangle to a rectangle, which is named '4-2-1 method' by Erik Henriksen (Henriksen 1973). 4-2-1 locating principle is frequently used for larger cast workpieces (Nee, Tao and etc., 2004). Since 4-2-1 is an over definition design, the fourth point has to be adjustable.

3.3 Multi-criteria decision analysis

Concept selection is an integral part of the product development process, which evaluates concepts with respect to customer needs and other criteria, see figure 3-1 (Ulrich & Eppinger 2012). It is true that there is no 'best' solution but appropriate one. A over qualified design with overall high performance may not an appropriate industry solution. This rule is applied in assembly tooling design as well. Therefore final decision has to be selected from concept designs with the best performance balance. Choosing appropriate design should take many aspects in consideration, which is a typical multiple-criteria decision analysis (MCDA) problem.

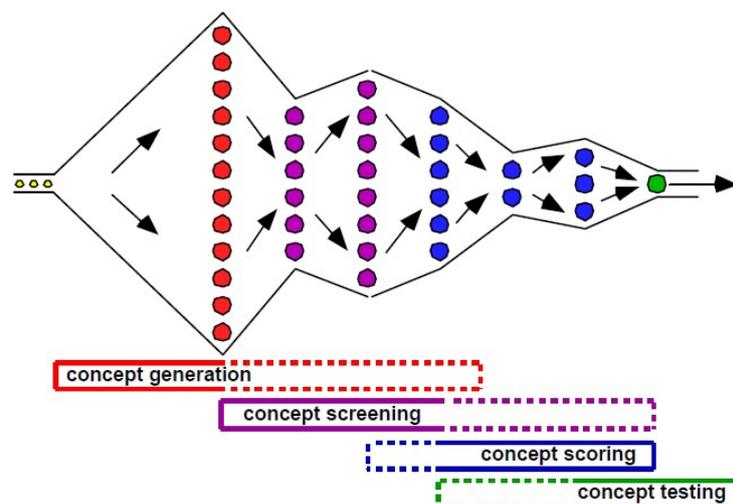


Figure 3-1. General process of concept selection (Ulrich & Eppinger 2012)

Multiple-criteria decision analysis or multiple-criteria decision making is a sub-discipline of operations research that explicitly considers multiple criteria in decision-making environments. The purpose of MCDA is to facilitate a complicated decision making process with providing reliable and objective data among the available solutions.

Many methods are used to solve MCDA problem. Six main types of concept selection methods are mentioned in other research: Utility Concept Selection Methods, AHP Concept Selection Methods, Graphical Concept Selection Methods, Quality Function Deployment (QFD) matrices, Fuzzy Logic Concept Selection Methods and Pugh Selection Matrix that is widely used as Concept Scoring Matrix (Ayag & Samanlioglu 2009, Lin, Gupta, etc. 2008). These methods are commonly used in business and engineering MCDA decision making, offering quantitative and qualitative analysis. QFD and Concept Scoring Matrix are chose in this thesis, because no precise quantitative data is required in these methods which are suitable in a concept design phase. Operation Strategy Matrix is also used as assist to classify criteria.

3.3.1 Concept Scoring Matrix

Concept scoring matrix is based on a method developed by the late Stuart Pugh in the 1980s. It is often used after concept screening method. In the matrix, concepts are evaluated in different score by a group of criteria. After evaluation, decision makers calculate the total score of each concept as an analysis data. Weighting is used to present the significant level of each criterion, see table 3-1.

		Concepts							
		A (reference) Master Cylinder		DF Lever Stop		E Swash Ring		G+ Dial Screw+	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Ease of Handling	5%	3	0.15	3	0.15	4	0.2	4	0.2
Ease of Use	15%	3	0.45	4	0.6	4	0.6	3	0.45
Readability of Settings	10%	2	0.2	3	0.3	5	0.5	5	0.5
Dose Metering Accuracy	25%	3	0.75	3	0.75	2	0.5	3	0.75
Durability	15%	2	0.3	5	0.75	4	0.6	3	0.45
Ease of Manufacture	20%	3	0.6	3	0.6	2	0.4	2	0.4
Portability	10%	3	0.3	3	0.3	3	0.3	3	0.3
Total Score		2.75		3.45		3.10		3.05	
Rank		4		1		2		3	
Continue?		No		Develop		No		No	

Table 3-1. Example of concept scoring matrix

Concept scoring process consists of six steps (Ulrich & Eppinger, 2011):

1. Prepare the Selection Matrix
2. Rate the Concepts

3. Rank the Concepts
4. Combine and Improve the Concepts
5. Select One or More Concepts
6. Reflect on the Results and the Process

Criteria

The function of criteria is accounting for the product performance with respect to customer needs and expectations (Kamal & Salhieh, 2007). In further development process, criteria should also include data of development feasibility, giving the picture of current technical and production capabilities of the company that will be producing the product. This concept was also agreed by Ulrich and Eppinger. Criteria were abstracted from customer needs and must be designed by a customer oriented way (Ulrich & Eppinger, 2011).

As Ulrich states, the customer-need oriented approach and the team work method were introduced, aimed to cover the product's key performance objects. However, there are few discussions on revealing the relationship among criteria. In most design situations, these criteria might admit or contradict each other, and their inclusion, in general, makes the decision making process more complex (Chunyu Lin etc. 2008).

Rating reference

Rating reference is used for the comparative ratings. This method suggests that the team chooses a concept to become the benchmark or reference concept. Scores are given by comparing concept with reference concept. The reference concept is commonly an industry standard or a straightforward concept (Ulrich & Eppinger 2012).

3.3.2 Operations Strategy Matrix

The operations strategy matrix (OSM) describes operations strategy as the intersection of a company's performance objectives with its decision areas, see figure 3-2. It emphasizes the intersections between what is required from the operations function and how the operation tries to achieve this through the set of choices made in each decision area (Slack & Lewis 2008). Although OSM developed for operation strategy decision, idea of discovering relationship between decisions and overall performance objectives has the potential to be applied in concept selection method. It gives decision maker a big picture on concept's overall performance rather than technique details, which easily involves people from manager level into decision making process.

