Generating lessons-learnt from welding capability studies at GKN Aerospace

Master's Thesis in Quality and Operations Management

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Abstract

This report presents a qualitative study conducted at GKN Aerospace Sweden (GAS), located in Trollhättan. The company supplies high quality products to global aerospace industry and develops and manufactures products both for commercial and military projects. The need of controlling the processes of development and production as well as the introduction of proactive thinking in the aerospace industry has increased, because it is one of the most important factors to maintain a competitive advantage in the global market.

The study has mainly focused on a process perspective, on a specific static component of the engine called Turbine Rear Case (TRC). It has been approached as a case study and the purpose has been to understand and define the welding capability of the welding method used on this case in the company. There have been studies that explain how the final product is dependent by the individual processes. If the factors that affect the outcome of each individual process can be controlled, then the outcome will be controlled and the company's competence will be of best use. Additionally, the need to communicate the knowledge that is produced during the development and production of a product to the rest of the company and the following similar projects is of vital importance. It has been observed that knowledge exists in the company and in people's minds, and this knowledge has to be documented in a structure that is useable.

On the specific sector of this case study's product, the product's critical characteristics that affect the design and manufacturing were identified and the design, but also the manufacturing perspective were presented. The factors that affect the manufacturing welding process of the part, the lessons-learnt and the characteristics that manufacturing would like to introduce to the future projects, or to maintain from current to future projects were documented. Other factors that facilitated the made choices about manufacturing parts were also brought up in combination with the creation of the "Flowchart for lessons-learnt management" to help reach decisions about manufacturing by using the company's welding capabilities.

Recommendations were made in short-, medium- and long-term perspective, as well as suggestions for future academic work that might add value to the company's research and development department. The most important recommendations made were the cross-functional working combined with physical proximity of the product and production development departments and manufacturing, the proactive thinking and the introduction of the important manufacturing parameters early in the design phase. Last but not least, the importance of documentation and communication of lessons-learnt in the company, preferably by using the

“Flowchart for lessons-learnt management”, so it can be used in future projects is of high importance.

Keywords: Welding capability, Flowchart for lessons-learnt management, Welding methods, Manufacturing capabilities, Producibility, Proactive thinking, Knowledge management, Lessons Learnt, Best practices, Critical characteristics, Robust design, Documentation, Turbine Rear Case (TRC).

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Karin Swedenborg and Maria-Eleni Kantilieraki
Gothenburg, June 2016

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1. Introduction

The introduction will include a presentation of the thesis topic and its relevance to the research. This thesis will initially present a high-level description of the general theoretical background to introduce the reader to the current situation and a company description will follow so that the nature of the problem and the need for suggestions will be better understood.

1.1 Theoretical Background

For the last decade, it is undisputable that aerospace system requirements are still evolving to higher levels of performance. However, the cost requirement for aerospace producers must remain low and at the same time, the produced goods must be affordable for the aerospace customers, which are the companies they supply with components. Additionally, the customers' needs for robustly designed products and resistant materials have led to severe considerations around the developing process and the manufacturing capabilities (Milner et al., 2013). Therefore, the need for further research of the manufacturing capabilities becomes more essential. Aerospace industry ought to understand the manufacturing capabilities in order to predict, control and keep their processes stable.

Within commercial and military production in Sweden and other countries, a large competition exists. Continuous improvements are necessary in order for the companies to be competitive. Especially for the aerospace industry where new market demands appear frequently due to regulations, the pressure to be competitive is more intense (Madrid et al., 2015). However, in aerospace industry, radical changes are not easily made, since the government and politics in the country control them. The regulation makes it difficult to change the product. The safety of the products will be considered as first priority. This hinders the product development cycle of aerospace components, since GKN Aerospace Sweden (GAS) is a business-to-business company. They cannot improve the parts they are producing on their own, without having an agreement with their customers first. Compared to the automotive industry where improvements and upgrades to product features are fast and frequent, the aerospace is a slow changing process and the technology behind the jet engine does not change in the same frequency as in the automotive industry. In this case, the material and fabrication processes need to be updated frequently to achieve all the latest environmental goals that are set for aerospace producers globally (Madrid et al., 2015).

During the development phase, the producibility of the products needs to be considered in detail. If the chosen production method is fabrication, it is known that the welding processes create variations. Reckoning with producibility and variations, the risk of jeopardising the quality of the product will be decreased and the customer requirements will be met. Each welding method has different capabilities and creates different variations that affect the product results for the internal and external customer.

1.2 Company Background

GKN is a British multinational automotive and aerospace components company founded in 1860s. GKN stands for Guest, Keen and Nettlefolds. The history of the company goes back 250 years, during those years a lot of change has taken place and innovation is always a priority. In the 1990s, the company focused on a few growth businesses: Driveline, CHEP (Commonwealth Handling Equipment Pool), Cleanaway, Aerospace/Defence and Off-Highway. In 2001, the company reshaped and the focus has been on four world-leading businesses: Driveline, Aerospace, Powder Met and Land Systems. Nowadays, GKN is the key supplier of components to many different companies. The Volvo Aero acquisition in 2013 made the company stronger and emphasized the aerospace division of the company even more. GKN exists in 35 countries and employs over 55.000 people. The quality and the innovation of the company are directly connected to company's strategy and reputation (GKN Aerospace, 2016).

GKN Aerospace is a market-leading company that designs and manufactures complex, high-performance, high-value integrated metallic and composite assemblies for aerostructures and jet-engine products that are provided to different customers, in commercial and military projects. GKN Aerospace contributes to 30% of the total GKN sales (GKN Aerospace, 2016). The capabilities inside GKN Aerospace are spray mat metallic deposition, microwave curving, advanced coatings and materials, multi-axis complex machining, additive manufacturing (AM[1]), automated fibre placement (AFP). Delta pressure forming, Electro-chemical machining (ECM) and resin transfer moulding (RTM).

This thesis was conducted at GKN Aerospace Sweden, in Trollhättan where the headquarters of GKN Engine Systems are located (GKN Aerospace, 2016). The specific department that this master thesis was conducted is called Process Engineering. It belongs to the Research & Technology (R&T) organisation of GAS. Research and Technology department's main positions are in the areas of Technology, Chief Engineering and Core Engineering. The department employs approximately 20 engineers that work on joining methods, inspection techniques, thermal spray, materials, automation and cutting technology. A high percentage of the staff has a PhD degree and, in average, 15-year working experience. This can prove the interest of the company to introduce an even more systematic way of thinking in the development of the projects and combine the academic perspective with the working philosophy. This department ensures targeted innovation and solutions with unique functionality and certifies the differentiation of Intellectual Property (GKN Aerospace, 2016). According to the department

[1] That includes 3D Printing, Rapid Prototyping, Direct Digital Manufacturing, Layered Manufacturing and Additive Fabrication

information, Technology as a functional area is an organisation which delivers key differentiating and valuable capabilities to GAS in the format of technologies, knowledge and skilled engineers. We can see Technology as a Knowledge Value Stream which articulates the alignment of strategy, tactics, operations and results within the company (Figure 1), (Research and Technology Centre, 2015).

