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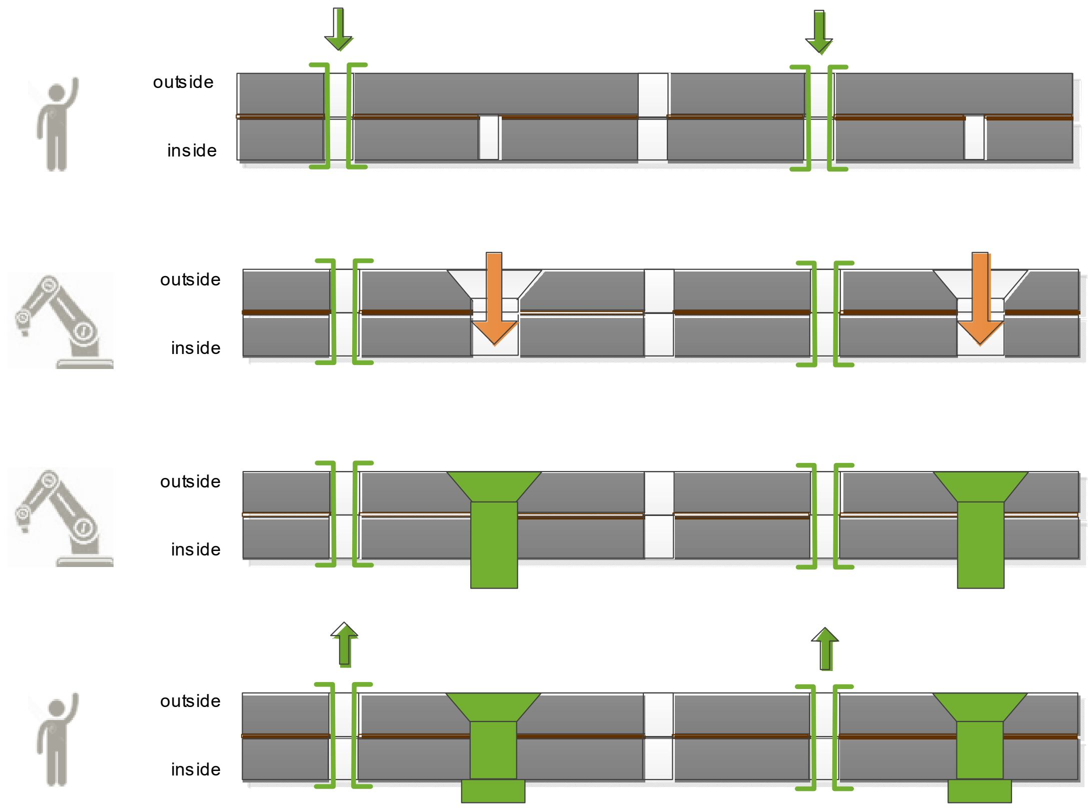

AUTOMATED CIRCUMFERENTIAL JOINT ASSEMBLY IN AIRCRAFT PRODUCTION

DEVELOPMENT AND ASSESSMENT OF A PRODUCTION PROCESS

MASTER'S THESIS IN PRODUCTION ENGINEERING

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Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

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Development and Assessment of a Production Process

Master's thesis in the Production Engineering programme
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Cover:
Extract from the developed assembly process

Department of Product and Production Development
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Abstract

The main goals of introducing automation in single aisle aircraft assembly are to ramp up production, increase efficiency by lowering costs and improve ergonomics as well as quality. However, old aircraft designs and the characteristics of aircraft production such as low production volumes, complex and long processes, large parts and high quality requirements make the implementation challenging; especially for high-level assembly which today is mostly preformed manually by high-skilled operators. While large, dedicated machines have been introduced for drilling and riveting applications in the past improved rigidity and accuracy solutions have made industrial robots a less expensive and more flexible alternative. This thesis analyses opportunities and limitations of an automated circumferential joint process for Airbus' A320 family final assembly line and develops and evaluates different concepts for an automated assembly. Finally, a future basic process including robots with special drilling and riveting end effectors as well as manual operations is presented. While the suggested process could not prove to be faster or save costs, it can significantly improve quality and ergonomics. The process is further validated in terms of lead time. The available time was exceeded by 4% but this value can be improved for instance by ensuring a stable automated riveting process. Moreover, a risk assessment is conducted which builds the basis for further recommendations in terms of tests to be performed and design modifications to be taken into account in order to address the issues resulting from the aircraft design.

Keywords: Process Evaluation, Aerospace, High-Level Fuselage Assembly, Drilling & Riveting Automation, Industrial Robots

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Hamburg, 2016-08-31

Katrin Jaacks

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ABBREVIATIONS

A/C	Aircraft
AFT	Aft (aft fuselage)
CAD	Computer Aided Design
DOF	Degree of Freedom
EASA	European Aviation Safety Agency
e.g.	exempli gratia (Latin), for example
EN	European Standard
ERP	Enterprise Resource Planning
FAL	Final Assembly Line
i.e.	id est (Latin), that is
ISO	International Organization for Standardization
FWD	Forward (forward fuselage)
MTM	Methods Time Measurement
neo	New Engine Option
NRC	Non Recurring Costs
NVA	Non Value Adding
OEE	Overall Equipment Effectiveness
PH	Pilot hole
RC	Recurring Costs
R&D	Research & Development
SA	Single Aisle
TCP	Tool Centre Point
TF	Temporary fastener
TMU	Time Measurement Unit
VA	Value Adding
W	Waste

1. INTRODUCTION

The introduction presents the background of the thesis and puts it into a broader context. Further, it describes the specific problem and clarifies the purpose and resulting objective which leads to the formulation of research questions. Moreover, the scope and delimitations are explained. Finally, the thesis approach (method) is introduced which at the same time provides the thesis outline.

1.1. BACKGROUND AND PROBLEM DESCRIPTION

Forecasts from Airbus and Boeing, the main aircraft manufacturers predict a continuing increase in the demand for civil aircrafts. Worldwide air traffic will double within the next 15 years. One main reason is the transport growth in emerging countries especially in the Asia Pacific region (Boeing, 2015). According to Airbus' forecast the passenger and freighter aircraft fleet will grow significantly. Adding the replacement of the airlines' aging fleets results in a total demand for 32,600 new aircrafts from 2015 to 2034. This number includes 23,000 single-aisle (SA) aircrafts such as Airbus' A320 and Boeing's 737 families, accounting for 70% of the units. (Airbus, 2015)

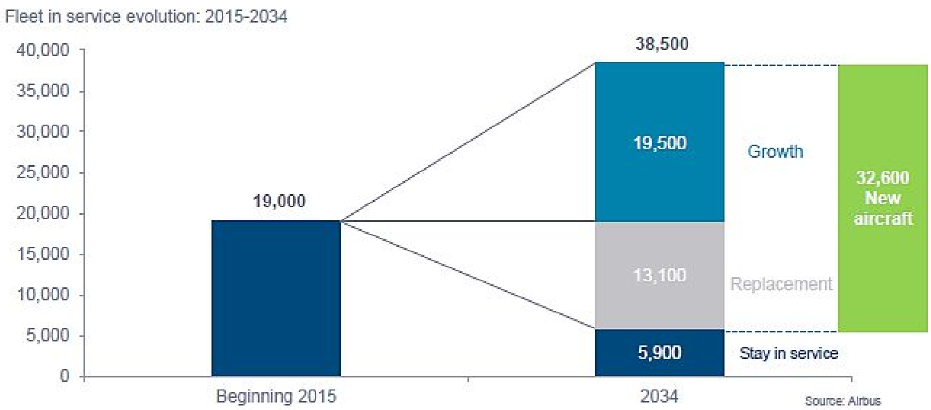


Figure 1 Passenger and freighter aircraft demand 2015-2034 (Airbus, 2015)

In order to satisfy the demand and reduce the customers' waiting time production rates have to be increased. Using capacities in the most efficient way will assure compatibility in the future. Furthermore, new competition from companies such as Bombardier and the Chinese Comac is developing for the SA market. Both Airbus and Boeing announced to further ramp up their monthly production rates for the SA aircrafts: from 42 to 52 (Boeing) and 60 (Airbus) aircrafts per month until 2018 and 2019. (Gates, 2015) (n.d., 2014)

Besides technical innovations integrated in the new SA versions A320neo and B737 MAX raising the product's attractiveness (Sforza, 2014), intern production costs have to be reduced. The need for an increased productivity (output/time) and for cost reductions call for automation in aircraft manufacturing as many processes are performed manually today. The potential quality improvement is another argument for automation. In addition to the benefits on the triangle of cost, time and quality automation could reduce the ergonomic risks of highly repetitive tasks - often performed in bad ergonomic postures.

Both Airbus and Boeing will not develop a new short range aircraft in the near future. But the automation of manufacturing processes based on an old design originally made for manual assembly is complex. "In aerospace, weight and aerodynamics take priority over design for assembly. Aircraft assembly is [traditionally] a manual process because the tasks require a high level of skill. People are constantly making decisions during the assembly process and adapting to the exact situation." Aerospace industry is further characterised by low production volumes, complex processes, large parts and high quality requirements with tight tolerances. In addition the high variety of components and tasks as well as long cycle times compared to other industries challenge aircraft manufacturers. (Weber, 2009)

A Boeing 747 contains 6 million parts, of which half are fasteners. The enormous number of fastener locations makes drilling and filling the largest areas of opportunity for automated applications in aerospace to reduce lead times. Another argument is quality: drilling high performance holes in high performance material requires high performance tools and machines. This is where automation can act a part. According to George Bullen (2013) mechanical fasteners account for 60% of the cost of airframe assembly, 80% of lost-time injuries and 80% of defects. That is why manufacturers are looking for new ways to drill and fill holes.

Manual drilling and fastening are performed by highly skilled operators using special equipment, often in bad ergonomic positions and with high repetitiveness. Automation can improve ergonomics, produce constant quality and speed production. It was once limited to dedicated, large and thereby stiff and accurate but at the same time extremely expensive, inflexible machines limited in access. The potential to save costs compared to large automation systems made articulated robots attractive alternatives. These have largely been limited in scope in aerospace assembly by deficiencies in positional accuracy. Thanks to improved rigidity and accuracy solutions they are now a potential automation solution for aircraft assembly. (Waurzyniak, 2013)

Using robots with end effectors for the assembly of aircrafts can be a turnkey solution. However, due to the characteristics of aerospace industry automation is faced by challenges. Especially, there is only limited experience with high level assembly automation and in particular with high-level automation by robots. Today robots are used for low level assembly and other applications such as composite manufacturing. Research and development focus on the feasibility regarding accuracy requirements etc. This thesis concentrates on the process development for a specific application, the automation of a circumferential joint assembly connecting the two halves of an aircraft fuselage.

1.2. Purpose and Objective, Research Questions

The purpose of this thesis is to

- Understand the current circumferential joint assembly process and its requirements,
- Analyse opportunities and limitations of an automated process,
- Develop concepts for an automated process and
- Evaluate and compare these alternatives with respect to several criteria.

The final objective is to suggest a future basic process for a circumferential joint assembly including robots with special drilling and riveting end effectors as well as manual operations. It will be validated in terms of lead time and a risk assessment. Several research questions can be derived based on the purpose and objective. They will be answered throughout the thesis:

- What are opportunities and limitations of using robots in the circumferential joint assembly?
- How can a future process including robots for circumferential joint assembly as well as manual work look like?
- Does the suggested process fulfil the required lead time and other important criteria?
- What are future actions and potential improvements?

1.3. Scope and Delimitations

The thesis is written at the Airbus Operations GmbH in Hamburg and focuses on the new A320 family final assembly line currently being designed (Flug Revue, 2015), in particular on the circumferential joint assembly. Robots with drilling and riveting end effectors are supposed to automate many of the required operations. Nevertheless, manual work will remain as well. While the station design as well as the resources are given a basic process has to be developed. All relevant components are of metal; no other materials such as composites are involved.

The work is narrowed down to the assembly, mainly drilling and riveting, process and does not consider logistics, the environment and other processes performed at the same station. For cycle time calculations it is assumed that handling and walking will be better or the same, so these are not further investigated. Also, all calculations are based on one version of the A320 family, the A321. As a decision for the type of automation is already made earlier during the FAL project no automation solutions other than robots are considered in this thesis. Furthermore, the robots will operate from the outside of the fuselage; counterparts or automated systems working from the inside will not be installed due to limited access and long setup times. Another limitation is that the robots and end effectors as well as their CAD data are not available for the student. Therefore, no practical tests or simulations could be performed.

1.4. Approach and Thesis Outline

The thesis starts with a background and literature review including the topics aircraft assembly, automation and robotics as well as state of the art and R&D in aircraft assembly automation (chapter 2). Moreover, the applied approaches and methods are explained (chapter 3). Afterwards, the as is process of the circumferential joint assembly is modelled by process mapping, cycle time analyses and explaining product and process requirements (chapter 4). Based on the overall project’s conditions and further analyses such as SWOT and capabilities of human and machine conceptual ideas are developed for a possible future assembly process (chapter 5). These concepts are evaluated in a utility analysis with the use of ranked criteria, cycle time calculations, tolerance analyses and further investigations (chapter 6). The results are presented in terms of a new process, a tacking and referencing map and a comparison to the as is process (chapter 7). Finally, the solution is validated by determining its lead time and conducting a risk assessment (chapter 8). The thesis ends with a discussion of the results, recommendations, method and using robots in aerospace industry in general (chapter 9) and the conclusion (chapter 10). Figure 2 shows the thesis outline.

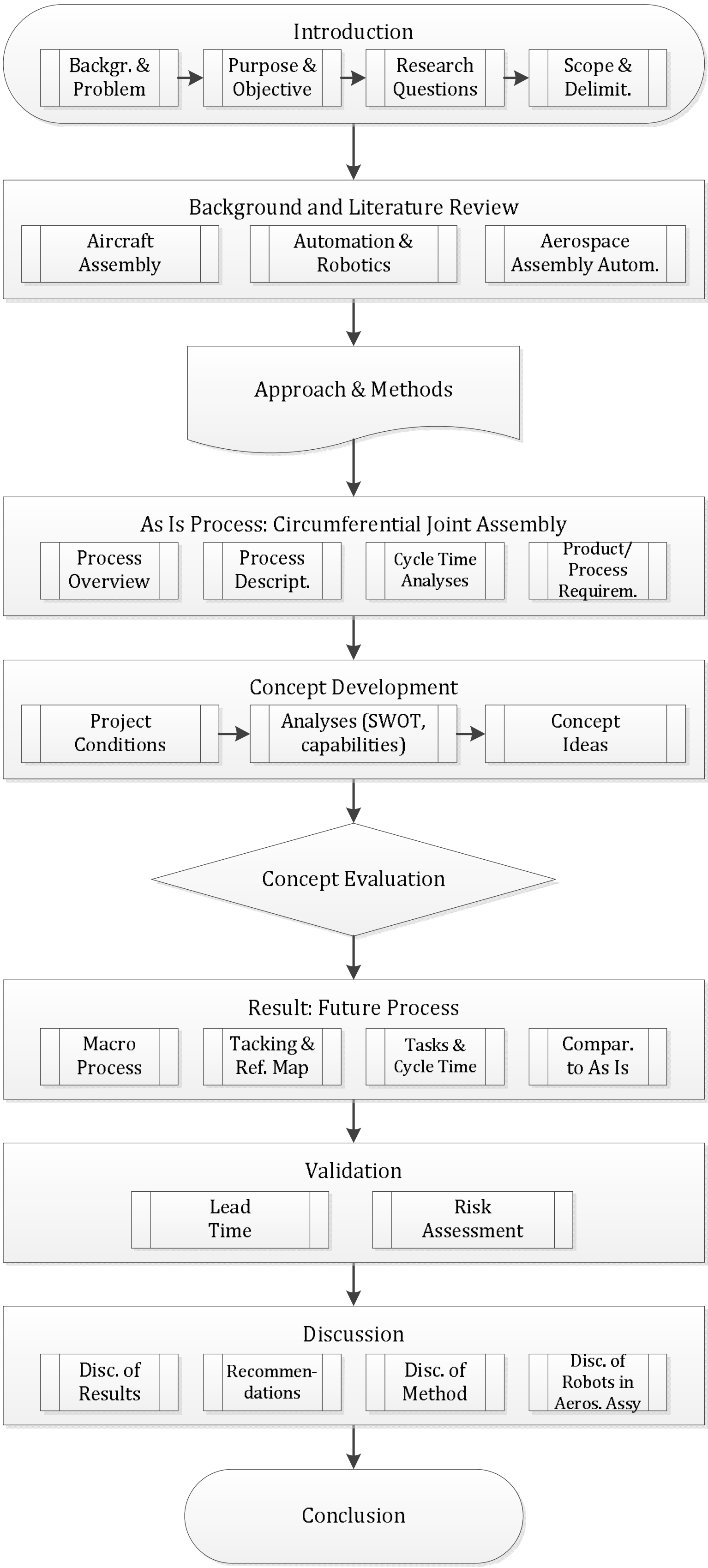


Figure 2 Thesis Outline (own figure)

2. BACKGROUND AND LITERATURE REVIEW

The background and literature review chapter is supposed to present the knowledge required to understand and follow the student's work. This thesis focuses on the development of a new production process, namely the automated assembly of the circumferential joint during the final assembly of an aircraft. However, a process is strongly affected by the product design and the resources performing the process. Also, it is controlled and constrained by quality requirements. Therefore, this chapter introduces the structural design of an aircraft (2.1.1) and gives an overview of the assembly process (2.1.2). Also, it addresses the resource, precisely the robot technology (2.2) and discusses state-of-the-art and R&D in aircraft assembly automation (2.3). Later, the specific product and process related requirements are explained (4.4).

Figure 3 Production and its input, output, resources and constraints (own figure)

2.1. AIRCRAFT ASSEMBLY

In the following the structural design of an aircraft and in particular the fuselage as well as the final assembly line process are explained and an overview of the final assembly line is given.

2.1.1. STRUCTURAL DESIGN: AIRCRAFT AND FUSELAGE

Today's aircrafts can be categorised into three construction groups: structure, power plant and equipment. The structure group can be further split into the

- the *wing* generating lift,
- the *empennage* (vertical and horizontal tail plane) stabilizing the aircraft,
- the *control unit* (rudders at wing and tail planes) controlling the aircraft's movements,
- the *landing gear* building the contact between fuselage and ground and
- the *fuselage* containing the cockpit, passengers and cargo. (Engmann & Grube, 2013)

Wings, tail planes and the landing gear are attached to the fuselage. Because human cannot survive at altitudes of 10,000 meters the passenger cabin is pressurized during flight. As shown in Figure 4 the fuselage structure is separated into sections (barrels) which each consist of several panels/shells that are connected by *longitudinal joints* (Engmann & Grube, 2013). The sections are then assembled via *circumferential (radial) joints* and the stringers are connected by couplings.

Most commercial aircrafts are built in a *semi-monocoque* fuselage design which means that the thin-skinned shell is reinforced by longitudinal stiffeners in flight direction (*stringers* and *longerons*) to stabilize and carry bending moments; *frames* attached transversely to the flight direction support the skin to prevent buckling and maintain the shape while *bulkheads* are placed at points of concentrated forces. A monocoque design would have the tendency to fail in buckling or crippling because the skin alone absorbs all forces. (Gudmundsson, 2014) (Niu, 1997)

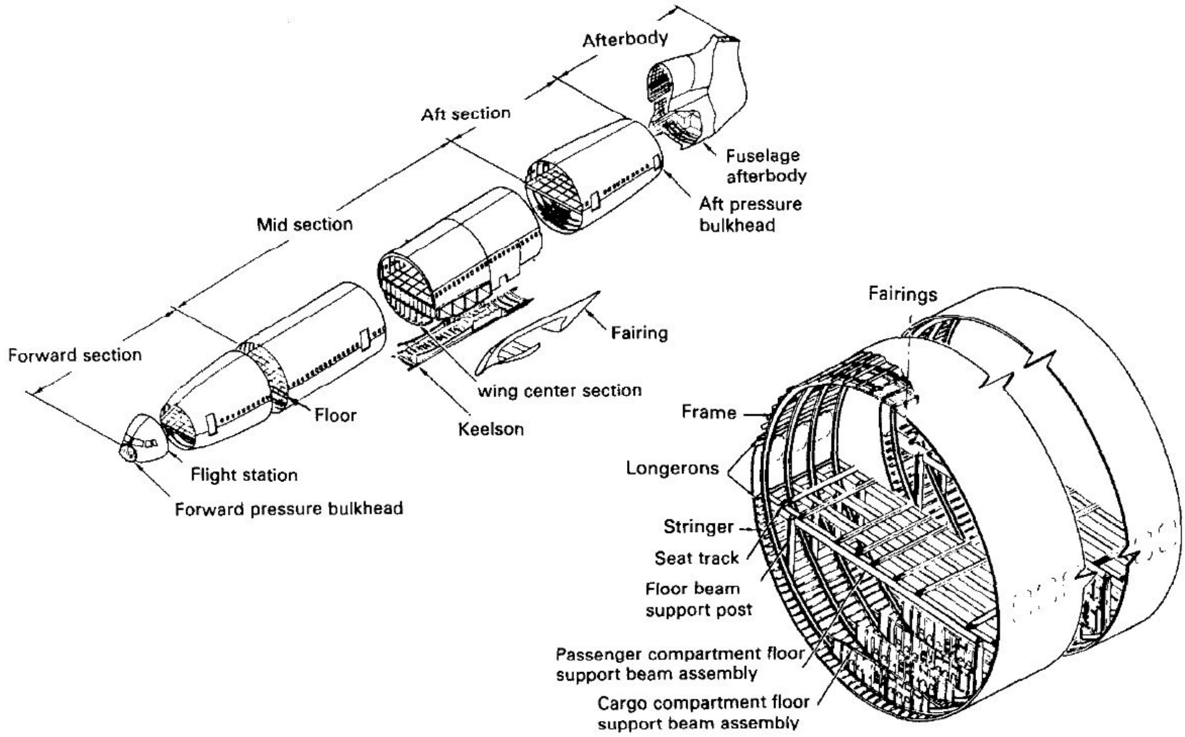


Figure 4 Typical semi-monocoque fuselage (Niu, 1997)

Since the cabin pressure has to stay constant the fuselage expands in high altitudes due to the decreasing air pressure. Radial tensile stresses are built up in the skin and rivets. In order to reduce these stresses in the rivet heads the frames are decoupled from the stringer-skin structure. They are assembled indirectly to the skin-stringer structure by using *clips* (or *shear plates*).

2.1.2. Final Assembly Line (FAL) Process

Prior to the final aircraft assembly the different sections are assembled in the major component assembly where all longitudinal and several circumferential joints are connected to form a forward and an aft fuselage half. Also, wings and other structural components are pre-assembled as much as possible.

The final assembly is performed by moving the aircraft through several stations. Figure 5 shows an overview of the entire process and further specifies the steps of the relevant station before showing the circumferential joint process in greater detail. At the first station the last circumferential joint, the one this thesis is referring to, is closed after the big cabin components such as galleys and lavatories are moved into the open fuselage. The two fuselage halves are joined and the stringer ends are connected by couplings. In addition, system connections are established and floor panels, the cargo loading system and commercial electronics are installed.

At station 2 the "marriage" is performed, i.e. the wings are assembled to the fuselage. Afterwards the engine pylons and main and nose landing gear are attached. Furthermore, the aircraft is connected to electricity for the first time. At station 3 the horizontal and vertical stabilizer as well as flaps, main landing gear doors, the radome, air conditioning and the fuel system are installed. Also, several systems and functions such as the cabin pressurization and the hydraulic system are tested. Station 4 is the main station for interior furnishing and further tests. The following steps consist of paint (station 5), engine assembly and customer acceptance check (station 6). Finally, the aircraft is delivered to the flight line for flight control tests and the first flight.

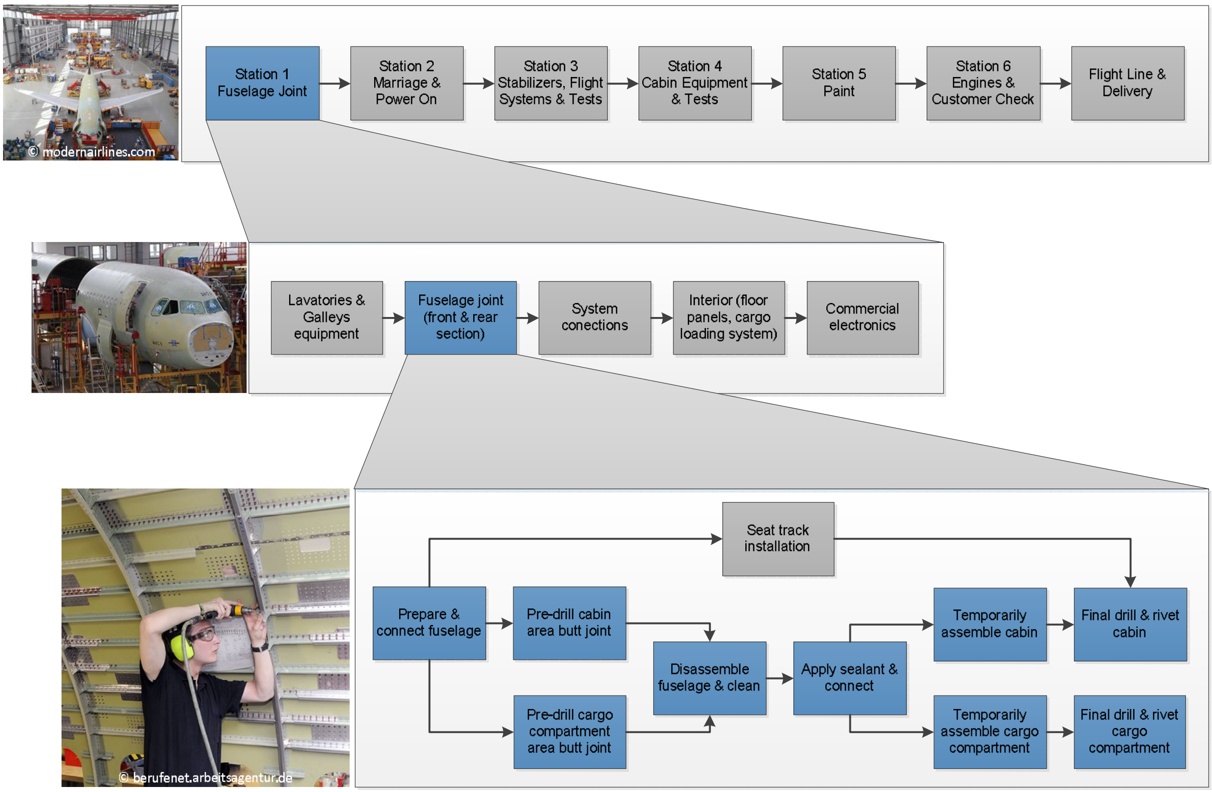


Figure 5 Final assembly process flow chart (own figure)

2.2. Automation and Robotics

The automation and robotics chapter gives a literature overview of automation in general and explains the technology of industrial robots (definition, mechanics, sensor and control system and programming) as well as the capabilities and performance of articulated robots relevant for aerospace assembly (accuracy, stiffness, loads and other criteria).

2.2.1. Automation

Automated manufacturing systems perform operations such as material handling, processing, assembly or inspection with a reduced level of human participation (Csanyi, 2016). The automation definition in general *"implies operations or acting, or self-regulating, independently, without human intervention"* (Nof, 2009). When automatic control was added to mechanization in the 1950s the advantages of automation became clear (Nof, 2009). Besides robotics, automation includes numerically controlled machining centres, dedicated automatic assembly machines and other special purpose machines (Appleton & Williams, 1987).

There are several reasons for automation of manufacturing processes. The most common are:

- Productivity increase in terms of production rate or labour productivity by operating at high speed and capacity,
- Reduction of labour cost by replacing manual activities,
- Improvement of product quality due to more constant process parameters and the elimination of human errors,
- Reduction of manufacturing lead time and response time,

- Elimination of repetitive and fatigue manual tasks and thereby improvement of working conditions and ergonomics,
- Improvement of operator safety in case of unsafe environments and
- Feasibility of certain processes that require e.g. high precision or miniaturization. (Beyer, 2004) (DeVlieg & Feikert, 2008)

Besides the questions why and when to automate the question what to automate has to be answered. According to Waurzyniak (2015) one should concentrate on high volume products/ processes with long product life cycles. "Other issues that indicate a potential for automation are excess material handling, operator dependent quality, and operations that are repetitive or difficult to do manually." The tendency to try to automate everything has been a failure of many automation projects as an extreme degree of automation does not necessarily achieve the desired goals. For instance limits are often reached when a work task requires a great deal of perception, skill or decisiveness.

In terms of industrial robots the use for handling, welding and painting operations is state-of-the-art. They are used for loading and unloading machine tools, die-casting machines or transport components between stations. Thereby cycle times are reduced and shop floor space can be saved. Automated assembly operations with robots are not that widespread and limited to applications with large production volumes because of the high hardware costs. The difficulty is that more than one work piece needs to be located with respect to any tools in the workplace. Also, they have to maintain certain orientations and relative positions while moving. (Appleton & Williams, 1987).

2.2.2. Industrial Robots Technology

Definition

Robotics is a subset of automation. The ISO definition of a robot is as follows:

> *An automatically controlled, reprogrammable, multipurpose, manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications.* (ISO 8373, 2012)

The aspect *programmable* refers to the development of microprocessors which enabled the design of general purpose electronic devices that can be produced in large, hence economic, quantities. Robots are adaptive, act upon the computers' instructions and translate these into physical actions. The ability to reprogram an action gives the opportunity to meet changing circumstances. Programs can further include logic and arithmetic routines with interactive use of sensor-generated data. The term *multipurpose* differentiates robots from most other forms of automation which are mainly used in mass production to recover the high costs for special purpose machine development. In contrary robots are flexible in application to a wide range of tasks. Further, they are *manipulators* for handling parts, tools and other specialized devices and have *multiple axes* (or degrees of freedom) enabling the robot to reach different positions and orientations. V*ariability* can be achieved by simple instruction devices such as conditional statements (e.g. by position sensors), repetitive loops with counters etc. The ability of robots to vary their response to changing task requirements allows such systems to respond to low levels of disorder in the manufacturing environment. (Appleton & Williams, 1987)

Mechanics

Robots can be specified by their manipulator configuration, actuator types, workspace, payload, speed or end effector and task:

- Within the group of stationary robots that do not change their position by themselves typical *manipulator configurations* refer to Cartesian/Gantry robots, spherical/polar robots, cylindrical and SCARA (Selective Compliance Assembly Robot Arm) robots, jointed-arm robots, also called articulated robots, and parallel robots.
- The *workspace* of a robot defines the boundary set by the limitation of motion of all robot axes and is determined by the extent, number and type of its basic axes. Besides reach it has to be ensured that the robot also does not collide with other equipment or the work piece itself. In many applications an extra axis of motion at the robot base is added. Figure 6 shows the configuration and work space of an articulated robot.
- *Actuators*, for instance DC motors, move the robot joints.
- Regarding *payload* and *speed* the engineer must often make a compromise.
- *End effectors* can be mechanical grippers for handling assembly applications, vacuum grippers for handling or special purpose tools such as welding guns, painting equipment or machining tools. (Appleton & Williams, 1987)

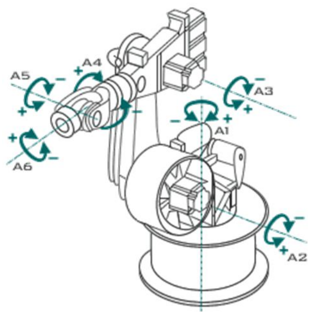
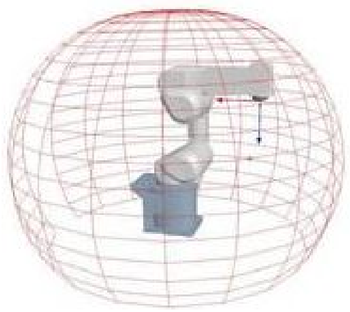
Principle	Workspace	Photo
 © looptechnology.com	 © ifr.org	 © directindustry.org

Figure 6 Articulated robot configuration and work spaces

Manipulators consist of (nearly) rigid links which are connected by *joints* that allow relative motion of neighbouring links. Most industrial robots have either revolute (rotating) or prismatic (sliding) joints (Figure 7). Consequently, the number of *degrees of freedom* of the robot arm - the number of independent movements in the coordinate system - is equal to the number of joints. "Since a rigid body in space has six degrees of freedom, the most general robots are designed to have six joints." This way, the end effector can reach any position or orientation. As in Figure 6, typically robots have three *axes* (or degrees of freedom) associated with the arm, often referred to as waist, shoulder and elbow, and three axes associated with the wrist whose motions are called roll, pitch and yaw. (Kumar) (Craig, 2005)

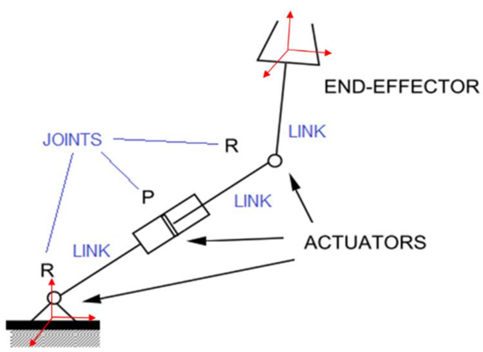


Figure 7 Manipulator with revolute & prismatic joints, coordinate frames, adapted from (Kumar)

In order to describe the position and orientation of an object in space a coordinate system, or frame, needs to be attached to the object. Any frame, e.g. the base frame (see Figure 7), can serve as a reference system, so transformations between frames are performed. (Craig, 2005)

SENSOR AND CONTROL SYSTEM

Sensors can either assess the internal state of the robot (positions, velocities and torques in the joints) or the robot environment (force, tactile and distance sensors, robot vision). They utilize physical phenomena such as resistance and capacitance change, the piezoelectric, photoelectric and Hall Effect.

Almost all manipulators are servo-controlled, that is, the force or torque command to an actuator is controlled and thereby based on the error between the sensed position and the desired position of the joint. The *position sensing* device is usually located directly at the shaft of the actuator. If the drive train is stiff and has no backlash the correct joint angles can be calculated from the shaft position. Often *rotary optical encoders* are used for the position feedback. As the encoder shaft turns, a disk containing a pattern of fine lines interrupts a light beam. A photodiode converts these light pulses into electric current (Figure 8). The shaft angle is determined by counting the number or pulses. For measuring linear displacements linear variable differential transformers (LVDT) are an example of the potentiometers that can be used. Velocities are derived by taking differences of sensed position over time or installing *tachometers* which use a magnetic field. (Craig, 2005) (Bajd, Mihelj, Lenarcic, Stanovnik, & Munih, 2010) (Jeong, 2009)

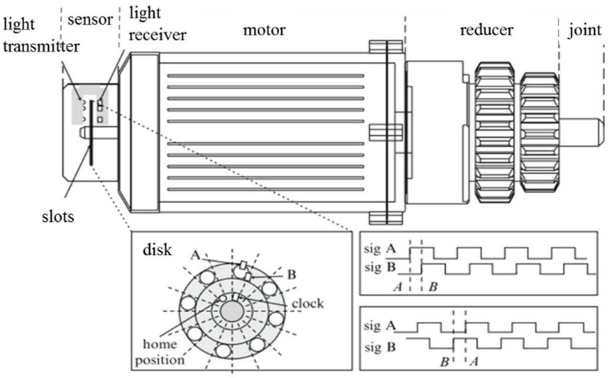


Figure 8 Model of an incremental encoder (Bajd, Mihelj, Lenarcic, Stanovnik, & Munih, 2010)

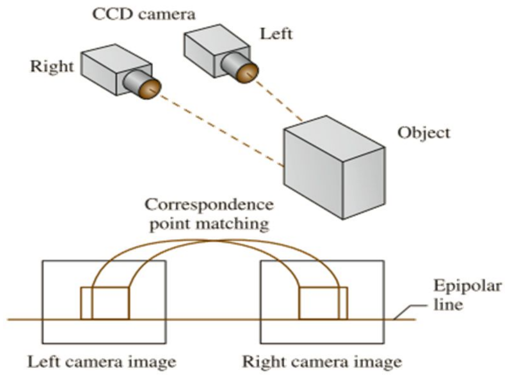


Figure 9 Stereovision method for 3D vision sensors (Inabu & Sakakibara, 2009)

Today robots cannot only play back motions that had been taught but they can perform highly complicated tasks and became intelligent mainly due to the implementation of vision and force sensors at the beginning of 2000. These also reduce the need for preparations and system monitoring. For *force sensing* most often *strain gauges* are used. These are bonded to a structure and produce an output proportional to the strain in the material as the gauge's electrical resistance changes when forces are applied. Such sensors are usually placed between the end-effector and the last joint of the manipulator at the "fingertips" of the end-effector to measure the forces and torques acting on the end-effector and thereby give robots dexterity. While the inner ring is in contact with the end-effector the outer ring is in contact with the environment (Figure 10). They are connected by elastic beams with strain gauges. The use of force sensors has enabled the robot to do such tasks as shaft fitting for precision machine parts assembly as in Figure 11 as well as deburring and polishing, which require a certain pressure. (Craig, 2005) (Bajd, Mihelj, Lenarcic, Stanovnik, & Munih, 2010) (Inabu & Sakakibara, 2009)

Robot vision sensors are used to recognize the geometry of the robot workspace from a digital image taken by a camera. They can measure shape, orientation, defects etc. 2D vision sensors determine the geometrical relation between the coordinates of the point in space (3D) and the point in the image (2D). For 3D vision sensors two methods are available. The structured light method irradiates slit light or pattern light on an object and takes images of the reflected light. From these the 3D position and posture of the object are calculated with high accuracy. This method is used for instance for bin picking which enables a much simpler peripheral equipment and eliminates the need for arraying work pieces. The stereovision method uses images taken by two cameras, by matching corresponding points on the left and right images to calculate the objects' 3D position and posture (Figure 9). This can enable a robot to recognize its surroundings. (Inabu & Sakakibara, 2009) (Bajd, Mihelj, Lenarcic, Stanovnik, & Munih, 2010)

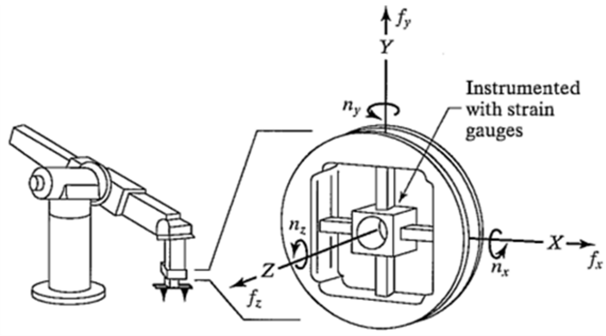


Figure 10 Structure of a typical force-sensing wrist (Craig, 2005)

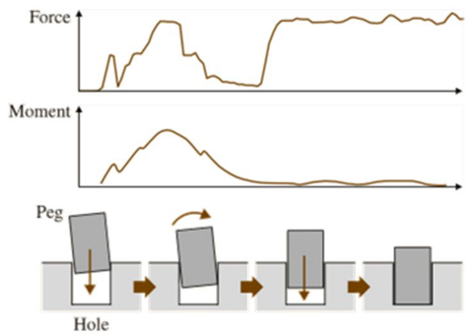


Figure 11 Peg-in-hole with force sensor (Inabu & Sakakibara, 2009)

In order to make use of the sensors and I/O signals *control algorithms* are implemented which compute force or torque commands for the actuators. Thereby errors in the knowledge of parameters in the mathematic model of the manipulator are compensated. "The end-effector pose is only controlled indirectly. It is determined by the kinematic model of the robot mechanism and the given values of the internal coordinates." In order to cause the manipulator to follow the desired trajectory a *position control* must be implemented. It uses sensor feedback to keep the manipulator on course. Figure 12 shows a general robot position control system. The input is the desired pose of the robot end-effector (x_f), which is obtained by trajectory interpolation methods. The vector $x = [x\ y\ z\ \phi\ \vartheta\ \psi]^T$ describes the actual pose. By the use of inverse kinematics the corresponding internal coordinates q_r (joint angle for rotational joints, distance for translational joints) are calculated. The desired internal coordinates are compared to the actual internal coordinates in the robot control system. On the basis of the positional error $\tilde{q}$ the control system output u is calculated. This one is converted from a digital into an analogue signal and delivered to the robot actuators. These ensure the forces or torques necessary for the required robot motion which in turn is assessed by the sensors. (Bajd, Mihelj, Lenarcic, Stanovnik, & Munih, 2010)

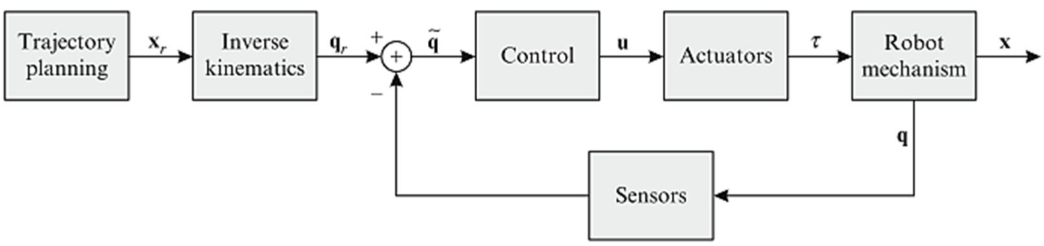


Figure 12 A general robot position control system (Bajd, Mihelj, Lenarcic, Stanovnik, & Munih, 2010)

PROGRAMMING

In robot systems the user instructs the robot by use of a specified *tool centre point* (TCP). Motions of the robot will be described in terms of desired locations of the operational point. Most often paths are constructed by specifying a sequence of points, speeds, smoothness criteria etc. From these inputs

- The *trajectory generation* algorithm generates a coordinated motion with each joint starting and ending at the same time. Therefore via points through which the manipulator must pass are defined (point to point movement) or the TCP is forced to follow a straight line
- The set of joint angles for the given position and orientation is calculated by *inverse kinematics*
- Similarly the related joint velocities are calculated by the *Jacobian matrix*. (Craig, 2005)

The programming technique can be differentiated into

- *On-line programming* such as teach in (manually moving the robot with the controller and saving the desired points with their axis positions) and play back techniques (manually guiding the robot along the desired path and saving the axis positions) and
- *Off-line programming* using coding in a programming language or CAD supported programming and simulation.

On-line programming eliminates accuracy errors of the robot while off-line programming reduces programming errors before the implementation in production and thereby accelerates programming and implementation.