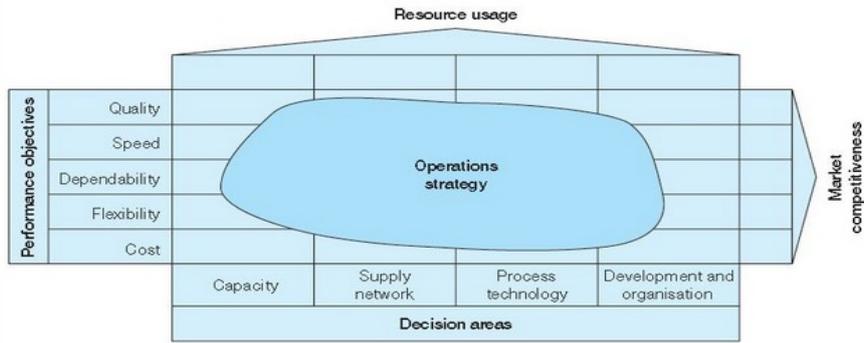


Figure 3-2. Operations Strategy Matrix

3.3.3 Quality Function Deployment

Quality function deployment (QFD) is a methodology that systematically identifies customer demands on product features and design parameters, translates these demands into product characteristics, and incorporates them into the manufacturing process (Bergman & Klefjö, 2010). Quality house is a tool that facilitates QFD work, see figure 3-3. On top of quality house is the roof with correlation matrix. Product characteristics are described under the roof and customer needs are along the left side. In the middle space of quality house, the relationship between product features and customer needs is signed by different symbol. Relations are classified into weak, medium, strong by different symbol.

HOWs		Features				Quality Plan	CUSTOMER RATING
		IMPORTANCE	Cut & Paste	User formulas	Template charts		
Good QFD Software	Easy to use	9	●	●	●	●	8.56
	Flexible layouts	7	○	△	○	○	11.23
	Printability	9	8	●	○	○	4.56
	Number crunching	6	●	○	2	○	8.41
	Easy to learn	9	?	○	●	○	9.23
	Work on screen	5	4	△	○	○	10.35
TARGETS		Whats/Hows	13 Built-in	30-400%			
ABSOLUTE IMPORTANCE		194	61	113	174	169	
RELATIVE IMPORTANCE							

Figure 3-3. Example of Quality House

4. Results and Discussion

4.1 Scaled up Dflex 201

In contrast Dflex 201 is only one standard which is not specific designed for wing final assembly. By testing Dflex 201 in Delmia Wing and LaWIB, size is the potential to be improvement. Dflex 201 is too smaller to support the weight of datum point and seems unfastened when the load is high. 6 degree of freedom structure of Dflex 201 makes it available to reach any datum point in complex wing structure. The Kinematic movement of Dflex in CATIA saves huge time to adjust flag posture.

In order to strengthen Dflex while keeping its structure, scaled up improvement is executed, see figure 4-1. Parts of Dflex 201 are scaled up twice. Then kinematics is added to the scaled product, see figure 4-2.

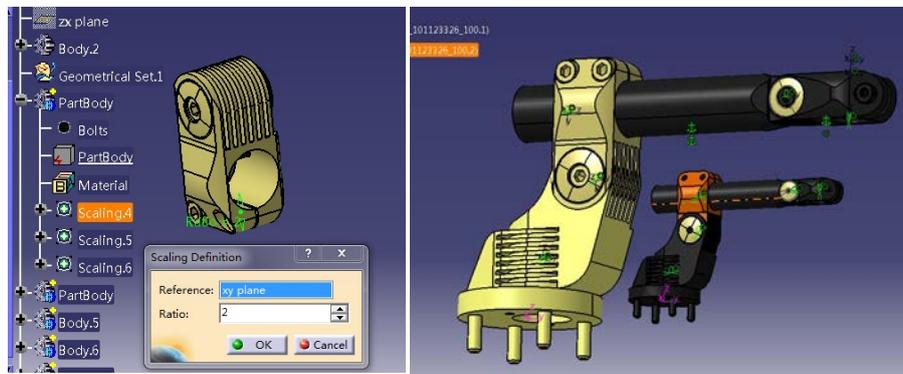


Figure 4-1. Scaling up Dflex 201 in CATIA V5

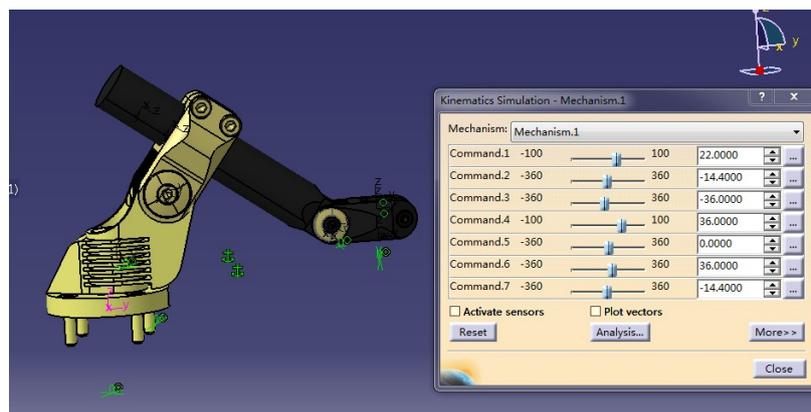


Figure 4-2. Kinematics in Scaled Dflex 201

After scaling up, new Dflex 201 is available to take heavier loads due to its increase strength, meanwhile still flexible enough to reach the datum points, see figure 4-3.

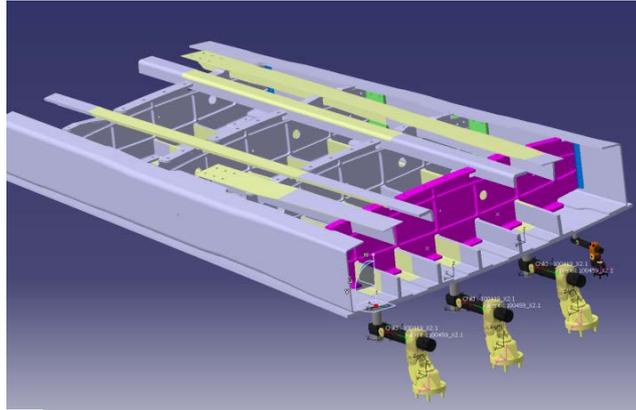


Figure 4-3. Comparison between scaled-up Dflex and Dflex 201 in LaWIB

4.2 Standard component and technique searching of electric manipulation

4.2.1 Basic Requirements for electric manipulation

As figures 4-3 and 4-4 provide, lug is the part of Dflex 201 used to reach datum point. It is adjusted manually by screws. Due to the characteristic of composite material, there are larger geometrical variations after manufacturing process than metallic material (see chapter 1.1.4). The variation is in centimeter level and tolerance is $\pm 10\text{mm}$, as shown in figure 4-5. There is potential to adjust lug with electrical linear motion to cover the variation. Several possible solutions to achieve the linear movement are found and will be introduced in this section.