Figure 1 Technology as a Knowledge Value Stream (Research and Technology Centre, 2015)

Last but not least, GAS is a business-to-business company that supplies its customers with high quality products. The customers are Rolls-Royce, Pratt & Whitney, Snecma (Societe Nationale d' Etude et de Construction de Moteurs d' Aviation) and General Electric (Wikipedia, 2016).

1.3 Purpose

Introducing a proactive thinking to be able to predict difficulties in the manufacturing during the conceptual phase of a New Product Development (NPD) is the ideal goal for a manufacturing company. During the conceptual design phase potential changes cost less and are easier to implement on the original design. If the correct information exists from the beginning of a project, better simulations can be made to predict the quality outcome. The purpose of this thesis is to recognise the different capabilities of the different welding methods and to identify the knowledge gaps that might exist internally which can affect the product development. Apart from this, the purpose has also been to generate lessons-learnt that can serve to support the development of current and future products.

Designers tend to prioritise the functions of the product over producibility during development phase. That happens because of the educational mind-set and background designers have acquired. It is expected of them to focus on their specialty. The vision is that designers should be able to think critically towards their own design to predict complications that can occur in the manufacturing and how the design will affect the producibility due to the chosen technique. To some extent, personnel can think critically towards their own work. The knowledge that exists in the manufacturing should be shared with the designers to increase producibility. This is understandably more complex than it appears. The sooner knowledge is added and improvements in mind-set occur, the sooner they can be applied. That will benefit the quality and cost of the designing processes. From this, the necessity of a structured lessons-learnt and knowledge management are highlighted.

Moreover, given the importance of introducing a proactive, system-thinking perspective when developing products, the researchers aim to create a structured sequence of steps to depict how the different design characteristics and manufacturing process parameters can affect the outcome and how they can be prioritised and evaluated. This structured sequence of steps will be used as a guide to show how decisions about projects should be made, how to document and manage lessons-learnt and what is considered as the important characteristics to preserve in future projects.

1.4 Problem Description and Research Questions

In aerospace industry some functional requirements changed recently. The weight of aircrafts' engines was a crucial functional requirement change, because it affected the cost, the fuel consumption and the environmental aspects of the CO_2 emissions. Another functional requirement was the increased temperature of the running engine that led to a change of material that is more heat resistant. The available technology has not been currently able to cast the specific material. Consequently, GAS made a strategic choice to use fabrication of smaller components instead of large castings of the whole products, in manufacturing (Figure 2). Fabrication is a preferred manufacturing solution that consists of several steps where smaller parts are combined in order to add building blocks to the product through the different assembly levels until the final assembly is completed (Madrid et al., 2015).

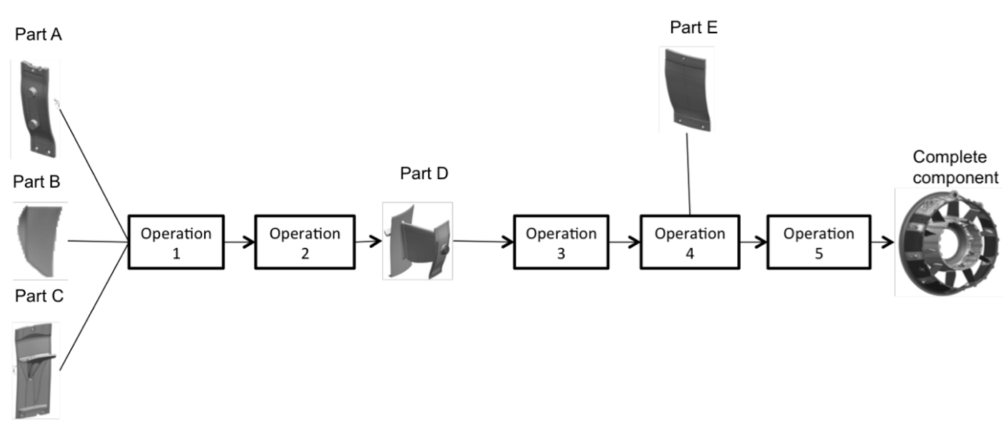

Figure 2 Fabrication Process scheme example at GAS

The complexity of the produced parts got higher after choosing fabrication as a method. That is why the attention is turned to joining processes, searching for effective ways to weld different parts together. The company approached the welding processes from an experimental level but also from the R&T perspective, where manufacturing worked in parallel with product development. The available welding methods in the company are four and the company's goal is to have technologically matured methods that they can choose from. If all methods are mature and the knowledge of their capability is obtained and shared in the design, the production can be adjustable and pervious to their customer requirements.

Considering that welding is the main process that takes place in order to fabricate GAS' products, there is a need to find out at what degree the welding affects the robustness of the product and how capable the processes are to produce the wanted manufacturing outcome. Additionally, it is of this thesis interest to find out what are the most critical characteristics of the product that affect the outcome, but also, the manufacturing parameters that is worth taking into account and the knowledge around those that is worth preserving to future projects within the company. That leads to the first research question.

1.What are the product's critical characteristics that should be documented and considered in future projects:

a) From the functional perspective?
b) From the manufacturing perspective?

The critical characteristics refer to the current practice that the company chose for the specific product. Since the goal is to introduce the needs and the important aspects of manufacturing early into the design phase a request for identification of the ideal characteristics for producibility leads to the second research question.

2.What are the factors that should be prioritised as important for future use, from the knowledge that the company already obtains?

Considering the parameters that are crucial from manufacturing perspective and combining those with theory and documented knowledge about welding capability, there rises the need to survey how this knowledge is combined with lessons-learnt, how it is accessible by everyone and how it can be better understood for future use and for improvements to on-going projects. That leads to the third research question.

3.How can the welding capability knowledge be used in the product development process?

By gathering knowledge and data from both internal and external sources and by categorising and analysing the incoming data, the thesis students attempt to answer the previously mentioned questions in order to fulfil the purpose of this research as well as approach a solution to a realistic problem in a manufacturing environment.