2.2.3. CAPABILITIES AND PERFORMANCE OF ARTICULATED ROBOTS

In the following critical capabilities and performance of standard articulated robots relevant for aircraft assembly are discussed: precision/accuracy and the ability to cope with loads which is also related to the robot's stiffness.

PRECISION/ACCURACY

Industrial robots are developed to conduct repetitive tasks such as spot-welding and pick-and-place. The *repetitive accuracy (repeatability)* of a robot specifies how precisely it can return to a point that was taught and whose joint angles were stored before. (Kihlman, 2005)

On the contrary if a desired position and orientation are defined in Cartesian terms the inverse kinematics of the device must be computed to solve for the required joint angles of a point to which the robot perhaps has never gone before. The precision with which such a computed point can be attained in reality is called *absolute (or positional) accuracy*. It is affected by the precision of parameters appearing in the kinematic equation of the robot. Errors in knowledge of parameters will cause the inverse kinematic equations to calculate joint angles with an error. Hence, although the repeatability of most robots is good (ca. ±0.2 mm for a new standard large-size robot), the accuracy is much worse (ca. ±2 - 4 mm). (Craig, 2005) (Devlieg, 2010)

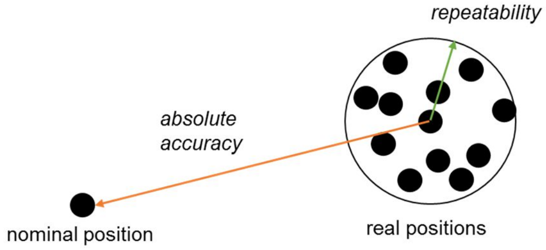


Figure 13 Absolute accuracy and repeatability, based on (Beyer, 2004)

Sources for errors include:

- Geometric zero position errors of the joints (80-90% contribution),
- Geometric errors in link lengths & offset angles due to manufacturing & assembly tolerances (5-10%),
- Thermal effects (0-10%),
- Lack of stiffness due to the serial (open frame) architecture and deflection under payload (3-8%),
- Backlash and inaccuracies in gearboxes (1-2%),
- Errors in load data and
- Resolution of position sensors. (Beyer, 2004) (DeVlieg & Feikert, 2008)

Typical calibration packages allow an improvement in accuracy to ca. ±0.8 – 1.0 mm. However, these values are not satisfying for aerospace industry which requires a positional accuracy of ±0.2 – 0.5 mm for parts and drilled holes. Hole accuracy may require positional accuracy of ±0.05 mm if the parts being drill are interchangeable and not drilled together in a stack. The positional error of a possible travel track which enlarges the work envelope adds to the robot's accuracy error. (Kihlman, 2005)

STIFFNESS AND LOADS

An important characteristic of manipulators is the *stiffness* of the structure and the drive system so that they do not deflect under gravity or loads. Stiffness is needed because typical robots do not have sensors to measure the TCP frame location directly but calculate those based on sensed joint positions. Furthermore, flexibilities lead to resonances which have an undesired effect on the robot's performance. (Craig, 2005)

If the force vector is from a direction other than in gravitational direction the controller cannot handle these loads. "When a robot is exposed to a force at the TCP it will not stay orthogonal to the work piece anymore. […] In drilling using an industrial robot forces change rapidly: [first when pre-pressurizing the drilling tool in a static manner and second during drilling in a dynamic, varying way]. Today, suppliers of drilling end-effectors handle this problem either by pre-pressurizing the drill bushing that the cutter is fed through, or using an additional pressure foot on the drilling end-effector. […] The pre-pressure force must be significantly higher than the thrust force in the drilling, which ensures that the drilling end-effector maintains its position and orientation during drilling." (Kihlman, 2005)

OTHER CRITERIA

For drilling and fastening operations most often huge and heavy end-effectors are needed. Therefore the *payload* of the chosen robot is an important criterion.

The robot's work envelope, the system environment, the end-effector and its nose piece and the work piece itself affect the *reachability as well as accessibility* required for the assembly process.

Speed and acceleration capabilities are less critical in aircraft production as very high speeds are not required.

2.3. AEROSPACE ASSEMBLY AUTOMATION

Automotive manufacturers have been using automation extensively to build mass-produced products at relatively low cost whereas aircraft structures are low-volume, large-scale products with high quality requirements including tight tolerances and cost millions of Euros. Furthermore, there is a greater amount *of tasks to be accomplished by one automation system. The small production rates with takt times of days or weeks instead of minutes as in automotive make it difficult to efficiently task an automation system during the day and potential shared work spaces between man and machine must be made safe. The 'volume' demand is not the product throughput, but rather the high number of process steps required. Faced with long order backlogs and health and safety risks for operators performing drilling and riveting operations aircraft manufacturers automate some of these processes at different aircraft assembly levels.*

First, this chapter explains the considerations before replacing manual assembly by automation. In the following the "traditional" state of the art automation by dedicated monumental machines as well as the last 15 years' developments using articulated robots with end-effectors are discussed.

2.3.1. CONSIDERATIONS BEFORE AUTOMATING

Bullen (2013) focuses on drilling and countersinking operations and "approaches the automation from a practical, low-hanging fruit perspective. There are holes in the airframe that would be prohibitively difficult and expensive to apply automation. Some things humans do better than machines. Some things humans do not do as well as machines, but they do them more efficiently at an acceptable quality level." (Bullen, 2013)

There are obvious benefits of automated assembly when designing an assembly line from scratch such as lower per hole cost, increased quality, consistent throughput, and fewer repetitive motion injuries. A different decision model must be used for an existing assembly line, including the considerations for changeover from hand to machine operation. The considerations necessary for automation application are (Bullen, 2013):

- *Feasibility analysis* including
  - Reach and access by the machines (analysis e.g. by simulation in CAD or shop floor measurements),
  - Ability of the flooring to support the added weight of the machine,
  - Ability of the fixtures, templates and tools to integrate with the machine (for example a machine will deflect the structure much more than hand tools),
  - Factory infrastructure and capabilities necessary to support the operation of the machine (e.g. maintenance, programming, personnel, etc.),
  - Disruption/impact on operations and supply chain that interact with the automation (performance, safety), e.g. tighter drilled holes need more consistent fastener sizes,
  - Environment (assessment, atmospheric conditions in the factory such as stable temperature and humidity) and
  - Readiness of labour to accept automation.
- *Risk assessment* based on the feasibility analysis and risk reduction plan
- *Cost benefit analysis* including
  - Manual process time study as a basis for comparison,
  - Automated drill time study (assumptions, industry benchmark),
  - Conversion of hourly to monetary numbers and comparison of the manual and automated process (cost benefit analysis).
- *Return on Investment (ROI)* calculation with
  - Machine cost (investment plus costs for tests, installation, training, maintenance),
  - Ancillary costs (effects on the environment and other processes),
  - ROI calculation:

$$\frac{hourly\ savings/aircraft\ [€]*number\ of\ aircrafts/year}{machine+\ ancillary\ automation\ costs\ [€]} = payback\ time\ [years].$$

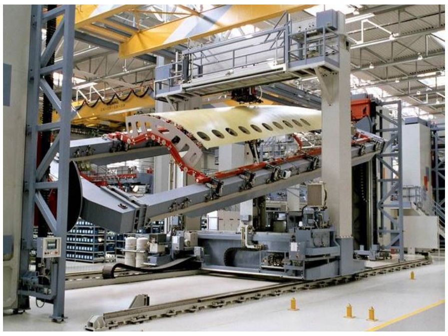
Finally, a decision for or against the automation project is taken. Most companies require two to five years payback. However there are other criteria such as quality improvements, complexity and precision needed or access and ergonomic issues that can weigh higher than the ROI. (Bullen, 2013)

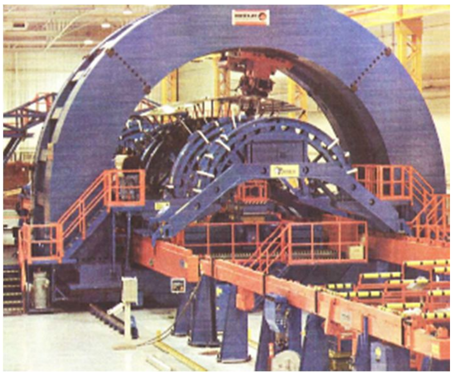
2.3.2. State of the Art – Dedicated Machines

Traditional automated aircraft assembly systems are custom-designed "where the combination of tight engineering tolerances, the need to reduce part variation, and large machine envelope drives large and expensive machines." Despite the high initial cost the use of automation addressed the need to improve quality, reduce lead times and costs and improve ergonomics. They are programmed to drill at a specified speed and feed which leads to a better and more consistent hole quality. For single and very large panels, C-frame and gantry riveting/fastening machines are commonly used. "The most suitable system to assemble [longitudinal and circumferential] joints of half-shells (fuselage barrels) is a ring riveter, and final aircraft assembly is performed manually using advanced hand tools." (Sarh, Buttrick, Munk, & Bossi, 2009) (Sarh, 2002) The automated systems drill holes and sometimes also insert fasteners. They have an outer and often also an inner device carrying end-effectors. The outer module usually performs the drilling and (temporary) fastener insertion or installation while the inner module can use a clamping tool and rivet upsetting or installation tool. If clamping of pieces is performed at the drilling location from both sides by using inner two modules or a ring riveter for instance a one-way assembly without disassembly is possible and efficiency can be improved significantly.

Table 1 shows some chosen dedicated machines. An example for FAL assembly by a dedicated machine is the S.O.J.A. (Système Orbital de Jonction Automatisée) of the Airbus A340. It fulfils requirements for holes of ±0.04 mm and positional accuracy of ±0.5 mm. S.O.J.A. consists of two mobile end-effectors that run outside of the aircraft guided by rails all around the circumferential joint. It selects a position, drills 6000 holes in total with countersinks, applies sealant and inserts lockbolts which are swaged by the operator inside the fuselage. 2000 fastener locations cannot be accessed and have to be assembled manually. (Ribère, 2002)

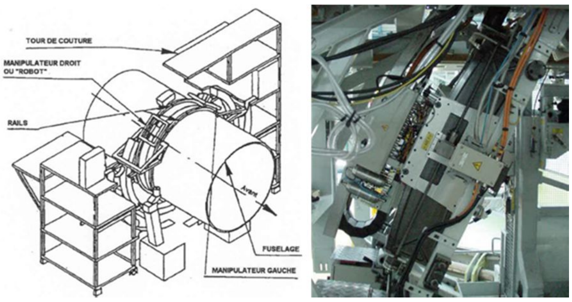
Table 1 Examples: dedicated machines

	Integrated Panel Assembly Cell (IPAC) from Brötje Automation: riveting system for panels with CNC controlled axes (Brötje Automation, 2016)
	A400M Composite Automated Wing Drilling Equipment system: 5 axis machine tool for automated drilling and bolt insertion for wing box assemblies (Electroimpact, 2016)



High level fuselage assembly by a ring riveter
(Sarh, 2002)

High level fuselage assembly by a longitudinal joint system on rails
(Sarh, 2002)



A340 FAL assembly by S.O.J.A. (Système Orbital de Jonction Auto-matisée)
(Ribère, 2002)

The large dedicated machines are able to ensure the required accuracy and stiffness in dynamic processes and cover a large work envelope. The downside of this approach is, however, that these machines are expensive, need long development times and are dedicated to "the narrow scope they are designed for". Once that purpose changes, these systems are very difficult and expensive to reconfigure and therefore often become obsolete. (Kihlman, 2005) (Devlieg, 2010)

2.3.3. Research and Development - Robots and End Effectors

The aerospace industry, where large dedicated machines have been the common method for automation, is now striving to reduce costs, shorten lead times and increase flexibility. (Kihlman, 2005) Robots offer airframe manufacturers benefits in both cost and application flexibility. "The articulated arm spans a large working envelope capable of navigating along highly curved surfaces and into tight spaces." (Devlieg, 2010) Other benefits over fixed automation include increased uptime, reduced maintenance costs and a reduction in jig-fixture requirements. However, there is a mismatch between abilities and requirements.

Standard robots typically have

- an absolute positioning accuracy of about ±2.5 mm,
- a good repeatability of ±0.2 mm and
- teach-mode supported off-line programming (eliminating accuracy errors).

Aerospace typically requires

- an absolute positioning accuracy of about ±0.2 to 0.5 mm,
- a good repeatability of ±0.1 mm,
- exact path accuracy for collision detection in virtual production,
- ±0.1° in normality with respect to the surface,
- safe integration and
- 100% off-line programming. (Eickhorst, 2011)

Variants and a huge number of process positions are common in aircraft structures. The location of assemblies within the automation cells are typically not tightly controlled, they often lack stiffness and during assembly single part tolerances add up, which are especially large if they belong to the older aircraft programs. Manufacturers therefore require the ability to program systems offline, whereby teaching methods become obsolete. These would have the advantage that errors become zero if the robot is repeatable.

Metrology systems such as *laser trackers* as in Figure 14, *photogrammetry* with camera systems (Whinnem & Nystrom, 2000) and *indoor GPS* are available for global accuracy improvement to the required level. Real time guidance can greatly improve positional accuracy. For instance, the F-35's J450 Wing Overlap drilling at Lockheed uses metrology (FARO laser trackers and pointers) guided drilling and achieves drilled holes within a 0.18 mm radius (Waurzyniak, 2013). However, the equipment is expensive, tends to restrict the working range and suffers from line of sight issues. The recent development of the accurate robot technology represents a paradigm shift for the use of articulated robotics in airframe assembly. (Devlieg, 2010) The positional accuracy of the robot is improved with the addition of

- high-order kinematic models (calibration),
- secondary position sensor (encoder) feedback at the output of axes and
- fully integrated conventional CNC control.

Robotic technology can now compete on a performance level with customized high precision motion platforms. Because the physical robot never exactly matches the nominal model due to manufacturing and assembly variation, a unique kinematic parameter set can be developed for the individual robot. By calculating the ideal transformations for the TCP and mounting skew are determined and the misalignment in additional axes is mathematically reduced. Deflections due to payload and working loads are predicted and compensated for by characterizing the stiffness of the arm. C*alibration* in general means to find the connection between input and output. It is done with the help of laser tracker position measurements for the specific robot (Figure 14). At each location, position data for each of the laser targets on the end effector along with the robot axis positions are captured and used to solve for the kinematic parameters. In practice, this has proven to achieve positional accuracies of nearly ±0.5 mm in a restricted range. (Devlieg, 2010) (DeVlieg & Feikert, 2008) Brötje's *compensation* package includes calibration of the robot geometry, temperature compensation, sag and torsion compensation with respect to the end-effector weight and process forces and grid compensation taking into account the work envelope (Eickhorst, 2011). Further, newer, more rigid robots like the new Fanuc Robotics M-900iB/700 are part of the trend of robots moving into more machining-type processes, like drilling and riveting. (Waurzyniak, 2013)

On a typical robot the position feedback for each axis is located at the servo motor. Ahead are numerous sources of error such as backlash and joint deflections due to payload and applied loads (5mm position alteration possible in total). Using *secondary encoders* at the output of the axes

(Figure 15) yields much tighter control on axis position and, in turn, reduces repeatability tolerances to nearly zero. Consequently, a more representative kinematic model is obtained. (Devlieg, 2010)

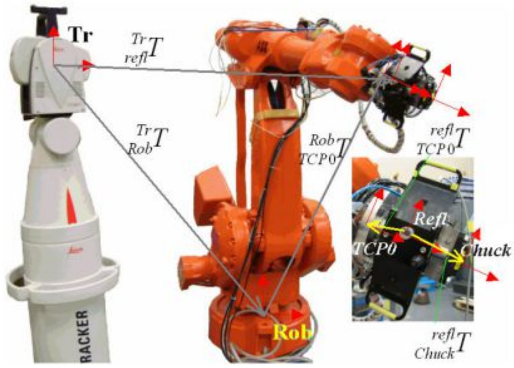


Figure 14 Laser tracker metrology system for accuracy improvement (Kihlman, Ossbar, Engströn, & Anderson, 2004)

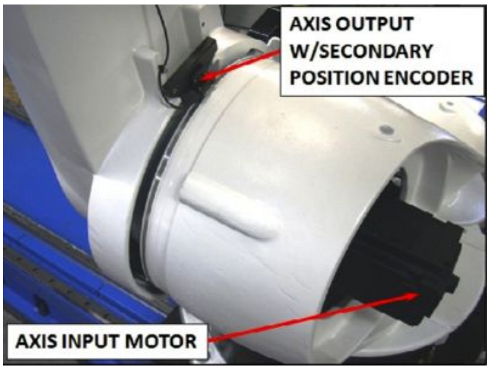


Figure 15 Robot axis with secondary encoder (Devlieg, 2010)

As calibration and secondary encoders improve the global accuracy, automated camera vision systems help to locally align the machine to the work piece. The principle is explained in chapter 2.2.2. For work piece *datuming* the machine drives to several nominal target locations (e.g. holes, fasteners, edges), captures an image and determines the offset between the nominal and the actual positions. This procedure allows for a best-fit corrected transformation. (DeVlieg & Feikert, 2008) As rivet edge distances specified by the design are often small compared to the minimum required distance in order to reduce weight the *referencing* capability of actual targets is also used to ensure that the edge distance to the structure is maintained when holes are positioned. This feature also addresses the need for 100% off-line programing. Alternative vision systems work with laser-line sensors (Mehlenhoff & Vogl, 2009).

Another type of inaccuracy that needs to be addressed is the ability to remain in position or on-path while loads are applied. During drilling clamp force is usually applied to avoid that chips and burr are lodged between the parts' surfaces. The drilling process itself generates a force as well. Consequently, moments are created about each of the six robot axes, the axes deflect slightly, which results in the loss of *normality* and a movement of the tool tip across the panel surface (called *slippage* or *skating*). The deflection at the joints makes up 50-80% of the total TCP deviation. If secondary encoders are used local joint error is negligible, however deflection still occurs in the links, bearings, etc. (Devlieg, 2010)

A possible solution is high-bandwidth force control via 6 DOF force/torque sensors that are mounted on the drilling tool close to a pressure foot in the form of a tripod (Figure 16). Compared to force sensors vacuum suction or electromagnetic forces to attach the drilling tool to the surface would be inflexible. "The goal is to apply a constant normal force to the drilled surface with the tripod prior to drilling, and to keep the tangential forces small enough to avoid sliding of the drilling tool on the surface during drilling […] by a combination of high-bandwidth control of the axial forces applied to the work piece, and active suppression of the sliding forces through a model-based force control scheme." (Olsson, Robertsson, & Johansson, 2007) The force feedback loop reads the force data and manipulates the robot. Suppressing torques at the TCP will eliminate normality problems while suppressing forces in the plane will eliminate slippage effects. Now the pressure foot can effectively be used to press the parts together to avoid chips and burr entering between them and to assure that the machine is kept stable during drilling. (Tomas Olsson, 2010)

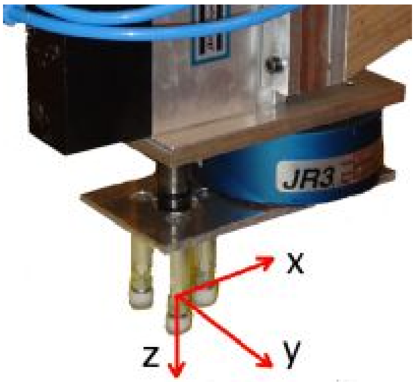


Figure 16 Robot drilling tool and tripod with JR3 force sensor (Olsson, Robertsson, & Johansson, 2007)

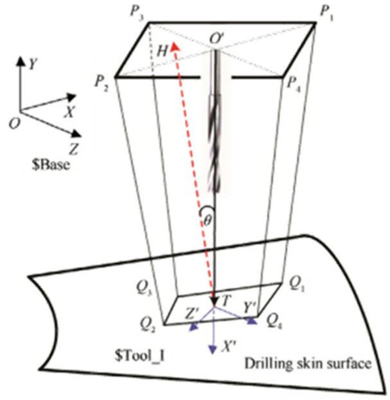
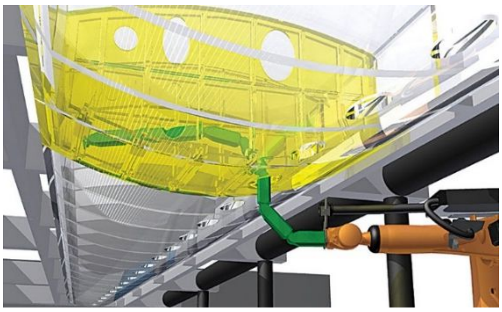


Figure 17 Geometric model of non-contact normality detection (Wei, Weixue, & Wei, 2012)

An approach for non-contact normality detection is the use of laser displacement sensors installed at the head of the end-effector. First these sensors each measure the distance to the surface to calculate the deviation between the normal vector and the spindle axis (Figure 17). Then, the robot target attitude is inversely solved in order to adjust the robot via rotations about the TCP according to the normal vector. Non-contact normalization can be used for panels with low stiffness and C-clamp end-effectors. (Wei, Weixue, & Wei, 2012)

Table 2 Examples: low level assembly using robots

	Robot cell for drilling and solid riveting in cargo door structures of an aircraft at EUROCOPTER (Mehlenhoff & Vogl, 2009)
	Shell assembly system from Dürr AG (Weber, 2015)
	Snake-like robot that can tighten fasteners inside wing structures and other confined spaces, recent development from the Fraunhofer Institute (Weber, 2015)

Today manufacturers such as Spirit AeroSystems use robots on several product lines, including Boeing 787 fuselage, pylon and wing structures, Boeing 737 fuselage and thrust reverser components; Sikorsky CH-53K cabins and cockpits. The primary reasons are to reduce manpower, increase throughput and improve quality but also reduce ergonomic risks associated with repetitive drilling and fastening. (Weber, 2009). Table 2 shows examples for low level automation.

Robots and automation in upper level assembly, however, are rare. Figure 18 shows the Fuselage Automated Upright Build (FAUB) pulse production line installed by KUKA Systems Aerospace to automate riveting of up to 60,000 fasteners per fuselage for the Boeing 777. It uses multi-function end effectors from Alema Automation.

Figure 18 FAUB robotic system right (Waurzyniak, Aerospace Automation Stretches Beyond Drilling and Filling, 2015)

Typical requirements on end-effectors as the ones in Figure 19 are process quality criteria, cycle times, size and weight limitations, autonomy and functionality. End-effector are often modular with separated units for drilling/countersinking, sealant application, rivet insertion/upsetting/ squeezing and quality control to allow for easy maintenance and reconfiguration. This might be necessary for different fastener types or sizes. Other functions can be clamping, automatic drill change, chip and dust removal and coolant supply. In a double sided process the second end-effector has clamping and rivet installation or squeezing functions as it provides a reactive force for the first end-effector.

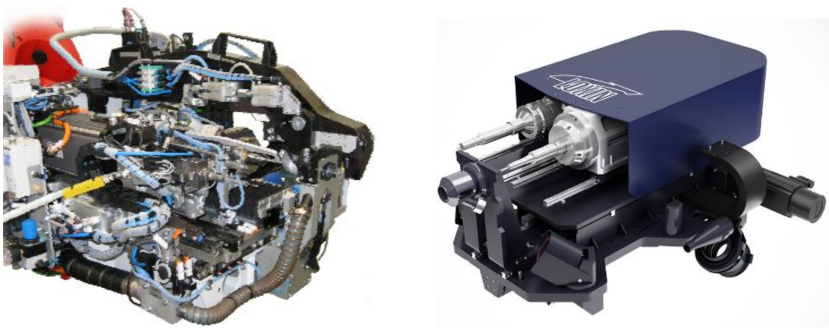


Figure 19 Multifunction End-Effectors from Brötje (Mehlenhoff & Vogl, 2009) and Loxin (Loxin, 2016)

The KUKA Systems Aerospace multifunction end-effector (MFEE) is shown in detail in Figure 20. It can carry out all operations without releasing the clamping force as the rotating barrel makes it possible to choose different modules such as for drilling, fastening, fastener hammering, countersinking, sealant application into the countersink, blind rivets, hole quality measurement and relocation of targets (vision system plus telemeter). It also includes a rotating nose (pressure foot) for clamping with 40-90 daN, an anti-slippage and normality system as well as a fastener distribution set with tubes for several fastener types or sizes, sealant application and insertion. Anti-slippage is achieved by having the front part of the end-effector (nose on XY table) mobile compared to the back side. Through measuring the forces by a sensor located between the robot wrist and the end-effector slippage and normality are compensated. Further options of the MFEE are non-contact normality, a monitoring camera, flushness control and a halo sensor system. The robotic system guarantees minimum positioning accuracy of ±0.5 mm and normality of ±0.16°. (KUKA Systems Aerospace, 2016)

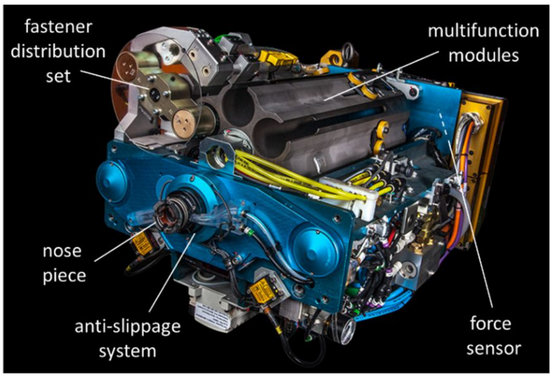


Figure 20 KUKA Systems Aerospace MFEE, based on (KUKA Systems Aerospace, 2016)

Other automation solutions besides articulated robots which are under development or recently implemented in production are parallel kinematic robots which have a higher accuracy and stiffness due to their geometric structure (Kihlman, 2005), crawler robots that move on the work piece surface without any fixture (Marguet, Cibiel, De Francisco, & Felip, 2008) and two-arm humanoid robots to perform repetitive assembly tasks in a collaborative environment, freeing up operators to work on higher value tasks (Weber, 2015).

2.4. Summary

In the assembly automation in aerospace industry tight tolerances and the need for stiffness and large envelopes led to the design of large machines, dedicated for one purpose. These could for instance be C-frame and Gantry systems for single and large panels or ring riveters for fuselage barrels while the final assembly is so far mostly performed manually with hand tools. The automated systems have an outer and sometimes also an inner device carrying end-effectors that drill holes, countersink and often also insert or even installs fasteners. The downside of this state-of-the-art approach is that the machines are expensive, need long development times and are dedicated to one task only.

Robot systems have benefits in terms of costs, flexibility and accessibility. However, standard robots cannot fulfil the requirements present in aerospace industry. The most important ones are absolute positioning accuracy, normality to the surface as well as the possibility for entire off-line programming. However, certain enablers make robots with end-effectors an alternative for aerospace assembly automation. These are the use of calibration delivering a high-order kinematic model for each individual robot, metrology systems such as laser trackers, secondary encoder feedback for the axes positions, camera vision systems for referencing, robots with increased rigidity built for machining operations and normality and slippage compensation via force control or laser sensors.

Nevertheless, aerospace industry is a challenging application area in terms of present aircraft design, volumes, quality requirements and manufacturing planning.

3. Approach and Methods

This chapter compiles all approaches, procedures and methods used throughout the thesis and in this way outlines the applied way of working. Each subchapter represents one major step in the project and presents all the required tools within the step. First, a thorough process modelling is conducted to introduce the current process. It includes process mapping and description, the work schedule with cycle times as well as relevant quality requirements. Second, the way of applying different process analysis tools in this thesis is explained. Those are a cycle time calculation and analysis, a SWOT analysis and a summary of resources' capabilities. Subsequently, production concepts are generated with the help of a morphological box. Afterwards, selected concepts are evaluated by a utility analysis. This includes certain analyses, such as cycle time calculations and a tolerance analysis. The next chapter explains how results are generated: the suggested basic process, a tacking map and the comparison to the as is process. Finally, the solution is validated by determining the lead time, conducting a risk assessment and an action plan is proposed.

3.1. Background and Literature Review

A background and literature review is conducted to gain the knowledge required to perform the following work. It introduces the structural design of an aircraft and gives an overview of the final assembly process. Also, it addresses the robot technology and discusses state-of-the-art and R&D in aircraft assembly automation. One main intention of the review is to understand the strengths and limitations of robots used in aerospace assembly. Also, general considerations before automating are discussed.

3.2. Process Modelling (Current State)

The first activity is a process modelling of the current state (as is process). It used production visits, operation instructions, work schedules, information from the ERP system as well as quality requirement documents as inputs to map and describe the process, calculate and analyse cycle times and formulate product and process requirements.

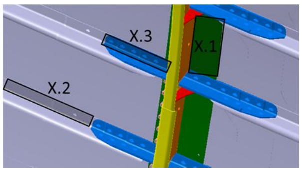
Process Mapping

Process maps are diagrams used to improve the understanding of activities of a process. They can vary in level of detail and appearance. A *flow chart* is used to introduce the FAL process in chapter 2.1.2 and give an overview of the circumferential joint assembly. A flowchart shows the sequence of activities. The start is a macro-map that in case of a manufacturing process can be the sequence of workstations. To enhance the level of detail micro-maps are added and integrated. (Accounts Commission, 2000)

Due to the complexity of the process and the presence of many variants for certain process steps in different assembly areas a literal description alone cannot fully explain the current process. Instead of using photographs standardized graphics are created to visualize the process in an easy way.

Table 3 schematically shows an example of the process table. For each overall process the work order (and variant) according to the different assembly areas is specified in a picture of a typical circumferential joint section followed by the basic process figures (separated into variants) and the tools and (temporary) fasteners used in this step.

Table 3 Example process table

	Process X		Process Y
Work order	X.1 assembly area 1 - V1 X.2 assembly area 2 - V2 X.3 assembly area 3 - V3		…
Basic process	Variant 1: pre-drill temporarily fasten …		…
Tools & (temp.) fasteners	Manual drilling machine Grip pins, collets Hi-loks		…

PROCESS DESCRIPTION

Complementing the process mapping the process steps are described in text as a list of tasks and pictures are located in the appendix. Furthermore, rivet and temporary fastener types and the use of tools are documented.

The process description as well as the process mapping are generated based on process instructions and the lean principle *genchi genbutsu* (go, look, see), i.e. time was spent on the shop floor to observe, understand and later describe and map the current process which is performed during 4-5 shifts in total.

CYCLE TIME CALCULATION, WORK SCHEDULE

Cycle time calculations are performed for the current process in order to analyse the cycle time of different process steps and also be able to modify the calculations based on the number of elements (e.g. drilling a hole 20 times) to generate different variants of a possible future process. As inputs serve the production plan (balanced work schedule) of the whole work station, MTM (Methods Time Measurement) calculations from the company's ERP system and the work instructions for the circumferential joint assembly.

As shown in Table 4 processes (e.g. pre-drilling or riveting) are further broken down into process steps and single operations. The process steps refer to the elements in the production plan whose times serve as a control reference and input for other processes than the circumferential joint assembly (e.g. floor grid assembly) as well as process steps that will not be affected by the implementation of automation (e.g. support angle assembly). The order and content of the operations correspond to the descriptions in the work instructions that are validated by visits in production. The MTM calculations in the ERP (Enterprise Resource Planning) system deliver information that can be used directly for the cycle time calculations, be added up to represent the listed operations or build the basis for further calculations in the content of this thesis.

MTM is a pre-determined time system. The company's calculations are available in different levels of detail that are based on each other. These levels shall be explained for the example of a drilling process. Level 1 is the task level, level 2 splits the task into the actual operation, preparations and additional body movements and level 3 is the MTM level with small blocks for each type of movement.

> "Pre-drill the couplings Ø 3.0mm" *(Level 1)*
>
> > Drilling, manual, Ø 3.0mm, feed material thickness etc. *(Level 2)*
> >
> > > "Handle coolant", #5, handle auxiliary resources *(Level 3: MTM)*
> > > "Dip drill bit into coolant", #5, handle auxiliary resources *(Level 3: MTM)*
> > > "Place machine for next hole", #50, place close, <200mm *(Level 3: MTM)*
> > > "Drilling operation", #50, cycle time drilling, manual, parameters *(Level 3: Formula)*
> >
> > Preparations *(Level 2)*
> >
> > > "Connect to compressed air", connect tube, first machine *(Level 3: MTM)*
> >
> > Body movements, additional *(Level 2)*
> >
> > > "Additional work overhead" stretch out arms *(Level 3: MTM)*
> > > "Kneel down" *(Level 3, MTM)*
> > > "Walk", walk per meter *(Level 3: MTM)*
> > > "Climb stairs", walk per meter *(Level 3: MTM)*
>
> "Remove chips behind couplings" *(Level 1)*

In order to modify the cycle time calculation later to generate different process variants cycle times for the single elements are determined based on the ERP data of the current process. For tasks such as station preparation, attachment of parts, cleaning, removal of chips etc. level 1 is used and divided by the number of elements (e.g. number of attached parts). On the other hand, tasks such as drilling, tacking, riveting etc. cannot simply be divided by the number of elements because only the process time (level 2) depends on this number. In a defined work area necessary preparations and additional movements will remain the same no matter if for instance 100 or only 10 holes are drilled. Therefore level 2 is used for these two operations while a new level "3+" between level 2 and 3 is generated. It represents one process cycle time element. These actions enable to modify the total cycle time based on the number of elements within certain tasks, e.g. if less holes shall be pre-drilled. For the as is process however, this is not relevant yet. Instead the total cycle time for one side of the aircraft is added up. Finally, the total time for one process for the whole aircraft and including 12% allowances is calculated. To summarize, information used and calculations performed are the following:

1) Number of elements in one operation (for one side of the aircraft, LH) [#]
2) For tasks such as station preparation, attachment of parts, cleaning, removal of chips etc.:
    a) Level 1 total cycle time for an operation [TMU]
    b) Calculation of cycle time for one element [TMU, s]
3) For tasks such as drilling, tacking, riveting etc. the operations (level 1) are split into
    a) Level 2 process times [TMU]
    b) Calculation of cycle time for one process element [TMU, s] and thereby generation of a new level between Level 2 and 3: "Level 3+"
    c) Level 2 preparation time [TMU]
    d) Level 2 additional movement not included in the actual process [TMU]
4) Calculation of total time for one side [TMU, min]
5) Calculation of the total time for the whole aircraft (LH+RH) including 12% allowances [min, h]

Table 4 gives an example for these calculations. Besides showing the different numbers it also lists the performed tasks (work content).

3.3. Process Analyses

Several process analyses are conducted. The determined cycle time is analysed regarding several aspects. While this step is part of the current state description a SWOT analysis, robotic compared to manual cycle times and task allocation prepare the development and evaluation of new assembly concepts.

Cycle Time Analyses

Based on the cycle time calculation several analyses are performed: A summary of the structure work content at the station displays the major cycle time contributors. Furthermore, the share of cycle times for overall process steps that are influenced by automation are broken down to a more detailed level and separated between the upper and lower floor (cabin and cargo area) of the aircraft. Moreover, operation element times for tasks such as pre-drilling one hole, inserting a rivet etc. are shown in a diagram with their variations throughout the whole assembly (Figure 21). This analysis shows weather a standard cycle time element can be used for all tasks.

Finally, lean ratios for the three main processes pre-drilling, sealing & temporary assembly and final drilling & riveting summarize the distribution of value adding, non-value-adding but necessary and waste activities (Figure 22).

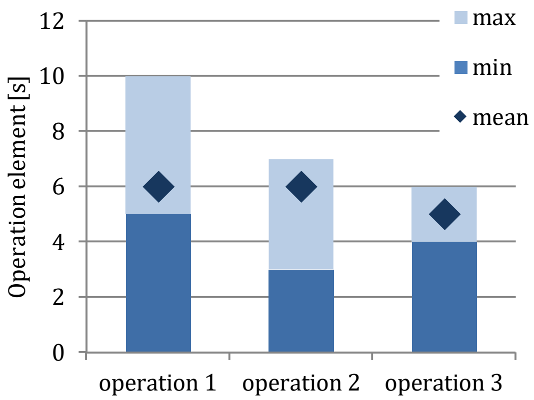


Figure 21 Operation element times

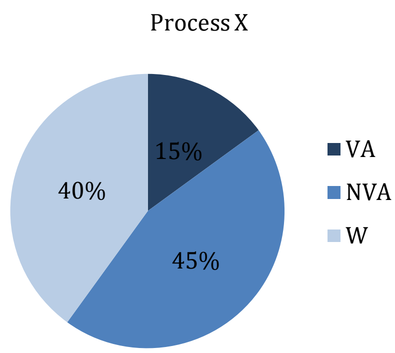


Figure 22 Lean ratio

Table 4 Cycle time calculations for the As Is process

Nr.	Area	Tasks	Lean category: VA-NVA-Waste	Nr. of elements per side	Total cycle time (Level 1)	Cycle time element (Level 1)	Cycle time element (Level 1)	Operation (Level 2) *	Operation element (Level 3+)	Preparation (Level 2) *	Add. Movements (Level 2) *	Total time LH **	Total time LH **	Total time LH+RH with personal allowances
				#	TMU	TMU	s	TMU	s	TMU	TMU	TMU	min	min (h)
1	**A/C**	**Process A**												**5,5 h**
2	**A/C**	**Process B**												**42,7 h**
2.1	**UF**	**Process Step a**												**1,7 h**
		- Task 1 (preparation)	VA	1	38336	38336	1380	-	-	-	-	38336	23	52
		- Task 2 (pre-drilling)	NVA	18	-	978	35	7803	16	2120	7680	17603	11	24
		- …	W	…	…	…	…	…	…	…	…	…	…	…
2.2	**UF**	**Process Step b**												**1,1 h**
		- Task 1 (chips removal)	W	10	28411	2841	102	-	-	-	-	28411	17	38
		- Task 2 (tacking)	NVA	5	-	1204	43	2990	22	2120	910	6020	4	8
		- …	W	…	…	…	…	…	…	…	…	…	…	…
3	**A/C**	**Process C**												**12,6 h**
3.1	**LF**	**Process Step a**												**2,9 h**
		- Task 1 (…)	W	…	…	…	…	…	…	…	…	…	…	…
		- …	VA	…	…	…	…	…	…	…	…	…	…	…

* process is split into operation, protection and additional movements for processes such as drilling, tacking, riveting etc.
** until here all values refer to one side of the aircraft (LH)
Abbreviations: A/C = aircraft, UF/LF = upper/lower floor. LF/RH = left/right hand, TMU = time measurement unit

SWOT ANALYSIS

SWOT stands for strengths, weaknesses, opportunities, and threats. It is a method that evaluates those four elements and can be carried out for a company, product, industry, or person. A SWOT analysis aims to identify internal and external factors seen as important to achieve an objective. (Lindemann, 2009)

Table 5 SWOT analysis

	Helpful	Harmful
Internal origin	Strengths	Weaknesses
External origin	Opportunities	Threats

For this thesis the SWOT analysis is used in a different way than originally defined. Instead of internal and external the categories as is process (manual or semi-automated) and automated are introduced. The analysis was performed after the shop floor visits in order to capture first impressions and estimate the potential and limitations of an automated solution.

CAPABILITIES AND BEST PRACTICES

In order to further understand the capabilities of human and machine (robots) and consider capabilities and best practices during the assessment of possible future assembly concepts for task allocation the capabilities are evaluated for different assembly tasks. As an input serve the product and process requirements previously specified before. Table 6 shows an example.

Table 6 Capabilities (example)

Criteria	Manual	Robot	Requirements
Positioning of couplings	X	(no access from outside, no flexibility)	Edge distances
…	…	…	…

COMPARISON OF ROBOT AND MANUAL CYCLE TIMES

In order to gain a first impression and collect input data for the cycle time determination of different variants the robot cycle times are compared to the manual cycle times. Thereby process chains such as for pre-drilling one hole are built based on their operation elements (e.g. positioning, pre-drilling, deburring). The robot's accumulated cycle time is compared to the minimum as well as maximum manual chain (in terms of its length) that is present in the circumferential joint assembly.

3.4. CONCEPT DEVELOPMENT

Based on the analyses carried out before as well as the project conditions in which the thesis is written several conceptual ideas are generated with the help of a morphological box.

EXPLANATION OF PROJECT CONDITIONS

In order to introduce the framework of this thesis to the reader the project conditions are described. It includes a presentation of the significance of automating drilling and riveting processes, the Airbus Hamburg project 4th FAL of which the automated circumferential joint assembly is part of, the visualization of the automation principle using two robots and preliminary work done within the project. Furthermore, the robot system's abilities and limitations are listed.

Morphological Box

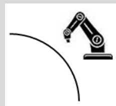
With the help of a morphological box several variants for each production process step are generated. A morphological box is a systematic creativity technique. A matrix is generated with attributes in the vertical direction and possible forms of the attributes in the horizontal direction. That way, a matrix with all possible combinations is generated and a variant from each line can be chosen and combined with others (Table 7). (Wikipedia)

Table 7 Morphological box

	Rustic model	Comfort model	Future model
Material	wood	plastic	Glass
Coulour	brown	green	red
Nr. Legs	4	3	2
Height	50 cm	70 cm	90 cm
Shape	quadratical	curved	round

Table 8 shows the matrix used in this thesis. The mentioned attributes are process steps and the form of the attributes can be a manual (as is), manual (alternative), combined or auto-mated operation.

Table 8 Thesis' morphological box

Process	Manual (as is) 	Manual (altern.) 	Cooperation 	Automated 
2 Pre-drill				
2.1 butt strap				
2.2 long. joints				
…				

Later, a more structured list of variants is generated for each step whose variants shall be evaluated and compared. This simplifies the understanding for the reader.

3.5. Concept Evaluation

The developed concepts are evaluated by a utility analysis. It includes qualitative but also quantitative criteria and thereby combines utility with efficiency (creating output with less rework, resources or money). This chapter further applies how certain criteria are evaluated and calculated.

Utility Analysis (with Pairwise Comparison)

The *utility analysis* (or *scoring model*) is a method for multi criteria assessments of several variants, e.g. technology or process variants. Thereby several qualitative criteria are quantified by subjective estimations and assessments of a multifunctional team. (Schuh & Klappert, 2011) First the assessment criteria are chosen. They are based on the author's valuation of what is important to consider when choosing between different concept variants.