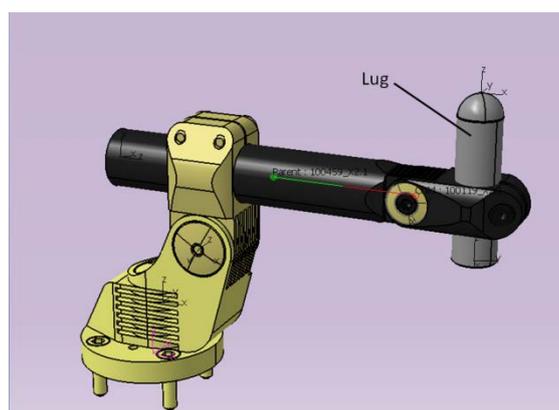


Figure 4-4. Scaled up Dflex 201 and lug

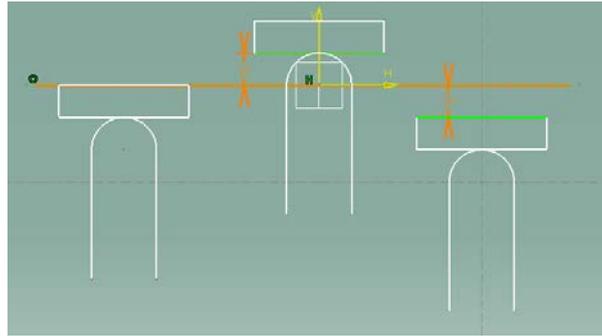


Figure 4-5. Linear motion to compensate geometrical variation

The basic requirements used to select the components are: moving range, accuracy, holding force and set-up time. Moving range represents the variation between products; long distance linear actuators are unnecessary and should be excluded or revised. The general tolerance for aircraft assembly is $\pm 0.3\text{mm}$ and less than 0.1mm for some precise location. The calculation of holding force is based such an assumption, applying aluminum material into the wing box model to get the weight then divided by the number of datum point. Because of less information about the hinge line and datum point, the holding force should be revised by future input.

Basic Requirements	
Moving Range	$\pm 10\text{mm}$
Accuracy	$<0.3\text{mm}$
Holding force	$150\sim 300\text{N}$
set-up time	$<3\text{min}$

4.2.2 Results of available electrical linear manipulation searching

Electrical linear manipulation with linear piezo motor

Piezo motor is a type of electric motor based upon the change in shape of a piezoelectric material when an electric field is applied. The operating principle is showed in figure 4-6. The most advantages of linear piezo motor are the high resolution and its self locked characteristic. When it stops, piezo motor can hold the position by the friction between actuator and piezoelectric material, even if turn off the driver. It is capable and safe, but since it is a new technique, the price is higher than other solution. High cost of the piezoelectric material is the main cause of the high price. To achieve high static force, more piezoelectric materials are needed to product higher frictional force.

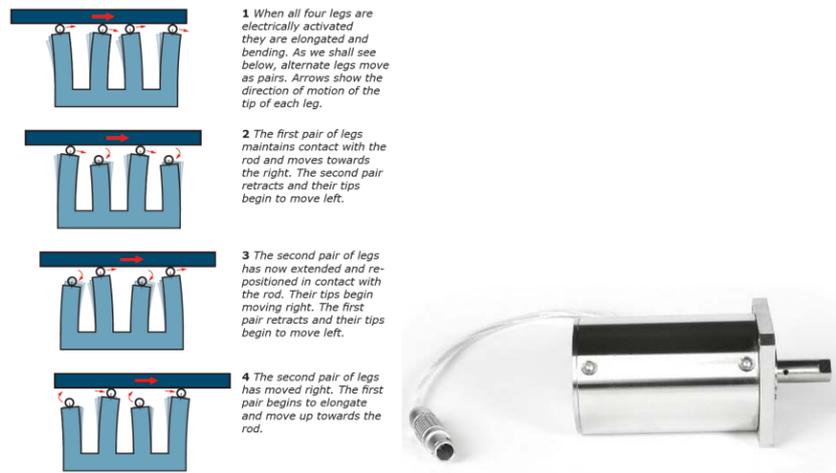


Figure 4-6. Operating principle of linear piezo motor

Electrical linear manipulation with lead screw

Lead screw is the component which can convert rotating motion of drivers into linear motion. Although it is different from the mechanism, lead screw performs well or even better on its self locked function compared with piezo motor. The screw is self-locking when the coefficient of friction is greater than the tangent of the lead angle. The holding force is depends on the strength of the material, stronger than piezo motor in general. The motor used to drive the lead can be different type: DC servo motor, step motor and rotating piezo motor. However they can be described in the same enclosed control circle system below. Advantages of lead screw are its simple structure and low cost. But the accuracy is affected by the backlash much, although there are technology such as pre load spring to decrease backlash, the accuracy is around 0.2mm which is just fulfill the general requirement.

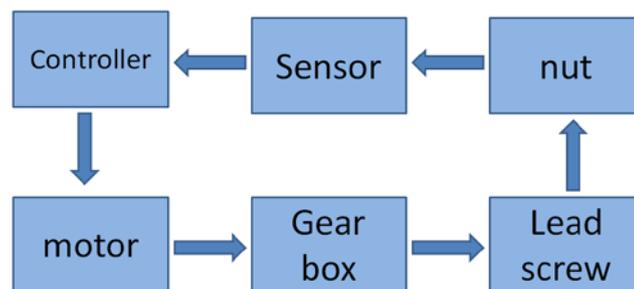


Figure 4-7. System structure of the electrical manipulation using lead screw



Figure 4-8 Linear system and lead screw offered by THOMSON

Electrical linear manipulation with linear motor

Using a linear motor is the most direct and simply to achieve a linear motion. Lacking of self locked is the critical problem. A break or clamp must be integrated in the system to ensure the position, which makes the system complicated.