1.5 Delimitations

GAS runs more than one projects, but the focus of this thesis work will be on a specific project and the welding methods that are used in order to fabricate it, which are Gas Tungsten Arc Welding (GTAW) for the H-Sector and Laser Beam Welding (LBW) at the 360-assembly. That is connected to the next delimitation, the rest of the in-house available welding methods will not be studied for the needs of this specific master thesis.

If we consider the different production steps as levels, the TRC consists of three levels. The first one is the vane, which is outsourced, the second level is the assembly of the H-sector (assembling three parts) and the third level is the 360- and final assembly. At the specific project, the focus was on the second level, which uses GTAW. So, the first level as well as the third level, and the processes that take place in these two are not included in the scope of this thesis work.

This master thesis has been delimited within the context of a bigger research project under the name “Producibility and Design for Manufacturing of Aerospace Engine components”. Therefore, some of the existing results, such as the framework created by Madrid et al. (2015) that is presented in Chapter 3.4, has been taken as a base approach for structuring the systematic thinking of understanding welding capabilities and factors that affect significantly the outcome.

This study was about welding capability analysis in GAS Trollhättan. The company having commercial and military projects running at the same time has as a consequence that confidentiality issues are raised and the accessibility to internal documents was limited for the thesis students. That can lead to the risk of not having included important documented knowledge from military projects to the literature study.

The last delimitation of this thesis is that the theory was used for deeper and better understanding of the current situation and the problem description. During the result presentation, the theory will not be recalled and clear connections will not be made. The reason is because literature study constituted data and not means to analyse them.

2. Methodology

The methodology will include and describe the way the students chose to approach this thesis as well as the conducted plan and the expected outcome. A motivation on why those methods were chosen is also included. A discussion around the triangulation of data, the validity of the research, the trustworthiness of the results and the ethical consideration follow.

This thesis includes a case study since it focuses on a specific product and a specific operation of the production line. A qualitative case study is chosen, because when the focus is on answering "how" and "why" questions, and when the researchers cannot influence the results or cannot affect the behaviour of those involved in a study, is this an appropriate approach. Even though this is a single case study, the findings are considered to be suitable to look into for further academic learning (Yin, 2014).

2.1 Literature Study

The literature studies that have been the base for this master thesis have in different areas affected various aspects of the work's performance. Theory has been used to understand the problem, define the research area and provide the ability to ask for relevant data and information. A better understanding through the literature study increases the credibility of this thesis. The purpose of this literature study is, therefore, not to summarise previous work in its entirety but to give an insight into what has been written and researched before around this topic (Bryman & Bell, 2011). The report describes the connection between different scientific publications, books and internal documents which were used to describe different aspects. Internal documents have been used to understand what knowledge the organisation has already had from previous work about the subject.

Scientific publications that has been the basis for this master thesis work has been acquired by Chalmers Library search engine, Google Scholar, GAS database (SAP), and articles provided by previous courses and by Julia Madrid, a PhD student and the project's supervisor. In the search process, the most recent scientific articles were the priority of the researchers. However, older publications, both books and articles, have also been used when the students considered them to be relevant. Most of the publications that have been used in the thesis have been of international character and written in English. Fewer have been in Swedish.

In connection to the article searching procedure in the different scientific search engines, the keywords used have been: Welding Methods, Robust Design, Design for Quality, Key Characteristics, Risk Analysis and Knowledge Management. The use of an asterisk character (*), known as wildcard, helped the researchers to look for articles when there where also unknown or wildcard terms (GoogleGuide, 2007). As a first screening, the title of the publication was used, afterwards, the screening was done by reading the abstract and if that proven the publication relevant, then the researchers used it.

In order to better visualise the theoretical foundation that this research is based on, but also the focus areas, a mind map inspired by the Relevance and Contribution Diagram (ARC diagram) has been created and used (Figure 3). At the centre of the map, we can see the basic focus of our research, and around that focus area, there are other complementary focus areas that will support the knowledge of the researchers and will function as theoretical background for the whole thesis (Blessing & Chakrabarti, 2009).

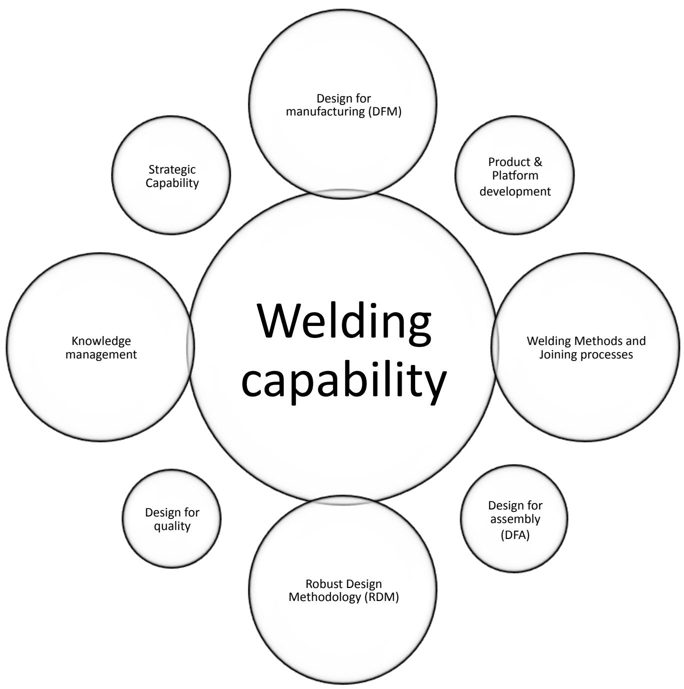

Figure 3 Visual mind map inspired by Relevance and Contribution diagram (ARC diagram) (Blessing & Chakrabarti , 2009)

It is obvious from the visual mind map, as well as mentioned in theory (Bryman & Bell, 2011), the fact that when literature research is conducted, the literature framework keeps growing like a snowball rolling down a hill, also known as *snowballing sampling*. All in all, the literature study is appraised as a part of the data that were collected during this master thesis and knowledge that was fundamental for structuring this research.

2.2 Interviews

Interviewing is a method used to collect information from people which can be helpful with the research process. The data collection methods were chosen in order to get a better understanding of the processes the company conducts. The interview types can be structured, semi-structured and unstructured. The main difference between these types is on how formally the interviews are performed (Bryman & Bell, 2011). The interviews in this thesis were either semi-structured or unstructured, depending on the situation. Semi-structured interviews were conducted after the researchers had structured some questions that would like to get answers from, but the possibility of adding questions, changing the questions' order or giving the chance to the interviewee to mention information in a form of an open discussion. According to Creswell (2014), the achievement of a more realistic and rich result from the interviews is related to a detailed description of the purpose of the question. This increases the validity of the research. Sometimes, interview question must have a rich and thick description in order for the interviewers to be clear about the type of answer they are seeking.