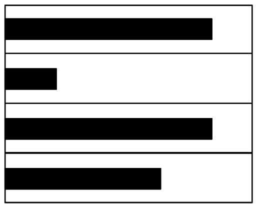
Afterwards the criteria have to be weighted. In order to determine a ranking of the criteria a *pairwise comparison* is conducted by the student and two other people involved in the project. In the method of pairwise comparison each criterion (or alternative in general) is compared one by one with each other criterion. Thereby all possible combinations are compared to each other once. Table 9 shows an example of a matrix for the pairwise comparison. A criterion (line) gets

- 0 points if it is less important
- 0.5 points if it is equally important or
- 1 point if it is more important

than the other criterion (column). The sum of the points per line results in the criteria's significance. The expression in percentage compared to the total score of all criteria represents the weighting for the utility analysis. (Lindemann, 2009) (Lotter & Wiendahl, 2012)

Table 9 Example pairwise comparison (own figure)

than/as more/less/equally important	Criteria 1	Criteria 2	Criteria 3	Criteria 4	**Sum**	**Percentage**
Criteria 1		1	0,5	0,5	**2**	**33%**
Criteria 2	0		0,5	0	**0,5**	**8%**
Criteria 3	0,5	0,5		1	**2**	**33%**
Criteria 4	0,5	1	0		**1,5**	**25%**



In the utility analysis the assessment of the criteria for different variants is performed by the determination of their utilities. The degree of performance (P) of each criterion, i.e. how well a variant satisfies the criterion, is generated by the subjective assessment of a multifunctional team. Often a scale from 1-10 is used to quantify the degree of performance. Each performance is then multiplied with the criterion's weighting factors (W) to determine the partly utility. By adding up the partly utilities the overall utility of a variant is calculated. The variant with the highest utility has the highest qualification or suitability. (Schuh & Klappert, 2011) (Lindemann, 2009) (Lotter & Wiendahl, 2012)

Table 10 Utility analysis (own figure)

		Variant 1		**Variant 2**		**Variant 3**		**Variant 4**	
Criteria	**Weight**	P	P*W	P	P*W	P	P*W	P	P*W
Criteria 1	33%	3	1	5	2				
Criteria 2	8%	9	1	7	1				
Criteria 3	33%	4	1						
Criteria 4	25%	6	2						
Overall Utility			**5**		**2**		**0**		**0**

It has to be noted that this assessment method is based on subjective evaluations. However, it allows assessing qualitative (technical as well as non-technical) criteria in a more structured and weighted way. Furthermore, this analysis generates easy result in the form of just one number per variant. On the other hand it also shows greatest areas of necessary improve-mints for certain variants. Moreover, the result can be adjusted with only small effort if the circumstances or priorities change.

In this thesis one adjustment of the method is carried out: instead of considering exclusively qualitative criteria quantitative criteria are included in the analysis as well. Of course, those criteria cannot be rated based on a subjective evaluation but certain data need to be analysed and calculations conducted. These are transferred into the performance rating of 1-10 points. The advantage of including qualitative criteria is that their weight can be considered. Thereby they can be set in relation to the quantitative criteria and an overall, all-inclusive evaluation result is obtained.

The weighted performances for the categories are visualized in a special pie chart as in Figure 23. Each piece of pie represents one criterion, its angle corresponds to the criterion's weight (e.g. a criterion weighted with 10% has an angle of 36°) and its length equals the criteria's performance rating. Thereby each piece of the pie represents the criteria's partly utility while the whole pie area represents the overall utility. The circle outlines the maximum possible rating

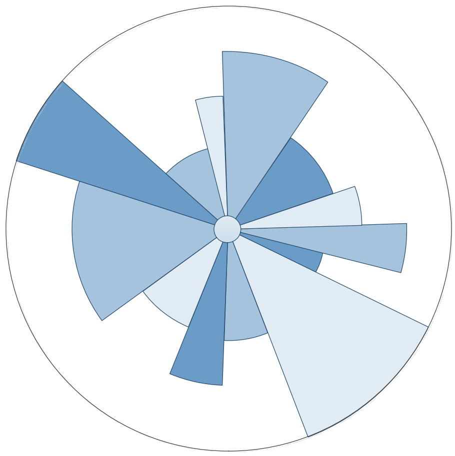


Figure 23 Utility analysis visualisation

Cycle Time Cost Calculation

As mentioned before pre-work is required in order to rate the qualitative criteria. One task is the calculation of the cycle time for different variants and based on them the costs (called cycle time costs). These differ between manual work and automated work. Information used and calculations performed are the following:

1) Number of elements in one operation (for one side of the aircraft, LH) [#]
2) For tasks such as station preparation, attachment of parts, cleaning, removal of chips etc.:
   a) Reference to cycle time for one element from as is analysis [s]
   b) Calculation of level 1 total cycle time for an operation [s]
3) For tasks such as drilling, tacking, riveting etc. the operations (level 1) are split into
   a) Reference to cycle time for one level 3+ process element from as is analysis [s]
   b) Calculation level 2 process time [s]
   c) Reference to preparation time [s]
   d) Reference to additional movement [s]
4) Calculation of total time for one side [s, min]
5) Calculation of the total time for the whole aircraft (LH+RH) including 12% allowances or 80% robot system OEE respectively [min, h]

6) Hourly rates for operators and the robot system
7) Calculation of cycle time costs based on manual and automated cycle times

Table 4 gives an example for these calculations. Besides showing the different numbers it also lists the performed tasks.

While the operator hourly rate is given the

$$Machine\ hourly\ rate = \frac{\sum Cost\ types\ (€/a)}{Yearly\ run\ time\ (h)}$$

has to be estimated. The model from (Lotter & Wiendahl, 2012) and (Schuh & Klappert, 2011) are taken as a reference. The machine hourly rate is calculated as follows:

$$Amortisation\ costs\ C_A = \frac{Investment\ costs}{useful\ life}\ [€/a]$$

$$Interest\ C_I\ = \frac{Investment\ costs}{2} * interest\ rate\ [€/a]$$

$$Building\ costs\ C_B\ [€/a]$$

$$Energy\ costs\ C_E\ [€/a]$$

$$Maintenance\ costs\ C_M\ \ [€/a]$$

$$Tool\ and\ material\ costs\ C_{TM}$$

$$Machine\ hourly\ rate\ = \frac{C_A\ + C_I +\ C_B +\ C_E +\ C_M +\ C_{TM}}{yearly\ run\ time}\ [€/h]$$

Generally it is important to calculate the costs per yearly run time instead of per machine's useful life or the total work hours per year.

CLASSIFICATION OF ACTIVITIES (LEAN)

In order to rate the distribution of value adding, non-value-adding and waste activities (called lean ratio) for the utility analysis the different shares have to be translated into numbers. Each percentage of VA gets 3 points, NVA 2 points and W 1 point. The sum can consequently reach from 100-300 points. For the utility analysis 100-120 points represent 1 performance points while 280-300 points represent 10 performance points. The values in between are distributed evenly with steps of 20 points.

DEGREE OF ROBOT UTILIZATION CALCULATION

The degree of robot utilization is calculated as the ratio between the robot's share and the total cycle time for a certain process variant.

Table 11 Cycle time calculation

Nr.	Area	Tasks	Lean category: VA-NVA-Waste	Nr. of elements per side acc. variant	Total cycle time (Level 1)	Cycle time element (Level 1)	Operation (Level 2) *	Operation element (Level 3+)	Preparation (Level 2) *	Add. Movements (Level 2) *	Total time LH **	Total time LH **	Total time LH+RH with personal allowances
				#	s	s	s	s	s	s	s	min	min (h)
2	**A/C**	**Process B (V1)**											**12,5 h**
2.1	**UF**	**Process Step a**											**1,7 h**
		- Task 1 (preparation)	VA	1	300	300	-	-	-	-	300	5	11
		- Task 2 (pre-drilling)	NVA	18	-	-	90	5	15	30	135	2	5
		- …	W	…	…	…	…	…	…	…	…	…	…
2.2	**UF**	**Process Step b**											**1,1 h**
		- Task 2 (tacking)	NVA	50	-	43	600	12	20	40	660	11	25
		- …	W	…	…	…	…	…	…	…	…	…	…

* process is split into operation, protection and additional movements for processes such as drilling, tacking, riveting etc.
** until here all values refer to one side of the aircraft (LH)
Abbreviations: A/C = aircraft, UF/LF = upper/lower floor. LF/RH = left/right hand, TMU = time measurement unit

Tolerance Analyses (Stack-up)

Several tolerance analyses (stack-ups) are part of the assessment of the quality criterion. Later, they also serve as a tool to investigate potentials of an automated process.

Variation is the amount a measured value deviates from a specified value. "It is the imperfection seen in actual as-produced parts, contrasted against the perfect models created in CAD and seen on drawings". In the context of design tolerances on the drawing set the limits for variation. Sources of variation can be e.g. manufacturing process limitations (capabilities), tool wear, operator errors, ambient conditions, differences in equipment or assembly process variations. The assembly sequence has a great effect on variations and the relation between features. (Fischer, 2011)

A tolerance stack up investigates whether the variation in an assembly is acceptable by determining the cumulative possible variation. The first step is to understand the dimensioning and tolerancing specification applied in the drawings as well as the tolerance chain to perform the tolerance stack-up in a second step. Figure 24 shows a simple example for a chain of dimensions and tolerances resulting in the variation of a gap.

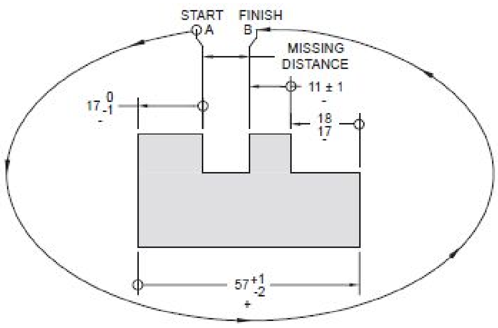


Figure 24 Chain of dimensions and tolerances (Fischer, 2011)

The thesis investigates minimum and maximum distances, in particular edge and rivet distances. The tolerance stack-ups are modelled manually and one dimensional. While arithmetic analyses determine the largest possible variation statistical analyses determine the probable maximum variation by assuming that it is improbable that all the dimensions in the tolerance stack-up will be at their worst-case limit at the same time. Generally, statistical tolerance analysis results in a smaller value for the total variation. A rule of thumb states that its validity increases as the number of tolerances in a tolerance stack-up increases. (Fischer, 2011) Three different types of tolerance analyses are applied in the thesis:

- Worst case (arithmetic) tolerance analysis representing the largest (worst case) possible variation as the sum of its intervals of tolerance (IT)

$$WC = \sum IT$$

- Root-sum-square (statistic) tolerance analysis considering statistics (Gaussian distribution) and thereby determining the likely maximum deviation

$$RSS = \sqrt{\sum IT^2}$$

- Airbus Safety Coefficient Result (statistic) tolerance analysis, a company intern calculation method further taking into account the size of the largest contributor in the tolerance chain (confidential formula)

Furthermore, a 3D computer-based tolerance analysis is conducted within the project (but not by the student) for two of the investigations needed in this thesis. Therefore a Monte Carlo simulation is applied. "Monte Carlo simulations take all the variables in a tolerance stack-up, assign each a random value within their range, derive a result, save the results, iterate this process thousands of times, average the results and possibly present predicted statistical distributions. This is a purely statistical approach." (Fischer, 2011)

Interviews

The criterion risk for quality and technical problems is assessed by interviewing several engineers that are already working with robot systems for drilling (and riveting) at other sites of the company. They are interviewed regarding their experiences with problems in certain operations such as pre-drilling, referencing, rivet supply etc.

3.6. Generation of Results

Future Basic Process

The future basic process is obtained from the evaluation of different variants for each process step. It is split into assembly areas and the work sequence and visualized in the same way as the as is basic process with standard graphics that now further specify if a task is done manually or automated.

Tacking & Referencing Map

During the evaluation of different concepts theoretical values for the tacking and other rates were investigated. After one variant is chosen for each process a detailed tacking and referencing map can be created based on the actual components. It uses the technical drawings of the circumferential joint to highlight which holes shall be tacked or referenced. Moreover, the map considers part geometries, non-accessible holes for the robot and holes in which rivets have to be inserted manually from the inside of the fuselage.

Comparison to As Is Process

At last the evaluation results are summarized in a comparison of the suggested future and the as is process. Therefore the criteria that were chosen between the evaluation of concepts are examined for the as is processes and each process variant that resulted from the evaluation.

3.7. Validation and Recommendations

The validation consists of an examination of the lead time and a risk assessment which build the basis for further recommendations.

Lead Time

One fundamental requirement for a future process is that the work can be conducted within the available lead time. In order to investigate the lead time a work schedule is developed based on the calculated cycle times as in Figure 25.

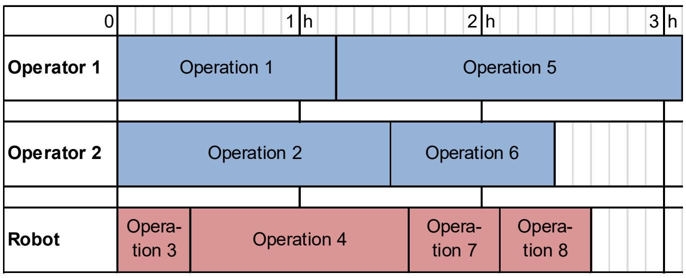


Figure 25 Work schedule example

Besides the durations for all processes the interaction between man and machine, inside and outside work and work in different areas as well as the predecessors and successors of certain processes have to be considered (see Figure 26).

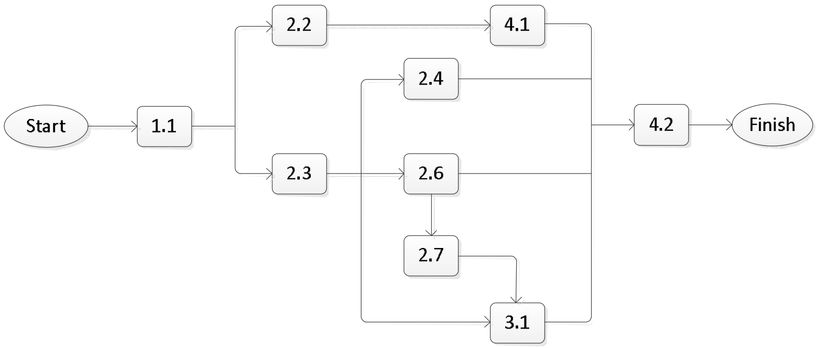


Figure 26 Precedence diagram

Risk Assessment

Throughout the thesis and evaluation of concepts the real product and resource were not involved. For further development, validation and verification and later installation a risk assessment is conducted to identify and classify risks. This classification of risks is done based on the severity of consequences and the probability (frequency) of scenarios in a 3x3 matrix. Once identified and ranked a risk mitigation plan can be put in place and tests defined that will be conducted before start of production. Thereby the risk assessment builds the basis for recommendations given in the discussion.

Table 12 Risk assessment matrix

		Severity of Consequences		
		low	medium	high
Probability of Scenario	high	medium risk	high risk	high risk
	medium	small risk	medium risk	high risk
	low	small risk	small risk	medium risk

Action Plan

As part of the discussion a way forward shall be recommended. It is based on the identified risks in order to define on which aspects validation and verification tests should focus and which further topics have to be addressed.

Design Modifications

The product requirements and the current aircraft design result in tolerance problems when automating the circumferential joint assembly. Therefore several scenarios are tested based on the previously performed tolerance stack-ups to be able to suggest design and process modifications that could solve the issues.

4. CIRCUMFERENTIAL JOINT ASSEMBLY: AS IS PROCESS

This chapter gives an overview of the current (as is) process with its area of interest, important terms and the assembly principle and describes the process with the help of visualization as well as tools, rivets etc. in use. Afterwards, cycle times are analysed and product and process requirements formulated. Figure 27 shows the process definition chart of the circumferential joint assembly.

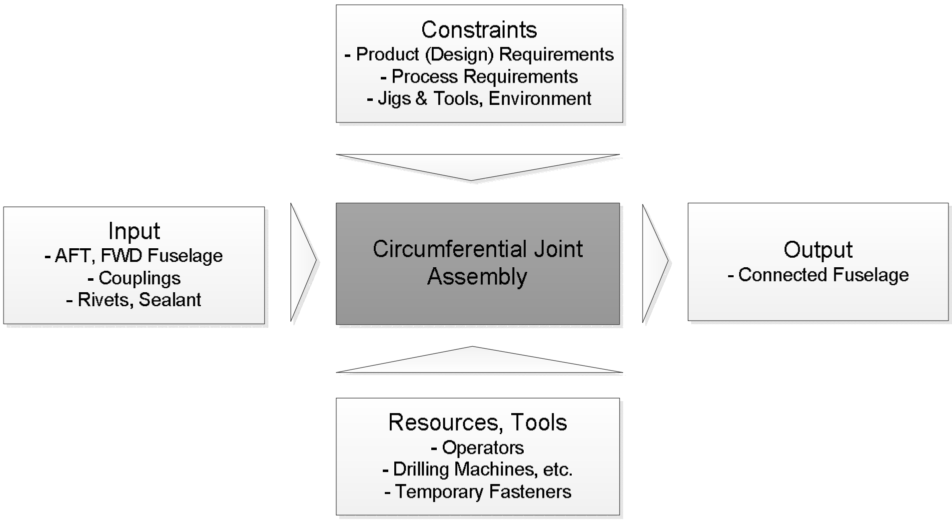


Figure 27 Process Definition Chart (own figure)

4.1. PROCESS OVERVIEW

This overview briefly explains the area of interest, relevant terms and the assembly principle.

AREA OF INTEREST AND DEFINITION OF TERMS

The circumferential joint assembly of the forward and aft fuselage sections is part of the FAL process at station 1. In Figure 5 the structural tasks were further broken down into seat track, cabin area and cargo compartment area process steps. This thesis focuses on the cabin and cargo area circumferential joint. It includes the

- Connection of the fuselage sections
- Pre-drilling
- Disassembly and cleaning
- Application of sealant and repeated connection
- Temporary assembly with temporary fasteners
- Final drilling and riveting
- Assembly of the longitudinal joints (open ends)

While the circumferential joint is built as a one-sided butt strap joint (Figure 28 left) the longitudinal joints are built as multiple row overlap (lap) joints (Figure 28 right).

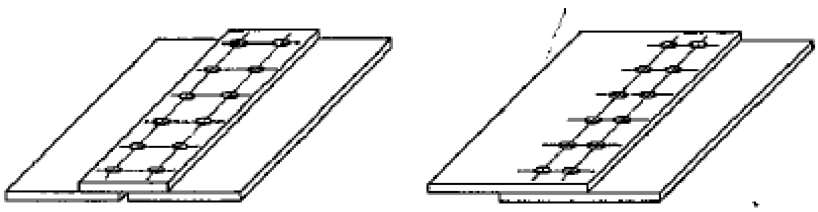


Figure 28 Butt strap joint (left) and lap joint (right) (Engmann & Grube, 2013)

Figure 29 (left) shows a typical section of the circumferential joint section after the connection of the fuselage and the positioning of couplings and support angles but before the fastening process is performed. The different components (skin, coupling, stringer, butt strap, frame, clip and support angle) are highlighted.

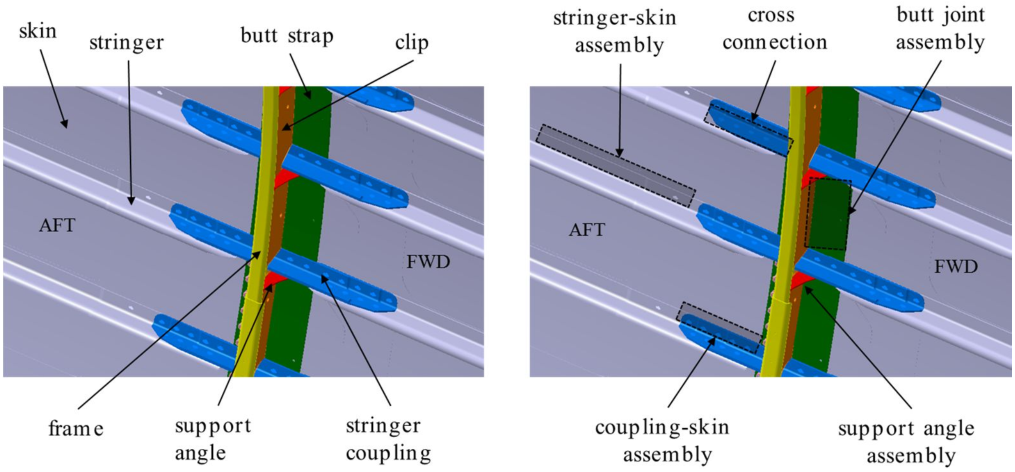


Figure 29 Circumferential joint components (left) and assembly areas (right) (own figure)

Figure 29 (right) explains the terms for assembly areas that are used in the thesis. At station 1 the personal performs the

- Butt joint assembly including the section ends and a butt strap with 2 or 3 rivet rows
- Coupling-skin assembly in the butt joint and stringer area
- Stringer-skin assembly next to the stringer couplings
- Cross connection between coupling and stringer parallel to the skin and
- Support angle assembly between support angle and coupling or frame.

Assembly Principle

The forward and aft fuselage section both lie on four attachment points. Those can drive the front section in x, y and z direction in order to position it to the rear section. The finally chosen position can be saved and reproduced within certain tolerances.

Due to the high requirements regarding hole concentricity the holes cannot be drilled before the parts are in their final assembly position and connected to each other. Therefore they are drilled together with the same tool in the FAL. Pilot holes serve as a reference for the drilling pattern. They are present in one of the parts which are to be assembled.

Figure 30 visualises the assembly principle. After bringing the parts into assembly position (a) all holes are first pre-drilled with a small diameter in an un-clamped state (b) and drilled back from the other side with a larger diameter (c). They are drilled to final diameter later because material inclusions such as burr or chips prevent the necessary contact between parts and therefore increase the risk for friction corrosion and inclusion of moisture. Even worse, they can lead to the development of fatigue cracks over time. Thus, the parts are disconnected, deburred, cleaned (d) and sealed (e) before some of the drilled pre-holes are used to tack (clamp) the stack together by the use of temporary fasteners (f). Thereby gaps are closed and applied sealant if distributed between the surfaces. Holes that are left open can be drilled to final diameter (g) and afterwards permanently riveted (h). Those rivets now assure enough clamping of the parts so that the temporary fasteners can be removed and the remaining holes drilled and riveted (i). If the disassembly and return to the original position creates a small hole mismatch it is eliminated during the step drilling to final diameter.

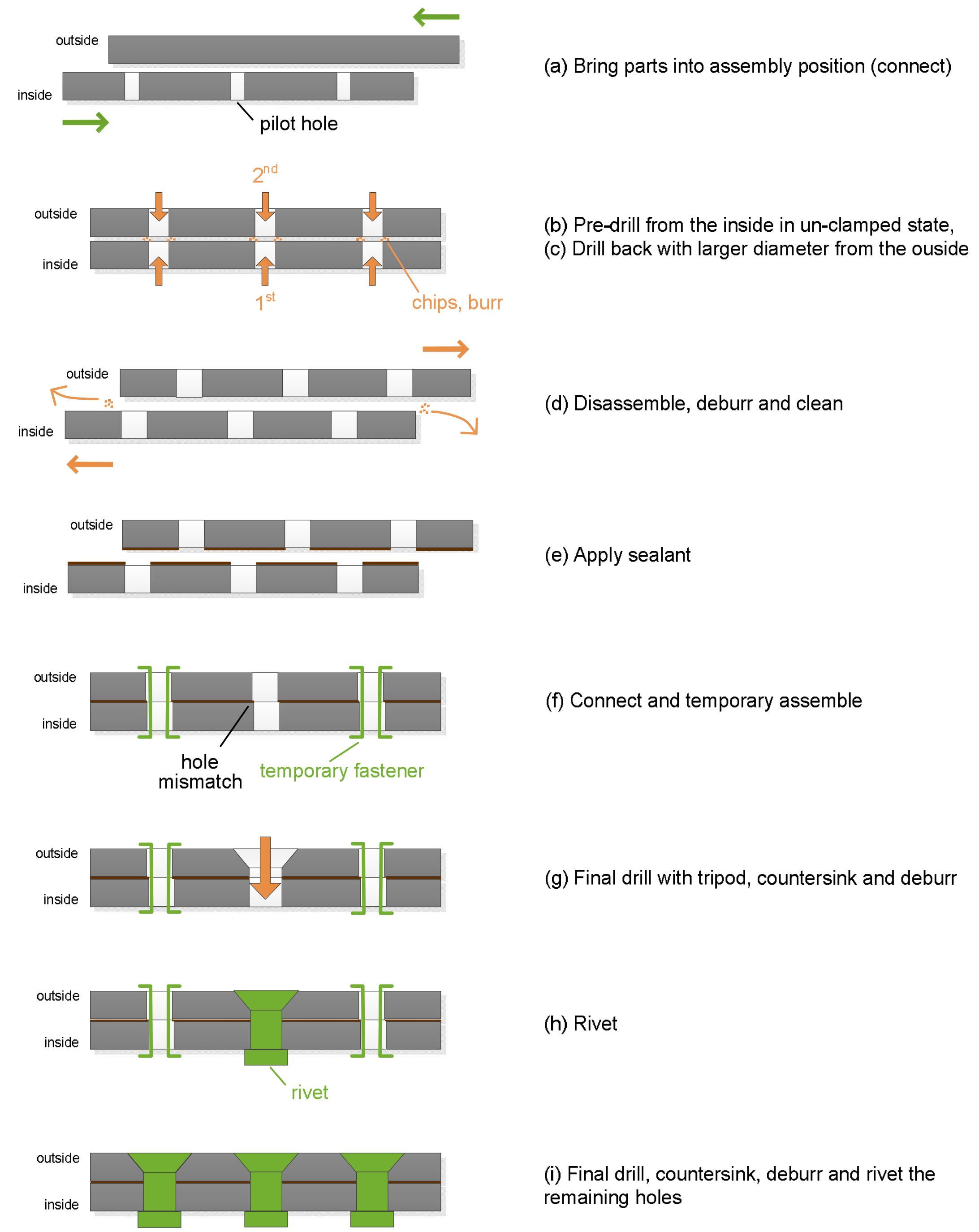


Figure 30 Assembly Principle (own figure)

4.2. Process Description

After showing an overview of the process a detailed description shall be given in this thesis. It is based on process instructions and the lean principle *genchi genbutsu* (go, look, see). The descriptions are related to the cabin area (upper floor) as it has less variations and specialties. There will be a chapter in the end focusing on the cargo compartment (lower floor) with its special features. The floor grid assembly is neglected because it will not be affected by an automated process working from the outside of the aircraft as all work is taking place inside the fuselage. This chapter includes the basic process using standardized graphics, rivets and tools used as well as a description in text for the upper floor and the characteristics of the lower floor.

4.2.1. THE BASIC PROCESS (UPPER FLOOR)

Due to the complexity of the process and the presence of many variants for certain process steps in different assembly areas of the circumferential joint graphics are created to visualize the basic process in an easy way. The different assembly areas (butt joint, coupling-skin, stringer-skin, cross connection, support angles) together with the work order are highlighted in a picture of a typical area of the circumferential joint.

CONNECT THE FUSELAGE

After the two fuselage halves are delivered to the station lead in guide clamps are installed on the fuselage skin edges. While the towers of the aft fuselage are fixed in flight direction (x-direction), the forward fuselage can be driven. Its skin is pushed on the butt strap which is already assembled on the aft fuselage. As the forward fuselage structure is less stiff it adapts to the AFT fuselage geometry. Afterwards defined positions are checked (e.g. alignment of seat rails, gap between seat rails and outer skins, gap between stringers and stringer couplings).

PRE-DRILL THE CIRCUMFERENTIAL JOINT

In this production step pilot holes are transferred to the corresponding counterparts, followed by pre-drilling the butt joint, stringers, couplings and support angles. During the previous major component assembly pilot holes were drilled into the sections. They serve as a reference for the drilling pattern in the FAL. Pilot holes are located in the butt strap, in the skin in the area of longitudinal joints and in the forward fuselage stringer feet. There are no pilot holes in the area of the coupling-skin assembly in the butt joint area because here the stringers are connected by couplings and the pilot holes are located in these couplings. The couplings own all pilot holes for the cross connection and for all holes of the coupling-skin assembly.

APPLY SEALANT, CONNECT AND TEMPORARILY ASSEMBLE THE FUSELAGE

Sealant consists of a matrix and hardener which cure in a chemical reaction and the evaporation of solvents. It has to be applied in areas where the aircraft has to be sealed against the leakage or entering of fuel or air, respectively, and if flat joints have a risk for friction corrosion. (Engmann & Mentzel, 2013). For the circumferential joint this is the case for all joints except of the support angle assembly. Sealant is applied with a pistol, a spatula or a roll. The temporary assembly enables final drilling and riveting in a state in which all parts are sufficiently clamped and gaps closed to avoid that burr and chips are generated and inserted between parts. Also, the tacking evenly distributes the sealant between the components.

FINAL DRILL AND RIVET

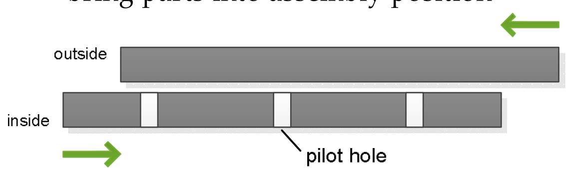
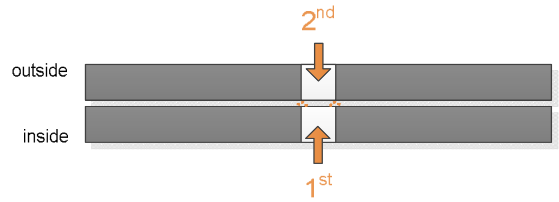
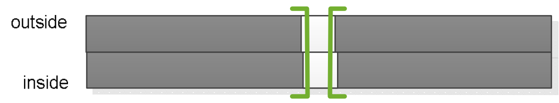
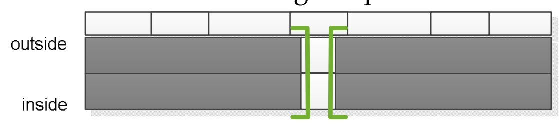
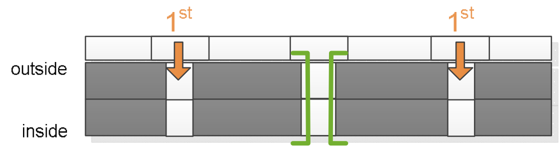
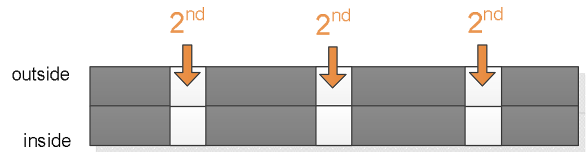
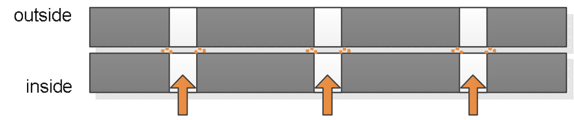
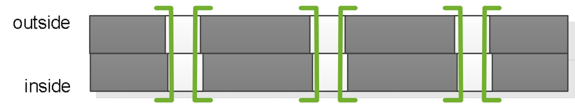
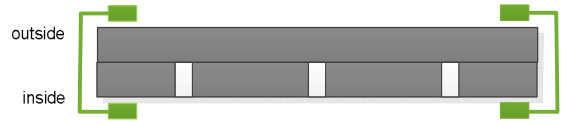
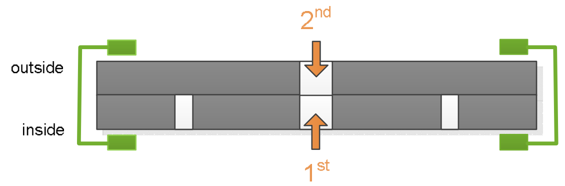
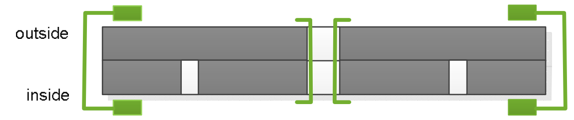
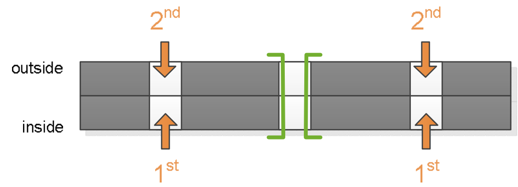
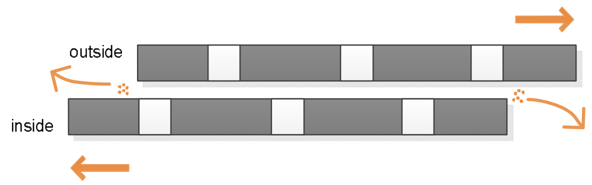
Due to the disassembly it is possible that the holes do not exactly match after the towers moved back into position, i.e. a hole offset occurs. Therefore the holes are final drilled with a bigger diameter when the fuselage halves are in their final assembly position. For the final drilling operation tripods are used to assure a normality of the hole.

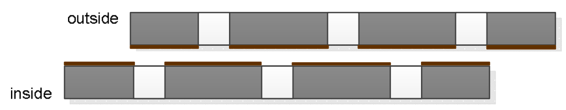
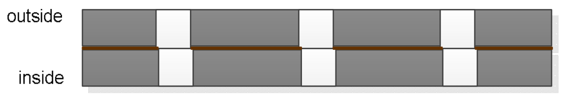
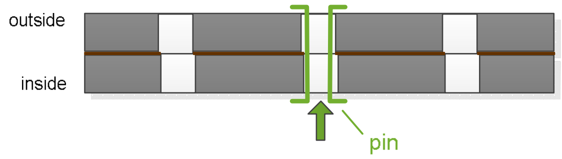
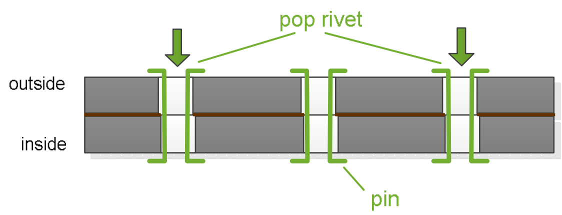
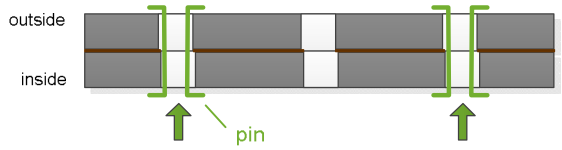
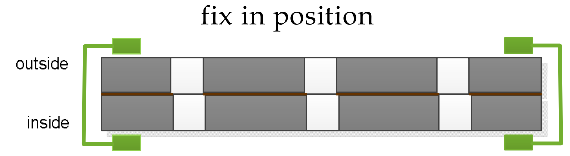
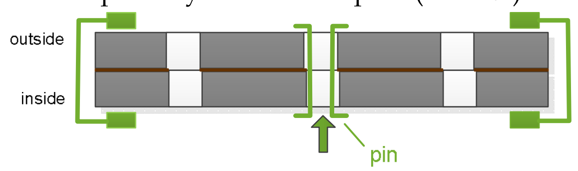
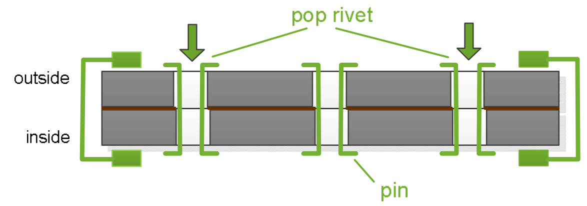
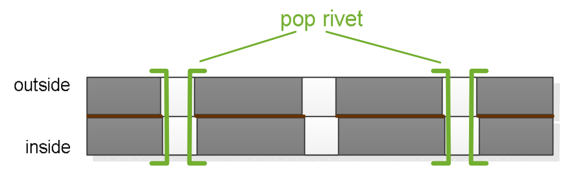
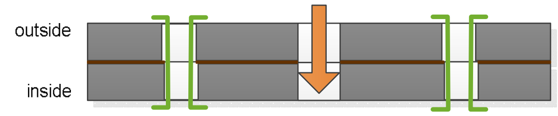
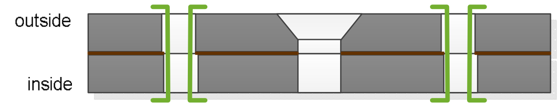
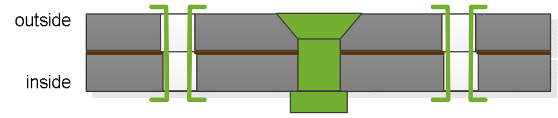
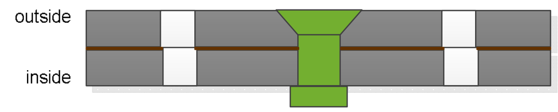
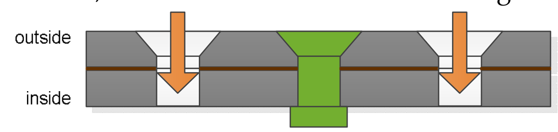
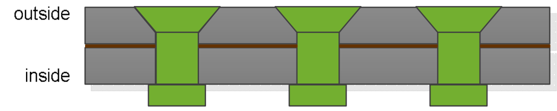
Table 13 is read from left to right; each column shows different characteristics of each process:

- the work order and applied variant according to the different assembly areas
- the basic process figures (separated into variants)
- the tools and (temporary) fasteners used in this step and
- notes for special features of the lower floor

Appendix 12.1 shows the legend for the basic process graphics while a detailed process description in text including photos from production are attached in 13.2.

Table 13 The Basic Process

	1 Connect the fuselage	2 Transfer pilot holes and pre-drill	3 Disassemble, deburr and clean
Work order	1.1 aircraft	2.1 butt strap (pilot hole transf.) – V1 2.2 longitudinal joints – V2 Split into several areas: 2.3-2.5 2.3 coupling-skin – V3 2.4 cross connection – V3 2.5 stringer-skin – V2 (only pre-drilling) 2.6 support angles – V2 2.7 butt joint (pre-drilling) – V4	3.1 aircraft
Basic process	bring parts into assembly position 	Variant 1: step 2.1 butt strap pre-drill, drill back with larger diam.  temporary fasten  Variant 4: step 2.7 butt strap fasten drilling template  pre-drill  pre-drill with larger diameter  Variant 2: step 2.2 long. joints, 2.5 stringers, 2.6 support angles pre-drill  temporary fasten  Variant 3: step 2.3 couplings, 2.4 cross connection fix in position  pre-drill, drill back with larger diam.  temporary fasten  pre-drill remaining holes 	removal of temporary fasteners, couplings & support angles disassembly of seat rails, removal of station platforms disassemble, disconnect the fuselage halves deburr, activate surfaces and clean  rivet support angles to the couplings
Tools & (temp.) fasteners		Manual drilling machine Cross connection with angle drilling machines Drilling tripod for second drilling step Drilling templates LISI grip pins, patent pins, screw pins, collets	Deburring machine

	4 Apply sealant and connect	5 Temporarily assemble	6 Final drill and rivet
Work order	4.1 butt joint 4.2 longitud. joint 4.3 connect A/C 4.4 stringer-skin 4.5 couplings	5.1 butt joint – V1 5.2 stringer-skin – V2 5.3 couplings – V3	6.1 cross connection 6.2 support angles Split into several areas: 6.3-6.5 6.3 stringer-skin 6.4 coupling-skin 6.5 butt joint
Basic process	apply sealant  connect aircraft (or part) 	<u>Variant 1</u>: step 5.1 butt joint temporarily fasten with pins (25-50%)  temporarily fasten with pop rivets (50%)  <u>Variant 2</u>: step 5.2 stringers temporary fasten with pins (25-50%)  <u>Variant 3</u>: step 5.3 couplings fix in position  temporarily fasten with pins (25-50%)  temporarily fasten with pop rivets (50%) 	if pop rivets are installed: remove grip pins (and collets)  final drill and deburr  countersink  rivet  remove pins/pop rivets  final drill, deburr & countersink remaining holes  rivet the remaining holes 
Tools & (temp.) fasteners		LISI grip pins, pop rivets, patent pins, screw pins, collets **Notes for LF:** tacking only with pins, from the outside	Manual drilling machine Cross connection with angle drilling machines Drilling tripod for final drilling step Hammer and mandrel Collar installation machines Rivets (hi-loks, lockbolts) and collars **Notes for LF:** no countersinks; mainly lockbolts (and some hi-loks), inserted from the inside

4.2.2. Rivet types, Temporary Fasteners and Tools in use

Drilling is a cutting process in which "layers of material are mechanically separated from the work piece in the form of chips by means of a rotating cutting tool". For drilling holes the drill's material and geometry play an important role for the hole quality. (Klocke, 2011) In the current process manual drilling machines are used to drill holes and produce countersinks. In order to drill the final hole as perpendicular as possible the drilling process can be performed with the help of tripods. When drilling is performed the exit point of the drill cannot be seen. Therefore, it is performed in several steps to be able to "pull" a hole in case position corrections are needed (Bullen, 2013). Furthermore, electrical deburring machines are used.

Temporary assembly is performed before the final drilling. Therefore different temporary fasteners are used to apply the required clamping force between two parts: pop-rivets (in combination with grip pins) are used in the butt strap-skin and coupling-skin connection while grip, patent and screw pins are used for the other connections. *Pop rivets* are a special type of blind rivets. They can be installed from one side by a pulling action and are used for tacking (and low stressed joints) only (Engmann & Grube, 2013). Later in the circumferential joint process they are drilled out in order to install the dedicated rivets. *Grip pins* are installed by a special screwing machine which pushes the fastener mandrel between two spring arms. Consequently these spread and thereby reach behind the component with their hooks and clamp the parts together. *Screw pin* and *patent pins* work in a similar way but have only one arm with a hook and are tightened by hand and tongs, respectively. All these temporary fasteners can be installed from one side only.

Moreover, *collet chucks* are used to position and fix (not primarily clamp) parts such as the couplings before they are drilled.

Figure 31 Grip pin, patent pin, screw pin and pop rivet (from left to right)

The selection of a fastener depends on its ability to transmit the expected design loads, its compatibility with the materials it joins, the application and the ability to install it. The connection type fastening belongs to the physical principle of form fit by mechanical interlocking. Riveting should be restricted to joints that are primarily loaded in shear with only secondary tension loading. *Solid rivets* are one piece fasteners consisting of a metal bolt with head and compressed closing head. They are installed by hammering or squeezing into final shape. During the installation several physical changes take place: the rivet diameter expands to fill the hole, the rivet hardness increases due to work hardening and the head is formed through plastic deformation. In *pin and collar fasteners* the pin, similar to a bolt, is mounted with a self-locking or swaged-on collar. They are used for high static and dynamic loads. There are two types: *Hi-loks* consists of a threaded pin and a collar, a nut with a breakaway groove which controls the torque and preload on the pin. *Lockbolts* are installed by pulling or swaging the collar from the backside. While Hi-loks have true threads that the collar is threaded onto, lockbolts have annular grooves that the collar is swaged into. (Engmann & Grube, 2013) (Campbell, 2006) Figure 32 shows the installation principles.