4.2.3 Comparison Matrix for available electrical linear manipulation

Available solutions are compared in different characteristics in following table. Among the solutions linear piezo motor is the most accuracy but less affordable one. Linear motor is almost as simple as linear piezo motor, yet without self-lock mechanism so that additional lock system should be added. Lead screw owns advantage in self-lock characteristics and affordable price, shortage is that high accuracy lead screw manufactures is limited.

Linear actuator with lead screw is applied into tooling system. This concept is in the selection matrix.

Possible Solutions	Linear Piezo Motor	Rotate motor and Lead Screw			Linear Motor
		DC motor	Step motor	Rotating piezoelectrical motor	
Accuracy	<0.003mm, the highest resolution can be 1 nm	0.2mm	0.2mm	0.2mm	0.05mm
Locking Function	Self-locked 15N~450N	Self-locked	Self-locked	double Self-locked	No Self-lock
Move Range	20mm~50mm	20mm~500mm	20mm~500mm	20mm~500mm	20mm~60mm
Size	130X50X50 (mm)	Big		Medium	Small
Weight	1200g				
Set-up Time	0.3mm/s	qualified		qualified	Fast
Price	60,000kr	2,000~3,000kr	2,000~3,000kr	40,000~60,000kr	1,500~2,000kr
Suppliers	PI	Thomson	Thomson;	PCBMOTOR	PCBMOTOR
	http://www.piezo-motor.net/	http://www.thomsonlinear.com/website/com/eng/products/ball_screws_and_lead_screws/lead_screws.php			http://pcbmotor.com/pcbmotors-17/
	PiezoMotor	Portescap	PCBMOTOR	PiezoMotor	LinMot
	http://www.piezomotor.se			http://www.piezomotor.se/products/linear/	http://www.linmot.com

Table 4-1. Comparison Matrix for available electrical linear manipulation

4.3 Assembly tooling scoring matrix

4.3.1 Criteria

In this project, team work in brainstorm was the first step. After the brainstorm, 16 criteria were generated. As the same rules in the concept generation, each criterion must be explained clearly when proposed so that the group members get the same meanings of it (Ulrich & Eppinger, 2011).

In order to find the relationship and organize the 16 criteria, sorting method derived from the Operations Strategy Matrix (OSM) is used. The performance objectives in OSM reflects the main decision making reference form the requirements of market and customer (Slack and Lewis 2008). It adapts to most industry in general. Each operation strategy must have its influence in one objective from quality, speed, dependability, flexibility and cost. The project expanded this conclusion as criteria can be sorted by performance objectives which generally reflect customer needs. Thus criteria can be organized in different groups. Criteria in the same group reflect the customer requirement from the same aspect. There are five performance objectives the OSM introduced, to improve the objectives more meaningful in aerospace industry, especially in product design of assembly tooling, criteria are organized in six performance objectives: Adaptability, Cost, Engineering Time, Set-up Time, Flexibility and Reliability.

In the following of this chapter, the six performance objectives and the criteria they concern will be described in detail.

Adaptability:

Adaptability shows the degree of how much the tooling can be integrated with other technique and manually process belongs to one system. During the assembly process measuring equipment, welding robots and operators are often working synchronized. Under this situation, assembly tooling must keep working without disturbing other process. The adaptability includes equipment integration, manual process integration and automation unit integration.

1. Operator Interaction: the degree of access to operators. The operators should be easy to get into the tooling system when changing the pick-ups, fastening the jigs, installing measuring equipment and etc. Ergonomics assessment also contributes to this criterion. Ergonomics in the workspace attempts to optimize interaction between humans and machines in order to achieve a set of system goals (Rodrigues 2001). The operator must successfully complete the process in harmless posture within limited load (Hägg, 2009). In wing assembly line, although lift machine are widely use to handle heavy parts, there is still ergonomics risk in extreme posture and heavy load in

manual work.

2. Automation unit integration: the level of automation and the potential to replace the manual work function with automation units. This criterion stands for the automation level also the flexibility in automation. From customer request, an affordable flexible tooling solution is desired (Kihlman 2005). High level in automation in some cases equals high cost and technical risk. In some concept design, the ability to change it into automation unit when necessary takes into consideration. According to the Theory of Constraints, it is the bottlenecks decide the capacity of the system (Liker 2004). Therefore the potential to be automatic is a critical characteristic in tooling design.

Cost:

The price of civil aircraft is becoming more market demand than cost demand, as the competition becoming intense in aviation market (Galchenko & Tegin 2009). The cost of assembly tooling must be controlled under limited number from buying to maintaining. However in the concept design phase, the total cost of the tooling is hard to calculate precisely due to lack of material cost, production cost, delivery etc. Therefore the cost scoring is a judgment based on quantities rather than qualities analysis. The criteria directly relevant to the total cost are: standard component utilization, operation simplicity, maintainability and technical risk.

3. Standard component utilization: Standard component utilization shows the level in using standard components. The direct benefit of using standard components is reducing the cost and easily maintained. The cost saving includes lower investment cost, lower purchase cost and reliable delivery compared with special designed component. High score represents the tooling widely use standard component, otherwise more customized components are used.

4. Operation simplicity: Simple building process and set-up process leads less operator training, thus cut down the cost. Building process includes the material logistics, tooling assembly process, Set-up process includes moving pick-up to datum point, fasten datum point and measure. High score will be given if the tooling needs less building process and set-up process which leads to a lower cost.

5. Maintainability cost: High performance in maintaining refers to easy cleaning, easy replacing components if broken and less down time.

6. Technical risk: Technical risk in assembly tooling concepts includes the utilization of new technology, new design and new material. Attention must be paid here is that small technical risk drives high score and high technical risk drives low score.

Engineering Time:

Engineering time for assembly tooling refers to the periods from design to build up the assembly tooling. The start point of set-up process is building 3D model or 2D draft in the CAD software, the 3D model or 2D draft will sent to customer and run the simulation integrated with measure equipments, robots and digital humans. For any conflict in the test, 3D model should be modified before product realization. When the final design is decided, the next work is to set a consequence how to mount the tooling. A standardized procedure should be documented or visualized to operators.