Employees were interviewed from different departments at GAS, in order to reassure that the opinions of different "sides" are included. People from Product and Production development as well as Manufacturing were chosen (Figure 4). The interviewees were engineers with different roles in the company named engineer in charge, project, product, design, thermodynamics, materials and process and manufacturing engineers. Taking into account that Product and Production development are partly happening in parallel, some engineering roles can be found in more than one departments. The employees' responsiveness satisfied the researchers and helped developing the understanding and the data collection.

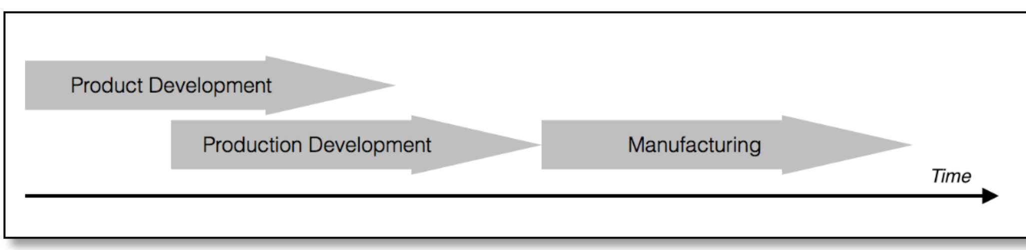

Figure 4 Three groups of people in GAS when developing products

Additionally, unstructured interviews took place, mostly with the employees at the shop floor, in order to get a clearer view of what is considered important and critical from the practical and manufacturing perspective that experienced operators can give to the researchers. The unstructured interviews are comparable to a conversation and can be combined with observations. The questions are not prepared beforehand and therefore there is no limitation or specific rules followed during this approach (Bryman & Bell, 2011). The reason that unstructured interviews were chosen for this group of people is because of the researchers did not aim at specific answers but were more interested in general ideas in the beginning, and specific later, information that the employees would consider crucial without being led by the research groups questions.

Some of those interviewed were conducted in Swedish and some in English. Interviews that took place at the office areas were recorded, after asking for the interviewees' permission, in order to have the opportunity to re-visit the data and process them. Afterwards, the interviews' notes and recordings were used to collect information and fill in the answered to the interview questions, but also acted as a reminder to points that were mentioned and perhaps escaped from the researchers' attention. The recorded tapings were not transcribed word by word. They were discussed between the group members and better knowledge assimilation was reached.

2.3 Interviews with mediating tools

Another research tool which was used by the thesis team was the mediating tools that were brought to the interviews and to the discussions. A mediating tool is a stimulus that helps enhancing reflections, discussions and understanding during an interview. It is a way to visualise better the subject of discussion and leads the focus on the specific product or idea that the research team is interested to investigate (Dagman et al., 2010).

In this case study, the students used preliminary results, pictures of the product, ideas and tables that were created in order to show the interviewees the way of the team's thinking, the product and the goal of the research. Parts of the actual product were also used in order for the interviewees to have the chance to indicate on the exact material part what the critical characteristics of the product's geometry are. That helped the interviewers to gain more information about the research, to explain in a more haptic and clear way their intentions and purpose and brought focus on the product during the discussions.

2.4 Observations

Observations can take place at different levels depending on how involved the observer is. There are four main roles: *Complete participation, Participant-as-observer, Observer-as-participant, and last Complete observer* (Bryman & Bell, 2011). The most suitable observation technique for this case was Observer-as-participant.

The first observation took place when the thesis students were given an introductory tour of the production site. At that time, the team was not aware of the product in detail. The purpose of the introductory tour was to observe the environment and familiarise with locations and the different sites of the production. This type of participation is more of a functional setting and the identity of the students is not yet known to the members (Bryman & Bell, 2011).

When students observed the actual process steps, they had prepared and studied the object of their observation. From literature and interviews, the team had taken cognisance of the welding procedure and the operations' instructions, which were provided by the internal documents of the company, had been under scrutiny, so that the students could be prepared on what the welding operator was going to perform. The team also produced some questions from the operations' instructions and performed a more standardised and structured discussion while observing. The purpose of that observation was to understand if the operations' instructions were followed and how different requirements were fulfilled. In this case, the students had asked for permission to observe and the operators were aware of the purpose of their presence and their thesis work.

Lastly, considering the observer-as-participant, the research team visited the production site on a daily basis to observe the processes since there was a need to observe different steps of different processes. Little time was spent on active participation. That is directly connected with the nature of the processes, since the thesis students are not certified welders and lacked welding experience. More time was spent on observing the handling of the robot welding machine. During these meetings, the operators were once again well aware of the project and the team's identity out of ethical considerations (Bryman & Bell, 2011).

Team members gained experience of the procedures and had the chance to ask more questions during testing and observing that took place in the production site. To be more specific, the team actually tried to weld some interfaces under the supervision of certified welders. From this, awareness of the challenges, the difficulties and the philosophy behind welding was gained.

2.5 Validity and Reliability

In every research, it is vital for the researchers to take into consideration the validity and reliability of their work. With the term validity, we refer to the appropriateness, quality and accuracy of the procedures and the results that are applied to a research process (Kumar, 1999). Additionally, the concept of reliability is connected with the degree of consistency and stability in a research instrument. If the method of researching is stable and consistent, then it will also be predictable and accurate, so the research is considered reliable (Kumar, 1999). The terms used to describe the criteria of judging the quantitative and qualitative research are the internal validity, external validity, reliability, objectivity and credibility, transferability, dependability, confirmability respectively (Kumar, 1999).

In this thesis, the validity was preserved to the best possible degree by continuously re-visiting the research questions and the results from the collected data. In that way, the researchers tried to reassure that the findings of the study are in accordance with what was designed to be found out. The method used and the theoretical framework that was followed helped to improve the validity of the outcome. As far as reliability is concerned, the researchers had multiple observations of the production site, to triangulate the results with different sources and to test the results by asking some questions twice. Since the research group came to an agreement on the findings and shared understanding of the data, the results can be seen as reliable.

2.6 Triangulation of data

To begin with, the research included two parts, an applied theory research and a case study. During the case study, numbers were used in the form of component dimensions in order to quantify some critical characteristics.

The data collected through the research originated from semi-structured interviews, observations and Gemba walks as well as literature review of internal documents and articles and books. The research team triangulated the information by comparing and contrasting the internal documents with the literature knowledge from books and other reviews and article publications. According to Bryman & Bell (2011), triangulation of data is important in order to rise the validity of the results. Additionally, the research group triangulated the data through discussions after observations and interviews and through comparison of the notes made during the previously mentioned data collection methods. That can be defined as unstructured triangulation (Bryman & Bell, 2011). In this way, information was not forgotten and everyone's view was taken into account, therefore, a better comprehension and interpretation of the observed facts were ensured.