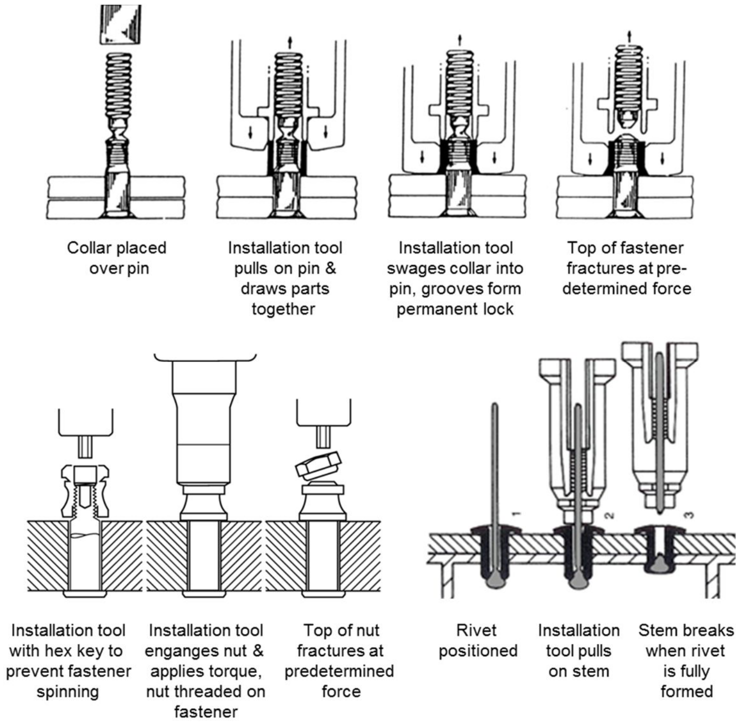


Figure 32 Installation of a lockbolt (top), hi-lok (bottom left) and pop rivet (bottom right), adapted from (Parker, 2001)

In the upper floor all joints to the skin are connected with hi-loks. They are inserted from the outside and installed with collars from the inside due to aerodynamic reasons. For the lower floor area hi-loks as well as lockbolts are used. In most cases they can be inserted from both sides because they are situated in an area behind the wing belly fairing which is irrelevant for the aircraft aerodynamics. However, in the current process they are inserted from the inside and installed with collars from the outside due to low accessibility for a machine inside the cargo compartment. The cross connection and the assembly of the small support angles is done with solid rivets. All these rivets have in common that access from both sides of the parts is required to install them.

4.2.3. CHARACTERISTICS OF THE LOWER FLOOR (CARGO COMPARTMENT)

In the following the special characteristics of the lower floor (cargo compartment) are explained. The general tasks at the upper and lower floor are the same but the differences of the lower floor result in varying processes. Furthermore, some special components have to be assembled.

The most relevant difference of the lower floor is the higher stiffness of the joint area. Since the circumferential joint is located in front of the wing box, which is - in contrast to the cabin and the cargo compartment – not pressurized, the aft fuselage contains a pressure bulkhead. This is manufactured as a single part by milling and is very stiff. Moreover, the skin is thicker and in the forward fuselage the stringers are already riveted to the skin and angle fittings reinforce and thereby stiffen the structure. Due to the higher stiffness the fuselage sections do not adapt their shape to each other as much as at the upper floor and higher clamping forces are required to close the gaps. Therefore only grip pins (50%) are used and not replaced by pop rivets. The tacking is done from the outside (in the upper floor from the inside) due to the limited access in the cargo compartment.

In general there is very limited space for the operators in the cargo compartment and the accessibility is smaller at the inside of the fuselage due to the pressure bulkhead as well as from the outside due to the geometry of the centre wing box and the assembly of additional parts such as the belly fairing, angle fittings, etc. Also, the inner side of the cargo compartment shows more variations than the cabin as the coupling geometry varies due to the pressure bulkhead that is located next to the circumferential joint and because some couplings connect the stringers by tension bolts through the pressure bulkhead while other stringers are only riveted to the butt strap. Furthermore, the skin thickness in general and in addition the angle fittings lead to the drilling of thicker stacks compared to the upper floor. Moreover, in some areas strain hardening of the holes is performed.

In the lower floor lockbolt rivets are used to a large extent, but hi-loks are present as well. Due to the belly fairing it is not important for the aerodynamics to insert countersunk rivets from the outside to achieve a flat surface. Consequently the rivets can be inserted from the inside and collars installed from the outside. This reduces the access need from the inside when using machines to install the collars.

4.3. Cycle Time Analyses, Work Content

The detailed cycle times for all tasks that are part of circumferential joint assembly processes and can be affected by the implementation of automation, namely transfer pilot holes & pre-drill, apply sealant & temporarily assembly and final drill & rivet, are calculated as described in chapter 3.3. Besides informing about the cycle times all tasks to be performed within certain process steps are listed. The table is not attached to this thesis as it would go beyond of scope in terms of its length. Instead the cycle times are summarized and displayed as compressed as possible in Figure 33. This is based on the production schedule and summarizes the structure work content at the station and at the same time highlights the major cycle time contributors by applying the pareto principle. All dark bars refer to the circumferential joint assembly while the first three, coloured ones are addressed by implementing automation, accounting for 61% of the station's cycle time. In the following diagrams the colours blue, green and red continuously refer to the same three processes highlighted in Figure 33.

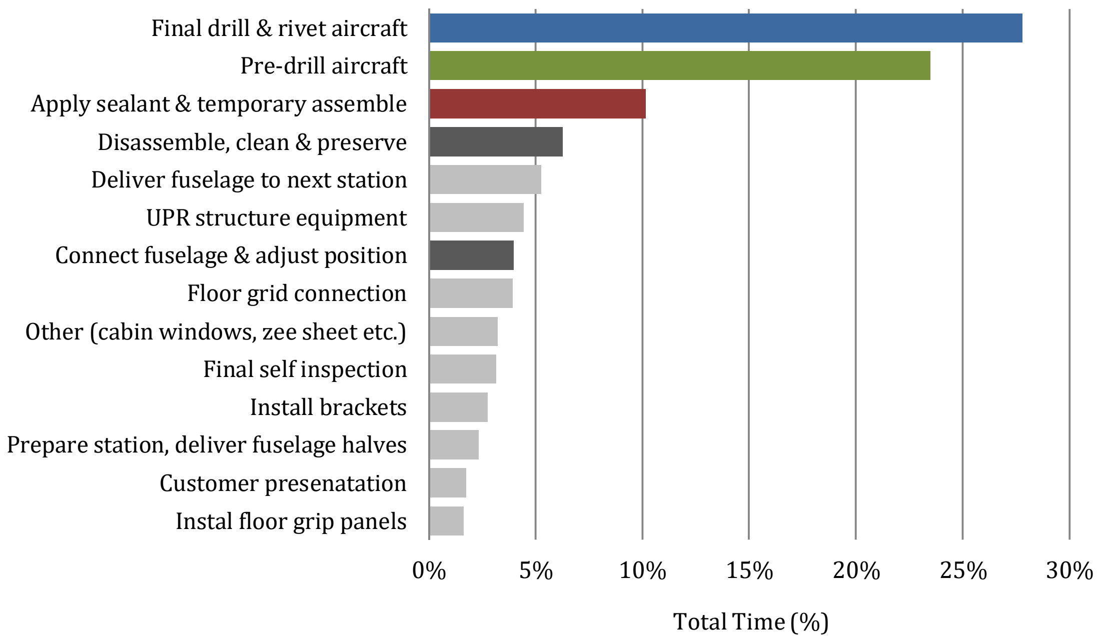


Figure 33 Work packages' total times A321 (own figure)

The share of cycle times for the overall process steps that are influenced by automation are broken down to a slightly more detailed level and separated between the upper and lower floor (cabin and cargo area) of the aircraft in the following figure.

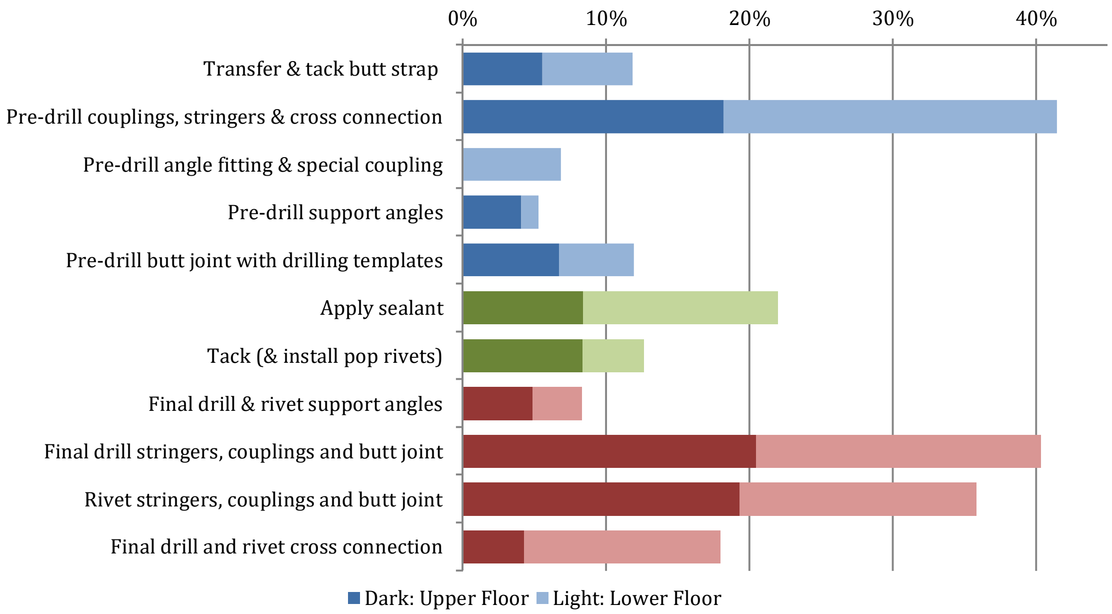


Figure 34 Total upper and lower floor cycle times for relevant process steps (own figure)

Moreover, operation element times for tasks such as pre-drilling one hole, inserting a rivet etc. are shown in the following diagram. This highlights the differences between minimum and maximum values for the same operation elements throughout the whole assembly process involving different components and areas (upper, lower floor) in the fuselage to be drilled, tacked etc. the large differences within most operations lead to the requirement that no mean or standard operation elements should be used for cycle time calculations but the specific elements for each task.

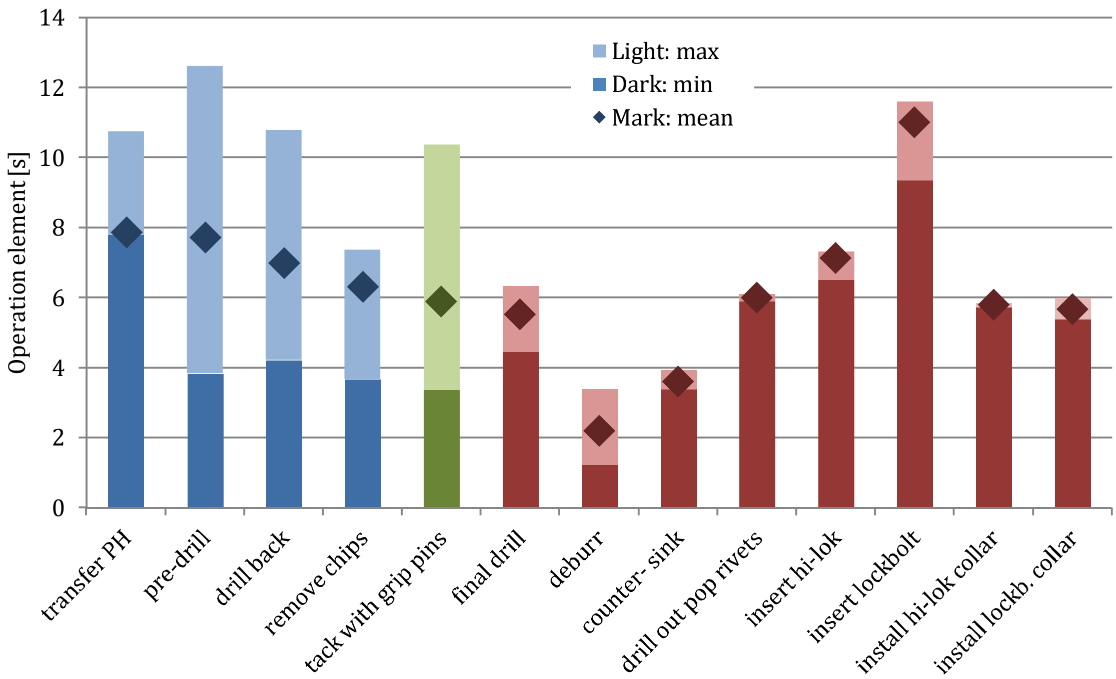


Figure 35 Operation element times (own figure)

Finally, lean ratios for the three main processes summarize the distribution of value adding, non-value-adding but necessary and waste activities (Figure 36). Table 14 shows which processes are defined as value adding, necessary but non value adding and waste as well as supporting explanations.

Table 14 Definition of operations according to the lean philosophy

Value Adding (VA)	Non Value Adding (NVA)	Waste (W)
attach part apply sealant final drill insert rivet install collars	transfer pilot holes pre-drill tack (needed to close gaps) countersink (can be integrated in final drill)	remove chips remove pins (pop rivets would not be removed) clamp (only preliminary before tacking) deburr clean drill back

Each operation in the cycle time calculation is specified as VA, NVA or W. In total the three processes that are relevant in this thesis contain 28% value adding, 22% non-value-adding and 50% waste time.

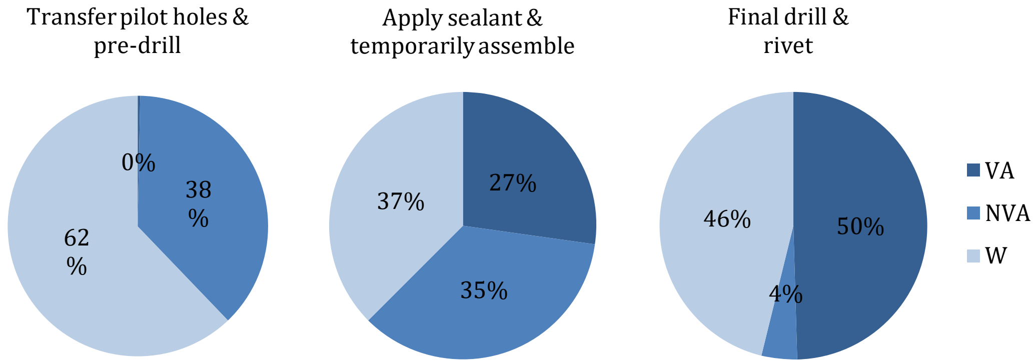


Figure 36 Lean ratios as is process (own figure)

4.4. Product and Process Requirements

In order to be able to develop a new assembly process all product (design) and process requirements have to be known. The requirements for the circumferential joint assembly are ordered according to the main process steps. Literature as well as various internal process specifications and norms served as references.

According to the widespread sand cone model, that explains competitive factors and how assigning priorities to operation objectives may result in lasting improvements in performance, quality is always the basis for deliverability (including reliability and speed), cost and flexibility. (Bellgran & Säfsten, 2010)

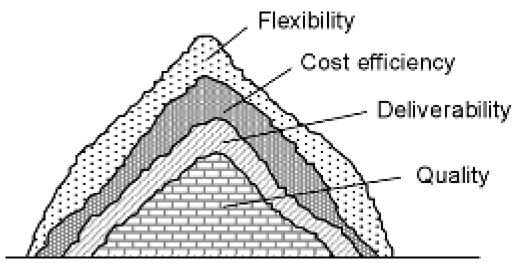


Figure 37 Sand cone model (Bellgran & Säfsten, 2010)

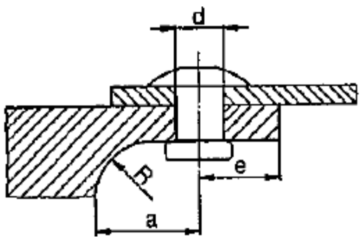
If an aircraft manufacturer wants to fulfil *EASA (European Aviation Safety Agency) Part 21*, which rules the design and production related certification procedures for aircrafts and related products, the company must set up and maintain a quality system that ensures airworthiness. This system must be aligned with the *EN 9100*, representing the quality norm ISO 9001 plus specific aerospace requirements. This requires the definition of risks resulting in critical items which would have a significant effect on the product. Those are further broken down into key characteristics that would have the greatest impact on the customer's perceived quality. The EN 9100 also prescribes design and development validation via tests.

An aircraft has a life expectancy of up to 40 years compared to 10-15 years for a car. It must function without problems despite the vibrations during flights at 10,000m close to Mach one. This demands high quality for all single parts, manufacturing and assembly processes (Kihlman, 2005). Errors in a single step can lead to costly fixes and disruptions in production. Even worse, they can cause product failure. Aerospace drilling and fastening applications require tight tolerances to produce high-strength airframes that can avoid the risk of cracking and fatigue failure. Therefore everything from hole diameter to critical edge distance to correct sealing is crucial.

POSITIONING OF PARTS AND HOLE DISTANCES

When the couplings are positioned between the corresponding stringers they already have pilot holes. Typical tolerances for hole locations lie between ±0,5mm and ±0,2mm. For positioning and after the final drilling and riveting step it is essential that the holes' edge distances to the coupling edges themselves and to edges of parts below them, especially the stringer end and the butt strap edge, meet certain minimal distances. Fasteners are subjected to random cyclic loading. In places with short edge distance, fatigue or creep failure can occur. The cracks slowly degenerate the structure if they are not detected and fixed. (Bullen, 2013) (Engmann & Mentzel, 2013) (Airbus Operations GmbH)

Another requirement is the distance to the flanged edge. Due to tool accessibility in production and mechanical strength as well as fatigue reasons (rivet tear out) the edge distance E should be as big as possible and the distance from the flanged edge A as small as possible (provided that a minimum distance is kept). The same requirements apply to the stringer edges and the butt strap and shell edge when drilling the butt joint with the drilling templates. (Engmann & Mentzel, 2013) (Airbus Operations GmbH)



$$e_{min} = 2 * d$$
$$a_{min} = R + d + 1mm$$

Figure 38 Edge distances with rule of thumb (Engmann & Mentzel, 2013)

Another requirement is the rivet hole and edge pitch as shown in Figure 39.

Dimension	Tolerance
A	+ 1,0
B	± 2,0

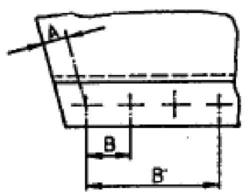


Figure 39 Rivet and edge pitches (Engmann & Mentzel, 2013)

PRE-DRILLING

Pre drilled holes are necessary for positioning, fixing and temporary fastening to prevent drilling chips under the parts when sealant already is applied. Manual drilling needs several pre-drilling steps while drilling large diameters while (semi)automated drilling can be done in one shot (*one shot drilling*). (Airbus Operations GmbH)

The important requirement during pre-drilling is to drill enough holes to assure a sufficient tacking rate and pattern. Also, waviness must be prevented. Therefore, when transferring the butt strap pilot holes one starts from the middle of each shell towards the open longitudinal joints and all holes are directly tacked before the next hole is drilled.

CLEANING

No chips, burr and other contaminations must remain at the components before they are connected. They can cause scratches during further assembly steps or increase the risk for fatigue cracks during the aircraft lifecycle if they are clamped between two parts.

APPLICATION OF SEALANT

Before the application of sealant pre-treatment of the surface such as cleaning with solvent and roughening with scotch-brite is required. If surfaces are sealed (wet assembly) a 0.15-0.30mm thick layer is applied to ensure that the gap is completely filled. Moreover, sealant must be applied on the rivets in the wet assembly areas. (Engmann & Mentzel, 2013) Figure 40 shows the sealant requirements for interfay sealant and sealant on rivets.

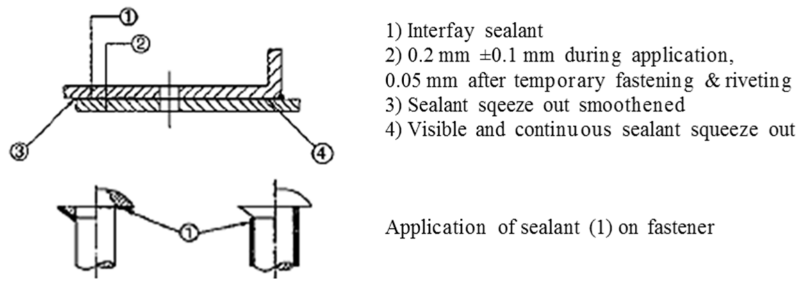


Figure 40 Sealant requirements, adapted from (Engmann & Mentzel, 2013)

It is permitted to drill through the sealed surfaces during all curing phases and after complete curing. If the sealing compounds are not yet fully cured, it must be ensured that the components are adequately tacked. (Airbus Operations GmbH)

TEMPORARY ASSEMBLY (TACKING)

The temporary assembly (tacking) with pins, pop rivets of other temporary fasteners has to apply enough clamping pressure to close the gap between the parts without damaging the component surface. Otherwise rivets might be pulled in and chips can remain between the parts during final drilling. Therefore, in the current process 100% tacking is required with a component thicknesses ≤ 3mm and 50% tacking with component thicknesses > 3mm. (Airbus Operations GmbH) By the use of automatic drilling machines or other automated systems a pressure foot can contribute to the clamping.

Components must be tacked in such a way that:

- the components are correctly positioned with respect to each other,
- warping is prevented (especially when riveting thin metal sheets),
- no foreign particles can get between the components,
- no burr can form between the components. (Engmann & Mentzel, 2013)

If riveting after expiration of the assembly time (on slightly or fully cured sealing compound) becomes necessary, the components must be clamped to ensure a layer thickness of ≤ 0.05 mm (in riveting area). If components are tacked, 100% tacking is required with component thicknesses ≤ 3 mm and 50% tacking with component thicknesses > 3 mm. There must be no gaps between the sheets when the tacks are removed for riveting or bolting. (Airbus Operations GmbH)

FINAL DRILLING

In order to manufacture faultless holes the drill type, point geometry and cutting material as well as processing parameters such as rotational speed (rpm) and feed and the concentricity of the clamped tool have to be observed. The choice of the drilling tool geometry depends on the material to be drilled and the requested hole tolerances. The hole diameter and its tolerances depend on the fastener type. Cutting parameters depend on for instance hole diameter, stack thickness, material, cutter material and lubrication.

Concerning the hole characteristics there are tight diameter and hole surface tolerances depending on the fastener type, component thickness (rivet length) and materials to be fastened. These parameters are strongly connected to the tool lifetime. A perpendicularity of 90°±1° is allowed for close tolerance bolts and blind rivets. Holes need to be deburred if the burr exceeds a height of 0.2mm. Furthermore, there are requirements regarding the eccentricity of holes (hole mismatch). (Airbus Operations GmbH)

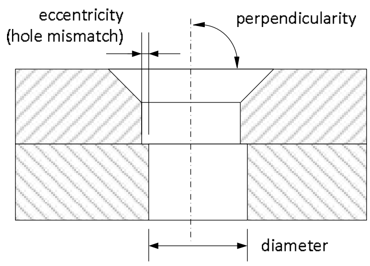


Figure 41 Final drilling tolerances (own figure)

COUNTERSINKING

The main requirements for countersinks are concentricity and coaxiality of countersinks and holes. The countersink angle and the countersink diameter are dependent on the fastener to be installed. The tolerance of the countersink angle is ±0.5°. The position of the countersink/hole axis must comply with the tolerances of ±0,05mm. The remaining cylindrical part must not be shorter than 0,2mm. Furthermore, a certain countersink depth is required to assure a flat outer surface. (Airbus Operations GmbH)

For the manual production of countersinks and holes in one operation stop holders and tripods shall be used. In order to meet the tolerances combined drilling/countersinking should be given preference.

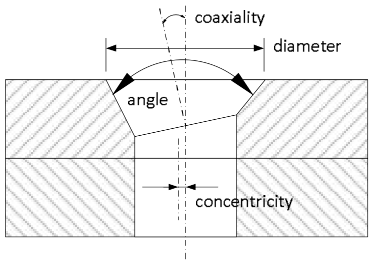


Figure 42 Countersink tolerances (own figure)

Riveting

During the riveting process the rivet heads must not be damaged and a rivet with the correct clamping length according to the stack thickness must be inserted. If the rivet is hammered into the hole a certain pressure must be applied.

After riveting the waviness or gap between components must not exceed 0.2mm while the gap limit at the rivet shank is 0.05mm when the sealant application time has expired.

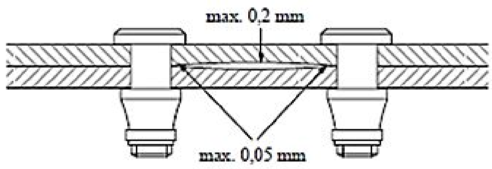


Figure 43 Allowed gap between components, adapted from (Engmann & Mentzel, 2013)

Ishikawa Diagram

In order to understand the influence parameters on the hole quality generated by a human or a machine an Ishikawa diagram (cause and effect diagram) was created. It structures the influence parameters into the areas process, people, equipment, material, environment and tolerance chain (Figure 44). Hole quality can be further specified as position, surface roughness, diameter, normality and countersink quality.

Tolerance Chain

The tolerance chain is usually not part of the typical Ishikawa influence areas and shall be further elaborated here. The tolerance chain leads to a certain quality of the hole position and thereby determines edge distances, etc. The length of the chain as well the variation of certain elements differs between manual and automated processes. For instance, a machine can assure better normality than an operator drilling with a hand tool. On the other hand, the manual tolerance chain is shorter as the operators' ability to reference a pre-drilled hole and position the tool is almost perfect and therefore only normality tolerances remain. The automated tolerance chain however, includes the tacking element used for referencing, the robot's referencing, positioning and drilling normality tolerances. Figure 45 shows the general tolerance chain for a manual and an automated process.

There are many contributors in the automated chain, only some of them could be included in the Ishikawa diagram. They belong to the different components, the assembly process and the robot's process. In case of a coupling the contributors are:

- stringer and coupling geometry tolerances (foot width, web thickness, length, etc.)
- position and diameter of pilot holes in butt strap
- diameter and position of pilot holes in stringer and coupling
- assembly gap between FWD and AFT section
- manual adjustment of coupling on stringer (optical)
- angular deviation during manual transfer of pilot holes from inside
- hole float and diameter of temporary fastener
- temporary fastener head centre tolerance (for referencing)
- sealant thickness
- robot optical measurement accuracy on reference point
- robot positioning accuracy
- robot angular deviation to surface.

A one dimensional tolerance analysis is conducted in chapter 6.2.2.

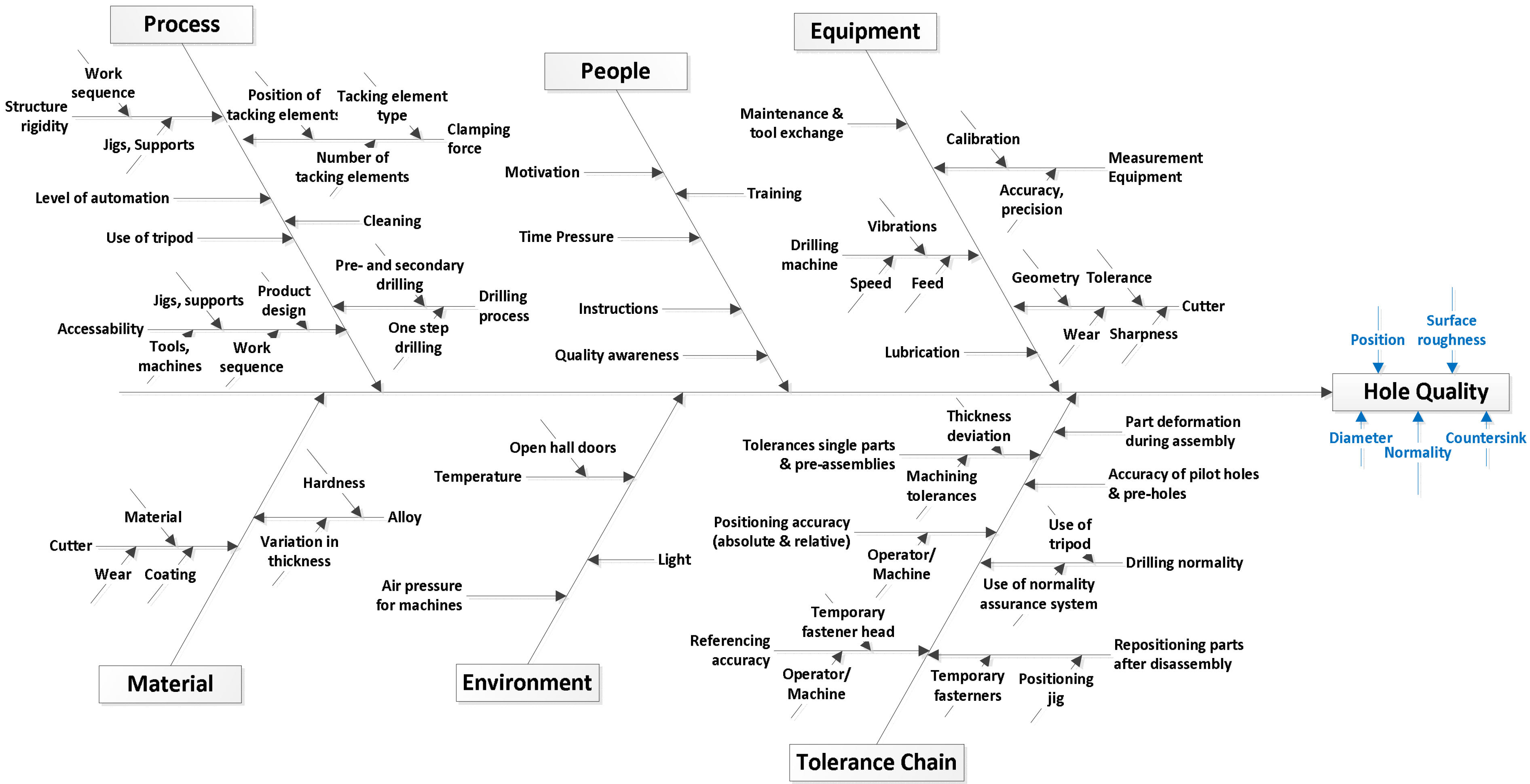


Figure 44 Ishikawa diagram: hole quality (own figure)

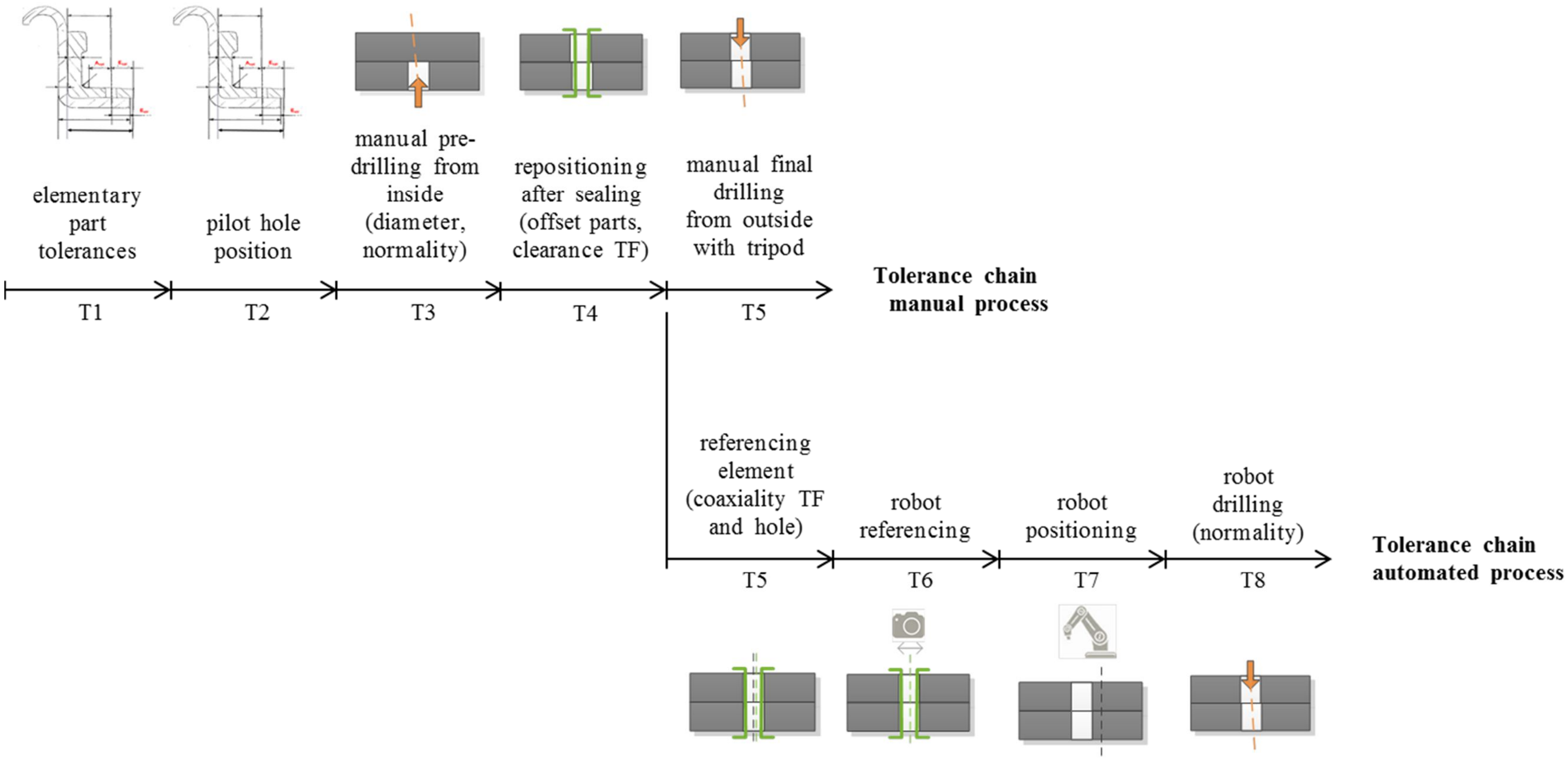


Figure 45 Tolerance chains for manual and automated process, adapted from (Kolle, 2016)

5. CONCEPT DEVELOPMENT

In order to enable the development of different assembly concepts the project conditions are explained first as they set the motivation and boundaries for this chapter. Afterwards a SWOT analysis is performed to understand the strengths and weaknesses of the manual as well as the opportunities and threats of an automated process and the process steps are analysed regarding capabilities and best practices of humans and robots (task allocation). Finally, the method of the morphological box is utilized to generate concept ideas.

5.1. PROJECT CONDITIONS

According to Bullen (2013) airframe assembly represents 65-75% of the cost of an airplane's production while fabrication activities represent 35%. Other costs generated besides production belong to engineering/support and materials (Figure 46). "The primary cost driver for the assembly of an airframe is the touch labour used to position, assemble, and fasten together the supplied parts, pieces, and components" and not material costs as during the fabrication of the components that are assembled later. Within assembly drilling and countersinking is by far the greatest contributor (Bullen, 2013). A commercial aircraft can have 1.5-3 million fasteners (Campbell, 2006). "One of the worst enemies in the battle to maintain aircraft quality is fatigue cracks." The long periods of vibrations during the flight are one reason why aluminium in the airframe structure is not welded as in cars but mostly assembled through drilling and fastening. (Kihlman, 2005)

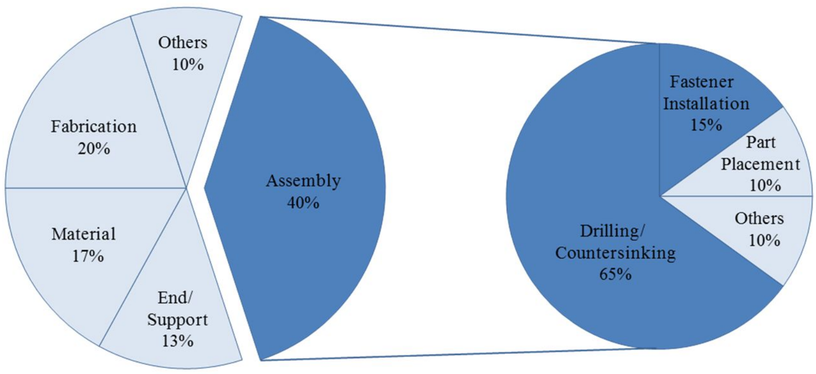


Figure 46 Airframe cost structure breakdown, adapted from (Bullen, 2013)

"When applied to the assembly process successfully, automated drilling/countersinking technology has shown that it not only reduces the touch labour hours needed to produce an airframe, but also impacts the burden added to each assembly hour. [...] Higher quality derived from automation reduces the cost of quality by defect associated rework. The removal of human beings from the strain of repetitive motion required by hand drilling/ countersinking also reduces the cost of lost-time injuries." (Bullen, 2013)

This thesis is written within the Airbus Hamburg project *4th FAL*. As the A320 family aircrafts have an order backlog of 5500 aircrafts and the demand is constantly high the production rate shall be increased from 42 to 60 aircrafts per month until 2019. Currently it would take more than 10 years to deliver these aircrafts to the customers who consequently complain about the long delivery times. One step towards this goal is the construction of a new final assembly line at the site in Hamburg until end of 2017 in order to increase capacities and efficiency as explained by Didier Evrard, Executive Vice President Programmes at Airbus (Flug Revue, 2015). The throughput/lead time per work station will be 2 days. While the circumferential joint of the fuselage is assembled manually in all currently existing FALs new technology, for instance robots for the circumferential joint assembly, shall be integrated into the new FAL. (von Borstel, 2015) (Horch, 2016)

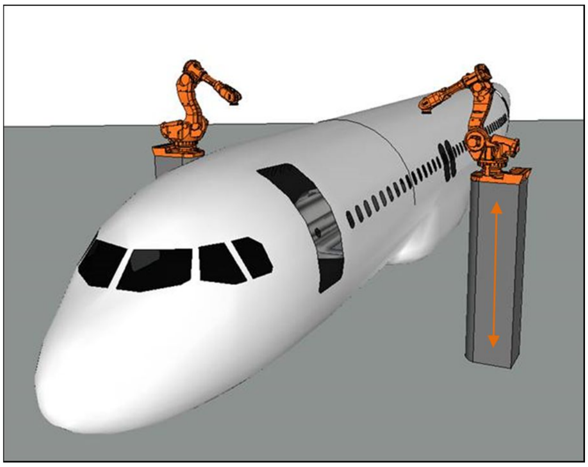


Figure 47 Automation principle with robots and end effectors (new figure)

Within the project the type of automation is already decided. Robots with special drilling and riveting end effectors as well as a 7th axis and required peripheral equipment will be purchased from a supplier specialized on aircraft assembly automation. During the thesis the concrete decision for a specific supplier was made. A general feasibility study, for instance the number of holes that can be reached and accessed by the robot, as described in chapter 2.3.1 (Considerations before Automating) was performed before and during the thesis. The automation concept is illustrated in Figure 47. It shows the location of the circumferential joint, the robots working on both sides, operators working in the inside of the fuselage and the robots' additional axis.

The chosen robot system is able to

- Drill or secondary drill and countersink in one step
- Apply pressure to the parts and thereby clamp them
- Adjust normality during drilling
- Reference targets such as edges, holes, temporary fasteners (sometimes only if installed from the outside) by the vision system
- Calculate hole positions by using references (e.g. by referencing two temporary fasteners, generating a virtual line between them and calculating hole pitches & positions between the reference elements) as exemplarily explained in Figure 48

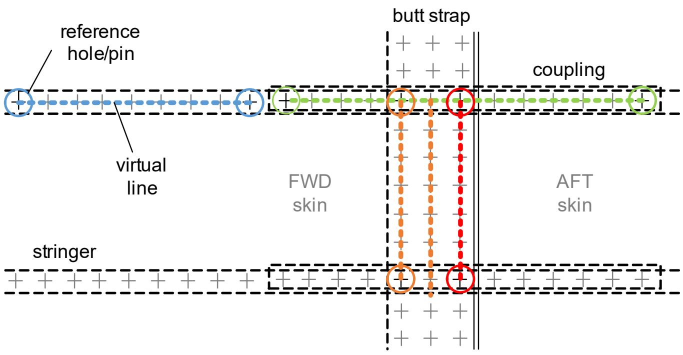


Figure 48 Referencing principle to calculate hole position (own figure)

- Place fasteners (hi-lok, lockbolt or hi-lite) & insert them by a hammering process
- Manipulate certain temporary fasteners (LISI and Centrix)
- Store different types of fasteners in an external rack & feed them to the insertion tool
- Apply sealant around the shank of a fastener

- Supply minimum quantity lubrication through the tool
- Extract dust and chips

It is not able to

- Install pop rivets
- Install rivet collars
- Reference certain temporary fasteners (Centrix) installed from the inside
- Change the drilling tool during the operation (needs to move to the tool changer)
- Control the sealant application on rivets

It is assumed that the robot usually works alone but needs supervision and calls for operators during 15% of the time (especially when the vision system is used and for instance a reference object is dirty) and that the system's OEE (run time without breakdowns, setups and scrap per planned production time) is 80%.

5.2. ANALYSES

In addition to the cycle time analyses in chapter 4.3 a SWOT analysis is performed and the process steps are analysed regarding capabilities and best practices of humans and robots.

5.2.1. CAPABILITIES AND BEST PRACTICES

In this chapter capabilities of human and robots are listed for all operations, including the related product and process requirements. The one more capable is marked with an X and green colour. Furthermore, some explanations are included. The information collected in Table 15 can be used for task allocation between human and robot and serves as a reference for the evaluation of process variants in chapter 6.2.