Since the assembly tooling consists of the process described above, the engineering time contains: design engineering time, assembly engineering time and re-design engineering time.

Higher score refers to less engineering time and high speed, lower score refers to long engineering time and low speed.

7. Design engineering time: Time consuming in tooling structure design, includes 3D model and 2D draft.

8. Re-design engineering time: Time consuming in modifying 3D model or 2D draft after testing or deployment of new requirements. For some reasons, the upper stream design, for instance the wing structure or the datum point has to be improved. In that case, the tooling design must be adapted to the new requirements. This workload is also counted in re-design engineering time.

9. Assembly engineering time: To set the method and procedures to assemble the tooling is part of the engineering work. Engineers and operators can work together to standardize and improve the process to meet the time limitation, ergonomics document and etc.

Set-up time:

After delivery, assembly tooling will be mounted on the shop floor. In wing assembly production, between each product, slight adjustment in the pick-ups is necessary, since the product variation in size and shape. Fixture structure even has to be reconfigured when the production changes between different product families. During the tooling set-up time, other machines have to be idle until the tooling ready. The speed of tooling set-up strongly affects the equipment efficiency and capacity.

Higher score refers to less set-up time and high speed, lower score refers to long set-up time and low speed.

10. Configuration Time: Configuration time refers to the time spent to deploy

assembly tooling on the shop floor.

11. Re-configuration Time: Re-configuration time includes the tooling change time between each product and each product family. Re-configuration process can be manual or automotive. Re-configuration time also present the tooling's ability to handle variation between products.

Flexibility:

In general, flexibility of a product has several meanings considering what characteristic would contribute to its competitiveness, for instance product flexibility, mix flexibility, volume flexibility and delivery flexibility (Slack and Lewis 2008). Among the various aspects of flexibility, reconfiguration is the most important characteristics from customer demands. Besides the degrees of freedom in pick-ups is also meaningful to eliminate the gap of variation. There are two criteria organized into this performance objective: Reconfiguration and Degree of Freedom (DOF).

12. Reconfiguration: Reconfiguration refers to the tooling's ability to be re-built for different product family or different process. Conventional tooling is consisted of welded metal beam which only can be used in one product family. When producing another product family, the tooling has to be moved away. Reconfiguration is the demand from high speed changing market. Reconfigurable tooling sharply decreases the set-up time and design cost, which is a significant improvement from conventional tooling.

13. Degree of freedom: In order to move pick-ups to reach datum points on the wing quickly, free movement in some direction and angle will simplify the set-up process. The pick-ups can easily reach the datum points by change the posture manually or automatically instead of re-assembling pick-ups or flags on the fixture. Theoretically the more degree of freedom, much more flexibly it is. However, the decision must considerate balance between DOF and structure stiffness and complication at the same time. For example, high DOF in some case increases the number of points that operator must fasten, therefore weakens the structure stiffness meanwhile add non-value adding time. Degree of freedom depends on customer requirement; customer may have their clear picture on it. For those reasons, offering various options in DOF is another possible solution which makes pick-up flexible in different number of DOF.

High score for criteria DOF should be given to the concept which is well balanced between DOF and other factors and which has potential being flexible in the number of DOF.

Reliability:

Assembly tooling must be capable of extremely high reliability in stiffness, thermal change and vibration, to ensure the tolerance of wing assembly. However in today limitations with assembly tooling represent a huge cost in the industry. Fixture movement during product lifecycle is one the limitation (Airbus 2010). Thermal change is one of the facts cause the fixture expansion. When a fixture expands, the product on the tooling will be moved as well and leads vital problem. Vibration and stiffness will also cause fixture and pick-ups movement, especially when pick-ups have high DOF.

14. Thermal stability: Tooling's ability to maintain the shape when temperature changes most depends on the material used, because materials deform linearly to the temperature change. Thermal expansion coefficient (TEC) presents the deformation caused by temperature change. As the equation shows below:

$$\alpha = \frac{1}{L_0} \frac{\partial L}{\partial T}$$

Where L_0 is the original length, L is the new length and T is the temperature. The TEC defines as the fractional change in length per degree of temperature change. The increase in temperature causes material to deform by the transfer of thermal energy, which is stored in the intermolecular bonds between the atoms (Airbus 2010). Therefore it is important to have in mind when selecting material that steel is three times stiffer, and has three times less thermal expansion, than aluminum (Kihlman 2005).

15. Vibration Stability: The vibration generated from the drilling process, robots and plant transfers to pick-ups, flags and fixture. If the datum point on the part moved, accuracy then can't be guaranteed. The pick-up design and fasten method are the key characteristics contribute to vibration stability.

16. Stiffness: Stiffness of assembly tooling presents the maximum loads it can take. Pick-ups and flags is often the bottle neck of loading. Maximum weight a pick-up and flag can suffer is used to compare the stiffness.

4.3.2 Weight:

Following the concept scoring method that Ulrich and Eppinger introduced, after decide the criteria, next step is adding importance weights to the matrix (Ulrich & Eppinger, 2011). Assigning an importance value from 1 to 5 or allocating 100 percentage points among them. The same rule as criteria determination, weight is determined thorough process of identifying customer needs. However, for the purpose of concept selection the weights are often determined subjectively by team consensus.

In the project, weights are determined by integrating voice directly from customer,

future demands in aerospace market and requirements from LOWCOMACHS. 100 percentage is first allocated to six performance objectives, then sub-allocated to the concerning criteria.

4.3.3 Rating reference

Conventional tooling is the reference concept in this project. As new tooling designs in the matrix is applied BoxJoint which is overall better performance than conventional tooling, conventional tooling rates 2 in each criteria.

Relative Performance	Rating
Worse than reference	1
Same as reference	2
Better than reference, almost qualified	3
Qualified performance	4
Satisfied unexpected customer needs	5

4.3.4 Concept Scoring Matrix

The results of concept scoring matrix are presented in Table 4-2. Total scores show the overall performance of each concept. Concept of BoxJoint with mini Flex gains the highest score with a good balance among 16 criteria which means it is the one well fulfilling customer requirements. In future phase, BoxJoint with mini Flex can be selected as the basic concept to be improved. This concept performs high quality with every criteria compared with conventional tooling, yet still has potential to be improved, especially on cost and engineering time.