A significant consideration of this thesis was the degree that the results could be generalised to other projects inside the company, but also to different companies. In other words, at what degree the results can be considered applicable to other projects. The research team focused their interest on a sector level of a product. This product is a part of a platform. That means that the results could be used for other products of the platform, but further research should be made for the different materials and the available technology.

2.7 Qualitative data analysis

According to Bryman & Bell (2011), it is difficult to find analytical paths to qualitative data analysis. Two commonly used strategies of analysing qualitative data is *analytic induction* and *ground theory.* General strategies to analyse qualitative data is to use a framework to guide the analysing process. In this master thesis case, the framework used to analyse qualitative data and structure the researchers' thinking is the P-diagram (Figure 5). The P-diagram illustrates an input, control factors, noise factors and an outcome (see Chapter 3), (Bergman & Klefsjö, 2010). In addition to P-diagram, the framework created by Julia Madrid (2015), which includes the P-diagram thinking, was used, not only to analyse the collected data, but also to lead the thinking and create a mind-set to approach aerospace capability issues. However, the logical path of this thesis is that the main studied process is in the central box, and the factors that are affecting this process in order to deliver the wanted outcome are around this process as inputs, as illustrated in the following figure.

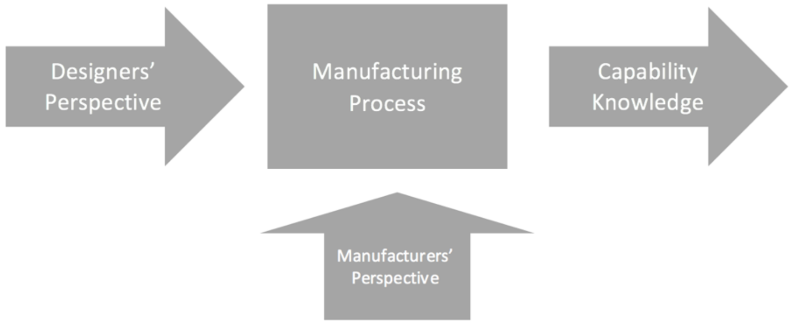

Figure 5 Framework for the Qualitative Data Analysis inspired by P-Diagram

The design perspective affects the manufacturing process, but a way to control the outcome and the process itself is by controlling the manufacturing perspective. The outcome of this process is the deeper understanding of the welding capability and in which way and what degree the design and the manufacturing perspective can alter or improve the outcome of the manufacturing process. In the manufacturing the control factors are decided after different tests, the knowledge from testing different factors of the robot was of interest for this thesis work, and to bring the know-how to the surface.

2.8 Ethics

In every research, there are several ethical considerations that must not be ignored. According to Diener and Crandall's (1978) theory which is mentioned in Bryman & Bell (2011), the four ethical principles are: whether there is harm to participants/ non-participants, a lack of informed consent, an invasion of privacy, and deception. Of course, there are further ethical and legal considerations like the data management, the copyright, the reciprocity and trust and the affiliation and conflicts of interest (Bryman & Bell, 2011).

The basic concern of the researchers was not to personally harm any of the participants, treat with respect all the employees of the company, be certain that the purpose of this research was well communicated among the research group and the participants. Moreover, during the interviews, the role and purpose of the research were analysed, and permission to use data and to record the interviews was always asked in advance.

Considering the nature of GAS and the projects they run, anonymity is a crucial ethical issue that belongs to the data management and the copyright, meaning how the data that were accessed were handled as well as, to whom the results of the research belong to and at what extend these results can be published or presented and used outside the company. Extra attention was paid to all the information that was classified, to the way the information was saved and to the extent that this information could be used in the report writing. On the other hand, anonymity of the interviewees was not considered as necessary, since the people who were interviewed were process owners or project leaders that were interested in this research and were willing to contribute as much as possible.

Finally, when observing the processes, the researchers tried not to make people feel uncomfortable, by again explaining the purpose of their presence and their research and by paying respect to the experience and the work position of every employee.

3. Theoretical framework

This chapter analyses the theory that the master thesis students approached in order to accumulate the necessary knowledge in order to conduct interviews, observations and structure the results during the duration of the thesis. Theory is a prerequisite for the following results, since without it, the analysis and the structure of the findings would not be plausible. This section includes a description of the product, the philosophy of joining and fastening methods, but also the fundamental manufacturing theories and knowledge management models.

3.1 Turbine Rear Case Description and Fabrication methods

The Turbine Rear Case is a part of the platform that GAS introduced (Figure 6). A platform mind-set is a base for organisations to build new system solutions for customers. The typical feature for platform projects is the common architecture for the product and process family. Normally, they have a design life of several years. According to Wheelwright & Clark (1992), the platform can be seen as a visual version of the future projects in order to help designers, manufactures, marketers and managers identify where value to the product can be added. The benefits with implementing platform project are to introduce high volume production with good quality, fundamental improvements in cost, and performance over the preceding generation (Wheelwright & Clark , 1992). To work with platform development is beneficial for GAS, since they have a core group of customer and the thinking behind the product development can be shared.

The purpose of this thesis will be better perceived if the product-under-study is fully understood. The structure of the product, its use, its functions as well as the reason why it is considered an important component of the aircraft engine will be described and explained.

A TRC (Turbine Rear Case) is a load carrying structure located at the end of the engine, where the hot air exists. TRC consists of 10 components called H-sectors, due to their shape. Each H-sector is a result of assembling three different units; the Case, the Vane and the Hub. Those three together make one H-sector and are assembled by using Tungsten Inert Gas (TIG) as a welding method. The TRC serves three main functions. The centre of the TRC includes the bearing house that supports the main shaft of the engine. The middle part of the TRC, the vanes as a 360-assembly help to exhaust the air flow and straighten it out towards the axial direction of the engine. That is necessary because the gas flow comes to the vanes inclined, with an angle. The outer case of the TRC is where the mounts are and that is the part that is attached to the rest of the aircraft (Olsson, 2014).