Table 15 Capabilities

Criteria	Human	Robot	Requirements
Positioning of couplings	X (human can check & "pull" the holes to ensure ED)	(no access from outside, no flexibility and judgement)	Edge distances (in coupling, to stringer & to butt strap)
Transfer of butt strap pilot holes	X (tacking from inside needed)	(no access from outside)	
Pre-drilling from inside	X		
Application of sealant on surfaces	X		Layer thickness, consistency
Application of sealant on rivets	X	(X) (control algorithms for aluminium available)	Consistency
Deburring	(deburring always necessary)	X (eliminated by drilling quality)	Max. burr height
Tacking rate	(mostly 50% tacking rate needed)	X (smaller rate due to higher clamping force of robot)	Clamping pressure, closed gaps
Tacking rate flexibility	X	Choice of pre-defined tacking rate?: 30/50/70%	Adjustment of tacking rate to gap sizes

Tacking speed (pins)	X		
Tacking speed (pop rivets)		X	
Drilling: hole quality	(manual machines: only speed control)	X (good and repeatable hole quality)	Speed, feed & lubrication control, diameter
Drilling: hole surface	X (visual check)		Surface quality (connected to tool lifetime)
Drilling: perpendicularity	(during final drilling improved by use of tripod)	X (controlled by sensor)	Hole angle tolerance
Nr. of required drilling steps	(3-4 drilling steps per hole)	X (one step drilling possible if clamping force closes gaps)	Hole mismatch (no one way assy), hole quality
Number of required pre-holes	(all holes must be pre-drilled)	X (programmed drilling pattern only needs a few holes as reference)	Ensure required tacking rate
Countersink quality		X ±0.005mm	Concentricity, coaxiality, depth, angle
Riveting: choice rivet length	(risk for human error)	X	Choice of correct rivet length acc. to stack thickness
Riveting: hi-lok insertion speed	(placement and insertion in separated steps, risk for surface damage)	X (placing and insertion in one step)	Full insertion
Installation of collars	X (from the inside)	(no access from outside)	

5.2.2. SWOT Analysis

The SWOT analysis was conducted after spending one week at the circumferential joint station. It structures the gained impressions and shall in the same way give the reader a first understanding of strengths and weaknesses of the current process as well as opportunities and threats of an automated process with robots and the specific end effectors. Table 16 shows an overview of the SWOT analysis.

Table 16 SWOT analysis

	Strengths	**Weaknesses**

As Is Process	• Each aircraft is unique; flexibility of human, cognitive skills, reaction to deviations
	  ◦ e.g. greater tacking rate in case of large gaps
	• Check and adjustments for critical edge distances
	  ◦ to shell edge, coupling edge, stringer edge, coupling hole to butt strap, at stringer end
	• Flexible tacking rate acc. to aircraft
		• 100% pre-drilling needed, drilling to final diameter in several steps
		• 50% tacking needed
		• Adjustment of drilling template, drawn lines to assure shell edge distance, drawing of butt strap holes (accuracy)
		• Bad ergonomics, repetitiveness
		  ◦ on knees, drilling above head, limited space in cargo and while assembling the floor grid

	Opportunities	Threats

Automation	• Turnkey solution? → reduced lead time/ cost but same/better quality, improved ergonomics
	• Good hole qualities due to automated drilling and no deburring needed (constant parameters)
	• Possibility for lower tacking rate
	  • robot higher clamping force to close gaps
	• One step drilling without pre-holes
	• Drilling and countersinking in one step
	• Many rivets in the LF can be inserted from outside → automation possible
		• Each A/C is unique, summation of tolerances in FAL, no design for automation
		• Robot: good repeatability but limited accuracy & rigidity, influence of 7th axis
		• Longer tolerance chain, hole position accuracy issues at couplings and stringers (edge distances)
		• Design modifications necessary?
		• Reachability and accessibility
		  • limited accessibility at lower floor
		• The worst ergonomics (inside LF, floor grid) cannot be improved
		• At the outside 4 operators can work at the same time, but only 2 robots

5.2.3. Robot Cycle Times

In order to gain a first impression and collect input data for the cycle time determination of different variants the robot cycle times are compared to the manual cycle times. Thereby process chains such as for pre-drilling one hole are built based on their operation elements. The robot's accumulated cycle time is compared to the minimum as well as maximum manual chain (in terms of its length) that is present in the circumferential joint assembly. These variations are caused by different accessibilities at the upper and lower floor and other variations.

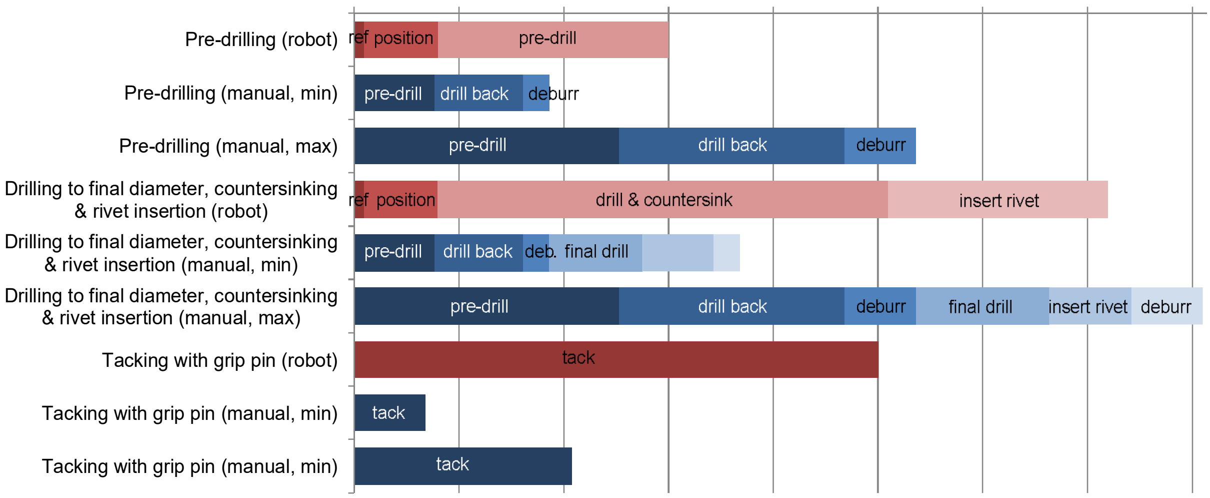


Figure 49 Comparison of robot and manual cycle times

For tacking both the minimum and maximum cycle time are significantly shorter than the automated process. For pre-drilling and final drilling & riveting the same is valid for the clearly more probable minimum values (see mean values in chapter 4, Figure 35) while the maximum values exceed the robot's cycle time.

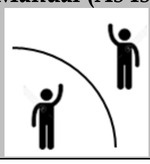
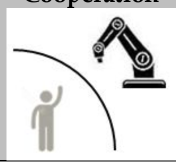
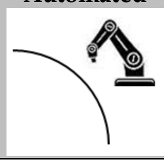
5.3. CONCEPT IDEAS

With the help of a morphological box several variants for the different production process steps are generated in a systematic but creative way.

Appendix 12.1 shows the morphological boy for the relevant circumferential joint processes that can be affected by the introduction of automation or that can be performed automatically. The different possible solutions are either performed manually, automated by the robots or they are a combination of manual and automated operations (see Table 17). That way, a matrix with all possible combinations is generated and a variant from each line can be chosen and combined with others. In the following chapter a more structured list of variants is generated for each process.

A prerequisite for all concepts is that a manual fall back solution must always be possible and that the remaining manual production lines must not be affected in a way that their processes do not function any more. This aspect limits for instance the possibility for design changes such as the removal of pilot holes.

Table 17 Concept Ideas: Morphological Box

Process	**Manual (As Is)** 	**Manual (Altern.)** 	**Cooperation** 	**Automated** 
…	…	…	…	…
…	…	…	…	…

6. CONCEPT EVALUATION

The developed concepts are evaluated by a utility analysis. It includes qualitative but also quantitative criteria. After explaining and ranking the criteria the evaluation is performed for each overall process separately. Tolerance stack-ups as well as a cost calculation for the rivets support the evaluation.

6.1. EVALUATION CRITERIA

The utility analysis is used for the assessment of several - in this thesis qualitative as well as quantitative - criteria in order to compare different process variants. The criteria listed and explained below are chosen for the circumferential joint assembly. They can be sorted into the categories efficiency, quality, human centred and technology.

Productivity & Efficiency	
Cycle time costs	Manufacturing costs are *calculated* based on cycle times and hourly rates for operators and the robots.
Parallelisation capability	Parallelization capability means the possibility for parallelisation of tasks. This results in a reduced lead time which addresses the need for faster delivery of the product. A precedence graph of the as is process showing predecessor and successor processes supports the evaluation in this category (appendix 12.6).
Robot utilization	The degree of robot utilization is c*alculated* based on its share of the cycle time. If a robot is purchased the utilization should be high and standstill due to the process planning low (e.g. because tasks are per-formed manually instead of automated).
Lean ratio	The term lean ratio was chosen in order to consider the lean philosophy of waste reduction (e.g. set-up times). It is c*alculated* as the relation be-tween value adding, necessary and waste activities (lean philosophy).
Quality	
Quality/technical risks	Risks for quality or technical problems have to be considered when choosing a variant for a certain production step. Experiences from other drilling/riveting machines serve as the input. Appendix 13.6 summarizes the answers received in interviews.
Complexity	Complex or complicated processes and technology increase the risk for errors and process instability. Examples are human mistakes or necessary tool changes due to the complexity. Another aspect is potential harmonisation, more precisely the number of (temporary) fasteners and tools as these influence the robot system complexity, logistics etc.
Accordance to capabilities	In Table 15 man and machine capabilities are specified in terms of the different process steps. These should be used in the best way when allocating the tasks.
Human centred	
Dependency man-machine	In case of cooperation, dependencies between the manual and the automated operations might increase the lead time as robot and opera-tor need to wait for each other.

Ergonomics	An important criterion is ergonomics of manual tasks. In areas that are difficult to access or require bad ergonomic body positions automation can improve ergonomics.
Safety	Safety considers the risk for injuries, especially those caused by the robots.
Technology	
Feasibility risk	The feasibility risk refers to technology readiness and experiences of operators with a technology or process. It is neglected if no new technology is introduced in a process.
Impact of design modification	In case of possible design modifications their (negative) impact on the other manual FALs or the previous manufacturing processes have to be considered.

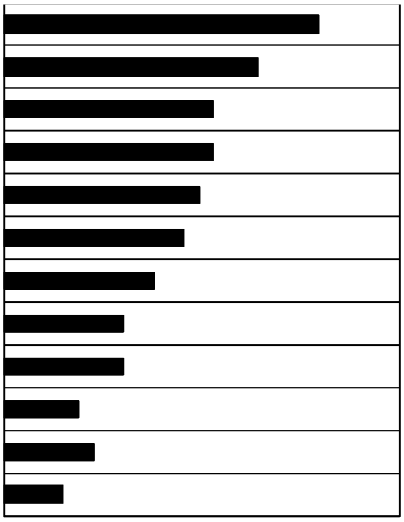
Table 18 Pairwise Comparison of evaluation criteria

		Efficiency				Quality			Human Centred			Technology			
	more/less/equally \ than/as	Cycle time costs	Parallelisation capability	Robot utilization	Lean ratio	Complexity	Quality/technical risks	Accordance to capabilities	Dependency man-machine	Ergonomics	Safety	Feasibility risk	Impact of design modification	**Sum**	**Percentage**
Efficiency	Cycle time costs		0	1	0,5	1	0,5	1	1	0,5	0	0,5	0,5	**6,5**	**10%**
	Parallelisation capability	1		1	1	1	0,5	0,5	0,5	0,5	0	0,5	0,5	**7**	**11%**
	Robot utilization	0	0		0,5	0,5	0	0	0	0,5	0	0,5	0,5	**2,5**	**4%**
	Lean ratio	0,5	0	0,5		0,5	0	0,5	0,5	0	0	0,5	0	**3**	**5%**
Quality	Complexity	0	0	0,5	0,5		0	0,5	0,5	0	0	0	0	**2**	**3%**
	Quality/technical risks	0,5	0,5	1	1	1		1	1	0,5	0,5	1	0,5	**8,5**	**13%**
	Accordance to capabilities	0	0,5	1	0,5	0,5	0		0,5	0	0	0,5	0,5	**4**	**6%**
Human Centred	Dependency man-machine	0	0,5	1	0,5	0,5	0	0,5		0,5	0	0,5	0	**4**	**6%**
	Ergonomics	0,5	0,5	0,5	1	1	0,5	1	0,5		0	0,5	0	**6**	**9%**
	Safety	1	1	1	1	1	0,5	1	1	1		1	1	**10,5**	**16%**
Technology	Feasibility risk	0,5	0,5	0,5	0,5	1	0	0,5	0,5	0,5	0		0,5	**5**	**8%**
	Impact of design modification	0,5	0,5	0,5	1	1	0,5	0,5	1	1	0	0,5		**7**	**11%**
														66	100%

These criteria have to be weighted for the utility analysis. In order to determine a ranking a pairwise comparison (Table 18) is conducted as described in chapter3.5.The pairwise comparison results in the ranking displayed in Table 19.

Table 19 Ranking of weighted criteria

1	Safety	15,9%
2	Quality/technical risks	12,9%
3	Parallelisation capability	10,6%
4	Impact of design modification	10,6%
5	Cycle time costs	9,8%
6	Ergonomics	9,1%
7	Feasibility risk	7,6%
8	Dependency man-machine	6,1%
9	Accordance to capabilities	6,1%
10	Robot utilization	3,8%
11	Lean ratio	4,5%
12	Complexity	3,0%



The evaluation criteria include several quantitative criteria that are based on calculations instead of subjective assessment. These are cycle time costs, robot utilization and the lean ratio. The determination of cycle times is the basis for all three quantitative criteria. Its method is described in chapter 3.5.

Manufacturing costs are calculated based on cycle times and hourly rates for operators and the robots. It is not sufficient to represent manufacturing costs by cycle times only as the hourly rates differ. For the calculation of the machine hourly rate as explained in chapter 3.5 the costs for tools and material are assumed to remain the same compared to the current process and are not included as they are not part of operator costs either. Also, building costs are neglected as they are unknown. Maintenance costs are further split into maintenance work hours and spare parts. The operator hourly rate and the calculation of the machine hourly rate are attached in appendix 13.3. The robot rate is ca. 20% higher than the operator rate. Its main contributors are amortisation and maintenance costs. As the machine hourly rate is based on many assumptions and experiences from other machines different scenarios are shown in the appendix to demonstrate the sensitivity of the calculation.

The degree of robot utilization is calculated as the ration between the robot's share and the total cycle time for a certain process variant.

The lean ratio is determined as described in chapter 3.3. Table 14 shows which processes are defined to be value adding, necessary but non value adding and waste as well as supporting explanations. Each operation in the cycle time calculation is specified as VA, NVA or W.

6.2. EVALUATION

In this chapter the different concepts for the overall production steps transfer of pilot holes and pre-drill, temporarily assembly as well as final drill and rivet are evaluated and compare with each other. In appendix 12.3 it is explained why some concepts are excluded prior to the evaluation and not further considered. In the following chosen variants for the overall process steps are evaluated and compared. The first variant always represents the current way of working.

6.2.1. TACKING RATES AND CONDITIONS

Essential information is the tacking rate as it influences all processes considered in this thesis. Referring back to chapter 4.4 a sufficient tacking concept has to

- clamp parts and close gaps during final drilling to prevent the inclusion of chips and creation of burr between two parts,
- clamp the parts during rivet insertion to prevent the separation of layers and
- assure the even distribution of sealant between the surfaces.

The various documents, databases and reality mismatch in terms of tacking rates. Table 20 shows the different statements as well as the scenarios applied in this thesis. The baseline scenario is adapted from the current process while a more progressive scenario could be possible as the robot has the possibility to close gaps by applying clamping force and tests have shown some promising results. The mixed scenario takes these results into account but at the same time considers part stiffness and critical areas.

General aspects and conditions that were considered when the scenarios were chosen are:

- The tacking rates demanded by the instructions aim to assure quality in any case. In reality tacking rates are decided for each aircraft based on the size of the gaps. One can assume that the MTM calculations, as they are the basis for costs, take into account these variations.
- Robots, however, are less flexible and the tacking rate also determines the pre-drilling rate and programming, i.e. it is not possible to increase the tacking rate if necessary during production.
- For the butt joint assembly 50% tacking is often required in the current process to pull waves in the skin to the open longitudinal joints (pilgrim step procedure). Therefore it is chosen as the lower limit in the scenarios for the thin-walled upper floor.
- In the lower floor the components are thicker and stiffer which can lead to even higher tacking rates up to 100% to close the gaps in the current process compared to 50% as usually applied.
- The longitudinal joints are critical areas for the aircrafts structural performance and often contain waves in the material.
- If riveting after expiration of the assembly time (on slightly or fully cured sealing compound) becomes necessary, 100% tacking (in the current process 50% grip pins and 50% pop rivets) is required in case of component thicknesses ≤ 3 mm (as it is the case for the skin in the upper floor) and minimum 50% tacking in case of component thicknesses > 3 mm (see chapter 4.4). This can be relevant for the UF butt joint assembly where sealant is applied already before the fuselage connection.
- For the couplings it is assumed that the assembly time will not be exceeded as sealant can be applied later just before final drilling and riveting. However, the cross connection has to be finished before.
- This cross connection has to be completed before the coupling-skin connection is riveted because if collars are installed in the coupling-skin connection there is not enough space to rivet the cross connection. Also, the structure needs a certain stiffness to be able to close gaps with the robot.

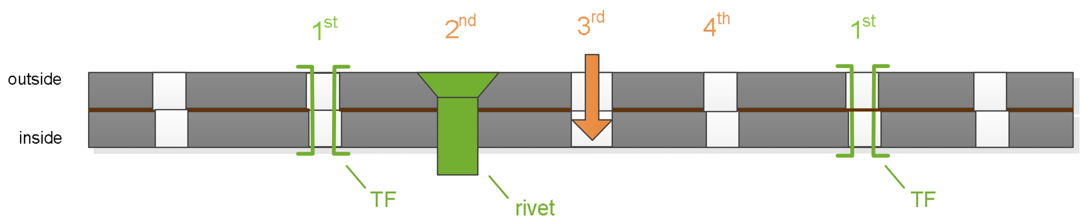


Figure 50 Principle of clamped neighbour

- The robot is able to apply pressure to the parts through the pressure foot and thereby close gaps during the drilling process. This offers the possibility to tack less than in the manual process. If the concept of the clamped neighbour is applied tests have shown that a tacking rate of 25% is possible if a rivet is inserted after drilling a hole. The principle is explained in Figure 50: 25% of the holes are tacked. Afterwards the neighbour hole of a temporary fastener is drilled and a rivet is inserted. Finally, the remaining holes in line are drilled. Due to the fact that the fits are press fits the inserted rivet clamps as well and assures that at least one hole next to the one to be drilled is clamped.
- Although the lower floor skin is thicker a reduced tacking rate should be feasible for the butt joint by using the robot because it can press against the stiff pressure bulkhead.

Table 20 Tacking rate statements and scenarios

Area	Instruc-tions	MTM calculation	Production reality	Conservat. scenario	Progress. scenario	Mixed scenario
Upper Floor						
Butt joint	50%	33%	33-50% (-100%)	50% (-100%)	50%	50%
Coupling	33%	33%	25-50% (+50% pop rivets)	50%	33%	33%
Stringer	25%	25%	25-50%	33%	30%	25%
Longit. joint	33%	25%	50%	50%	33%	50%
Lower Floor						
Butt joint	50%	50%	50-100%	50%	33%	33%
Coupling	50%	25%	50-100%	50%	33%	50%
Longit. joint	50%		50-100%	50%	33%	50%

6.2.2. Tolerance Analyses (Stack-up)

Several tolerance analyses serve as input for the assessment of quality risks within different variants. The differences between one step and secondary drilling are of interest when deciding about tacking rates and a referencing principle. Also, the general issue of edge distance in stringers and couplings and distances to the coupling radius shall be investigated. The risk for snowman (double) holes is relevant for the size of pre-drilled holes and thereby clamping forces of temporary fasteners with a corresponding diameter. Finally, for pre-drilling the butt joint an analysis shall investigate whether an automated process can assure edge distances and rivet pitches.

Coupling and Stringer Tolerances

Critical tolerances are edge distances of holes in the couplings and stringers to the part edges in tangential direction and the edge distances of coupling/stringer holes to the butt strap edge in flight (x) direction. The latter is mainly caused by the tolerance of the gap between the two fuselage halves as well as the pilot hole tolerance in the coupling while the edge distances to the part edges are influenced by the single parts' tolerances themselves as well as the assembly process. Another critical distance is the one from the final hole to the coupling radius because a clash with the internal radius when a repair fastener is used.

Tolerance analyses within the project (Siewert, Bahr, & Kleen, 2016) were performed with 3D software based on a great number of Monte Carlo simulation runs for the first stringer position at the thickest stack position. Similar analyses were performed in a manual one-dimensional way within this thesis (appendix 13.5.3) in order to use them for further investigations. The 3D analysis have shown that at a non-tacked position, i.e. during automated one step drilling using references, the main contributors to the final edge distance in the stringer below the coupling in tangential direction are with decreasing importance

- the stringer foot width tolerance
- the stringer web deflection
- the coupling pilot hole position tolerance
- the angle misalignment (normality deviation) of manual drilling inside to outside (±3°)
- the positioning tolerance of the end effector (min. ±0.2 mm).

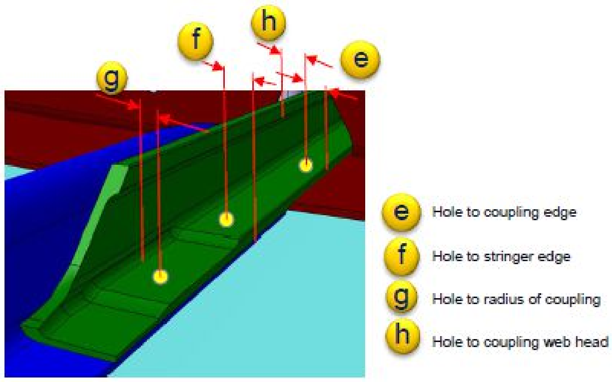


Figure 51 Critical tolerances (Siewert, Bahr, & Kleen, 2016)

The manual analysis shows similar results but in another order, e.g. the angle misalignment is ranked highest. All three of the WC, RSS and ASCR calculations result in too low minimum edge distances that are not allowed. But as already indicated the single part tolerances are the main contributors with 60% influence in total. The manual pre-drilling (as is also done in the as is process) further contributes with 21% in the manual analysis. Its influence will further increase for thicker stacks in the lower floor of the aircraft. The robot positioning accuracy contributes with 8%. These circumstances will most likely make a design modification necessary.

The main difference between one step drilling into full material and secondary drilling is that for the first a tack hole is used as a reference and thereby temporary fastener tolerances as well as the end effector's positioning accuracy belong to the contributors while for secondary drilling the existing per-drilled hole can be detected by the end effectors vision system. The simulations show that the difference between those two processes is very small. However, this simulation considers that temporary fasteners are installed from the inside. Therefore another manual one-dimensional tolerance analysis is conducted within this thesis to include the angular misalignment of a temporary fastener installed from the outside (see Figure 52).

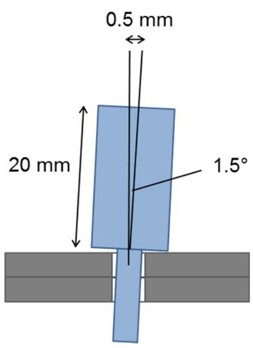


Figure 52 Normality deviation of a temporary fastener (own figure)

If a Centrix faster is installed from the outside instead of the inside its contribution in the tolerance chain increases from 2% to 17% with the increase of the coaxiality between hole and faster middle point from ±0,05 to ±0,5mm. The analysis can be found in Table 49 (appendix 13.5.3). The total contribution of a temporary fastener inserted from the inside (clearance and coaxiality) accounts for 6% in case of the tangential stringer edge distance at the first stringer position.

While the coupling's edge distance is at least sufficient for the (most optimistic) RSS calculation in the manual analysis the distance to the coupling's inner radius shows results that are out of tolerance for all calculation methods. Its main contributors are the

- normality deviation during manual drilling
- coupling pilot hole position
- coupling inner radius
- coupling web thickness and
- robot positioning accuracy.

Snowman Risk

Another tolerance analysis of interest is the risk for so called "snowman" holes. This phenomenon describes double holes that can occur

- during drilling back from the outside (secondary drilling) due to normality deviations or hole mismatch because of jig tolerances after re-connection of the fuselage or
- if non-transferred pilot holes in the couplings and the drilled hole through skin and coupling (one step drilling into full material) do not match properly due to hole mismatch after re-connection, pilot hole position variations according to the tolerances specified in the design and the robot's positional accuracy of the fuselage.

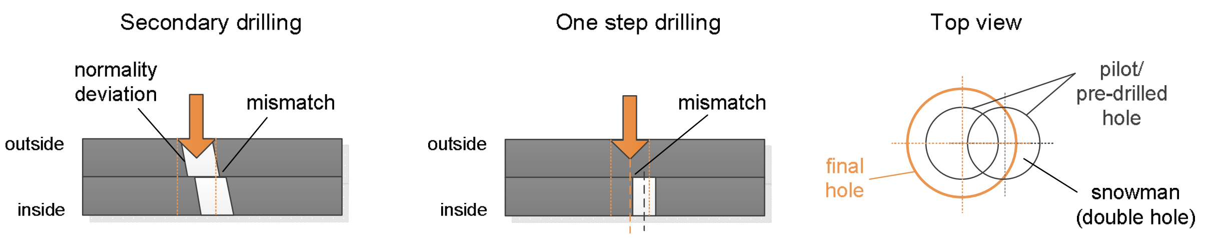


Figure 53 Snowman phenomenon (own figure)

The tolerance analysis shows a considerable amount of 35% double holes for the manual (as is) scenario and 7% for secondary drilling of a transferred hole in the automated process as it has a smaller tolerance for normality deviation. However, the feedback from the current process is that only few double holes occur. In case of one step drilling into full material no holes were out of tolerance. The first scenario (automated secondary drilling) addresses the question whether holes should be transferred with 2,5mm instead of 3,3mm as it is done in the current process to mitigate the snowman risk. Based on this tolerance analysis and the experiences from production smaller transferred holes will probably not be needed. However, the occurrence of double holes is more critical in the automated process as it will most likely not be detected from the inside because the rivet is inserted by the robot directly after drilling which makes it difficult to see a double hole.

Butt Strap Tolerances

The last tolerance analysis investigates the edge distances and rivet pitches in the butt strap. Appendix 13.5.4 contains the detailed tolerance analyses for one exemplary stringer field. A simplified referencing principle that can be analysed within a manual one-dimensional analysis is defined for the automated drilling process (see Figure 54): the left row's hole positions in x are calculated with the aid of a hole in the coupling while the right row is calculated in x based on the shell edge. The middle row uses the tack hole in the middle of the stringer field as its reference.

The left edge distance to the butt strap on the inside of the fuselage is not critical according to the tolerance analysis. The main contributors are with decreasing relevance

- the normality deviation during manual pre-drilling of the coupling's reference hole
- the width (edge) tolerance of the butt strap and
- the manual (optical) alignment of the coupling.

The tolerance chain for the right row is very short as the robot vision system can directly detect the shell edge and use it as a reference. Therefore this edge distance is not critical either.

For the rivet pitches the position of the middle row as well as the left and right row serve as input for the pitch between left and middle row. The allowed minimum distance is not critical but the maximum distance is likely to be exceeded. For the right rivet pitch a separated tolerance analysis has to be conducted as the tolerances of the skin-butt strap assembly are included in the chain. The rivet pitch is critical both in terms of its minimum and maximum distance. Main contributors are with decreasing relevance

- the deviation of the left row's holes and
- the gap between the sections.

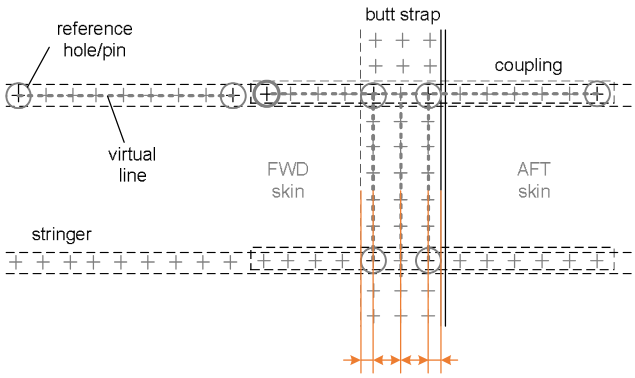


Figure 54 Critical tolerances and referencing principle (own figure)

In the real process the tack hole in the middle of the butt strap will be included in the calculation of all hole positions. This could not be taken into account in a manual analysis but it will improve the rivet pitches with respect to their tolerances. Therefore, the butt strap tolerances are considered non critical in the thesis.

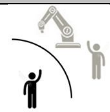
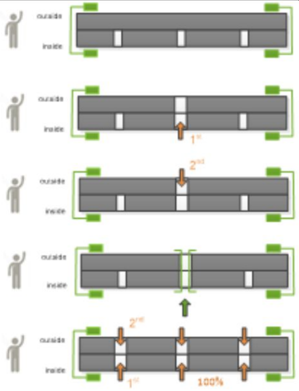
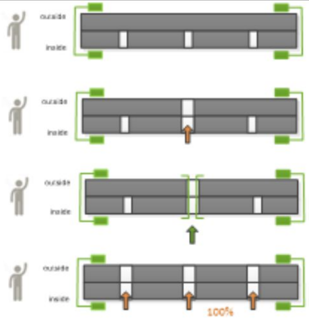
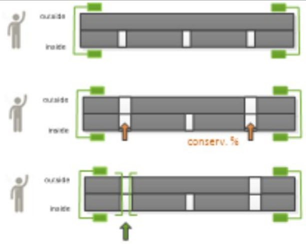
6.2.3. Transfer of Pilot Holes and Pre-drilling

The transfer of pilot holes and pre-drilling process evaluation is split into pre-drilling of couplings, lap joints and stringer and pre-drilling the butt joint.

Pre-drilling of Couplings, Lap joints & Stringers

First the variants for pre-drilling the coupling-skin connection, longitudinal lap joints and stringers are discussed. The first variant represents the as-is process where all holes (100%) are manually transferred and drilled back. V1 is the same except that drilling back to a larger diameter is not needed for holes that will be drilled to final diameter by the robot. Nevertheless, non-accessible holes have to be drilled back as before. The advantage of pre-drilling 100% of the holes is that the robot can reference each hole directly during secondary drilling. Thereby the error in the robot's absolute accuracy is eliminated as no holes are drilled by using other holes as references and calculating the desired hole position. Furthermore, transferring all holes reduces the risk for the snowman effect.

Table 21 Variants for pre-drilling of coupling-skin, lap joints & stringer-skin connection

	As Is	V1	V2	V3	V4
Principle					
Process Visualization					
Process Description	- position and fix couplings - transfer 25% of each coupling, lap joint & stringer 3,3mm - drill back couplings 4,1mm - tack (25%) - pre-drill remaining holes (→ **100%**)	- position and fix couplings - transfer 25% of coupling, lap joint & stringer 2,6/3,3mm - (drill back non-accessible) - tack (25%) - pre-drill remaining holes (→ **100%**)	- position and fix couplings - transfer **conservative scenario** 2,6/3,3mm - tack only couplings (for stiffness of structure) - (drill back non-accessible) - [final drilling remaining holes by robot]	- position and fix couplings - transfer **> mixed scenario*** 2,6/ 3,3mm - tack only coup-lings - (drill back non-accessible) - deburr reference holes - [later mixed scenario tacking rate; final drilling by robot with open holes as ref.] * UF coupling 50%, stringer 40%, LJ 65%, LF coupling 65%, LJ 65%	- position and fix couplings - transfer **progressive scenario** 2,6/3,3mm - tack only couplings - (drill back non-accessible) - [final drilling remaining holes by robot]

In V2, V3 and V4 not all holes are pre-drilled as the robot is able to final drill holes in one step given that the parts are sufficiently clamped. Also, drilling back is not required (except for holes that cannot be accessed by the robot). Holes are manually transferred/pre-drilled to be used for tacking later during the process according to the conservative (V2) or progressive (V4) scenario. If the decision is made to transfer the pilot holes with 2,6mm instead of 3,3mm to mitigate the risk for snowman holes the clamping force of a low tacking rate with smaller diameter might not be high enough. Later the remaining holes are final drilled by the robot in one step while the transferred holes serve as a reference and are drilled to final diameter in a secondary drilling step afterwards. V3 has a slightly higher pre-drilling rate than V2 in order to offer the possibility to tack fewer holes (mixed scenario) later and use the holes that are left open for referencing during the final drilling step. This shortens the tolerance chain as no tacking elements are included.

Tests have been promising that a lower tacking rate for the couplings is sufficient in an automated process. Pre-drilling of the open stringer ends and lap joints is similar to the one of the couplings. The difference is that the final holes are smaller and therefore only pre-drilled once from the inside. In this case the change to 2,5mm pre-drilled holes is necessary in order to enable a secondary drilling by robot with satisfying quality. Compared to the couplings a lower stringer tacking rate is possible due to the stringers' geometry.

Appendix 12.4 contains a table for each process (such as pre-drilling the couplings etc.) listing its variants and explanations for all evaluation criteria. When the pre-drilling variants were explained many aspects related to cycle time costs and quality were already discussed. The tolerance includes further information. The criterion accordance to capabilities is rated good in all cases as the human flexibility and ability to take decisions can be used during the positioning of the couplings as well as their ability to "pull" pilot holes in the couplings in case edge distances are critical. The requirements on pre-drilled holes are low compared to final drilled holes. Parallelization of work can be done easily (with 4 operators per side) for the as is process as work from the inside and outside is similar in terms of time. In the other variants holes are not drilled back from the outside but in case more than 2 operators are working on each aircraft side they can work in parallel on the forward and aft side of the frame. However, the amount of work content differs on each side (ca. 60:40). The performance of the ergonomics criterion is based on the pre-drilling rate and thereby number of repetitive operations.

Due to the length of the tables the complete cycle time calculation will be attached only for the variants that will be part of the final solution. For the different variants of each process results are shown in summarizing and simple to overview graphs of the cycle time (costs) and lean ratios in appendix 12.5. Figure 55 visualizes the evaluation's results in pie charts as explained in chapter 3.5. The related evaluation matrix (utility analysis) can be found in appendix 12.5.

The overall utility rating does not show big differences between the variants as several criteria are rated the same for all of them. Variant 3 (pre-drilling slightly more than the mixed scenario and later using open reference holes) is rated the highest. The main reason is the quality criterion as a sufficient tacking rate is assured and open holes are used for referencing later. As mentioned earlier this is an advantage especially if temporary fasteners are installed from the outside or to change temporary fastener positions for the cross connection assembly.

The as is process as well as V1 mainly score worse than V3 because of the long cycle time and bad ergonomics. However, the cycle times do not differ as much as one might expect because the process includes many other tasks than influenced pre-drilling steps (e.g. preparations, tacking, support angle and cross connection pre-drilling). V4 bears the risk of a low tacking rate which can lead to insufficient clamping.

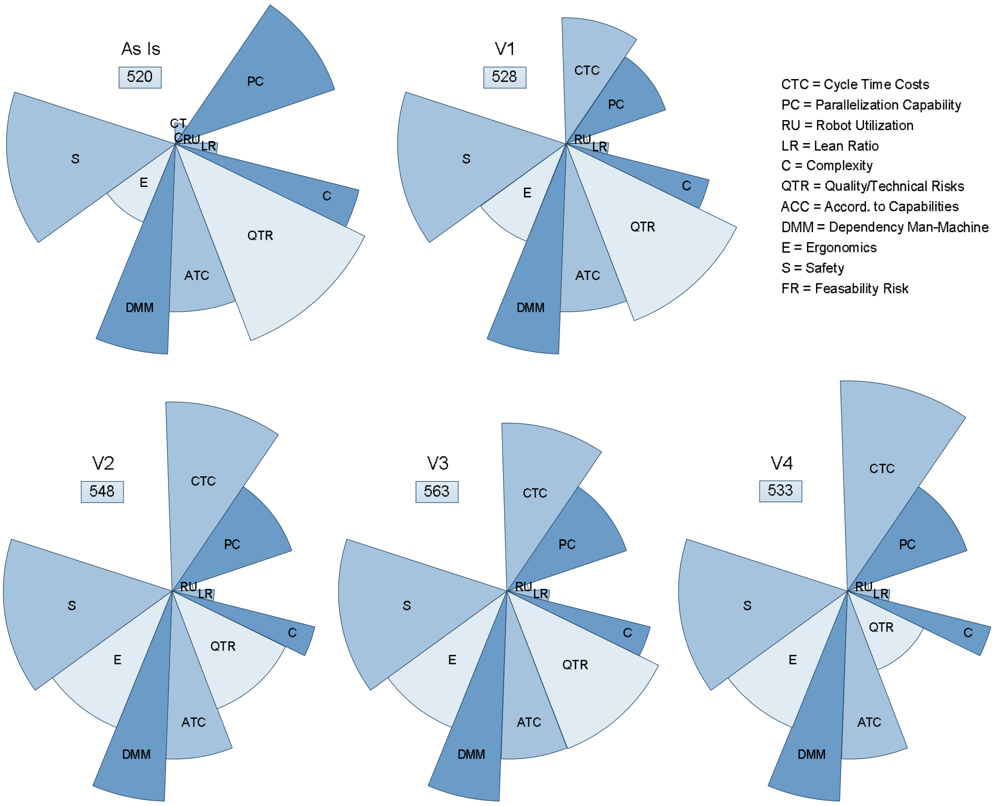


Figure 55 Pie charts for pre-drilling couplings, stringers and lap joints process

PRE-DRILLING THE BUTT JOINT

In the following the variants for pre-drilling the butt joint are discussed as specified in Table 21. The as is process uses drilling templates, same as V1 and V2 but here the conservative and progressive scenario respectively are pre-drilled and not drilled to a larger diameter. Later the remaining holes are final drilled by the robot. The conservative scenario assures that it is possible to tack the upper floor 100% (temporary fasteners plus pop rivets) if necessary because of the sealant's assembly time. Sealant with a shorter pot life would reduce the cleaning effort. However, sealant with a longer pot life that does not need this possibility could be applied instead. In V3 and V4 the pre-drilling is done by the robot instead of manually with templates. Templates do not have to be handled, no lines have to be marked but on the contrary pre-drilling a hole with a robot takes longer than drilling manually, especially if no second drilling step is required.

Although the templates assure a constant hole pitch they have to be adjusted according to the edge distance to the skin edge because the pilot hole positions used for attaching the templates vary to a certain amount. The manually marked lines on the skin support this adjustment. It is a flexible procedure resulting in satisfying quality but at the same time adding complexity to the process and requiring high operator skills. If a robot is used for pre-drilling it has a longer tolerance chain as discussed previously. However, the robot can use the pilot holes as well as the skin edge as a reference when calculating the desired hole positions. The tolerance analysis indicates that the butt strap edge distance is not critical in an automated process.

Another important criterion is the ability to parallelize processes. As the butt joint process needs a certain stiffness of the structure couplings and stringers should be pre-drilled and tacked before. Pre-drilling the support angles, however, can be done in parallel. Nevertheless if a robot is used from the outside and operators working on the inside they should work on different floors or protection has to be installed to separate the work areas. Comments regarding other criteria can be found in appendix 12.4.

Table 22 Variants for pre-drilling the butt joint

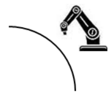
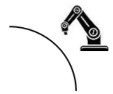
	As Is	V1	V2	V3	V4
Principle					
Process Visualization					
Process Description	- mark hole lines on skin - fasten templates - pre-drill **100%** 3,3mm - drill with larger diame-ter 4,1mm - remove templates	- mark hole lines on skin - fasten template - pre-drill **conservative scenario** - (pre-drill non-acces-sible area with small and larger diameter) - remove tem-plates	- mark hole lines on skin - fasten template - pre-drill **progressive scenario** - (pre-drill non-acces-sible area with small and larger diameter) - remove tem-plates	- global and local refe-rencing - pre-drill **conservative scenario by robot** (pilot holes & shell edge as reference) - (manually pre-drill non-accessible area with small and larger diameter)	- global and local refe-rencing - pre-drill **progressive scenario by robot** (pilot holes & shell edge as re-ferrous) - (manually pre-drill non-accessible area with small and larger diameter)

Figure 56 shows the pie chart visualizing the utility analysis evaluation. It results in V4 (pre-drilling the progressive scenario by the robots) being the most promising alternative. Pre-drilling of 100% (conservative scenario) should be avoided as it takes too much time, especially if it is done by the robot. Therefore a slowly curing sealant is required. If this is not the case templates should be used as in V2. Its rating is almost as good as the one of V4. The greatest disadvantage of V4 is the long cycle time compared to using templates but it is generally short compared to other processes and thereby less relevant.

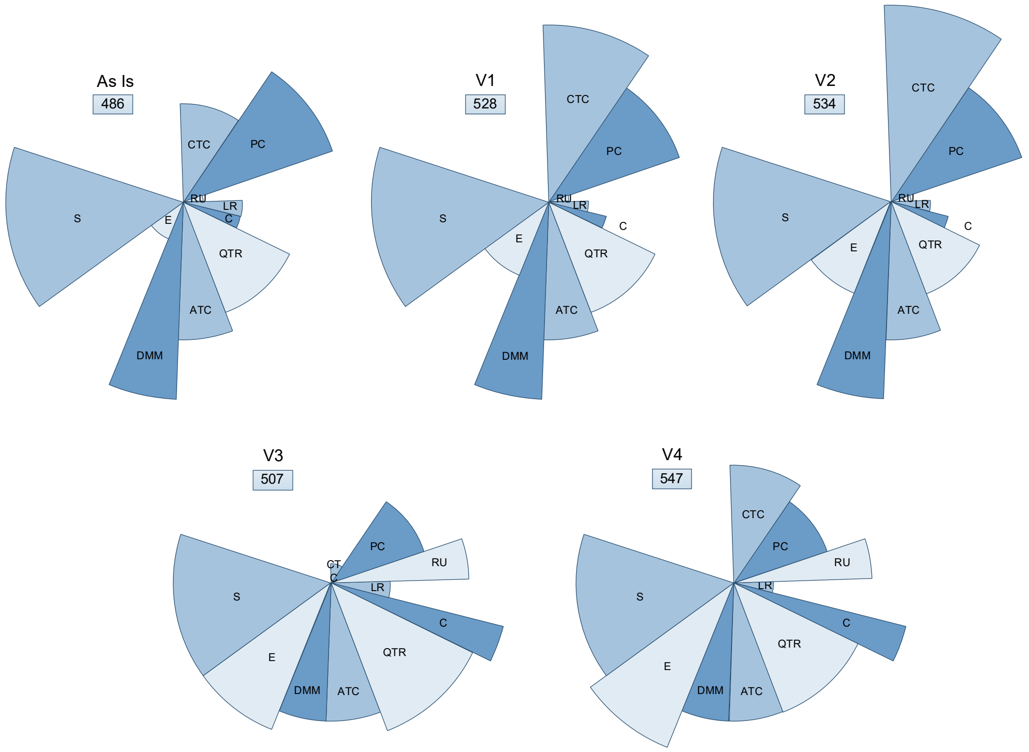


Figure 56 Pie charts for pre-drilling the butt joint

6.2.4. Temporary Assembly

The temporary assembly concept is evaluated regarding the choice of a temporary fastener type and the temporary assembly (tacking) process itself.