Having a closer look at scores of each performance, different concepts are outstanding in different aspects. In order to get a clear picture of advantages and weaknesses for each concept, scores are organized in a radar chart, see Figure 4-9.

			Concept									
			Conventional Tooling (Reference)		BoxJoint with scaled up Dflex 201		BoxJoint with Flexapod		BoxJoint with mini Flex		BoxJoint with linear electrical manipulation	
Performance	Selection Criteria	Weight	Rating	Weighed score	Rating	Weighed score	Rating	Weighed score	Rating	Weighed score	Rating	Weighed score
Adaptability 10%	Operator Interaction	5%	2	0.1	4	0.2	3	0.15	5	0.25	4	0.2
	Automation unit integration	5%	2	0.1	3	0.15	3	0.15	4	0.2	5	0.25
Cost 24%	Standard component utilization	10%	2	0.2	4	0.4	4	0.4	5	0.5	4	0.4
	Operation simplicity	4%	2	0.08	3	0.12	3	0.12	4	0.16	5	0.2
	Maintainability cost	5%	2	0.1	5	0.25	5	0.25	4	0.2	2	0.1
	Technical risk	5%	4	0.2	3	0.15	4	0.2	4	0.2	2	0.1
Engineering Time 23%	Design engineering time	10%	2	0.2	5	0.5	5	0.5	4	0.4	4	0.4
	Re-design engineering time	10%	2	0.2	5	0.5	5	0.5	4	0.4	4	0.4
	Assembly engineering time	3%	2	0.06	4	0.12	4	0.12	4	0.12	4	0.12
Set-up time 20%	Configuration Time	10%	2	0.2	4	0.4	4	0.4	4	0.4	5	0.5
	Re-configuration Time	10%	2	0.2	4	0.4	3	0.3	5	0.5	5	0.5
Flexibility 13%	Reconfiguration	10%	2	0.2	5	0.5	5	0.5	5	0.5	5	0.5
	Degree of freedom	3%	2	0.06	4	0.12	5	0.15	5	0.15	3	0.09
Reliability 10%	Thermal stability	5%	2	0.1	4	0.2	4	0.2	4	0.2	4	0.2
	Vibration Stability	2%	2	0.04	3	0.06	4	0.08	5	0.1	4	0.08
	Stiffness	3%	2	0.06	3	0.09	4	0.12	5	0.15	4	0.12
	Score in adaptability	10%	2.00	0.20	3.50	0.35	3.00	0.30	4.50	0.45	4.50	0.45
	Score in cost	24%	2.42	0.58	3.83	0.92	4.04	0.97	4.42	1.06	3.33	0.80
	Score in engineering time	23%	2.00	0.46	4.35	1.00	4.35	1.00	3.48	0.80	3.48	0.80
	Score in set-up time	20%	2.00	0.40	4.00	0.80	3.50	0.70	4.50	0.90	5.00	1.00
	Flexibility	13%	2.00	0.26	4.77	0.62	5.00	0.65	5.00	0.65	4.54	0.59
	Reliability	10%	2.00	0.20	3.50	0.35	4.00	0.40	4.50	0.45	4.00	0.40
	Total score			2.10		4.16		4.14		4.43		4.16

Table 4-2. Concept Scoring Matrix

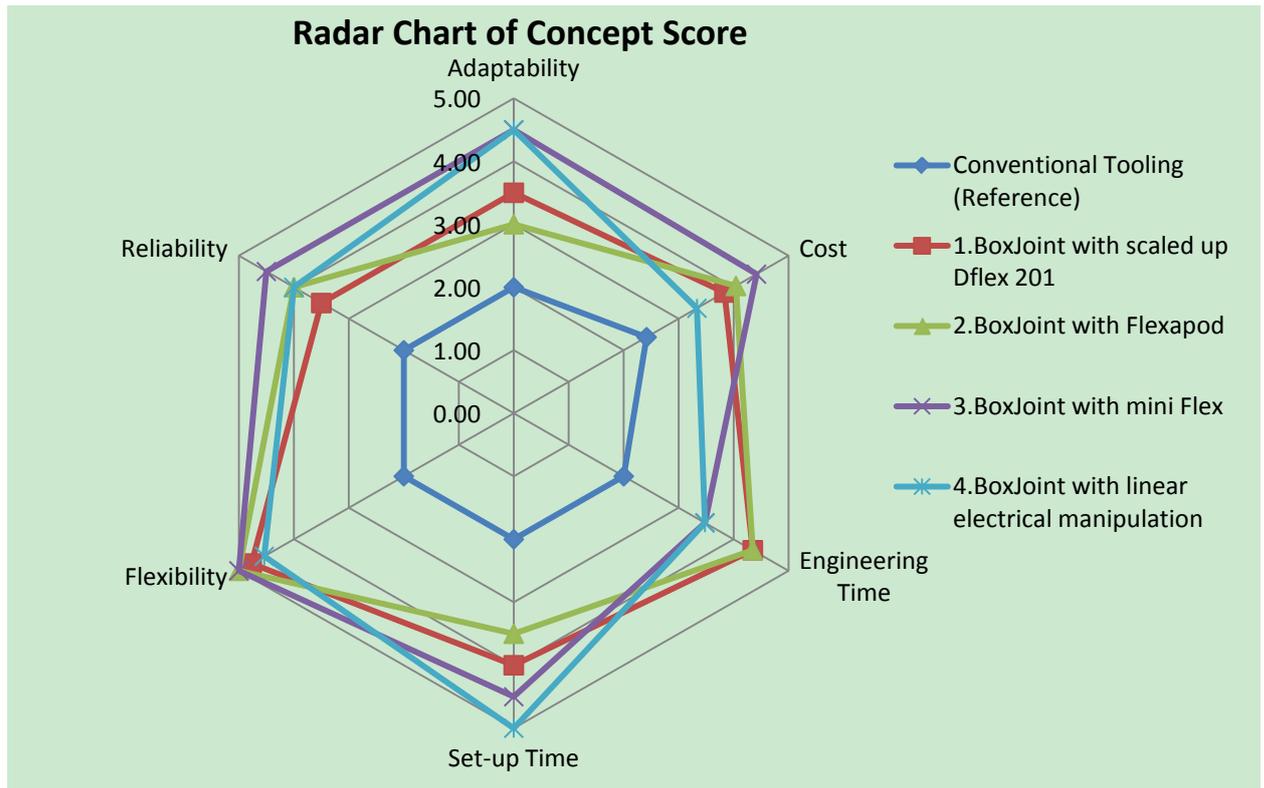


Figure 4-9. Radar chart of concept score

Firstly, see from Figure 4-9, all the BoxJoint concepts are better fulfill requirements than conventional tooling. And each concept is great in different aspect.