There are three different types of H-sectors in the 30K TRC; The Mount, the Ground Handing and the Tube. Each type plays a different role on the final assembly and has different functions depending on where the sectors are located on the TRC. The Mount can be divided into two sections; Failsafe and Left & Right (L&R). The Failsafe is placed at twelve o'clock and has one mount. On the left and right side of the Mount Failsafe there are the L&R Mounts and have two mounts each, and they are the primarily "load carriers" and the Failsafe the secondary "load carrier". If one of the primarily "load carriers" would break down, the Failsafe Mount will take the load. The tube sector's main task is to provide the end bearings house with oil, for lubrication, for temperature adjustment and for cleaning. Therefore, the Tube has a wider diameter for the oil pipes to fit. Ground Handling does not have a specific function on the TRC. To obtain efficient propulsion of the aircraft the vane is designed to have one concave and convex side, also known as the pressure and suction side. That geometry leads the concave side to higher speed and lower pressure and the convex side to higher pressure and lower speed (Olsson, 2014).

The amount of material is varying between the parts, the thicker areas need to be robust and hard enough to sustain a probable broken blade from the engine. Looking at the whole TRC as one part, the three Mount sectors are the most critical ones, because they are connected to the engine and wing. This is the primal area from a design perspective, since it takes most of the tensile loads from the engine. The second critical area of the TRC is the other H-sectors going in a clockwise direction. The Tube and Ground Handling are the secondary priority of the H-sectors.

According to Jakubowski & Peterka (2014), a proactive thinking is the best way to solve complex problems. The TRC has a complex geometrical shape and that means that more complex problem can occur which need to be dealt with, best done proactively, at the design phase (Jakubowski & Peterka, 2014). Proactive thinking is the preferred way to solve complex problems cost-wisely if compared to reactive thinking. Due to the complex geometry, GAS has chosen to produce the TRCs in several parts (fabrication) and weld them together by using the welding technology available in the company. Since the welds are minimum 26 metres/TRC, welding is considered to be the major operation and that is a reason for this thesis' focus on welding capabilities to the specific product (Olsson, 2014).

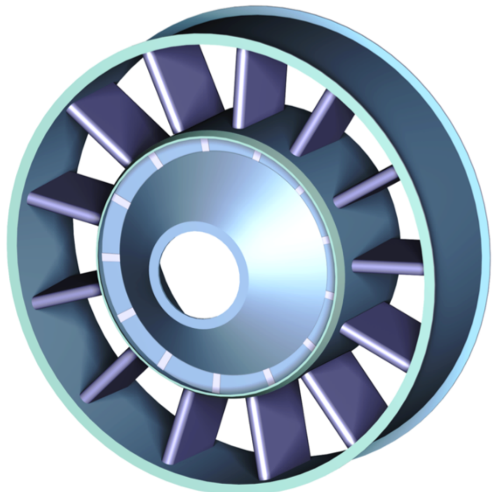

Figure 6 Turbine Rear Case (Olsson, 2014)

3.2 Joining and Fastening Processes

Joining and fastening processes are a general expression covering many processes that are important for manufacturing operations. It supports the possibility to produce more complex products. Joining is a good alternative when a product is uneconomical to produce in one piece or when it is easier than to produce in a single piece (Kalpakjian & Schmid, 2003). Joining or fastening single pieces can increase the design freedom on complex products, for example a turbine, automobile bodies and printed circuit boards, compared to casting in one piece. Joining and fastening can be divided into different categories. Joining is normally referred to as fusion-welding processes that melt and merge together metals by using a heat source. Most of the joining processes require a heating source and the heat that occurs during welding induces stress and deformation, which can lead to geometrical variation (Madrid et al., 2015). Fusion welding consists of a consumable or non-consumable electrodes, either in arc welding or in high-energy-beam welding process (Kalpakjian & Schmid, 2003) and (Kou , 2003).

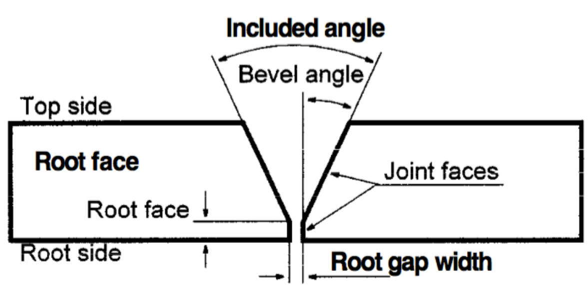

Figure 7 Joint Terminology (Weman , 2012)

3.2.1 Arc Welding

Welding means heating up two pieces of metal and join them through a fusion, this creates a welded joint. Arc welding has two main methods, Gas tungsten-arc welding and Plasma arc welding. An arc occurs between the tungsten electrode and the work-piece by an electrical short circuit.

Gas tungsten arc welding (GTAW) is the method formerly known as TIG welding (tungsten inert gas) or non-consumable-electrode arc-welding process. At GAS, they use the name TIG. TIG-welding is a process which consists of an electric arc maintained between a non-consumable tungsten electrode and the work-piece that is surrounded by an inactive gas i.e. the gas does not participate in a chemical reaction (Figure 8). It is the arc that melts the selected material (Svets-Kommissionen, 2016). The inactive gas maintains the arc and protects the molten metal from atmospheric contamination (Hicken & Grant, 1993). The molten joint and electrode are protected from the atmospheric oxygen and nitrogen by the shielding gas, which is usually argon and helium (Kou, 2003). A TIG process can either be manually or machined performed.

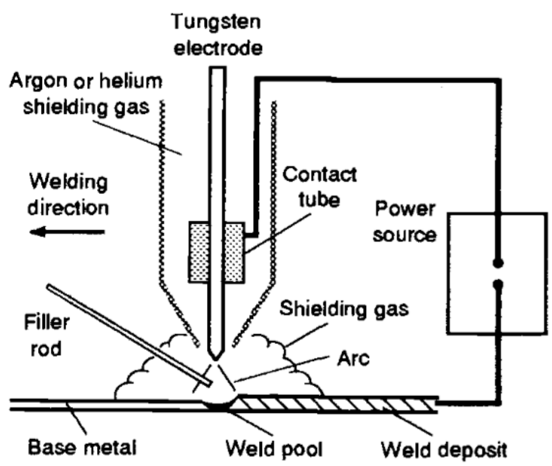

Figure 8 Key Components of GTAW Process (Hicken & Grant, 1993)

The TIG process remains of a torch that holds the tungsten electrode and feeds the shielding gas through the torch body, and is directed by a gas nozzle to protect the electrode from air (O'Brien, 1991, p. 75). The process uses one terminal of power source, either alternating current (AC) or direct current (DC). For metals which are more indigestible, such as aluminium and magnesium, AC is used as a power source, and for metals which do not emit indigestible oxides, the negative terminal of DC is used (Kou , 2003). The author also mentions the electrode tip as an important parameter for the welds' final shape. In particular, an electrode width between 60 to 120 degree is a stable choice and gives a good weld penetration according to depth-to-width ratios. They also mention welding-current as an important parameter, since it controls the welding operation, and gives a good outcome to the depth of penetration, quality of the weld, deposition rate and welding speed. The benefit of TIG is the number of different materials that can weld: primarily it is applicable to stainless steels such as aluminium, magnesium and copper (Hicken & Grant, 1993). The advantages of using TIG are: producing high quality, generally free from defects, low-distortion and the chance to precisely control the welding heat (Hicken & Grant, 1993). In the work by O'Brien (1991, p. 75), some other advantages with using TIG are presented. It allows increased control of root pass weld penetration, it can be used with or without filler wire and the machining costs are less compared to other welding methods. When high quality is required, TIG is the most commonly used welding method, since it is useable for most metals and the weld-operators have control over the heat and their vision is not obscured by fumes and smoke (Hicken & Grant, 1993).