Choice of Temporary Fastener Type

An important decision to be made for the temporary assembly process is the choice of a temporary fastener type (or several types for different areas). It requires a different utility analysis focusing on other criteria, gaining experience with different types of fasteners and undertaking some tests. A recommendation for a certain type of temporary fastener is out of scope of this thesis. However, the criteria are listed in appendix 12.7 and important information that influences other processes is explained. These are based on interviews with (Stermann, 2016).

Figure 57 shows possible temporary fasteners that close the gaps and can be used for referencing. The choice of one or several temporary fastener types affects if temporary fasteners can be installed from the inside or outside of the aircraft – or the other way around: the choice of an installation direction which is assessed in the next subchapter influences the choice of a temporary fastener type. Furthermore, the choice affects the tacking strategy and the other way around. Aspects to consider in other process evaluations are:

- Pop rivets as used in the as is process cannot close gaps themselves. They have to be used in combination with other temporary fasteners.

- The screws have a sufficient clamping force for both 2,6mm and 3,3mm diameter, for Centrix fasteners the force is lower and for LISI fasteners too low for a diameter of 2,6mm; the characteristics of Sertibolts are not known.
- The installation of screws is a time-consuming two-sided process with two operators needed at the same time from the top to the middle of the aircraft and with one operator in the lower fuselage area (taking into account gravity).
- LISI fasteners are too large to be installed from the outside (robot accessibility).
- Cleaning of the fastener closing heads is required for relocation in case of LISI and Centrix fasteners installed from the inside.
- Installing fasteners from the inside leads to accessibility issues during the cross connection drilling and riveting. Fasteners in the coupling-skin either need to be installed from the outside, be very small (screws or Sertibolts inserted from the inside) or their position has to be changed during the cross connection assembly.
- From the inside there is no access to install grip pins (LISI, Centrix fasteners) next to the frame at the UF and the pressure bulkhead at the LF due to the size of the tool. Screws can be installed in areas with limited access.

Figure 57 Temporary fastener types: from Centrix, LISI and AHG (Sertibolts), screws

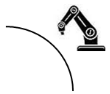
TEMPORARY ASSEMBLY (TACKING) PROCESS

Now the variants for the temporary fastening (tacking) process are evaluated. Only the as is process uses pop rivets in the upper floor. Besides allowing 100% tacking if necessary they simplify the insertion (and hammering) of rivets from the outside as no grip pin heads or bodies are interfering. Also, they make the cross connection assembly possible because grip pins can be removed. In the as is process grip pins are installed from the inside in the UF and from the outside in the LF. In the automated process the robot end effector path can be programmed in a way that no collisions with temporary fasteners occur, provided that small temporary fasteners are chosen or that they are installed from the inside.

In general the variants differ in the type of operation, manual (V1, V3) or automated (V2) and in the orientation of the tacking elements, placed from the inside (V1) or outside (V2, V3). The automated installation and removal of LISI and Centrix fasteners is technically possible; however, currently it takes significantly more time than the manual installation. Regarding the installation from the inside or outside there are several aspects to consider: If pins are installed from the outside advantages are that:

- the robot has the possibility to undertake this task (however, the technical risk is great),
- the technical readiness for referencing Centrix fasteners is better and
- there are no access issues next to the frame, at the lower floor and during the cross connection assembly. If fasteners are placed from the inside their positions have to be changed (V1a) for the cross connection or screws have to be installed (V1b) as they are smaller. The latter also applies for the areas with limited access from the inside.

Table 23 Variants for the tacking process

	As Is	V1a	V1b	V2	V3	V4
Principle						
Process Visuali-zation						
Process Descrip-tion	- manually in-stall grip pins from inside (UF) or out-side (LF) in all assembly areas - install 50% pop rivets and remove pins in butt joint and couplings in UF - remove TF later	- manually tack from inside: grip pins in accessible areas, screws in non-accessible areas - later change TF positions in coup-ling for cross con-nection - remove TF later	- manually tack from inside: grip pins in accessible areas, screws in non-accessible areas and couplings - remove TF later	- tack by robot from outside - later remove TF by robot	- manually tack from outside: grip pins (Centrix) - remove TF later	- manually tack couplings, strin-gers, longit. joints from outside with grip pins (Centrix) - tack butt joint from inside with grip pins & screws - remove TF later

Disadvantages of temporary fasteners installed from the outside are that

- the choice of a temporary fastener is limited due to their sizes (LISI cannot be installed from the outside)
- the final drilling and riveting process cannot be performed in parallel to the temporary fastener removal (robot needs to be removed and working platforms have to be set up) while if the fasteners are installed from the inside they can be removed in parallel to the installation of collars while the robot is final drilling and riveting and
- for referencing the angle deviation of the fastener head to the hole middle point is larger (in case of a 20mm long fastener and an angle deviation of 1.5° the centre is shifted by ca. 0,5mm, see Figure 52).

Because V3 (manual installation from the outside) shows many good characteristics but also a great quality risk for referencing due to normality deviations a further variant (V4) is generated. As the couplings, stringers and longitudinal joints can use open holes for referencing there is no issue for these parts. The butt joint on the other hand is tacked from the inside with grip pins as well as screws next to the frame where there is no access for the grip pin installation tool. Nevertheless, the edge distance issue is smaller for the butt joint and there is also the possibility to use holes from the coupling for referencing instead.

The baseline for tacking rates builds the mixed scenario for the couplings, stringers and longitudinal joints and the progressive scenario for the butt joint as those are the suggested solutions from the previous evaluations.

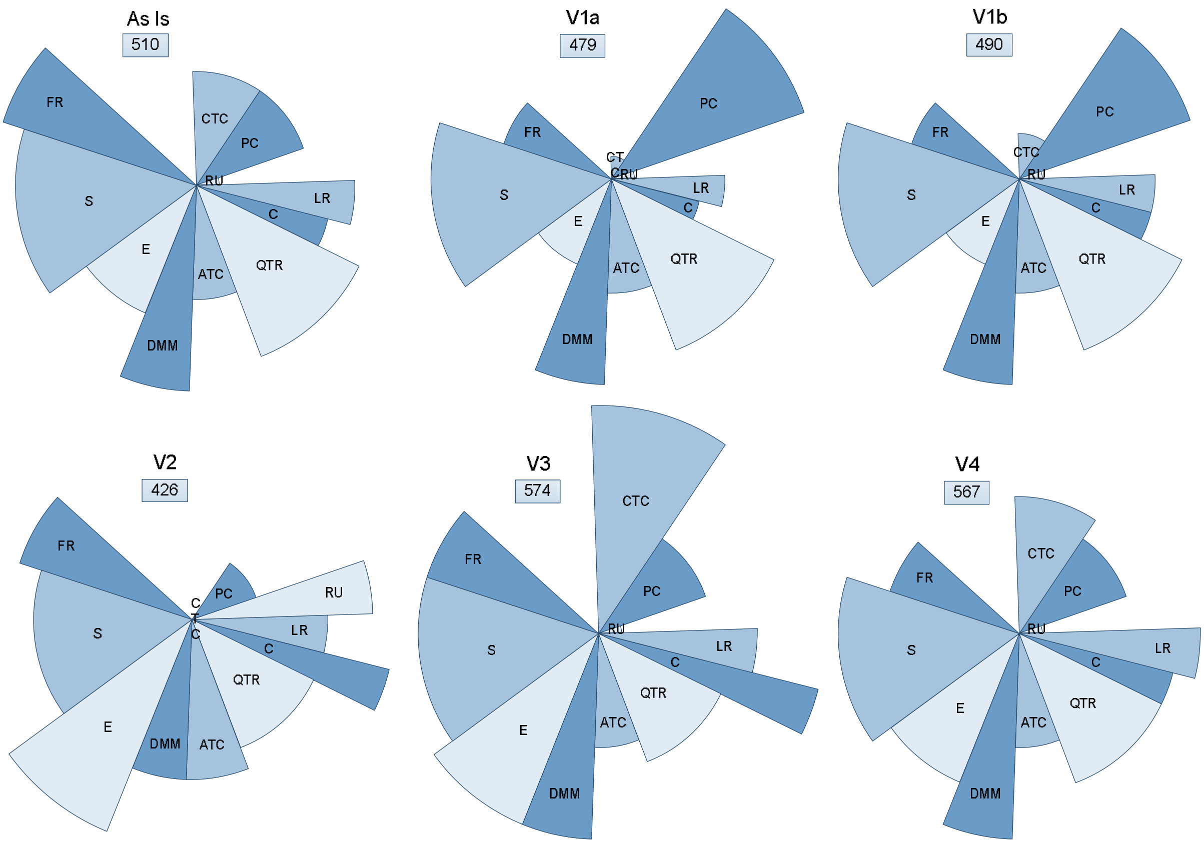


Figure 58 Pie charts for the temporary assembly process

First of all one should note that the as is process cannot be performed in the same way anymore as for instance cleaning of the temporary fastens inserted from the inside would be required for referencing and pop rivets would need 100% pre-drilled holes.

V3 and V4 are rated the highest with a small advantage of V3 (tacking all components from the outside). Advantages of V3 are low cycle time costs as human are faster than robots in this application, only grip pins are used and cleaning of temporary fasteners is not required. Furthermore, the complexity is low as only one fastener type and one installation direction have to be considered and access is always guaranteed. The latter also justifies the good ergonomics. A disadvantage is that the parallelization capability is reduced during temporary fastener removal because it cannot be performed while the robot is working; another is the small quality risk related to smaller clamping forces of grip pins compared to screws.

Both variants of the tacking process involve tacking from the outside and thereby automatically suggest a fastener type: Centrix fasteners. These have to be validated in tests regarding the criteria listed in the appendix, especially the mentioned normality deviation and the costs. Other variants also offer the possibility of using LISI fasteners from the inside for the couplings and stringers as additional holes are pre-drilled and temporary fastener locations can be changed consequently.

6.2.5. Final Drilling and Riveting

The final drilling and riveting concept is evaluated regarding the process itself and the choice of rivet type in areas where it is not limited to one rivet type by the design.

Choice of Rivet Type

A choice must be made regarding the type of rivets. Most of the circumferential joint is riveted with hi-loks. However, in the current process lockbolts are used as well in some areas. As they are specified as interchangeable in the design drawings the two variants differ between as many lockbolts as possible (V1) and using only hi-loks (V2). The evaluation is based on advantages of each rivet type and a cost calculation comparing hi-loks and lockbolts.

The advantages of lockbolts are

- A better performance (higher clamping force, lower weight, no friction during installation) and
- That the collar can be installed faster because it is squeezed instead of screwed as for hi-loks (cycle time costs).

The advantages of using only hi-loks for the circumferential joint assembly is

- The harmonisation of rivets. A reduced number of fastener types also reduces the process complexity, especially if a robot is used. (complexity)
- The tools used for hi-lok collar installation are lighter and smaller and therefore improve ergonomics and accessibility in the aircraft. For example, collars can be installed also if temporary fasteners are installed from the same side. (ergonomics, quality)
- The hi-lok collar can be removed if necessary (quality).
- If a mix of rivet types would be used the robot would need to change its tool (set-up) which increases the risk for problems as well as the cycle time (cycle time, technical risk)
- Finally, hi-loks are shorter which reduces the possibility that they get stuck in the rivet feeding system (technical risk).

The cost calculation for rivets includes material and cycle time costs. The cycle time costs are based on the manual insertion, pull in and collar installation. However, the main difference of lockbolts and hi-loks lies within the time needed to install the collars which will still be done manually even if a robot is introduced. The values presented in Table 24 show correct relations but the real values cannot be published.

Table 24 Rivet cost calculation (for manual installation)

	Lockbolt (D1)	Lockbolt (D2)	Hi-Lok
Material costs			
Rivet	0,91 $	1,04 $	0,48 $
Collar	0,08 $	0,08 $	0,22 $
Costs [$]	0,99 $	1,12 $	0,70 $
Costs [€]	0,62 €	0,70 €	0,44 €
Cycle time costs			
insert	108 TMU	108 TMU	224 TMU
pull in	129 TMU	129 TMU	0 TMU
install collar	136 TMU	136 TMU	244 TMU
Sum [TMU]	372 TMU	372 TMU	468 TMU
Sum [s]	13 s	13 s	17 s
with allowances	15 s	15 s	19 s
Costs [€]	0,24 €	0,24 €	0,30 €
Sum [€]	**0,86 €**	**0,94 €**	**0,74 €**

These facts and calculations serve as inputs for the utility analysis visualized in Figure 59 with lockbolts as V1 and hi-loks as V2. The utility analysis suggests using only hi-loks as their advantages outweigh, especially the harmonisation. Although the installation time is longer the total costs are smaller due to lower material costs. Furthermore, a potential exists that the cycle time for installing a hi-lok collar can be reduced in the future.

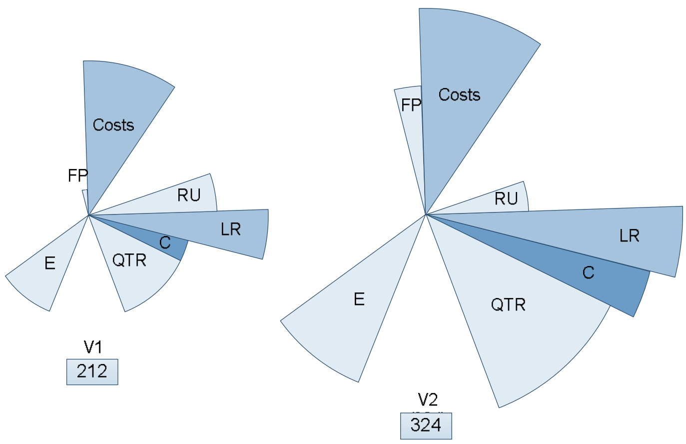


Figure 59 Pie charts rivet types

Final Drilling and Riveting Process

The last process to evaluate is drilling to final diameter and riveting. The variants for temporary fastener removal before secondary drilling and riveting are included in the evaluation in chapter 6.2.4. According to the previous evaluations the following rates are now drilled:

Table 25 One step and secondary drilling rates

Floor	Area	One step drilling	Secondary drilling (tacked + ref.)
UF	Butt joint	50%	50%
	Couplings	50%	50%
	Stringers	60%	40%
	Long. joint	35%	65%
LF	Butt joint	67%	33%
	Couplings	35%	65%
	Long. joint	35%	65%

Safety requirements are most relevant for the final drilling and riveting process where the collars shall be installed manually from the inside while the robot is drilling and inserting rivets from the outside. Apart from safety equipment installed on the outside of the fuselage detecting operators that come close to the robot the safety requirements regarding work that is done in parallel on the inside of the fuselage is of interest. The safest variant consisting of operators not entering the fuselage while the robot is working has large disadvantages in terms of production lead time. According to safety experts the robot does not pose a high risk as it applies a defined and limited feed during drilling. Therefore parallel work is assumed to be allowed. However, safety precautions will be necessary. While the robot is working (most of the time drilling) from the outside an operator should not work in the same area from the inside or the robot must be stopped. For instance three areas in the upper and two in the lower floor could be defined and protection for the operators installed in the area the robot is currently working in. Special equipment on the inside could indicate the robot's position on the outside.

The as is process consists of the tasks drilling of non-tacked holes to final diameter, deburring, countersinking, inserting (and hammering) rivets and installing their collars. Afterwards all grip pins and pop rivets are removed and the same procedure is performed for the remaining holes. In V1 drilling (and secondary drilling) of all accessible holes and the insertion of rivets is done by the robot. Collars are installed from the inside by the operators in parallel. Thereby a certain safety distance must be kept as defined by the work areas. The process of V2 is the same except that the work areas for the robot and operators are split into upper and lower floor. On the one hand this further improves safety but on the other hand the robots can interfere with each other if they work at the same level simultaneously. Moreover, it increases lead time significantly as less work can be done in parallel. In V4 the operator follows the robot with a delay between drilling and collar installation. Thereby it applies only a small safety distance instead of defining separated areas.

In V3 the robot performs only drilling while the rivets are inserted manually. This approach addresses some of the quality risks that were identified in interviews with engineers working with other robotic assembly systems (see appendix 13.6): Automated drilling significantly improves the hole quality and thereby reduces cost of non-quality. While the countersink quality is good as well, but has to be checked regularly, the experiences with the application of sealant on rivets and the rivet feeding process differ to a large extent. Sealant application is stable in some stations but generates problems at others. Algorithms that control the application of sealant exist but not for the end effector in use. Some stations also have problems with rivet feeding as it is technically complex and requires great maintenance. For instance rivets can get stuck during feeding. Other systems on the other hand have no problems. In general the riveting process generates a considerable amount of errors or notifications that require presence of an operator and reduces the system's OEE to approximately 70% (considered in the cycle time calculations). V3 however has one main disadvantage: it requires high tacking rates as the principle of clamped neighbour cannot be applied if rivets are not inserted immediately to clamp the parts by the press fit (see Figure 50). With the currently chosen tacking rate the quality risk is still comparatively low.

As the time to install a collar is significantly shorter than to drill a hole and insert a rivet with the robot the last variant V5 suggests to manually perform the secondary drilling of the lower floor where no countersinks are needed in parallel from the inside so that the robot only needs to insert rivets in these holes. But problems can occur as the structure moves during the hammering process which will influence the drilling quality. Also, a robot is generally more capable to perform final drilling (see chapter 5.2.1). This variant requires that temporary fasteners are installed from the inside.

Table 26 Variants for the final drilling and riveting process

	As Is	V1	V2	V3	V4	V5
Principle						
Pocess Visualization						
Process Description	- final drill non-tacked holes - deburr - countersink - insert rivets - install collars - remove pins/pop rivets - same for remaining holes (50%)	- final drill non-pre-drilled holes by robot (TF/holes as reference) - insert rivets by robot - **install collars manually in parallel** - remove TF - same for remaining holes (sec. drilling) - manually final drill & rivet non-accessible holes	- as V2 but **robot and manual process separated** (UF/LF)	- final drill non-pre-drilled holes by robot in one step (TF/holes as reference) - **insert rivets manually** - install collars manually in parallel - remove TF - same for remaining holes (sec. drilling) - manually final drill & rivet non-accessible holes	- only **small delay** between robot drilling & riveting and installation of collar instead of defined areas (operator “follows” robot)	- final drill non-pre-drilled holes in one step (TF/holes as reference) and insert rivets by robot - **install collars and secondary drill LF manually in parallel** - rivet insertion again by robot

For all processes that perform drilling and countersinking by the automation system the holes and countersinks in the components do not have to be controlled. Instead a test coupon is drilled before and after the process and each time a tool is replaced. In general all automated processes have a longer cycle time than the manual process due to long robot cycle times for drilling and riveting. The lead time or parallelization capability is investigated in Figure 97 in appendix 13.5.8. The manual as is process has a great advantage as four operators can work from the outside of the fuselage at the same time but only two robots. V5 can save time compared to V1, V2 and V4 by performing secondary drilling in parallel in the lower floor while V3 saves time by performing the riveting process manually. This results from reduced cycle times.

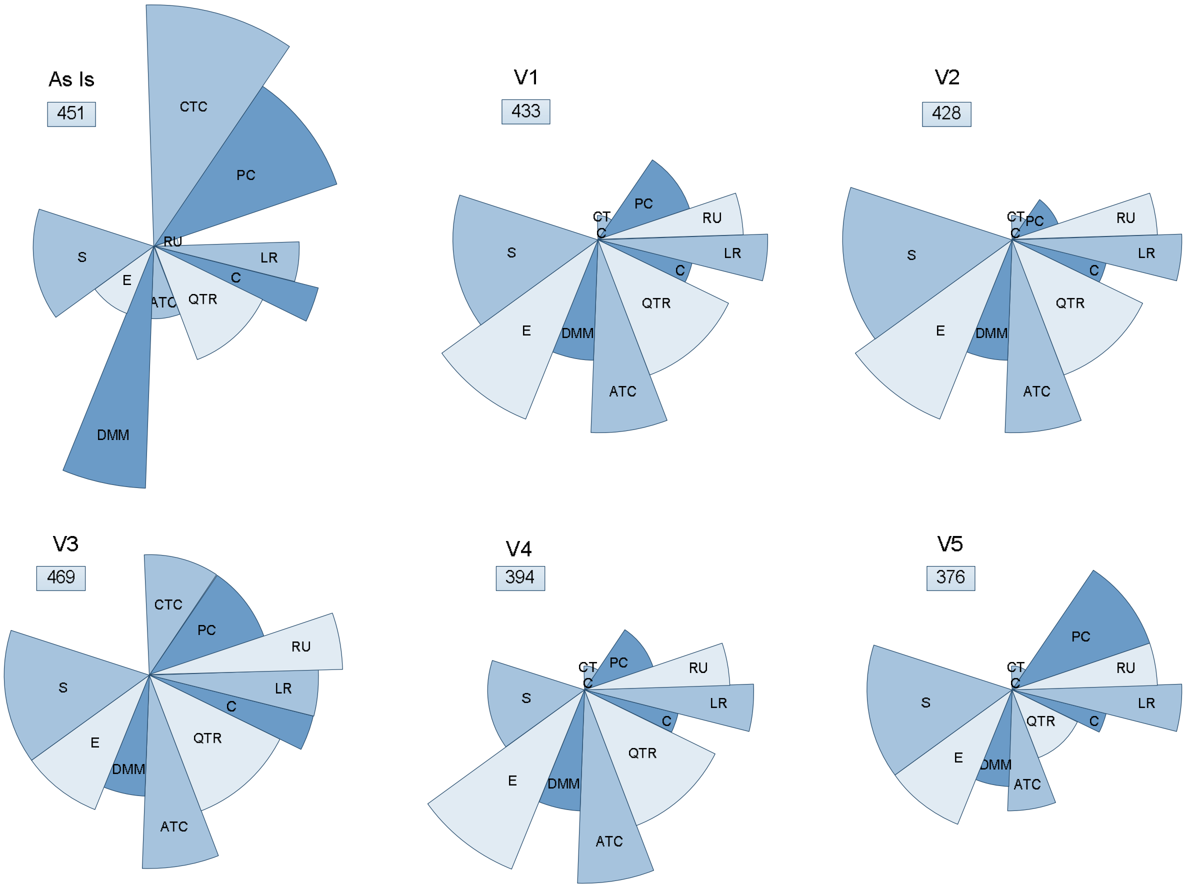


Figure 60 Pie charts for the final drilling and riveting process

Figure 60 shows that none of the variants got a good rating. V3 (manual insertion of rivets) reduces the risks for problems with the riveting system. A riveting function included in the end effector reduces the systems OEE by 10-20% and refers to approximately 25% of the investment costs. On the other hand, V3 does not apply the principle of the clamped neighbour as rivets are not inserted directly after final drilling and would therefore require a higher pre-drilling and tacking rate. The application of V3 would further eliminate the potential for future improvements regarding these rates.

V1 (final drilling and rivet insertion by robot) follows according to the utility analysis but it is the variant with the longest cycle time and also the parallelization capability is better for other variants. Although the automated process will not be faster or more cost efficient than the manual process it can significantly improve quality and ergonomics.

7. RESULT: FUTURE PROCESS

The results chapter presents the future basic process, precisely assembly principle and a more detailed version for the different assembly areas, the tacking and referencing map, tasks and cycle times similar to the as is process analysis. Finally, it is compared to the as is process in terms of the chosen criteria.

7.1. BASIC PROCESS

The objective of the thesis is to suggest a future basic process based on the evaluation of different variants. The main characteristics are that the pre-drilling rate is higher than the tacking rate in order to use open holes for referencing during final drilling by the robot, the butt strap is pre-drilled by the robot, tacking is done from the outside and final drilling and countersinking can be performed in one step by use of a robot. Figure 61 visualizes the assembly principle while Table 27 displays the basic process for the changed steps pre-drilling, temporary assembly and final drilling and riveting. The figures represent the upper floor; rates for the lower floor are highlighted in the descriptions.

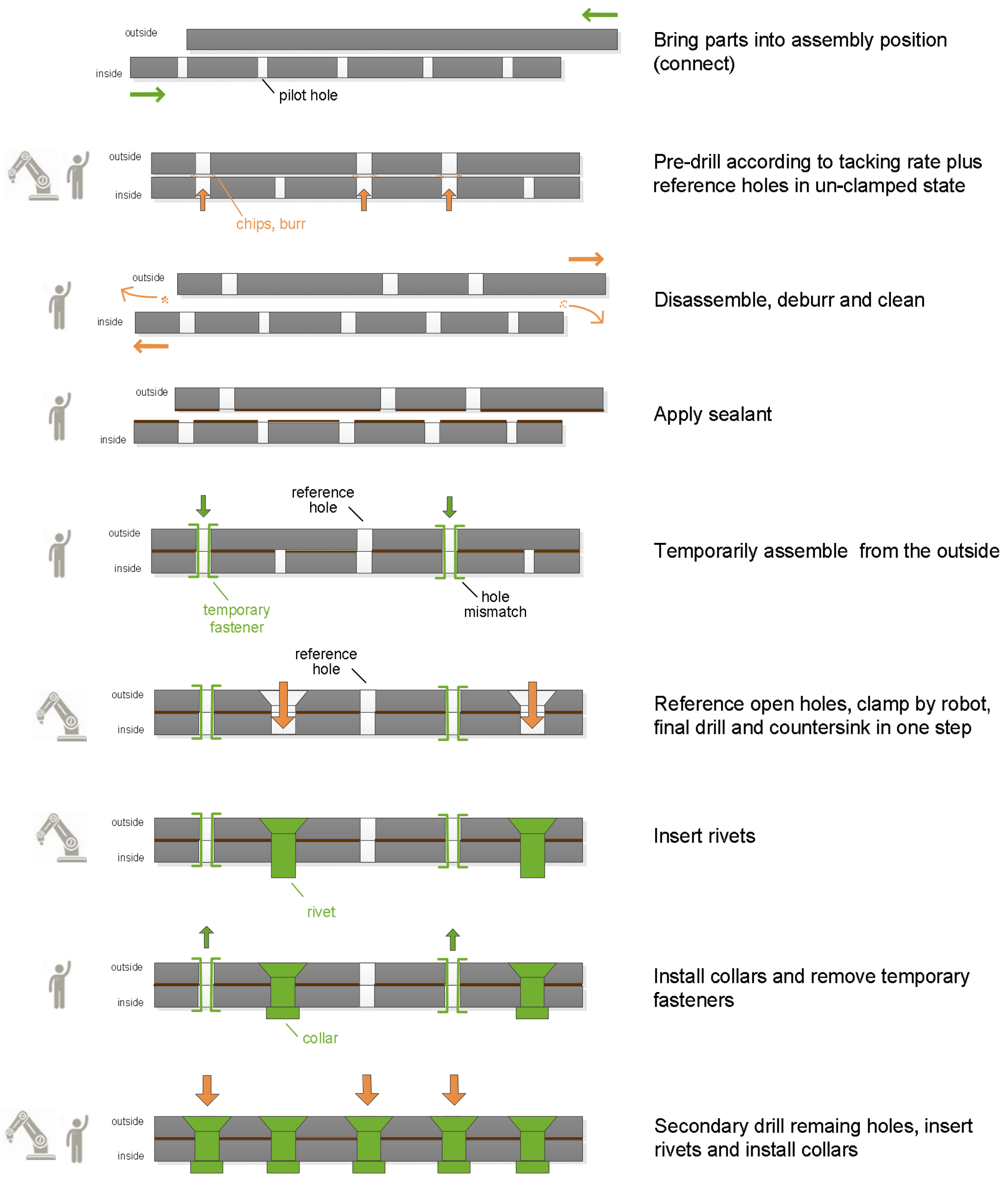
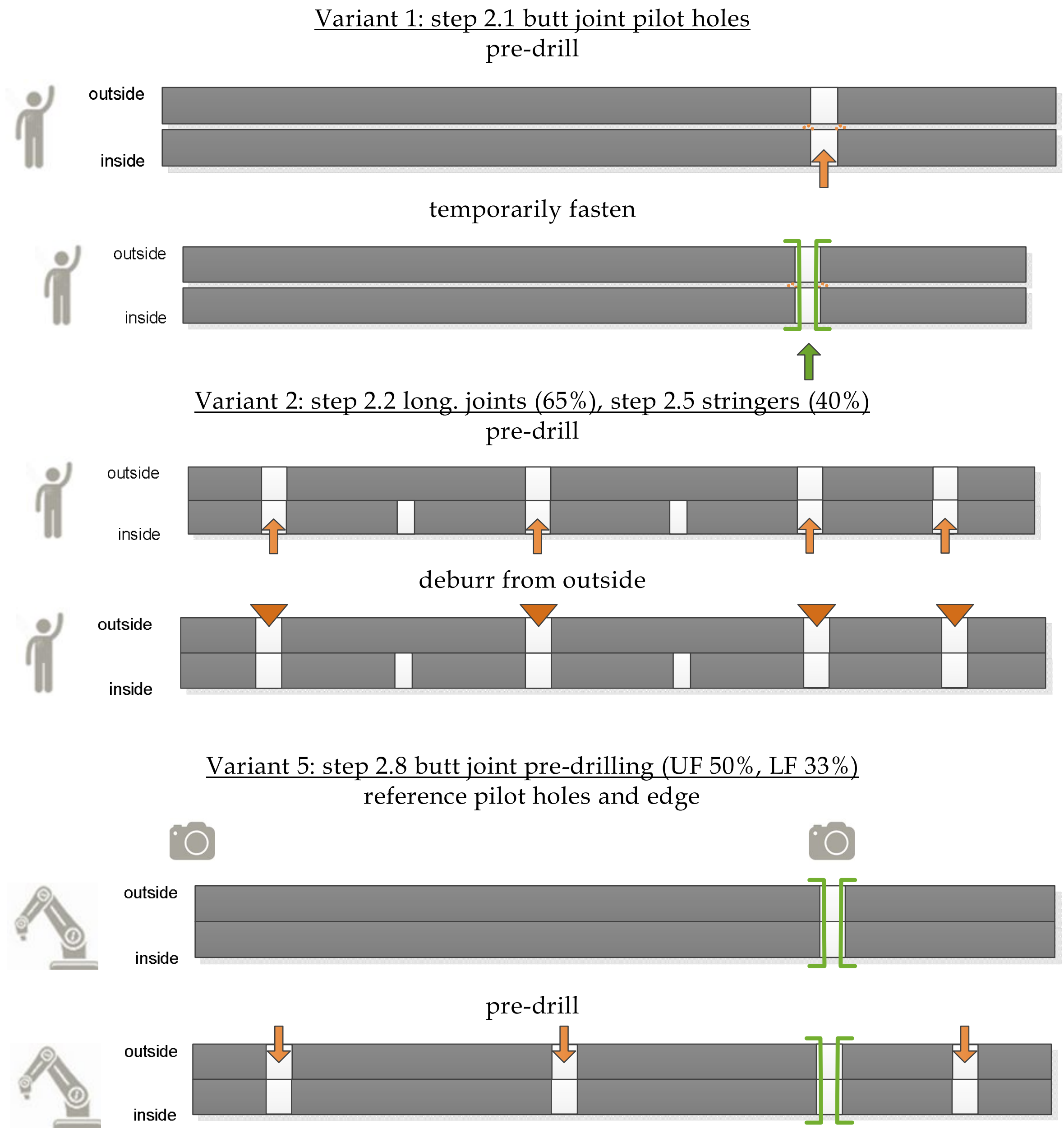
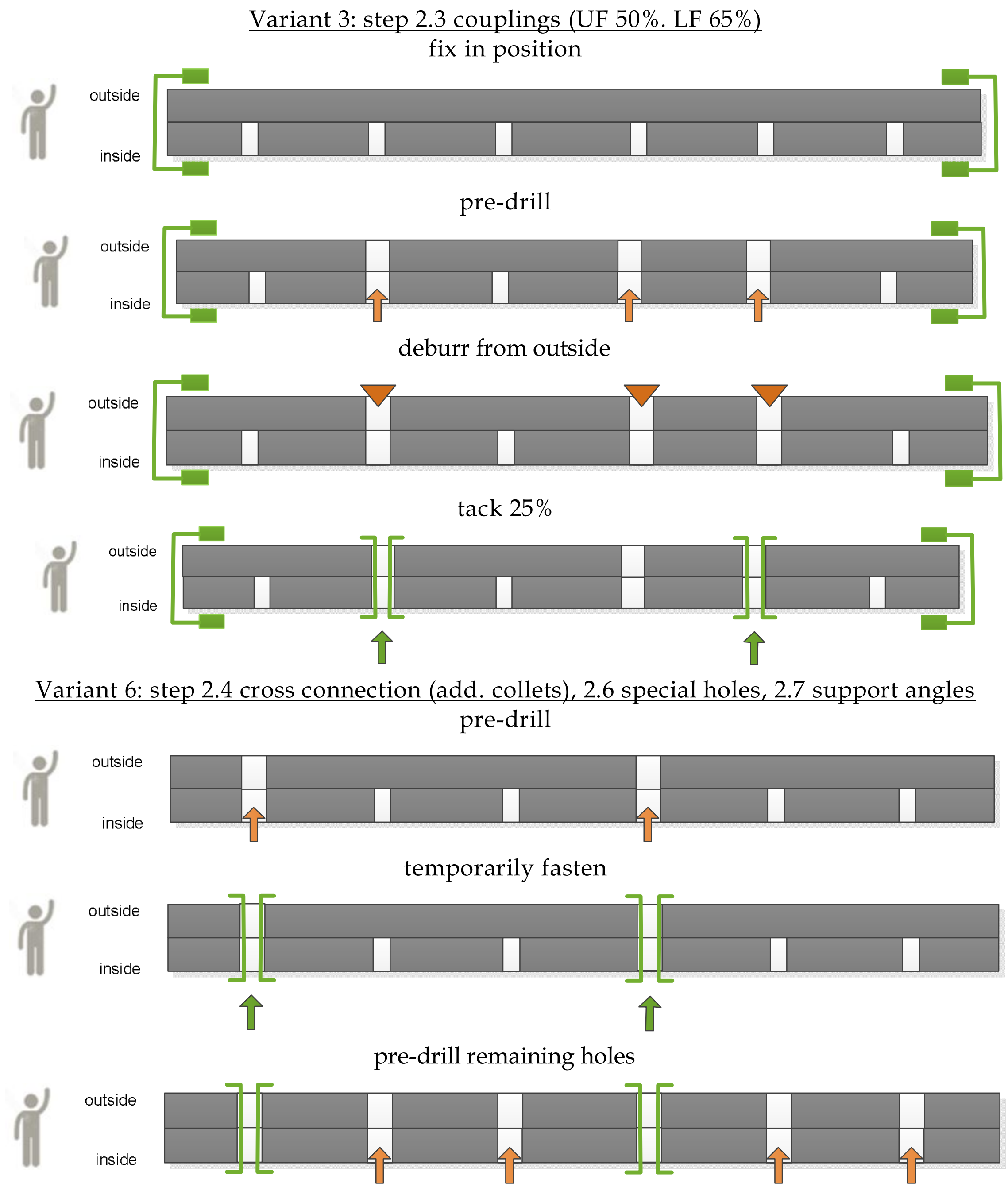
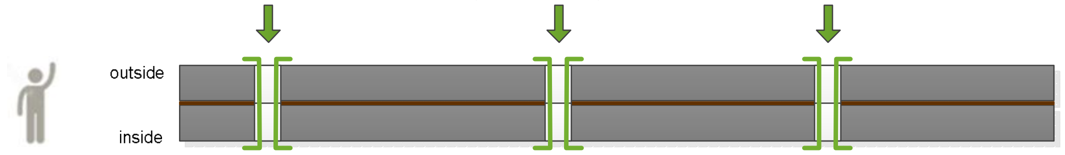
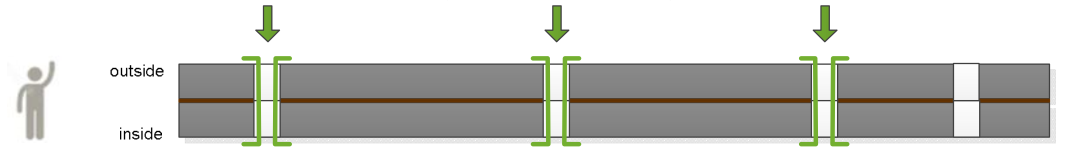
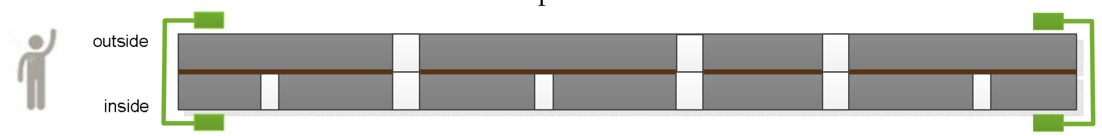
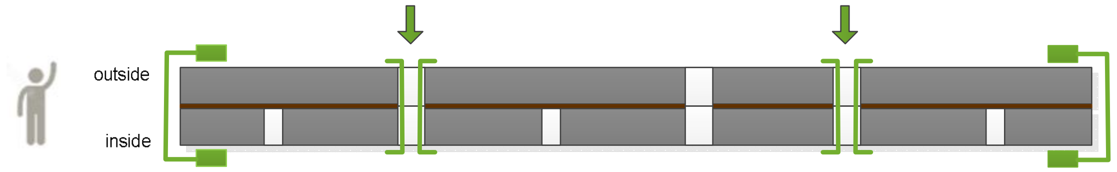
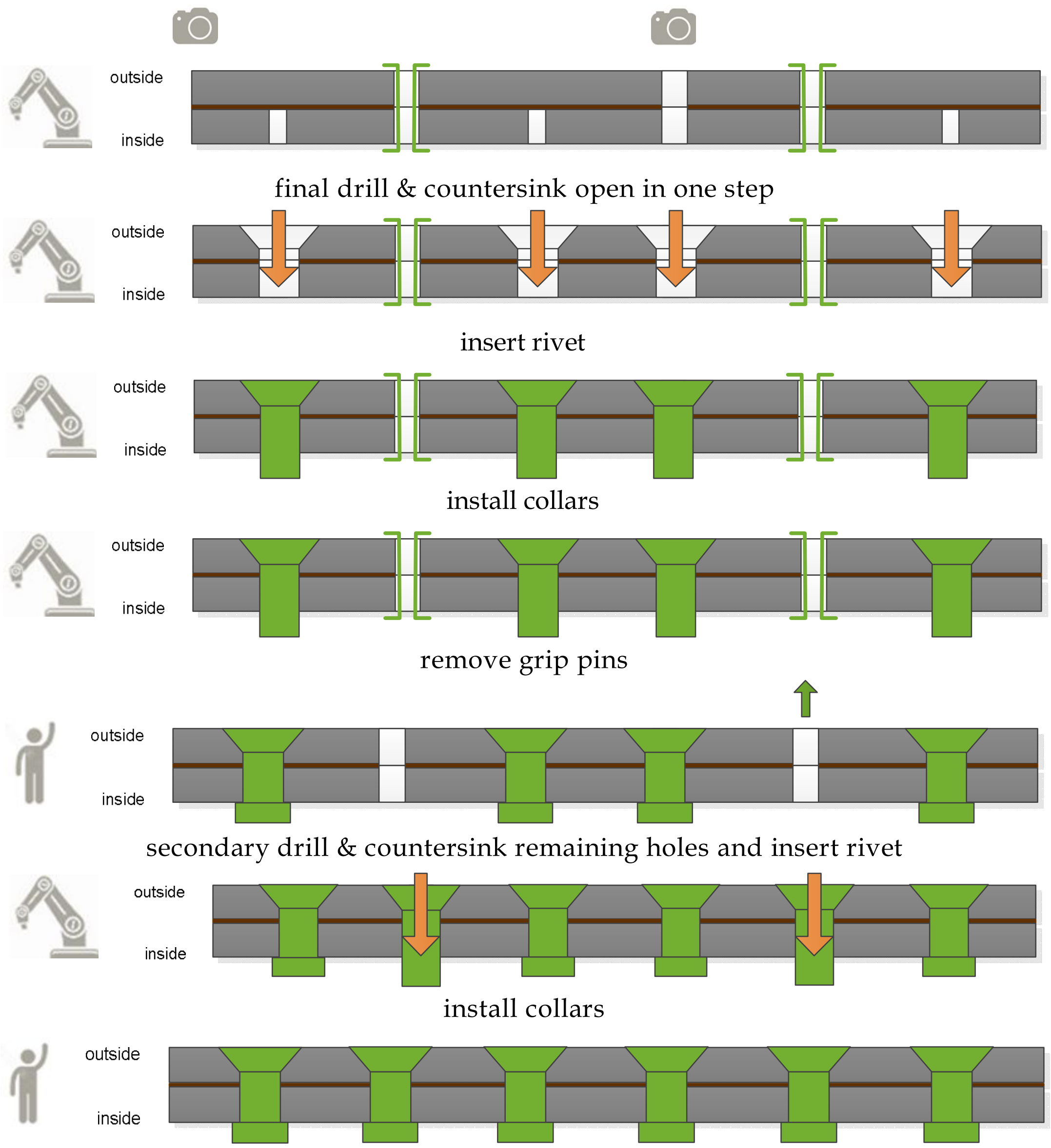
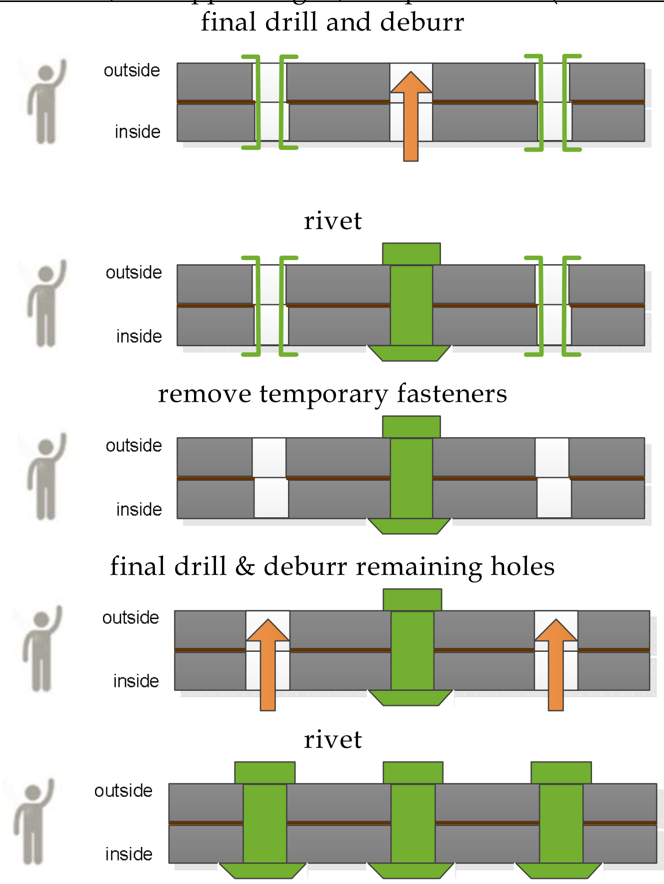


Figure 61 Assembly principle automated process

Table 27 Result: Basic Process

	2 Transfer pilot holes and pre-drill
Work order	2.1 butt strap (pilot hole transf.) – V1 2.2 longitudinal joints – V2 2.3-2.5 split into several areas 2.3 coupling-skin – V3 2.4 cross connection – V5 2.5 stringer-skin – V2 2.6 *holes that are not accessible for the robot & where rivets will be inserted from inside* – V6 2.7 support angles – V6 2.8 butt joint (pre-drilling) – V5
Basic process	 
Tools & (temp.) fasteners	Manual drilling machine Cross connection with angle drilling machines Drilling tripod for second drilling step Drilling templates LISI grip pins, patent pins, screw pins, collets

	5 Temporarily assemble
Work order	1.1 butt joint – V1 1.2 longitudinal joints – V2 5.3 stringer-skin – V2 5.4 coupling-skin – V3
Basic process	<u>Variant 1: step 5.1 butt joint (UF 50%, LF 33%)</u> temporarily assembly all holes  <u>Variant 2: step 5.2 long. joints (50%). 5.3 stringers (30%)</u> temporarily assemble tacking holes  <u>Variant 3: step 5.4 couplings (UF 33%, LF 50%)</u> fix in position  temporarily assemble tacking holes 
Tools & (temp.) fasteners	Centrix grip pins collets

	6 Final drill and rivet
Work order	6.1 cross connection – V2 6.2 support angles – V2 Split into several areas: 6.3-6.5 6.3 stringer-skin – V1 6.4 coupling-skin – V1 6.5 butt joint – V1 6.6 *holes that are not accessible for the robot & where rivets will be inserted from inside* - V2
Basic process	V1: step 6.3 stringers, 6.4 couplings, step 6.5 butt joint stringers & couplings: reference open holes butt joint: reference shell edge and coupling holes/rivets  V2: step 6.1 cross connection, 6.2 support angles, 6.6 special holes (rivet from inside or outside) 
Tools & (temp.) fasteners	Manual drilling machine Cross connection with angle drilling machines Drilling tripod for final drilling step Hammer and mandrel Collar installation machines Rivets (only hi-loks) and collars

7.2. Tacking and Referencing Map

During the evaluation of different concepts theoretical values for the tacking rates etc. were investigated. After one variant is chosen for each process a detailed tacking and referencing map can be created based on the actual components. It uses the technical drawings of the circumferential joint to highlight which holes shall be tacked or referenced. Both of these types have to be pre-drilled manually and are later secondary drilled by the robot while the remaining holes will be drilled into full material in one step by the robot.