Concept 1 and concept 2 have less engineering time due to larger move scale in 6 DOF, which save time by roughly setting beams and boxes.

Concept 4 is the fastest to be set-up, however electrical device enhances the cost and reduces the reliability in some degree.

Concepts have similar performance from a flexibility point of view. The high scores are derived from application of BoxJoint, which makes the tooling are easy to be configured and reconfigured.

Reliability is strongly affected by the complication in tooling structure. Simple structure with standard components such as concept 3 is most stable to maintain a right position.

In order to be adaptable in various working environment, simple structure and small size are the key to be easily integrated with operators and machines.

Following the weight of each criterion, concept 3 has the highest score. But since each concept has its advantage, therefore they may good choice in other scenarios. Such as

when set-up time is extremely important and cost is less important, then concept 4 is the suitable choice, see table 4-3.

		Concept									
		Conventional Tooling (Reference)		1.BoxJoint with scaled up Dflex 201		2.BoxJoint with Flexapod		3.BoxJoint with mini Flex		4.BoxJoint with linear electrical manipulation	
Score in adaptability	10.00%	2.00	0.20	3.50	0.35	3.00	0.30	4.50	0.45	4.50	0.45
Score in cost	5.00%	2.42	0.12	3.83	0.19	4.04	0.20	4.42	0.22	3.33	0.17
Score in engineering time	20.00%	2.00	0.40	4.35	0.87	4.35	0.87	3.48	0.70	3.48	0.70
Score in set-up time	45.00%	2.00	0.90	4.00	1.80	3.50	1.58	4.50	2.03	5.00	2.25
Flexibility	10.00%	2.00	0.20	4.77	0.48	5.00	0.50	5.00	0.50	4.54	0.45
Reliability	10.00%	2.00	0.20	3.50	0.35	4.00	0.40	4.50	0.45	4.00	0.40
Total score			2.02		4.04		3.85		4.34		4.42

Table 4-3. Scores when set-up is given more attention.

Concept 1 is workable when engineering time and adaptability are import to customer.

		Concept									
		Conventional Tooling (Reference)		1.BoxJoint with scaled up Dflex 201		2.BoxJoint with Flexapod		3.BoxJoint with mini Flex		4.BoxJoint with linear electrical manipulation	
Score in adaptability	20.00%	2.00	0.40	3.50	0.70	3.00	0.60	4.50	0.90	4.50	0.90
Score in cost	5.00%	2.42	0.12	3.83	0.19	4.04	0.20	4.42	0.22	3.33	0.17
Score in engineering time	40.00%	2.00	0.80	4.35	1.74	4.35	1.74	3.48	1.39	3.48	1.39
Score in set-up time	5.00%	2.00	0.10	4.00	0.20	3.50	0.18	4.50	0.23	5.00	0.25
Flexibility	15.00%	2.00	0.30	4.77	0.72	5.00	0.75	5.00	0.75	4.54	0.68
Reliability	5.00%	2.00	0.10	3.50	0.18	4.00	0.20	4.50	0.23	4.00	0.20
Total score			1.82		3.72		3.67		3.71		3.59

Table 4-4. Scores when engineering time and adaptability are important.

Concept 2 is preferable when balancing cost performance. Since Flexapod is the largest in size compared to others. It can be used when there is a long distance between fixture and datum point.

		Concept									
		Conventional Tooling (Reference)		1.BoxJoint with scaled up Dflex 201		2.BoxJoint with Flexapod		3.BoxJoint with mini Flex		4.BoxJoint with linear electrical manipulation	
Score in adaptability	10.00%	2.00	0.20	3.50	0.35	3.00	0.30	4.50	0.45	4.50	0.45
Score in cost	15.00%	2.42	0.36	3.83	0.57	4.04	0.61	4.42	0.66	3.33	0.50
Score in engineering time	40.00%	2.00	0.80	4.35	1.74	4.35	1.74	3.48	1.39	3.48	1.39
Score in set-up time	5.00%	2.00	0.10	4.00	0.20	3.50	0.18	4.50	0.23	5.00	0.25
Flexibility	15.00%	2.00	0.30	4.77	0.72	5.00	0.75	5.00	0.75	4.54	0.68
Reliability	5.00%	2.00	0.10	3.50	0.18	4.00	0.20	4.50	0.23	4.00	0.20
Total score			1.86		3.76		3.77		3.71		3.47

Table 4-5. Scores when balancing cost performance

4.4 Assembly Tooling Design Philosophy

Author puts efforts in tooling design with BoxJoint engineering tool in this project. Although plenty of tools are offered by Delfoi tooling kit, experience is still playing an important role when building fixture structure and choosing pick-ups. Aircraft

assembly process is a complex problem, and it is hard to design tooling for it in a quantitative approach. Yet learn from tooling design process, author believes that there is potential for integrating tooling principles introduced by Erik Henriksen.

Other location principles are introduced by Henriksen such as cylindrical locators and V-shape locators for large geometrical variation shape. However these location principles are summarized from workpiece manufacturing other than product assembly. Lack of principles guides assembly tooling design. Designer works with experience to build fixture structure and tests its performance in simulation tools following a try and error way. No tooling principle is used to guide the pick-up choice from clamp, vacuum cup or bolt joint. Reasons why designer seldom considerate 3-2-1 principle in design process are from several aspects below:

1. It is the aircraft structure engineer who allocates datum points, then tooling engineer build the fixture to reach datum points. It is not the tooling engineer who decides at which point and in what way locating the product.
2. 6 DOF principle is used to define the location of object, by fixing 6 DOF with 3-2-1 method, the object cannot move during processes. However the object can be completely defined only when it is a rigid object. Non-rigid object as metal or composite sheet in aircraft structure can still deform, twist or wrinkle. To avoid deformation, sheet work piece has to be over defined by adding locators.