Plasma arc welding (PAW) has been developed from the TIG method with the purpose to improve productivity by increasing the arc density and the arc speed, by being forced through a constricting nozzle (O'Brien , 1991, p. 330). The shielding gas is similar to the one used in TIG welding and is provided thought an outer gas cup (Figure 9). The orifice gas is surrounding the electrode that goes directly through the torch (O'Brien, 1991, p. 330). The arc is more concentrated in PAW than in TIG welding and less sensitive for arc length variations (Svets-Kommissionen, 2016). The PAW process is commonly applied to stainless steel in a wide range of thickness, and can also be used for carbon, aluminium alloys, copper and nickel alloys, titanium alloys, and more specialised materials such as tantalum (Harris & Ian D., 1993).

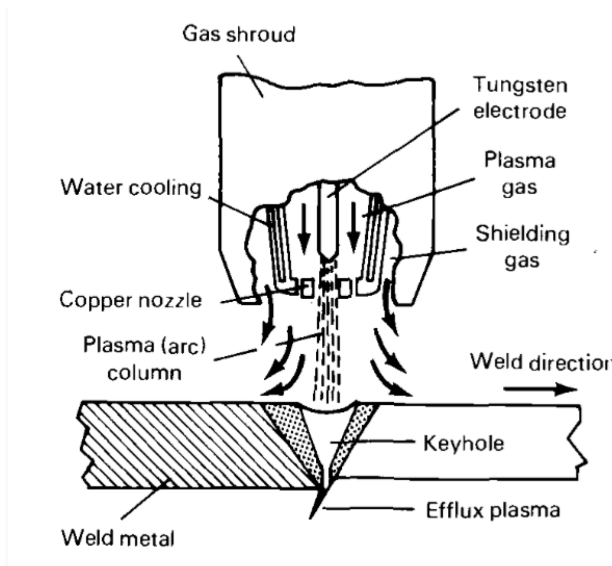

Figure 9 Plasma arc welding process (Harris & Ian D., 1993)

There are two main operating modes for PAW processes often described as the melt-in-position and the keyhole mode (Harris & Ian D, 1993). The keyhole mode has a positive impact to complete a full penetration of the weld and can use considerably higher welding speed than TIG (Kou, 2003). The melt-in-position is normally used when welding very thin materials from 0.025 – 1.5 mm, (O'Brien, 1991, p. 330). PAW process has some advantages over other arc welding methods. It has greater energy concentration, higher welding speed and heat content, and has improved arc stability. A result of these has provided PAW with greater penetration capabilities and has a stiffer arc than TIG (Connor, 1989, p. 11). A drawback with PAW is the relatively high capital cost for equipment and the need for more substantial training of operators. Moreover, plasma has been considered as a more complex welding method (O'Brien, 1991, p. 330). Even though it achieves high penetration, it also reduces the tolerance to the process to joint gaps and misalignment, compared to TIG (Kou , 2003).

3.2.2 High-Energy-Beam welding

Joining with high-energy-beam mainly refers to laser-beam and electron-beam welding. It brings many advantages in modern manufacturing due to the good quality, high precision welds and financial benefits.

Laser Beam Welding (LBW) is a process that joins and melts material by heating it with an electron beam. The nature of laser beam allows the light to be very focused on a small spot that leads to high energy density using either reflective focusing elements or lenses (Kou, 2003) and (O'Brien, 1991, p. 714). Laser is a shortening for Light Amplification by Stimulated Emission of Radiation (Mazumder & Jyoti, 1993). The laser beam occurs when the gas is reflected between the mirrors. This reflection gives the atoms a higher energy level than normally and the coherent light that reflects between the mirrors leads to light amplification, which allows the system to emit beam of laser (Figure 10) (O'Brien, 1991, p. 714).

With the high precision on a single location, the use of laser welding provides a variety of metals and alloys that can be chosen. Welding techniques can be either pulsed laser or continuous wave (CW) and pulsed laser is commonly used. Micro-welding with pulsed laser has found its way into almost all types of manufacturing industries including aerospace, consumer durables, electronics, and manufacturing (Mazumder & Jyoti, 1993). Previous tests made by Mazumder & Jyoti (1993) has shown that laser welding has high quality and high precision in materials like iron alloys, nickel alloys, and titanium alloys, which are normally considered as difficult-to-weld materials. LBW is today a competitor against Electron-Beam Welding (EBW) (Mazumder & Jyoti, 1993). The applications of laser welding are of direct interest for the aircraft industries, since welding titanium alloys are the most popular material in the specific industry and titanium is normally difficult to weld (Mazumder & Jyoti, 1993). Laser can produce narrow and deep welds with a constraint heat-affected zone[2] in high welding speeds, the through-put time is higher than other arc welding methods. Little distortion of the work-piece is also observed. It can be used for welding dissimilar parts or metals varying greatly in mass and size. (Kou , 2003). Other advantages of laser are that it can be used in room atmosphere, no electrode or filler material is required, and welds with little or no contamination can be produced (Mazumder &

[2] Heat-affected zone (HAZ) is the area of base material which is not melted and has had its microstructure and properties altered by welding (Kou, 2003).

Jyoti, 1993). In the theory, they mention some drawbacks with laser. To list some, very high reflectivity of a laser beam by the material surface is occurred, precise joint fit-up and alignment are required, and the equipment cost is significantly high (Kou, 2003).