Besides taking into account the suggested tacking rates and the referencing principle as explained in chapter 5.1 the map considers part geometries, non-accessible holes for the robot and holes in which rivets have to be inserted manually from the inside of the fuselage. Holes that are not accessible for the robot have to be pre-drilled 100% as their assembly has to be done manually. They are excluded from the tacking rates. Also, if rivets are inserted from the inside this part of the process is performed manually and therefore requires a pre-drilling rate of 50% as the robot will only drill but not insert the rivet.

The tacking and referencing map therefore also includes information about the mentioned exceptions. It is located in appendix 13.7. Table 28 lists the real tacking rates etc. compared to the theoretical values.

Table 28 Theoretical and real tacking, referencing and drilling rates

Area	Tacking		Referencing		Pre-drilling/sec. drilling total ****		One step drilling	
	theory	real	theory	real	theory	real	theory	real
UF								
Butt joint	50%	50%	0%*	0%	50%	50%	50%	50%
Couplings	33%	33-36%	17%	11-21%	50%	44-61%	50%	39-56%
Stringers	30%	30%	15%	20%	45%	50%	55%	50%
Long. joint	50%	48%	15%	10%	65%	58%	35%	42%
LF								
Butt joint	33%	33%	0%	0%	50%	50%	50%	50%
Couplings**	50%	48-57%	15%	0-13%	65%	61-100%	35%	0-39%
Long. joint	50%	50%	15%	0%	65%	100%***	35%	0%

* Reference holes located in couplings

** Some LF couplings are so short that all holes are pre-drilled

*** Done manually as non-accessible by robot

**** Pre-drilling rate = tacking + referencing

7.3. Tasks and Cycle Times

An overall cycle time calculation and list of tasks for the resulting process is attached in appendix 13.8. The total cycle time for all structural work performed at the station remains almost the same as in the as is process. The suggested solution saved 4.2% of the time. Parts of these savings also result from corrections in the MTM calculations after some mistakes were found in the ERP system.

Figure 62 compares the process steps related to the circumferential joint assembly of the as is process (in blue) and the solution (in red) split into upper and lower floor. While the solution saves time during pre-drilling of couplings, stringers, longitudinal joints and the butt joint the final drilling and riveting process requires more time.

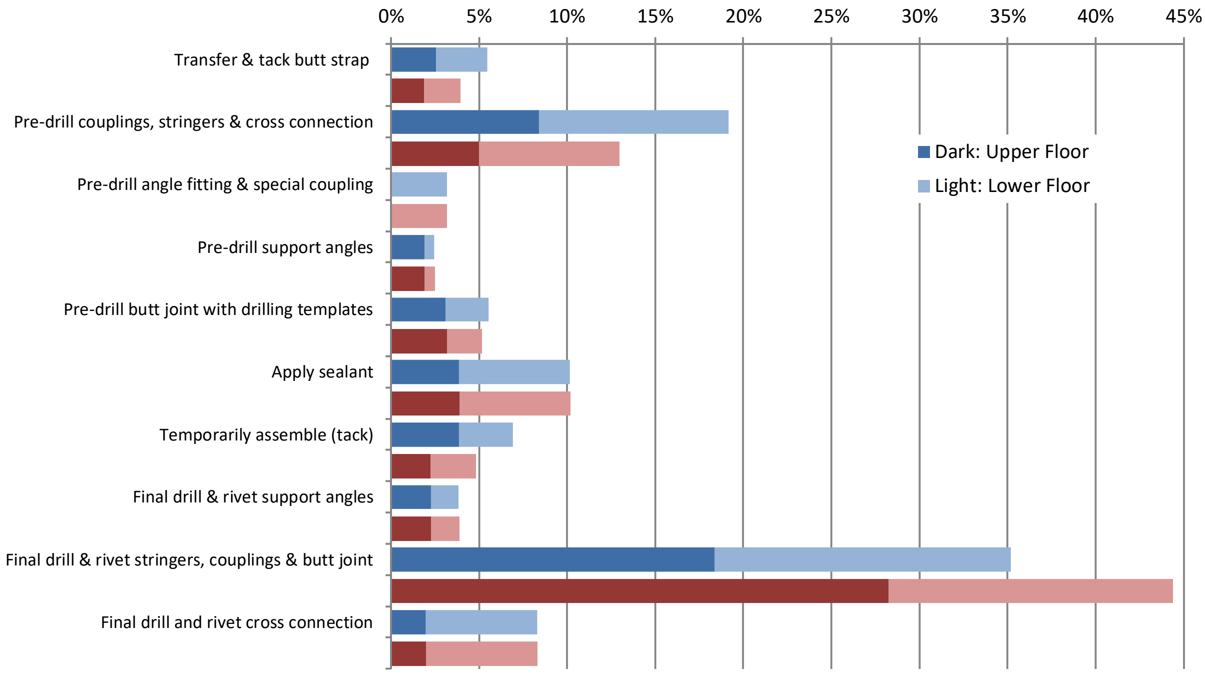


Figure 62 Comparison of circumferential joint cycle times: as is process (blue) and solution (red)

7.4. Comparison to As-Is Process

Last, the suggested future process is compared to the as is process with respect to the evaluation criteria that were divided into the categories efficiency, quality and human centred. The cycle time can be improved significantly for pre-drilling the couplings etc. and tacking which results from the reduction of tacking and pre-drilling rates. The same applies to the butt joint pre-drilling but as the robot needs more time than a human the improvement is only small. This disadvantage also leads to the great degradation in the final drilling and riveting cycle time. The use of robots also reduces the parallelization capability as only two robots but four operators in the manual process can work from the outside at the same time. This circumstance will significantly affect the lead time. The robot utilization is of course enhanced but for tacking it was decided not to use the robot due to extremely long cycle times and technical risks. Although the waste is slightly decreased by eliminating the need for drilling back, countersinking is included in the drilling step and the amount of value adding work was increased by 20% for the final drilling and riveting process no big changes could be achieved in total. In total the considered process account for 46% VA, 15% NVA and 39% W.

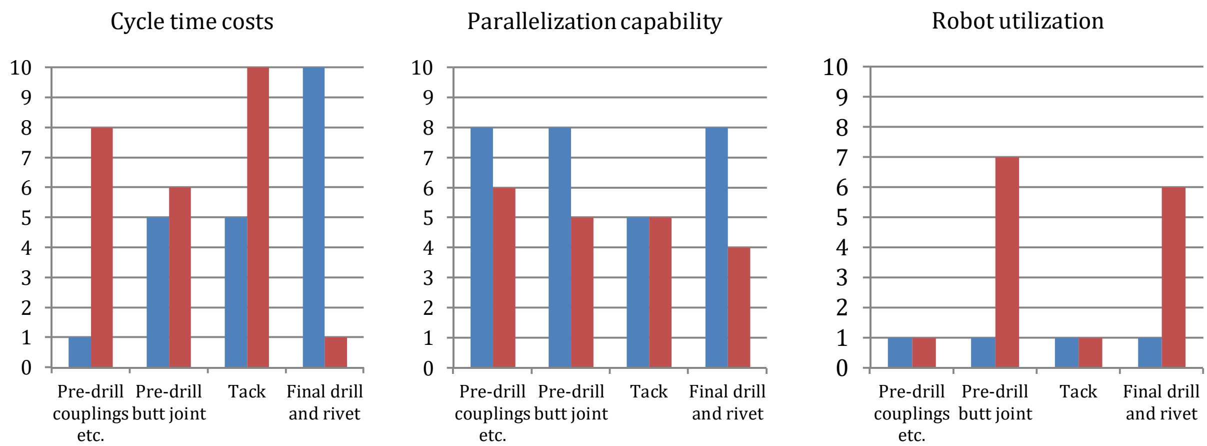


Figure 63 Productivity & Efficiency criteria

The complexity criterion differs between the processes. It increases for pre-drilling mainly because only some of the holes will be pre-drilled and for final drilling as using robots for drilling, sealant application and riveting is more complex than the manual process. However, complexity is reduced for pre-drilling the butt joint because the templates are not needed any more and for tacking as it can be done easily from the outside of the aircraft. Pre-drilling and tacking with smaller rates induces a small but manageable quality risk as it is suggested with more conservative than progressive rates where a risk is seen. The robot's functions riveting and sealant application create a significant technical and quality risk for the drilling and riveting process but on the other hand automated drilling and countersinking can produce repeatable high quality holes. This fact also leads to the good rating in terms of the accordance to capabilities. In the other cases the rating remains the same.

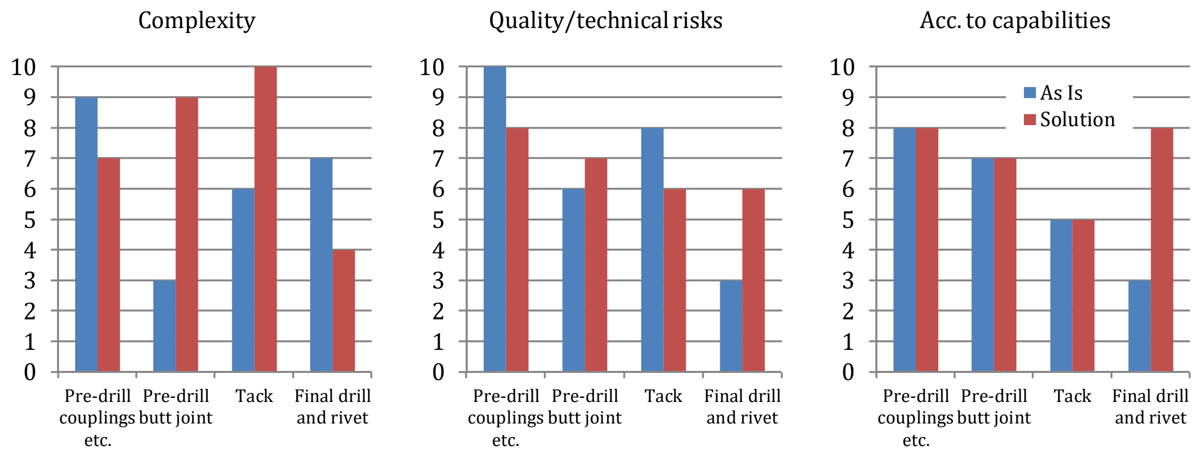


Figure 64 Quality criteria

The criterion dependency between man and machine is only changed within the processes that actually use the robots and naturally increased but less than it would have been the case for other variants. The significant ergonomic improvement in all processes is a main advantage of introducing automation in production. It is mainly caused by the smaller number of repetitive operations to be performed manually and especially in the lower floor often carried out in bad ergonomic positions. Safety is clearly affected by the implementation of robots but does not show great issues for the chosen variants.

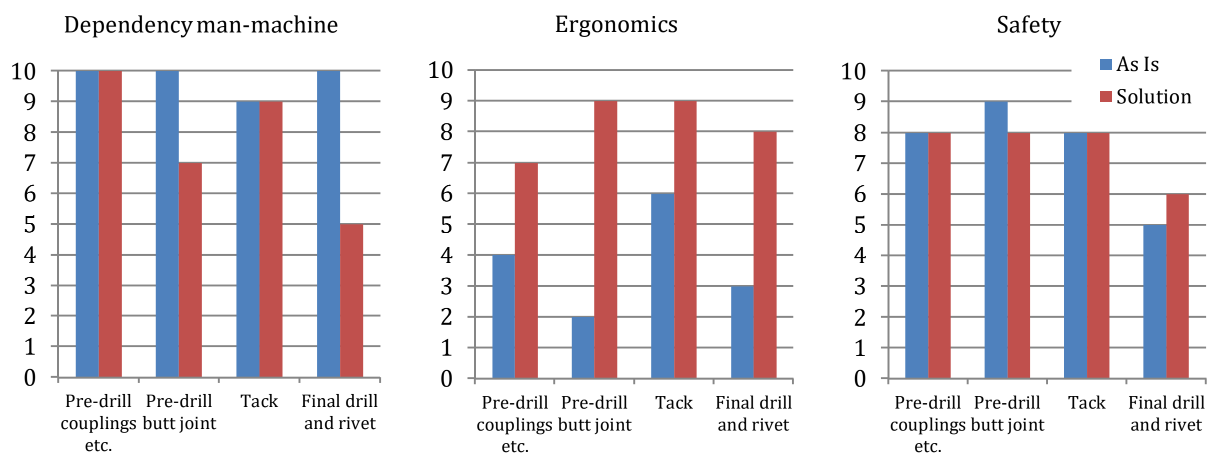


Figure 65 Human centred criteria

8. VALIDATION

This chapter validates the process with respect to its lead time and conducts a risk assessment that leads to an action plan described in the discussion chapter.

8.1. LEAD TIME

One fundamental requirement for a future process is that the work can be conducted within two days lead time. In the current process eight operators work in two shifts per day.

In order to investigate the lead time of the structural work at the station a work schedule is developed based on the calculated cycle times for the suggested process. Besides the durations for all processes the interaction between man and machine, inside and outside work and work in different areas as well as the predecessors and successors of certain processes have to be considered. The latter is attached as a precedence graph of the as is process in 0. Specific examples for "guidelines" are that

- Butt strap and longitudinal joint transfer should be done in parallel,
- Couplings, stringers and longitudinal joints should be pre-drilled and couplings tacked before the butt joint is pre-drilled in order to increase the rigidity of the fuselage structure,
- While the robot is working no manual work can be performed from the outside,
- Man and machine must not work in the same area from inside and outside (4 areas defined on each aircraft side),
- Drilling (and riveting) is performed towards the longitudinal joints (pilgrim step procedure), see Figure 66,
- In the lower floor usually maximum two operators can work at the same time form the inside and outside respectively due to the limited space,
- The cross connection has to be finished before the couplings are drilled and riveted,
- Different work orders should be applied for the robots so that they do not interfere (see Figure 66).

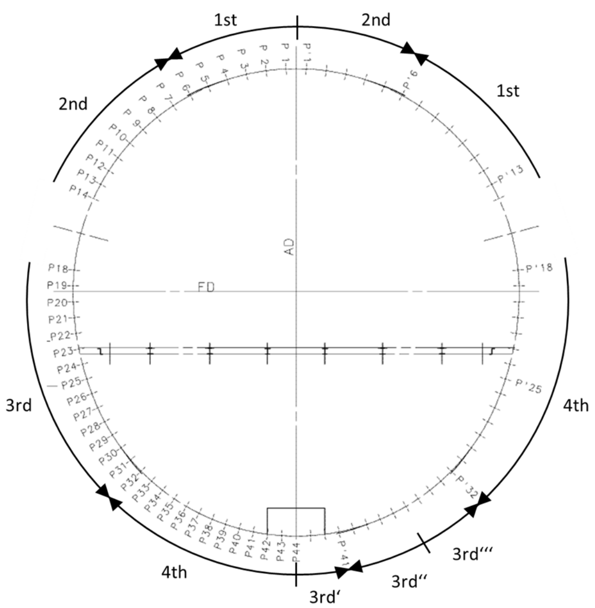


Figure 66 Work order for drilling and riveting

The following figures show the work schedule for the suggested process with six operators and two robots. Two shifts are not feasible when using robots as the parallelization capability is strongly reduced during the final drilling and riveting process when the robots are working. While eight operators can work in parallel in the current process only two robots are available in an automated process. A maximum of six shifts (42 hours) is available in order to fulfil the lead time requirement. The task allocation shown in the figures, however, requires ca. 44 hours which is 104% of the available time.

A great amount of "white space" is visible for the operators during the final drilling and riveting process as there are only few tasks they can perform from the inside at the same time. During the two days four of the six operators cannot work for 17-20 hours while the robots are drilling and riveting with only a short interruption for the removal of temporary fasteners. This circumstance has to be solved by an appropriate line balancing between the stations.

The work schedule further indicates the need for a specific sealant type. Between the start of sealant application and the last collar that is installed 26 hours pass. Adding the 3 remaining hours per day and 48 weekend sealant with a minimum assembly time of 80 hours should be applied. To reduce risks in case of disturbances a more slowly curing sealant is preferred.

8.2. Risk Assessment

Throughout the thesis and evaluation of concepts the real product and resource were not involved. For further development, validation and verification and later installation a risk assessment is crucial to identify and classify risks. This classification of risks is done based on the severity of consequences and the probability (frequency) of scenarios in a 3x3 matrix. Once identified and ranked a risk mitigation plan can be put in place and tests defined that will be conducted before start of production.

Within the thesis a risk assessment is conducted for the developed solution, i.e. only risks related to the automated process are considered but no risks related to the system design, logistics etc. Risks that are directly related to the chosen variants are highlighted in bold; the others are related to the automated process in general.

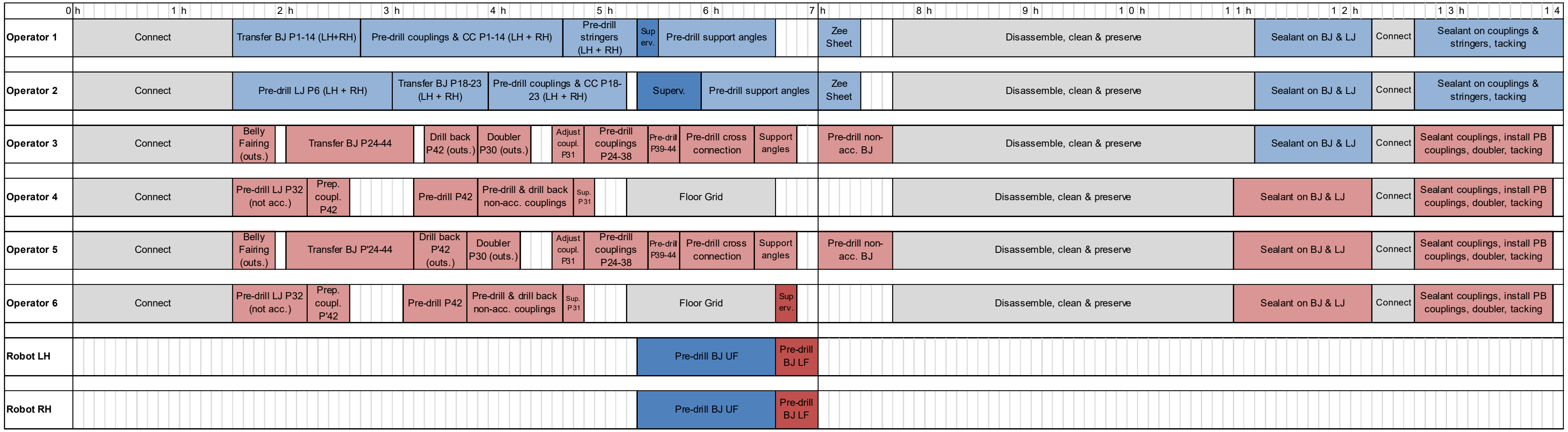


Figure 67 Lead Time (part 1)

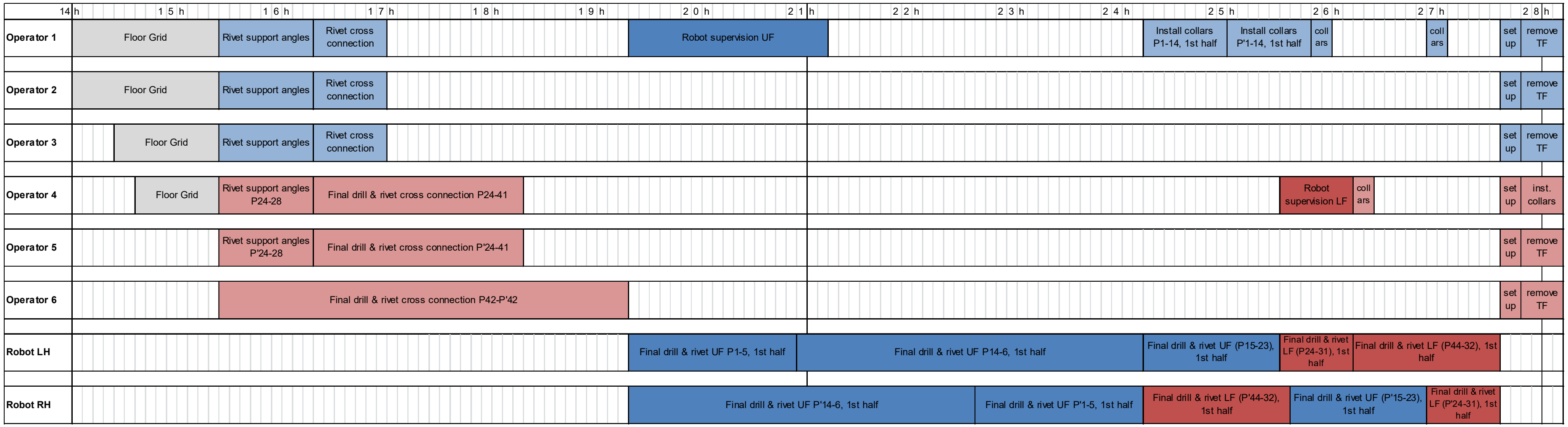


Figure 68 Lead Time (part 2)

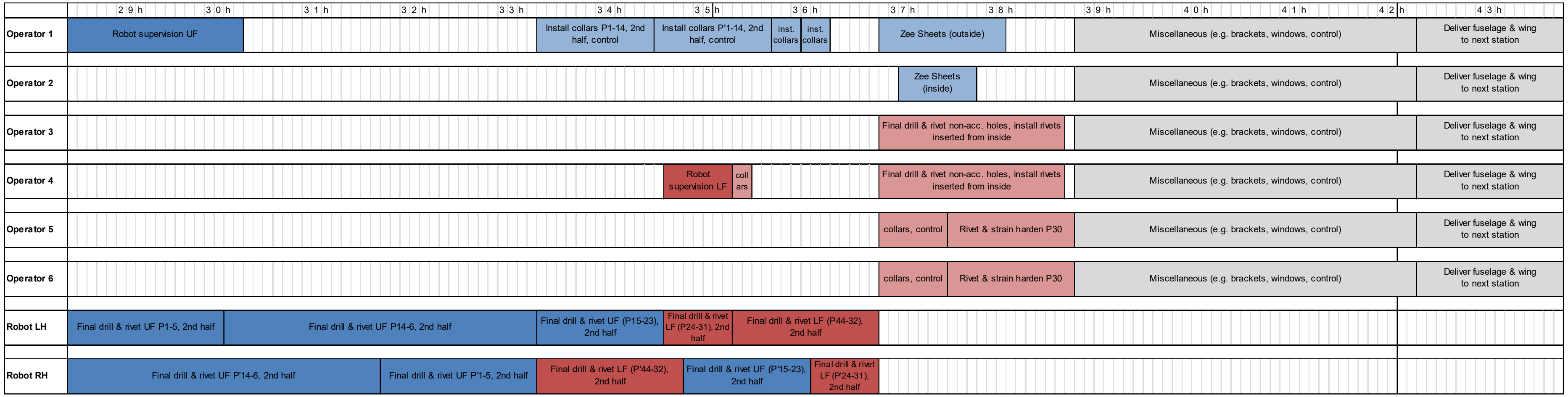


Figure 69 Lead Time (part 3)

Table 29 Risk assessment

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="3">Severity of Consequences</td></tr>
<tr><td>low</td><td>medium</td><td>high</td></tr>
<tr><td rowspan="2">Probability of Scenario</td><td>high</td><td>- Many “white spaces” for operators in work schedule (line balancing)</td><td>- Greater amount of robot supervision needed (15% assumed)
- Rivet grabbed incorrectly
- Inflexible tacking rate in an automated process</td><td>- Out of tolerance hole due to programming
- Coupling and stringer edge distance
- Butt strap rivet pitch (related to referencing method)
- Noise during hammering of rivets
- Improper sealant application on rivet (too much, too little, not constant)</td></tr>
<tr><td>medium</td><td>- Vision system: dirty cameras
- Hole not found during referencing
- Collision against structure during referencing due to deviated/non-existent hole or hole with bad quality
- Cleaning effort due to dirty pressure foot or hammering module (sealant)</td><td>- TF cannot be removed because it is locked/damaged
- Scratches on part or inclusion of chips under rivets due to long chips or bad chip suction
- Rivet insertion fails due to collision with piece
- Rivet is lost by end effector
- Rivet stuck in tubes during supply
- Influence of gravity/different end effector orientations on accuracy
- Pre-drilling hole diameter has to be adjusted to TF
- Too high deflection due to applied pressure resulting in elongated holes or deformed parts</td><td>- Exceedance of 6 shifts lead time
- Incorrect measuring of vision system
- Out of tolerance hole due to programming
- Out of tolerance countersink due to calibration, drilling parameters/tool quality
- Out of tolerance hole due to robot accuracy
- Insufficient tacking rate
- Supply of wrong rivet
- Normality deviation in manual drilling >3°
- Rivet not inserted completely because of hole size
- Unsatisfying performance and costs of suggested TF (Centrix)
- Quality control only before and after process cycle is insufficient
- Safety issues with interaction man/ machine inside/outside</td></tr>
</table>

	Low	- Tool change problems	- Mark on structure by pressure foot - Normality problems in automated drilling - **Hole/TF cannot be referenced because of contamination with sealant**	- Lower OEE than 80/70% - **Machine collision with part** - **Insufficient distribution of sealant between parts (related to tacking)** - Tool break while drilling - Out of tolerance hole due to calibration - Out of tolerance hole due to drilling parameters or tool quality - No gap closure by pressure foot - Slippage of end effector on part - No alignment between hole to be drilled and corresponding drilling speed & feed - Operators must not walk in the fuselage while the robot is working because this could lead to small movements of the whole fuselage - **Butt strap edge distance** - Exceedance of selant's assembly time - **Occurrence of snowman holes (→ 2,6mm pre-drilled holes needed)**

9. DISCUSSION AND RECOMMENDATIONS

In this chapter the results as well as possible improvements, recommendations about the way forward and how to increase the robot's potential, the method and using robots in airframe assembly in general are discussed.

9.1. DISCUSSION OF RESULTS

In general one notices that in most cases the "simple" variants are rated highest while the ones with many variations and complexities lose points. In the following some specific are discussed. For sufficient rivet pitches in the butt strap another referencing method has to be applied than it can be displayed in the one dimensional analysis. A 3D analysis could include the tack hole in the butt strap middle as explained before and validate the necessary improvement. The evaluation of the tacking process suggested manual tacking from the outside and consequently the use of Centrix fasteners as the process and the fastener type influence each other. However, this decision cannot be made without the evaluation of the temporary fasteners which should be one of the next steps within the project. An assessment of the costs (see appendix 13.9) shows that Centrix fasteners are more expensive in terms of NRC due to their high price and also RC although the time for installation is short. If the lead time would not be critical one could consider using the more time consuming screws due to their good technical properties and low costs.

Another topic that has to be discussed is the question whether the riveting function of the robot should be used or rivet insertion should remain manual. The latter would reduce quality risks and technical risks and at the same time decrease the cycle time by almost 20% which is more than one can gain by the currently chosen tacking and pre-drilling rates that are slightly lower than in the as is process. However, tests have shown that these could be further decreased. And if the riveting function is eliminated the advantages of the robots cannot be fully used in case of the circumferential joint assembly. These are improved ergonomics and less repetitive tasks for the operators and high-quality repeatable drilling and countersinking in one step. But applying sealant and inserting rivets by the robot will require a consistent quality and rivet feeding without disturbances and technical problems in order to use the robot in the best way.

A functioning automated riveting process would also reduce the lead time whose major contributor is final drilling and riveting and in which a robot OEE of only 70% is assumed. The lead time is the greatest problem of the developed process with two days as the maximum available time per station. Therefore, great potential lies in the capability and technical stability of the riveting function. If an OEE of 80% is applied as for the pre-drilling process a lead time reduction of 2.1 hours (12.5%) could be achieved so that it would be short enough to finish the work within 6 shifts. Before the evaluation it was also expected that the robots are able to drill and rivet in less time because several steps (drilling back, separated countersinking) are not needed in the automated operation. A reduction of the robot's drilling (and riveting) cycle time per hole would lead to a similar lead time improvement. The fact that parallelization of work is not possible in the same way as in a manual process is difficult to change when using only one robot per side. This discussion also refers to how important the interaction and coexistence of man and machine is in airframe assembly. It influences the topics of lead time, robot utilization, safety and the existence of the so called "white spaces" in the work schedule one needs to cope with. Inspired by the lean thinking of the supporting but not replacing purpose of automation one must not forget about the most important resource, the operators. Regarding the robots' utilization and safety issues Gates (2015) pointed out that "automotive production rates are in average 50 to 60 units per hour. By contrast, a fast production rate for aerospace is one [aircraft] per day, and that day may be comprised of multiple shifts. This can make it difficult to efficiently task a robot for that period of time, as there may be multiple manual tasks that interrupt a given operation leaving the robot idle. This creates potential 'shared' work spaces between manual and robotic activities that must be made safe."

As already mentioned there is potential to decrease the tacking and consequently also pre-drilling rates. In case of a scenario with 25% tacking a cycle time decrease of 11% for pre-drilling and reduce the lead time by approximately 2-3%. For instance smaller rates are likely to be sufficient for the upper floor butt joint. Therefore the offline programming of the robot should be performed in a way that it can be adapted with only little effort. Nevertheless, quality should always have priority so that a more conservative scenario is proposed for the start of production. However, these potential improvements are not as large as expected and show how many other processes are involved besides the actual circumferential joint assembly. The on-going temporary fastener tests offer further potential. If for instance the angle misalignment of Centrix fasteners installed from the outside is proven to be smaller than expected no additional referencing holes would be needed and thereby pre-drilling rates reduced by 11-20% depending on the position in the fuselage. Also, there is potential that more holes are accessible by the robot than assumed which would reduce the effort for manual drilling of holes (10% of the cycle time for pre-drilling).

In total the developed automated process could not prove to be faster, or save costs which are goals of the implementation of automation. However, it can improve quality and ergonomics. Quality is the most important requirement in aerospace industry. Also, companies have to deal with the demographic development of an aging work force and the limited availability of highly qualified workers which sets new demands on the workplaces in the future. These arguments justify the use of robots even though some trade-offs have to be made. Furthermore, the 4th FAL will be an additional line, so of course the capacity and thereby production rate per month can be increased.

9.2. RECOMMENDATIONS

After indicating possibilities for improvements and potentials of the process a way forward shall be recommended. It focuses on the identified risks. Furthermore, possibilities to increase the robot's potential in the case of the circumferential joint – both practically possible in the short term as well as theoretical – are discussed.

9.2.1. WAY FORWARD

Tests have to be performed to verify and validate the intended outcome of the process, the technical readiness as well as the required product and process characteristics. Generally spoken the machine and process' capability have to be proven. According to the risk assessment they should focus on the verification/validation and investigation of the

- Programming,
- Accessibility and possible collisions,
- Functionality of the vision system,
- Positional accuracy of the holes and their edge distances & rivet pitches (for different heights and end-effector orientations),
- Hole and countersink quality and the corresponding process capability,
- Chip removal,

- Occurrence of snowman holes,
- Rivet insertion process (stability and disturbances, rivet supply, rivet insertion, noise),
- Application of sealant on rivets (amount, consistency) and if necessary implementation of a control system,
- Appropriate tacking rate with respect to quality (closing of gaps to prevent inclusion of chips or creation of burr, distribution of sealant between the surfaces) and lead time,
- Choice and evaluation of the temporary fastener type(s) in terms of performance and costs (see chapter 12.7 for relevant criteria),
- Need for additional (referencing) holes,
- Overall system's stability (disturbances, maintenance, OEE) and amount of super-vision needed.

A detailed test plan should be set up for this purpose whereas some test descriptions (e.g. the ink dot test) can be found in (Bullen, 2013). Moreover, some more topics need to be addressed. The process or work schedule has to be adjusted in a way that the required lead time of six shifts can be fulfilled. Another task is an intelligent line balancing due to the "white spaces" in the operators' workload. Moreover, safety assurance needs special attention. Last, it is suggested to consider developing several robot programs based on different tacking rates or building these of separated modules. That way a progressive but likely to be sufficient version could represent the baseline process while one or several other versions or modules could be applied in case greater gaps occur and a higher tacking rate is needed for a specific aircraft. Thereby both efficiency and flexibility would be increased. Further measures related to the design requirements are suggested in the next chapter.

9.2.2. Increase of Robot's Potential

From the author's view there are two main reasons why the robots' potential cannot fully be used (yet) for the circumferential joint assembly. Those are the aircraft design as well as the chosen technology. Changing the aircraft's design is costly, extremely time consuming and affecting other processes and members of the supply chain. However, it is possible and to some extent necessary in order to be able to fulfil the product requirements such as edge distances.

In the manual as is process insufficient hole positions are most often detected by the operators. As they drill in several steps they are able to "pull" these holes into the desired direction and thereby correct the position. This is not possible with robots which cannot see the couplings and stringers on the inside. Instead the conducted tolerance analyses lead to several suggestions for design (larger parts and tighter tolerances) and process modifications:

- Enlargement of the stringer foot to solve the edge distance issue by increasing its nominal value. This measure would increase weight and means a great effort and influence on suppliers.
- Decrease of the stringer foot width tolerance to further improve the edge distance (only slightly smaller tolerances possible here).
- Decrease of the coupling's pilot hole position tolerance also contributing to the edge distance issue. This modification is technically possible nowadays, has the smallest impact on design drawings and other processes but cannot solve the problems alone.
- Enlargement of the coupling foot improving the available space for both the edge distance and distance to the inner radius. This modification requires great changes as well.

- Decrease of the coupling radius tolerance to improve the repair nut issue. However, in case of the investigated stringer position not even the nominal distance fulfils the design requirement.
- Use of a drill block or a specially designed tripod for manual pre-drilling from the inside to ensure a normality deviation of ±1°. This measure reduces the process related variations for both distances.

The adaptation of the pilot hole tolerance (from ±0.5 to ±0.2 mm) and the use of a special tripod (from ±3° to ±1° normality deviation) are the simplest to implement and are therefore recommended to be addressed first. For the tolerance analysis (performed at the first stringer position) the ASCR value is considered most relevant as WC would be too unrealistic and RSS too optimistic. The mentioned modifications result in a sufficient edge distance in the coupling with an improvement of 6% (see appendix 13.9). The stringer edge distance improved by the same amount but is still out of tolerance. Therefore different scenarios were tested within the one dimensional tolerance stack-up. As the improvement by decreasing the stringer foot width tolerances is only small it can be disregarded. A sufficient ASCR value for the distance in the stringer can be achieved by increasing the stringer foot width by (minimum) 1.2mm, representing an enlargement of 6% and a total edge distance improvement of 20% (see appendix 13.9).

To summarize, a combination of process improvements, tighter tolerances in the single parts and adjusting single part geometries could possibly solve the edge distance issue. A further improvement of the robot's accuracy would not be proportional to the required technical challenges and related costs. Nevertheless, these findings can only give a first impression and have to be examined in the 3D analysis as well because this one is more reliable. Furthermore, only one stringer position (which is however representative for the whole upper floor up to the windows) with a relatively thin stack and the distances in tangential, not flight, direction were analysed so far. When it comes to the distance to the coupling's radius one should make use of the operators' ability to assess the quality produced in the process and "pull holes". Consequently repairs, precisely de-installing/drilling out rivets, drilling with a larger diameter and installing a larger repair rivet and collar, should be done manually. This reduces the criticality of the distance to the coupling radius and mitigates the need to enlarge the couplings' width.

As stated before also the chosen technology can be seen as restricting the robot's potential. A weakness of the system is that pre-drilling is required in the process. This results from the need to clamp the parts by temporary fasteners during final drilling and transfer pilot holes. A breakthrough in the development concerning one way assembly could lead to great improvements. The original aim of one way drilling is to use a device that clamps the parts during drilling by using for instance magnetic, vacuum or other forces in order to eliminate the need for disassembly, cleaning and deburring. In case of the robotic process one way assembly would exclude the need for pre-drilling, too. All holes could be drilled into full material in only one step and riveted afterwards. However, an appropriate clamping device cannot solve this problem alone. Since the robot cannot look inside the aircraft to measure the coupling and stringer positions it needs holes that were transferred from the inside to the outside as references to be able to drill at the right positions. Therefore the concept of using ultrasonic waves to detect parts from the outside (see appendix 12.3), the use of other physical phenomena or maybe scanning the fuselage from the inside could be further investigated.

Another possibility is the use of an automated inner system in addition to the robots located at the outside. An inner system, for instance similar as in the FAUB production line (see Figure

18), would be able to generate opposing forces to the forces generated by the robot's end effector and thereby close the gaps during drilling. Moreover, the inner system would enable referencing of the parts and their locations on the inside. Besides higher purchasing costs and the limited space especially on the lower floor, the proper distribution of sealant would be a challenge as no tacking elements are used in such a process.

9.3. Discussion of the Method

In the following noticeable aspects of the applied approach and methods shall be discussed. A detailed understanding of the current process was necessary to develop concrete variants for a possible future process. Besides the product and process requirements which were crucial to understand and work with, the process itself had to be described and mapped. Therefore, the basic process with its visualizations and clear indication of the work order and tools used, supported by a description in text, was a great aid. Throughout the thesis it was helpful to refer back to the basic process overview.

The production visits were the greatest aid towards understanding the process and its requirements but also dealing the contents of the ERP system, the work schedule and work instructions in detail to calculate the cycle time of the as is process contributed to a large extent. This cycle time calculation, however, took an enormous amount of time of several weeks and long preparations to collect the data which was not expected. The initial issue was that no data were available in the needed level of detail so that they could be varied according to the chosen variants. Therefore own calculations had to be performed based on different inputs that had to be combined. Furthermore, corrections had to be made to the company's calculations and it was not seen as appropriate to use standard elements for the same operations in different assembly and fuselage areas due to the high variations or to remain on "level 2" for all types of tasks which increased the effort even more. Simplifications and assuming cycle times would have been possible but as detailed data are available and the 4th FAL project is progressed considerably far the author's opinion is that these detailed data should be used. Also, a detailed calculation can be used later during the project and for the lead time calculation in a more accurate way. One weakness are the robot cycle time elements as they are not differentiated for different areas and for instance stack thicknesses of the circumferential joint and in some cases based on assumptions. However, once further data are available the calculations can be adapted with little effort. Another approach would have been to conduct a time study of the real production times. This would require to take videos to analyse them later, which is usually not allowed, to invest a huge amount of time or alternatively involve a whole team in the time study because eight operators are working in parallel at the station at different floors inside and outside of the fuselage so that they cannot be observed by only one person.

One remarkable because simple and effective tool that was used is the SWOT analysis. It summarized strengths and weaknesses of the manual process and opportunities and threats of an automated process. Although the SWOT analysis was already performed in the beginning of the thesis work it set the focus and its findings were valid until the end. Also, it facilitated to gather first impressions from the project and production visits in a structured way. The morphological box on the other hand has not proven to be a great creative support. The reason is probably that the development of such kind of a production processes is not the intended use application of designing new products. Instead, some new variants were generated during the detailed planning and evaluation of others.