Although difficulties exist above, there is still potential for tooling design to practice 3-2-1 principles. Two suggestions are provided by the author:

1. Integrate tooling design in aircraft structure design. Today the structure design and tooling design are separated process. Tooling design is at downstream, any change from upstream would add workloads on the tooling designer. Moreover tooling design has to follow datum point requirement without assembly tooling consideration. Collaborated structure design with tooling engineering involved can gather information from production level and make it more efficient in some degree.
2. When choosing different types of pick-up (surface, strip or point), small area around datum point can be defined as rigid body without deformation that connected with other parts. For instance, hanging ear structure as figure 5-1 showing is connected with spar. Coordinate system refers to the datum point. The connection area is equivalent to a strip due to the thickness of metal sheet. The possible movement for hanging ear is rotating around intersection line with one degree of freedom. It is a typical incomplete definition that locating cylindrical surfaces by side and an end strip (Henriksen 1973). For the purpose of complete definition, the fixture must be provided with one additional locating element which eliminates one rotation freedom (Henriksen 1973) as showing in figure 5-2. Therefore clamp at datum point can be used as pick-up without over definition.

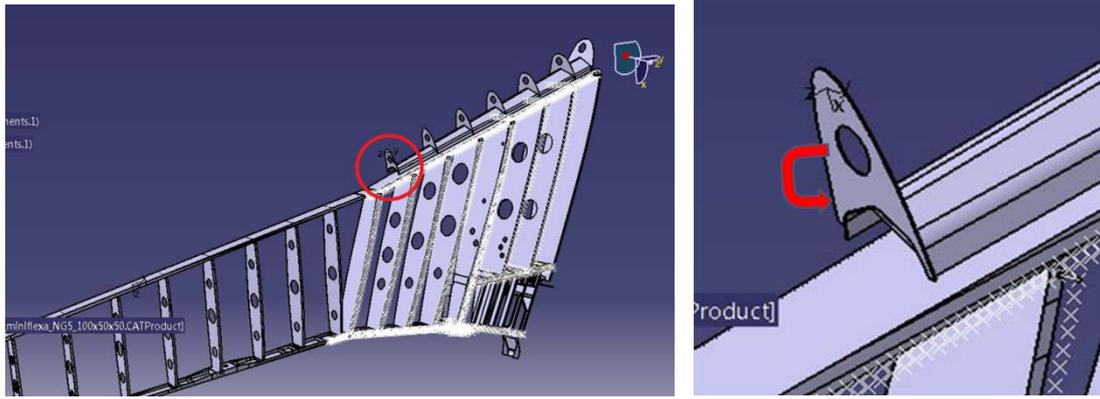


Figure 5-1. Hang ear structure

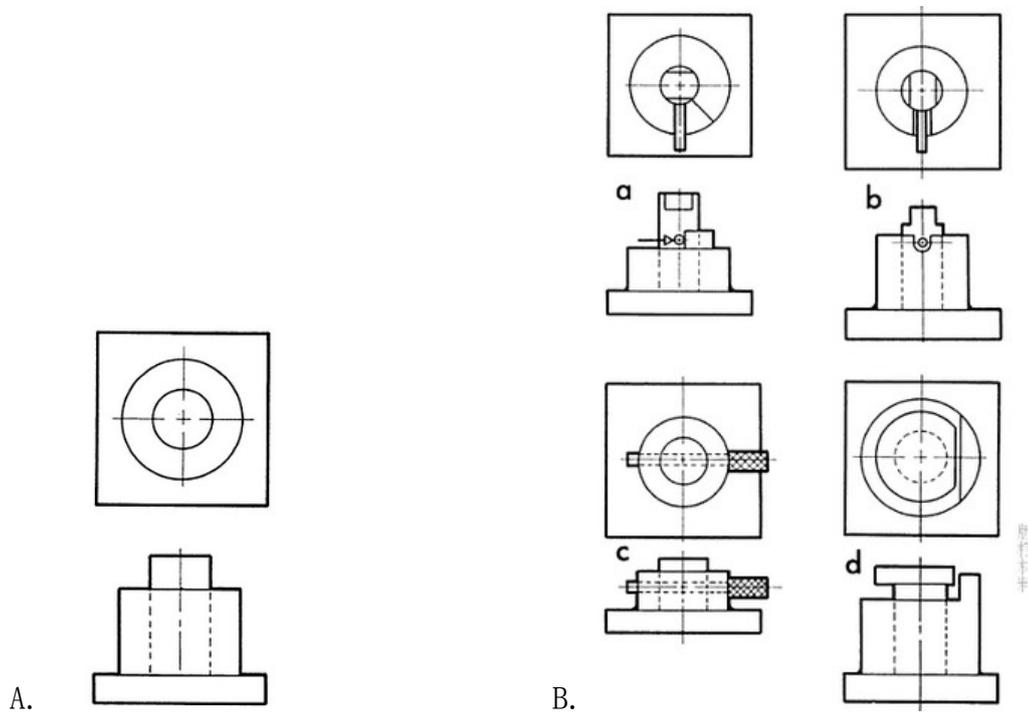


Figure 5-2. A: incomplete locating by means of a simple cylindrical locator;
 B: complete locating of cylinder by means of an outside cylindrical locator and a radial locator.

5. Conclusion

In the beginning of this thesis, BoxJoint was tested in CATIA 3D model. Dflex 201 was found inappropriate in size, thus scaled-up Dflex 201 was given as a solution. In the second phase current linear motion techniques were searched and evaluated. As a result, electrical linear manipulation with lead screw was selected as an additional tool in Delfoi tooling kit. In the third phase, four concept designs are compared and scored following LOCOMACHS requirements. From the results of concept scoring matrix, it can be concluded that Delfoi tooling kit generally fulfills requirements of LOCOMACHS and future market demands, also has a big step forward from conventional tooling. As well as shown is the results, there are potentials to improve Delfoi tooling kit a better product:

- a. Balancing between set-up time and DOF by offering customized DOF solutions. 6 DOF brings large movement scale to cover geometrical variation, meanwhile takes more time to be fixed. Also there are risks in position stability when choosing 6 DOF. Delfoi should help customers achieve minimized DOF with low set-up time and low risk.
- b. Introducing automation adjustment in mini Flex and linear manipulation to achieve high position accuracy with short set-up time.
- c. Considerate applying tooling philosophy in the design work, which will help to find out a systematical way to guide the work.

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