The method and criteria applied to evaluate and compare the concepts are another topic to reflect on. Although a utility analysis is usually performed early in a project the included quantitative criteria as well as the tolerance stack-ups make it credible and reliable. However, it has to be noted that a utility analysis remains subjective in some aspects and its results can change by only small adaptations in the performance rating. The pairwise comparison is an appropriate way to weight the evaluation criteria. However, the criteria themselves could be further improved. Besides the cycle time (or cycle time costs) the lead time could be determined already as part of the evaluation instead of using the vague criterion "parallelization capability". But this would considerably increase the work effort. Nevertheless, as proven by the validation the lead time is important. Similarly the robot utilization could be calculated with regard to the lead time instead of cycle time. An uncertainty in the criteria is the robot hourly rate which is used for the cycle time cost calculation of automated operations. It is mainly based on experiences and could differ significantly for the case of the circumferential joint assembly (see appendix 13.3). One weakness was that the robot's work per year had to be assumed as they were not known before the variants were chosen. Luckily the calculations were based on 2400h while the suggested process ends up with 2380h. For the evaluation the overall processes were assessed separately. It turned out that many aspects could not be considered separately and that the processes and choice of variants interact and influence each other. As it would go beyond scope to compare all possible combinations for the whole process one has to think ahead to the following processes when creating and evaluating the variants. Complex relations are hard to force into a matrix but it would be even more difficult to assess the variants without the frame of a defined method that also ensures that all aspects are taken into account. A general difficulty during the evaluation was that no tests have been conducted to validate certain presumptions and hypotheses due to the limited amount of time and resources.

9.4. Discussion of Robots in Aerospace Assembly

Last, the general topic of using automation and robots in airframe assembly shall be discussed. During the 4ht FAL project and the thesis the existing, old design continuously affected the work and caused problems. The first A320 was built in 1988 and was designed for a maximum rate of six aircrafts per month. Today an aircraft of the A320 family starts or lands every 2 seconds somewhere in the world (von Borstel, 2015). Of course a design for aircraft assembly automation was not considered in the 80's. This reflects for instance in edge distances that do not allow further variations caused by the longer tolerance chain of an automated process. And while the manual process and highly skilled operators are able to cope with inconsistent circumstances such as varying gaps, compensate tolerances and variations during the assembly and take corrective action if necessary an automated system (even if a robot is more flexible than dedicated machines) is not able to react in such a way. Each A320 aircraft and its assembly can be seen as unique, for instance in the current production the decision about the tacking rate is based on the present gaps. Although the robots are able to take references and thereby adapt to the real part their flexibility is restricted due to a pre-defined programming and limited cognitive abilities.

Despite the great improvements in terms of capability certain drawbacks remain regarding the use of robots and automation in general for high-level aircraft assembly. Airbus raised a shop floor challenge in 2016 because "the robots currently able to perform point-based tasks at accuracy demanded […] have a bad weight/payload ratio in order to be able to resist the loads generated by the operation. These already heavy machines use end effectors capable of multiple operations which further increase their weight. Such solutions cause a multitude of problems and constraints. […]There are further limitations regarding aircraft accessibility and [still] high costs" (Airbus Group, 2016). Henrik Kihlman stated already in 2005 that the "trend in aerospace industry to buy large robots for handling multi-functional end effectors weighting several hundred kilograms […] conflicts with the fact that larger robots have inferior accuracy compared to smaller robot" (Kihlman, 2005). The shop floor challenge invited teams to create innovative solutions for light, modular and open robots to drill as many holes as possible with good accuracy and the right diameter (Airbus Group, 2016).

These heavy end effectors also refer to the question of multi-functionality and complexity leading to quality and technical risks. Throughout the thesis the impression was gained that functionality for drilling and countersinking, riveting and even installation of temporary fasteners might not always be appropriate. "Drilling and fastening operations are the most common application in our assembly process as a whole, and that is unlikely to change any time soon," said Curtis Richardson from Spirit AeroSystems Inc. (Waurzyniak, 2013), so these applications do offer large potential for automation. Although composites and processes such as bonding and Z-pinning advance, it will be a long time before drilling holes en masse will disappear from aircraft assembly floors. But on the other hand George Bullen, a leading expert in aerospace automation, advised to focus only on one task, drilling and countersinking and not to buy too many options as they complicate acquisition, installation and operation. However, in case of the circumferential joint assembly the ability to drill and rivet with the robot is seen as an enabler to further reduce the tacking and pre-drilling rates because clamping pressure can be applied by the robot and a press fit rivet is inserted directly. Although there are many opportunities to improve production using robotics and other types of automation there are also a great number of complex and specialized operations that will always need to be performed by human. Also, while automation can improve throughput, ergonomics and quality, the production rate must be high enough to justify the investment.

10. CONCLUSION

The main goals of introducing automation in single aisle aircraft assembly are to ramp up production, increase efficiency by lowering costs, increase productivity and improve ergonomics as well as quality. However, old aircraft designs and the characteristics of aircraft production such as low production volumes, complex and long processes and high quality requirements make the implementation challenging; especially for high-level assembly which today is preformed manually by high-skilled operators in most cases. While large, dedicated machines have been introduced for drilling and riveting applications in the past improved rigidity and accuracy solutions have made industrial robots a less expensive and more flexible alternative.

The purpose of this thesis was to understand the current circumferential joint assembly process and its requirements in Airbus' A320 family final assembly line, analyse opportunities and limitations of an automated process, develop concepts for an automated process and evaluate and compare these alternatives. The final objective was to suggest a future basic process for the assembly including robots with special drilling and riveting end effectors as well as manual operations. It will be validated in terms of lead time and a risk assessment. Based on the thesis' purpose and objective the research questions can now be answered.

What are opportunities and limitations of using robots in the circumferential joint assembly?

The single aisle production has been continuously optimized since the first A320 was built in 1988. Introducing robots into the FAL to perform the circumferential joint assembly of the fuselage can be a turnkey solution for major improvements in terms of costs (RC), quality and ergonomics. Also, an additional line will enable to ramp up production. The repeatable drilling process with its constant parameters assures good hole qualities and can be done with final diameter in one step which eliminates to need for multistep manual drilling and countersinking. Also, an automated drilling and riveting process frees the operators from those highly repetitive tasks often performed in bad ergonomic positions especially in the lower floor. Furthermore, there is the possibility to apply reduced tacking rates as the robot has a greater ability to close gaps during the drilling and riveting process due to the clamping force applied by the end effector's pressure foot.

However, there are several threats as well. For instance the robots will not have an opposing force from the inside in the chosen system, so tacking, a certain amount of pre-drilling and the disassembly in order to clean and deburr will remain necessary. Also, even though robots have a good reach they will not be able to access all holes due to the fuselage geometry and the large end-effectors. Besides that, he worst ergonomic conditions at the station are present at the floor grid assembly which will remain unchanged. Furthermore, although some tasks become unnecessary the operation cycle time for a robot including referencing, drilling etc. is longer compared to the manual process. Also, four operators can work in parallel from the outside of the fuselage in the as is process while only two robots work from the outside at the same time. This fact significantly increases the lead time. Last, each aircraft is unique and the tolerances of all parts sum up during final assembly, so lots of flexibility is required. Because the robots have a longer tolerance chain and the old design is not made for automation or assembly in general there are issues with e.g. edge distances in couplings and stringers assembled from the inside. In order to gain a clearer impression a possible future process was developed based on the evaluation of different variants. The following research question summarizes the results.

How can a basic process including robots for circumferential joint assembly as well as manual work look like?

The detailed process is slightly different for each assembly area and position in the fuselage (upper or lower floor) but the basic process always starts with the connection of the fuselage and positioning of further parts such as the couplings. Afterwards pre-drilling is performed according to the defined pre-drilling rates which are based on the determined tacking rates plus additional reference holes. It is done manually in case of couplings, stringers and longitudinal joints as holes have to be transferred from the inside to the outside and automated by the robots in case of the butt joint by using previously transferred holes and the shell edge as references. After disassembly, cleaning and the application of sealant tacking is performed completely from the outside of the fuselage to clamp the parts (close the gaps) and distribute the sealant. The reference holes used to determine the position of holes that are not drilled yet are left open in order to improve accuracy. These holes are final drilled and countersunk by the robot in one step and a hi-lok rivet is inserted. Afterwards collars are installed to these rivets from the inside and the temporary fasteners are removed by the operators. Finally, the remaining holes are referenced by the robots, drilled and riveted. Holes that cannot be accessed by the robot have to be drilled and riveted manually. The next research question refers to the evaluation results as well as the validation of the suggested process.

Does the suggested process fulfil the required lead time and other important criteria?

The most important criteria assessed during the evaluation were safety, quality or technical risks, parallelization capability, cycle time costs and ergonomics. In total the developed process could not prove to be faster or save costs. However, it can significantly improve quality and ergonomics. These arguments justify the use of robots although some trade-offs have to be made. Furthermore, the 4th FAL will be an additional line, so of course the capacity and thereby production rate per month can be increased. The parallelization capability was further analysed by the determining the process lead time which is an important aspect of the validation. The available time was exceeded by 4% but it is believed that it can be improved, for instance by ensuring a more stable riveting process than it was assumed as the main contributor to the long cycle time is the final drilling and riveting performed by the robot. The last research question refers to conclusions that can be drawn from the discussion.

What are future actions and potential improvements?

Tests have to be performed to verify and validate the machine and process capability in terms of technical readiness and the required product and process characteristics. Major identified risks of the developed process and the automation system in general are to achieve the tolerances required by the design, the quality and technical stability of the riveting and sealant application process as well as the amount of robot supervision needed. Also, it should be analysed if sufficient tacking rates were chosen or whether these can be reduced. Further-more, one or several temporary fastener types have to be chosen and evaluated in terms of performance and costs and the process adapted to the choice. Moreover, the process or work schedule have to be adjusted in a way that the required lead time of six shifts can be fulfilled, an intelligent line balancing has to be done, safety assurance needs special attention and last, it is suggested to consider developing several robot programs based on different tacking rates or building these of separated modules. Furthermore, measures related to the design requirements are suggested: 3D tolerance analyses performed for several representing positions of the circumferential joint should validate whether the reduction of the pilot hole position tolerance in the coupling, the improvement of the normality deviation during manual drilling and the enlargement of the stringer foot width can result in sufficient edge distances in the couplings and stringers. Afterwards the aircraft design has to be modified.

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12. OPEN APPENDIX

12.1. BASIC PROCESS LEGEND

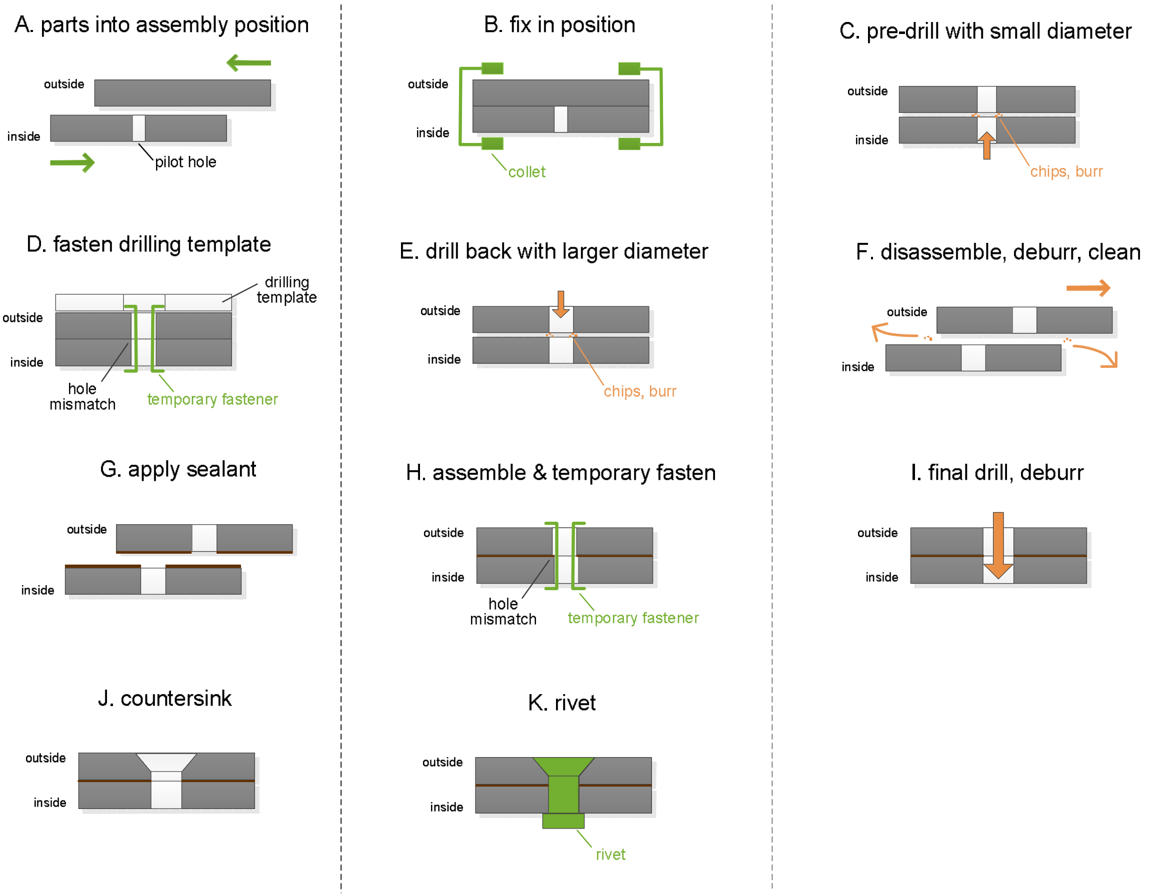
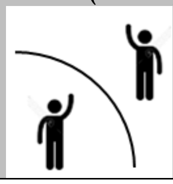
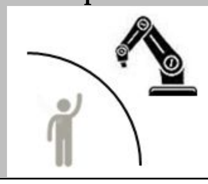
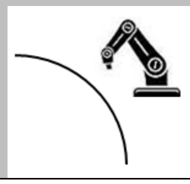


Figure 70 Basic Process Legend (own figure)

12.2. MORPHOLOGICAL BOX

Table 30 Concept Ideas: Morphological Box

Process	**Manual (As Is)** 	**Manual (Altern.)** 	**Cooperation** 	**Automated** 
2 Transfer pilot holes & pre-drill			do not drill back	
2.1 butt strap (transf. PH)	transfer and tack pilot holes	-	-	"scan" and store the pilot holes before connection, pre-drill butt joint by robot after connection
2.3 coupling-skin	fix couplings, transfer ca. 30%, drill back, tack, pre-drill remaining holes (→ 100%)	same as As Is but w/o pre-drilling (→ 100%)	fix couplings, transfer conservative scenario and tack	enlarge coupling + stringer width (design modification) → fix only, pre-drill by robot
				pilot hole detection from outside by use of halo sensors → fix only, pre-drill by robot
			fix couplings, transfer > mixed scenario and tack (predrilling rate > tacking rate)	coupling position detection from outside by ultrasound → fix only, pre-drill by robot
			fix couplings, transfer progressive scenario and tack	coupling position detection from inside by scanning
2.4 cross connection	fix, pre-drill ca. 50%, drill back, tack, pre-drill remaining holes	-	-	-
2.2 longitud. joints, 2.5 stringer-skin	transfer 100%	Same as 2.3	Same as 2.3 (w/o tacking)	Same as 2.3 (but special clamping device needed as collets cannot be used)
2.6 support angles	fix, pre-drill 100%	-	-	-
2.7 butt joint (pre-drilling)	fasten template, pre-drill 100%, drill with larger diameter	pre-drill conservative scenario		pre-drill conservative scenario by robot (pilot holes & shell edge as reference)
				pre-drill progressive scenario by robot (pilot holes & shell edge as reference)

<table>
<tr><td></td><td></td><td>pre-drill progressive scenario</td><td></td><td>butt strap edge detection from outside by ultrasound, shell edge as ref. → pre-drill by robot</td></tr>
<tr><td rowspan="2">5 Temporarily assemble</td><td rowspan="2">manual installation of pins (inside) and pop rivets (outside), removal of pins</td><td>tack from inside: grip pins in accessible areas, screws in non-accessible areas</td><td>temporary fasteners from inside</td><td>end effector with clamping mechanism</td></tr>
<tr><td>tack from outside: grip pins (Centrix)</td><td>temporary fasteners from outside (manual)</td><td>temporary fasteners from outside (installation and removal by robot)</td></tr>
<tr><td>5.1 butt joint</td><td>UF: tack 25-50% with pins, install 50% pop rivets, remove pins
LF: tack with pins from outside</td><td></td><td>tack ca. 30% with pins, no pop rivets
LF: tack from inside? (new TF)</td><td></td></tr>
<tr><td>5.2 stringer-skin</td><td>tack 25% with pins</td><td></td><td>pop rivets instead of pins (no removal necessary but higher tacking rate)</td><td>pop rivets instead of pins (no removal), installed by robot</td></tr>
<tr><td>5.3 couplings</td><td>UF: fix, tack with pins 25-50%, install pop rivets 50%, remove pins
LF: tack with pins from outside</td><td>tack from inside: grip pins in accessible areas, screws in non-accessible areas and couplings</td><td>LF: tack from inside? (new TF)</td><td></td></tr>
<tr><td rowspan="4">6 Final drill and rivet (all areas)</td><td rowspan="4">UF: final drill 50%, deburr, countersink, rivet with hi-loks (from outside), install collars, remove pins/pop rivets; same for remaining holes (50%)
LF: no countersinks, mainly lockbolts (and some hi-loks), inserted from the inside</td><td>install collars</td><td rowspan="2">final drill holes by robot and insert rivets, install collars manually (protection areas)
LF: insert as many rivets as possible from outside by robot</td><td rowspan="4">Hi-loks or lockbolts?</td></tr>
<tr><td>insert rivets manually</td></tr>
<tr><td rowspan="2">secondary drilling in LF manually in parallel</td><td>separated areas</td></tr>
<tr><td>only small delay between robot drilling & riveting and installation of collar</td></tr>
</table>

12.3. CONCEPTS EXCLUDED FROM EVALUATION

Some concepts included in the first generation of ideas (morphological box) are excluded from the evaluation as they are not likely to be successful, for instance due to technical reasons. The excluded concepts are:

Excluded Concept	Explanation
"Scan" and store the butt strap pilot holes before connection	This concept would eliminate the need for manual transfer of the butt strap pilot holes. However, they represent only a very small number of holes and need to be tacked (manually) immediately after drilling each hole. Even more importantly, during the connection of the AFT and FWD fuselage their shape will change slightly and there will be a certain amount of variation, i.e. the exact location of the scanned holes cannot be determined without a new measurement. However, the pilot holes can only be seen from the inside after the connection.
Pilot hole detection from outside by halo sensors	If the pilot holes on the inside in the couplings and stringers could be detected from the outside the manual transfer of pilot holes to the outside would not be necessary. Halo sensors make through skin sensing possible by utilizing of magnetic fields (HALOSENSOR® systems, 2016). As these systems are expensive and the magnets have to be placed in each hole and cannot be reused, this concept is not considered further.
End effector with clamping mechanism, clamping during final drilling	The approach was to develop a new end effector module with a clamping mechanism. If the parts are clamped through the holes by the robot 50% of pre-holes will probably be necessary to use the concept of the clamped neighbour but the installation and uninstallation of temporary fasteners would become unnecessary. However, certain aspects concerning sealant (how to attach the parts, how to distribute the sealant etc.) lead to the exclusion of the concept due to technical and quality uncertainties and the lack of technological readiness.
Pilot hole or coupling/ stringer position detection from the outside by ultrasound	The approach is to locate holes or component edges of components on the inside of the aircraft by ultrasound measurements from the outside. Ultrasonic sensors generate high-frequency waves and evaluate the echo received back by the sensor. Thereby they determine the distance to an object and can also detect defects in the material. (Jeong, 2009) Via thickness measurements holes and edges could be detected. The idea is visualized in Figure 71. Thereby holes could be drilled by the robot from the outside or if certain edges of the component could be detected the optimal hole position could be calculated and drilled by the robot and one would not depend on the pilot hole tolerances any more. Consequently, the edge tolerance problem might be reduced significantly.

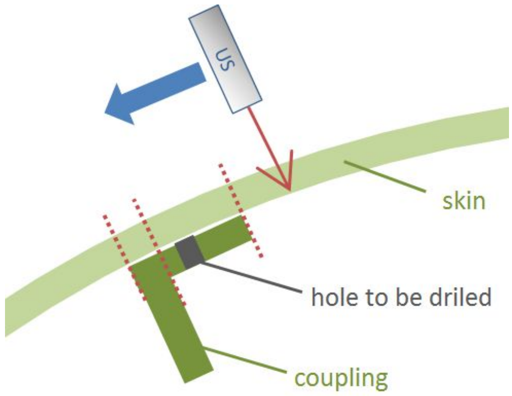


Figure 71 Ultrasound concept (own figure)

After discussions with ultrasound experts (Kiel, 2016) the concept is not further followed up as the air between different components will most likely prevent that the ultrasound waves propagate through the material. With the application of sealant this issue would be reduced for other materials than aluminium (such as composites) but in the case of aluminium the detection will probably not be possible. Further tests might lead to different conclusions but they could not be conducted within this thesis.

Final drilling and riveting sequence: drill & insert rivet (robot) – install collar & remove TF in next hole (human) – confirm – start again

This sequence eliminates the need for repeated referencing as the robot can perform one step and secondary drilling at once. It is eliminated because the end effector in use does not carry several drills and thus would need to change the drill for each hole.

12.4. CONCEPT VARIANTS

Table 31 Variants for pre-drilling of coupling-skin, lap joints & stringer-skin connection

Criteria	As Is	V1	V2	V3	V4
Description	- position and fix couplings - transfer 25% of each coupling, lap joint and stringer 3,3mm - drill back couplings 4,1mm - tack (25%) - pre-drill remaining holes (→ **100%**)	- position and fix couplings - transfer 25% of coupling, lap joint and stringer 2,6/3,3mm - (drill back non-accessible) - tack (25%) - pre-drill remaining holes (→ **100%**)	- position and fix couplings - transfer **conservative scenario** 2,6/3,3mm - tack only couplings (for stiffness of structure) - (drill back non-accessible) - [final drilling remaining holes by robot]	- position & fix coupl. - transfer **slightly more than mixed scenario*** 2,6/3,3mm - tack only couplings - (drill back non-acc.) - deburr reference holes from outside - [later mixed scenario tacking rate; final drilling by robot with open holes as ref.]	- position and fix couplings - transfer **progressive scenario** 2,6/3,3mm - tack only couplings - (drill back non-accessible) [final drilling remaining holes by robot]
Cycle Time Costs	100% pre-drilled; CT and CTC 100%	100% pre-drilled, no drilling back, CT and CTC 87%	deburring of holes needed if used for referencing later, less tacking and removal of chips during pre-drilling necessary CT and CTC 76%	deburring of holes needed if used for referencing later, less tacking and removal of chips during pre-drilling necessary CT and CTC 76%	even smaller pre-drilling and later tacking effort, no tacking and removal of chips during pre-drilling necessary CT and CTC 74%
Parallelisation capability	inside and outside in parallel	FWD and AFT side in parallel but much more work inside than V2-V4	FWD and AFT side in parallel	FWD and AFT side in parallel	FWD and AFT side in parallel
Lean ratio	0-30-70	0-33-67	0-27-73	0-27-73	0-25-75
Robot utilization	0%	0%	0%	0%	0%
Complexity	low	low, but difference for non-accessible	low, but difference for non-accessible	low, but difference for non-accessible	low, but difference for non-accessible

Quality/technical risks	100% pre-drilled, no snowman holes	robot can reference each hole, almost no snowman risk	increased risk for snowman holes but non for clamping	smaller tacking than pre-drilling rate: open holes can be used for referencing , sufficient test results for lower coupling tacking rate; increased risk for snowman holes	increased risk for snowman holes, clamping risk (esp. for stringers and lap joints)
Accordance to capabilities	good	good	good	good	good
Ergonomics	100% pre-drilling (also in bad positions)	100% pre-drilling (also in bad positions)	less pre-drilling (also in bad positions)	less pre-drilling (also in bad positions)	even less pre-drilling (also in bad positions)

Table 32 Variants for pre-drilling of the butt joint

Criteria	As Is	V1	V2	V3	V4
Description	- mark hole lines on skin - fasten templates - pre-drill **100%** 3,3mm - drill with larger diameter 4,1mm - remove templates	- mark hole lines on skin - fasten template - pre-drill **conservative scenario** 2,5/3,3mm - (pre-drill non-accessible area with small and larger diameter) - remove templates	- mark hole lines on skin - fasten template - pre-drill **progressive scenario** - (pre-drill non-accessible area with small and larger diameter) - remove templates	- global and local referencing - pre-drill **conservative scenario** by robot (pilot holes and shell edge as reference) - (manually pre-drill non-accessible area with small and larger diameter)	- global and local referencing - pre-drill **progressive scenario** by robot (pilot holes and shell edge as reference) - (manually pre-drill non-accessible area with small and larger diameter)
Cycle Time Costs	100% pre-drilling and drilling back, handling of templates, CT and CTC 100%	100% in UF, 50% in LF, no drilling back, manual drilling with template faster than robot; CT and CTC 66%	progressive pre-drilling rate, no drilling back, manual drilling with template faster than robot; CT and CTC 61%	100% in UF, only 50% in LF, no drilling back, no template to be attached, manual drilling with template faster than robot; CT 72% and CTC 66%	progressive pre-drilling rate, no drilling back, no template to be attached, manual drilling with template faster than robot; CT 63% and CTC 59%

Parallelisation capability	support angles parallel	support angles parallel	support angles parallel	support angles parallel but in separated work areas	support angles parallel but in separated work areas
Lean ratio	0-41-59	0-24-76	0-19-81	0-43-57	0-35-65
Robot utilization	0%	0%	0%	55%	48%
Complexity	high due to template adjustments	high due to template adjustments	high due to template adjustments	low	low
Quality/technical risks	100% pre-drilled, robot later has a reference for each hole, edge distance risk if the template is not adjust-ted correctly	edge distance risk if the template is not adjust-ted correctly	edge distance risk if the template is not adjust-ted correctly	skin edge as reference, high tacking rate	skin edge as reference, lower tacking rate
Accordance to capabilities	good	good	good	good	good
Dependency man-machine	no dependency as no robot used	none	none	low-medium (manual pre-drilling of non-accessible area from outside required, parallel work from inside)	low-medium (manual pre-drilling of non-accessible area from outside required, parallel work from inside)
Ergonomics	100% pre-drilling, also in the bad positions	less holes to be drilled	even less holes to be drilled	only little manual work, no drilling on the knees on the aircraft	only little manual work, no drilling on the knees on the aircraft
Safety	no issues	no issues	no issues	separated/protected work areas needed	separated/protected work areas needed

Table 33 Variants for the temporary assembly process

Criteria	As Is	V1a	V1b	V2	V3	V4
Description	- manually install grip pins from inside (UF) or	- manually tack from inside: grip pins in accessible areas, screws in	- manually tack from inside: grip pins in accessible areas, screws in	- tack by robot from outside - later remove TF by robot	- manually tack from outside: grip pins (Centrix)	- manually tack couplings, strin-gers, longitudinal joints from

	outside (LF) in all assembly areas - install 50% pop rivets & remove pins in butt joint and couplings in UF - remove TF later	non-accessible areas - later change TF positions in coupling for cross connection - remove TF later	non-accessible areas & couplings - remove TF later		- remove TF later	outside with grip pins (Centrix), - tack butt joint from inside with grip pins and screws - remove TF later
Cycle Time Costs	CT and CTC 100%	no pop rivet installation but grip pins position changes later during cross connection assembly, next to frame no grip pin installation in butt joint (access), CT and CTC 123%	couplings tacked with screws (time consuming), CT and CTC 188%	much longer time for temporary fastener installation or removal than in manual process, CT and CTC **266%**	faster than robot, no screws or position changes in couplings, no cleaning; CT and CTC 87%	faster than robot, no screws or position changes, no cleaning; CT and CTC 93%
Parallelisation capability		removal in parallel with collar installation to drilling/ riveting	removal in parallel with collar installation to drilling/ riveting (but not for screws in couplings)	none	in parallel with all operators but has to be done separately from drilling/ riveting (CT saving ~ time needed for removal)	in parallel with all operators but has to be done separately from drilling/riveting
Lean ratio	29-65-7	23-53-25	24-62-14	9-84-7	33-59-8	33-70-10
Robot utilization	0%	0%	0%	74%	0%	0%
Complexity	access to cross connection, position change of grip pins needed, flexible tacking rate	different types of TF, access to cross connection, position change of grip pins needed, complexity final	different types of TF	no access problems during installation and cross connection assembly	only one fastener type, no access problems during installation and cross connection assembly	two fastener types, limited access during installation at LF, no problems

		position of TF before drilling				during cross connection assembly
Quality/technical risks		grip pins lower clamping force than screws (but enough in case of 3,3mm diameter)	grip pins lower clamping force than screws	normality risk of grip pin during referencing for butt joint (however, not critical), grip pins lower clamping force than screws	grip pins lower clamping force than screws, normality risk of grip pin during referencing for butt joint (however, not critical)	grip pins lower clamping force than screws, no normality risk of grip pin during referencing
Dependency man-machine				still P30 and special holes assembled from outside		
Ergonomics	LF (limited access): installation from outside	installation from inside, limited access	installation from inside, limited access	almost everything automated	installation from outside, good access and more space than inside	installation from outside, good access and more space than inside
Feasibility Risk		development of new referencing method for Centrix fasteners needed	development of new referencing method for Centrix fasteners needed			

Table 34 Variants for final drilling and riveting

Criteria	As Is	V1	V2	V3	V4	V5
Description	- final drill non-tacked holes - deburr - countersink - insert rivets - install collars - remove pins/pop rivets	- final drill non-predrilled holes by robot (TF/holes as reference) - insert rivets by robot - install collars man. in parallel	- as V2 but robot and manual process separated (UF/LF)	- final drill non-predrilled holes by robot in one step (TF/holes as reference) - insert rivets man. - install collars manually in parallel	- only small delay between robot drilling & riveting and installation of collar instead of defined areas	- final drill non-predrilled holes in one step (TF/holes as reference) and insert rivets by robot - install collars and secondary drill

	- same for remaining holes (50%)	- remove TF - same for remaining holes (sec. drilling) - manually final drill and rivet non-access. holes		- remove TF - same for remaining holes (sec. drilling) - manually final drill & rivet non-accessible holes	(operator "follows" robot)	LF manually in parallel - rivet insertion again by robot
Cycle Time Costs	drilling and countersinking separated, deburring and quality control effort; CT and CTC 100%	no deburring and cleaning needed (chip removal by robot) needed, drilling and countersinking in one step but drilling by robot takes longer than if done man.	no deburring and cleaning needed (chip removal by robot), drilling and counter-sinking in one step but drilling by robot takes longer than if done manually, automated rivet insertion reduces OEE	no deburring and cleaning needed (chip removal by robot), drilling and countersinking in one step but drilling by robot takes longer than manually, manual rivet insertion saves time	drill has to be changed for secondary drilling (takes longer then new referencing)	operator is faster and robot does not need to change drill
Parallelisation capability	2 operators can work in parallel from the outside compared to only 1 robot	robot and human can work in parallel from outside and inside	increased lead time due to less parallelisation and interference of robots compared to V1	short lead time due to short riveting CT but rivet insertion and collar installation not in parallel	only small delay reduces lead time for last area to be assembled	parallel work possible
Lean ratio	53-6-41					
Robot utilization	0%	58%	58%	45%	53%	
Complexity		referencing with the vision system relatively complex, rivet insertion can be technically complex	referencing with the vision system relatively complex, rivet insertion can be technically complex	technical complexity low due to absence of automated rivet insertion (TF are interfering during rivet insertion)	referencing with the vision system relatively complex, rivet insertion can be technically complex	

Quality/technical risks	reduced drilling quality, no risk during riveting	improved drilling quality by robot, rivet insertion risk (OEE 70% assumed)	improved drilling quality by robot, rivet insertion risk (OEE 70% assumed)	improved drilling quality, mitigated rivet insertion risks, quality risk as principle of clamped neighbour cannot be applied with low tacking rates	improved drilling quality by robot, rivet insertion risk (OEE 70% assumed)	structure moves during hammering, final drilling quality better by robot
Accordance to capabilities	human has lower drilling competences					human has lower drilling competence
Dependency man-machine					high	
Ergonomics	inserting rivets from inside ergonomically worse than installing collars, 100% manual work	installing collars from inside better than inserting rivets				
Safety	inside/outside in parallel, risk for injuries		safety increase	safe parallel work inside/outside possible	poorer safety	
Others						- only possible in LF (no countersinks) - requires TF removal from inside - new tripod needed for use from inside

12.5. EVALUATION MATRICES (UTILITY ANALYSES)

Table 35 Evaluation matrix pre-drilling couplings, stringers and lap joints

			As Is		Variant 1		Variant 2		Variant 3		Variant 4	
	Criteria	**Weight**	P	P*W	P	P*W	P	P*W	P	P*W	P	P*W
Efficiency	Cycle Time Costs	10	1	10	6	58	9	87	8	77	10	96
	Parallelisation capability	10	8	82	5	51	6	62	6	62	6	62
	Robot utilization	4	1	4	1	4	1	4	1	4	1	4
	Lean ratio	4	2	9	2	9	2	9	2	9	2	9
Quality	Complexity	3	9	29	7	22	7	22	7	22	7	22
	Quality/technical risks	12	10	122	9	110	6	73	8	97	4	49
	Accordance to capabilities	6	8	46	8	46	8	46	8	46	8	46
Human Cent	Dependency man-machine	6	10	64	10	64	10	64	10	64	10	64
	Ergonomics	9	4	36	5	45	7	63	7	63	7	63
	Safety	15	8	118	8	118	8	118	8	118	8	118
Technol.	Feasibility risk	7	-	0	-	0	-	0	-	0	-	0
	Impact of design modification	10	-	0	-	0	-	0	-	0	-	0
	Overall Utility			**520**		**528**		**548**		**563**		**533**

Table 36 Evaluation matrix pre-drilling butt joint

			As Is		Variant 1		Variant 2		Variant 3		Variant 4	
	Criteria	**Weight**	P	P*W	P	P*W	P	P*W	P	P*W	P	P*W
Efficiency	Cycle Time Costs	10	5	48	9	87	10	96	1	10	6	58
	Parallelisation capability	10	8	82	7	72	7	72	5	51	5	51
	Robot utilization	4	1	4	1	4	1	4	7	31	7	31
	Lean ratio	4	3	13	2	9	2	9	3	13	2	9
Quality	Complexity	3	3	10	3	10	3	10	9	29	9	29
	Quality/technical risks	12	6	73	6	73	5	61	8	97	7	85
	Accordance to capabilities	6	7	40	7	40	7	40	7	40	7	40
Human Cent	Dependency man-machine	6	10	64	10	64	10	64	7	45	7	45
	Ergonomics	9	2	18	4	36	5	45	8	72	9	81
	Safety	15	9	133	9	133	9	133	8	118	8	118
Techno	Feasibility risk	7	-	0	-	0	-	0	-	0	-	0
	Impact of design modification	10	-	0	-	0	-	0	-	0	-	0
	Overall Utility			**486**		**528**		**534**		**507**		**547**

Table 37Evaluation matrix temporary fastening process

			As Is		Variant 1a		Variant 1b		Variant 2		Variant 3		Variant 4	
	Criteria	**Weight**	P	P*W	P	P*W	P	P*W	P	P*W	P	P*W	P	P*W
Efficiency	Cycle Time Costs	10	5	48	1	10	2	19	-5	-48	10	96	6	58
	Parallelisation capability	10	5	51	9	92	8	82	3	31	5	51	5	51
	Robot utilization	4	1	4	1	4	1	4	8	36	1	4	1	4
	Lean ratio	4	7	31	5	22	6	27	6	27	7	31	8	36
Quality	Complexity	3	6	19	4	13	6	19	9	29	10	32	7	22
	Quality/technical risks	12	8	97	8	97	8	97	6	73	6	73	7	85
	Accordance to capabilities	6	5	29	5	29	5	29	7	40	5	29	5	29
Human Cent	Dependency man-machine	6	9	58	9	58	9	58	7	45	9	58	9	58
	Ergonomics	9	6	54	4	36	4	36	10	90	9	81	7	63
	Safety	15	8	118	8	118	8	118	7	103	8	118	8	118
Techno	Feasibility risk	7	9	0	5	0	5	0	8	0	8	0	6	42
	Impact of design modification	10	-	0	-	0	-	0	-	0	-	0	-	0
	Overall Utility			**510**		**479**		**490**		**426**		**574**		**567**

Table 38 Evaluation matrix rivet types

			Variant 1		Variant 2	
	Criteria	**Weight**	P	P*W	P	P*W
Efficiency	Cycle Time Costs	10	6	58	8	77
	Parallelisation capability	10	-	-	-	-
	Robot utilization	4	5	22	4	18
	Lean ratio	4	7	31	10	45
Quality	Complexity	3	4	13	9	29
	Quality/technical risks	12	4	49	8	97
	Accordance to capabilities	6	-	-	-	-
Human Cent	Dependency man-machine	6	-	-	-	-
	Ergonomics	9	4	36	7	63
	Safety	15	-	-	-	-
Techno	Feasibility risk	7	-	-	-	-
	Impact of design modification	10	-	-	-	-
	Overall Utility			**209**		**329**

Table 39 Evaluation matrix drilling and riveting

			As Is		Variant 1		Variant 2		Variant 3		Variant 4		Variant 5	
	Criteria	**Weight**	P	P*W	P	P*W	P	P*W	P	P*W	P	P*W	P	P*W
Efficiency	Cycle Time Costs	10	10	96	1	10	1	10	5	48	1	10	1	10
	Parallelisation capability	10	8	82	4	41	2	21	5	51	3	31	6	62
	Robot utilization	4	1	4	6	27	6	27	5	22	6	27	6	27
	Lean ratio	4	6	27	7	31	7	31	7	31	7	31	7	31
Quality	Complexity	3	7	22	4	13	4	13	7	22	4	13	4	13
	Quality/technical risks	12	3	37	6	73	6	73	6	73	6	73	3	37
	Accordance to capabilities	6	3	17	8	46	8	46	8	46	8	46	5	29
Human Cent	Dependency man-machine	6	10	64	5	32	5	32	5	32	5	32	4	26
	Ergonomics	9	3	27	8	72	8	72	6	54	8	72	6	54
	Safety	15	5	74	6	88	7	103	6	88	4	59	6	88
Techno	Feasibility risk	7	-	0	-	0	-	0	-	0	-	0	-	0
	Impact of design modification	10	-	0	-	0	-	0	-	0	-	0	-	0
	Overall Utility			**451**		**433**		**428**		**469**		**394**		**376**

12.6. Precedence Graph (As Is Process)

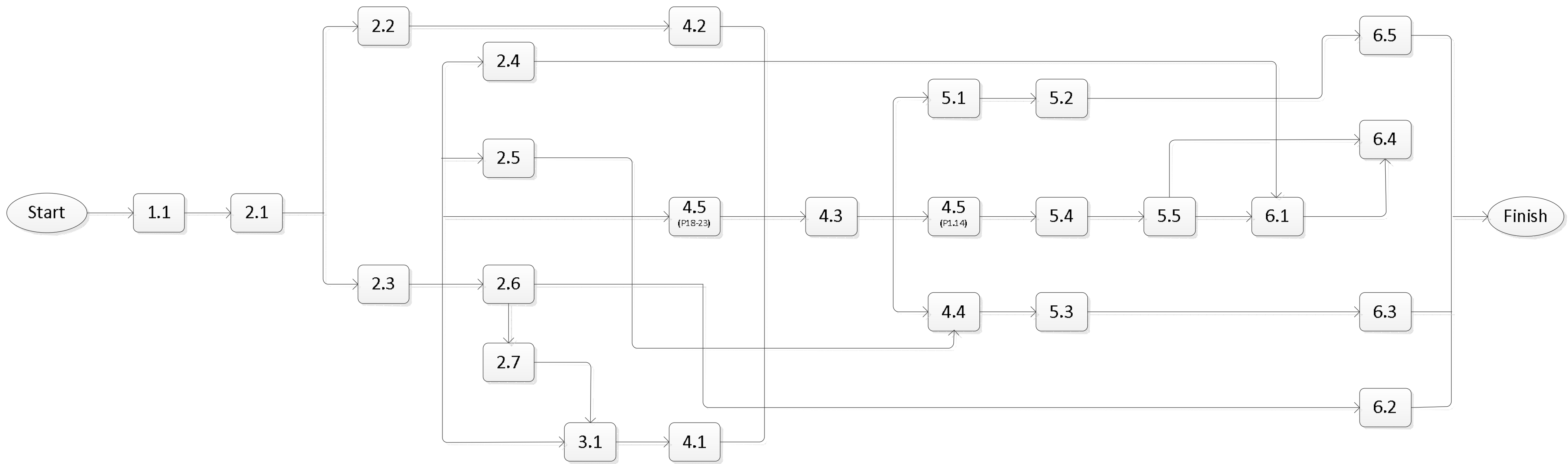


Figure 72 Precedence graph of the as is process (numbers refer to ch. 4.2.1 The Basic Process)

12.7. Criteria for Temporary Fastener Choice

Technical:

- Ability to close gaps
- Clamping force
- Ability to apply a constant clamping force, for instance during sealant squeeze out (e.g. by use of springs)
- Ability to align holes in case of a mismatch
- Centring capability in the hole (as they are used for referencing the centre of the hole)

Geometrical:

- Capability and accuracy of relocation and use for referencing by the robot (either of the body or the closing head)
- Clamping length range for different stack thicknesses
- Size of the body (height and diameter), related to the robot's accessibility
- Installation possibility: size of installation tool

Process-related:

- Installation time
- De-installation time
- Need for cleaning for relocation
- Usability
- Frequency of problems during installation
- One- or two-sided installation
- One- or two-person installation process
- Leaving of marks on the metal surface
- Operators' experience with temporary fastener type
- Harmonisation within the company/site/aircraft family/production line

Cost related:

- Recurring costs (RC):
  - cycle time costs (process),
  - cleaning costs after use and
  - material costs (either the fastener is a consumable or replacements are necessary due to loss and lifetime)
- Re-usability
- Investment costs, NRC (temporary fasteners, installation tools)
- *A cost calculation for different scenarios that are possible for the 4th FAL is attached in 13.9*

13. CLOSED APPENDIX

13.1. NON-DISCLOSURE NOTE

Non-disclosure instruction for final thesis:

Automated Circumferential Joint Assembly in Aircraft Production: Development and Assessment of a Production Process.

This final thesis, in particular the closed appendix, contains confidential data of Airbus Operations GmbH which are subject to data protection and secrecy. The contents of the closed appendix may only be made accessible to the supervisors and members of the examination office and shall not be disclosed to a third party. They shall not be published or reproduced neither digitized unless the express written consent of Airbus Operations GmbH has been obtained.

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31 August 2016,

Date, signature Katrin JAACKS