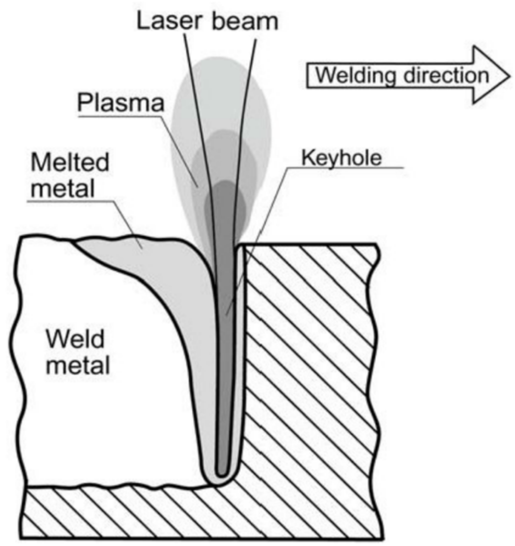

Figure 10 Penetration of Laser beam (Weman , 2012)

Electron Beam Welding (EBW) is a fusion welding process with a high energy density. This is accomplished when the welding joint is bombarded with a concentrated beam of electrodes. This energy is converted to thermal energy that is needed to melt joint (O'Brien , 1991). This method can be used in three different ways, either with a high vacuum, medium vacuum or non-vacuum and the only difference is the environmental pressure. The centre of the electron beam process is the electron gun (Olson, Siewert, Liu, & Edwards, Electron Beam Welding , 1993).

The process involves four basic variables that control the energy input to the weld joint: *Accelerating voltage, Beam current, Beam focus and Welding speed* (O'Brien , 1991). The electron beam comes from the cathode (Figure 11). The voltage between the cathode and anode accelerates the beam at a high speed and then the beam passes by the magnetic focusing coil and magnetic deflection coil towards the working piece. The magnetic focus coil reduces the diameter of the electron beam. In the theory, they state that this reduction increases producibility of small, high-intensity beam spots and lower density on the work-piece (Olson, Siewert, Liu, & Edwards, Electron Beam Welding , 1993). The result of using EBW leads to full penetration welds, ability to weld in a single pass with nearly parallel sides and a high welding speed. It also minimizes the shrinkage and distortion from the welding operation (O'Brien , 1991).

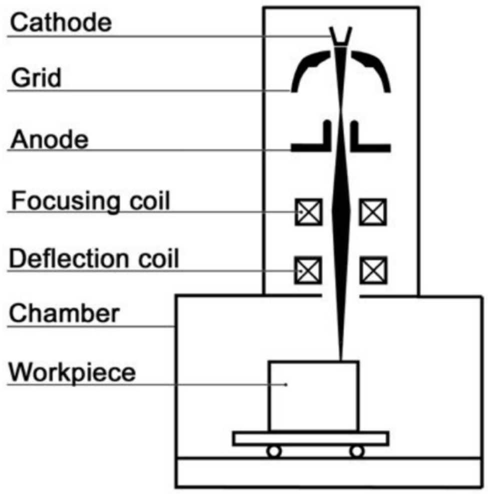

Figure 11 Electron beam welding (Weman , 2012)

3.2.3 Weld Quality

In the theory, the term "*weld discontinuities*" is used to explain the influencing factors of physical structure of the weld. The factors are referred to as weld defects. When weld defects are found, they need to be reworked, since it affects the weld's life length and consequently that will affect the life of a product. In the theory, the concept Fitness-for-service is also used in order to equilibrate the weld according to quality, reliability, and cost of welding procedure. Critical engineering assessments of the weld quality are performed to define acceptable, harmless discontinuities in a systematic way that will not influence the weld reliability negatively. Discontinuities can be divided into three categories: design-related, welding-process related and metallurgical discontinuities (Gordon & Robin, 1993).

Geometric weld discontinuities are those welds with unacceptable shape, like undercut, underfill or overlap. Undercut is "*a groove metal into the base metal adjacent to the toe or root of a weld and is left unfilled by weld metal*". Underfill is a groove weld condition in which the weld face or root surface expands below the adjacent surface of the base metal. Overlap is "*the protrusion of weld metal beyond the toe, face, or root of the weld*" (Kou, 2003) (Gordon & Robin, 1993, p. 1073).

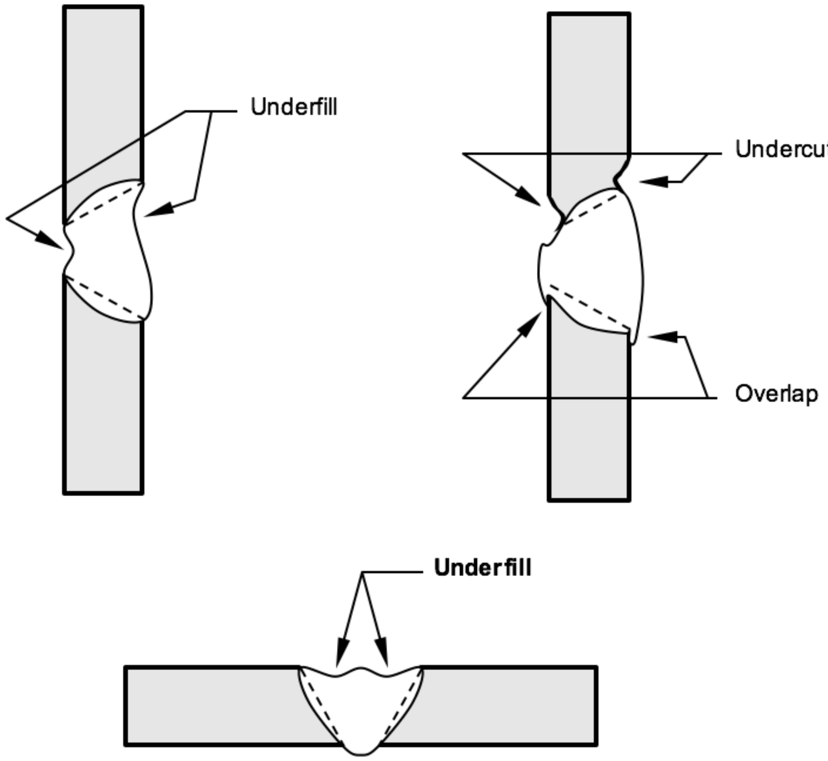

Figure 12 Geometric Weld Discontinuities (Internal Document)

Porosity occurs under the surface of the weld and defects are formed by gas entrapment during solidification. Pores are modified by a rounded or elongated teardrop shape whit or without a sharp point. They are caused by gas entrapment in the molten material by insufficient cleaning preparation or too much moister on the base or filler material (Gordon & Robin, 1993).

Cracks "*can appear in a wide range of shapes and types and can be localised in numerous positions in and around the welded joint*" (Gordon & Robin, 1993, p. 1075).

Shrinkage affects the products' final shape, normally when the material is heated up the solidification step and the heat increases the material and when it cools down the material is decreased. It gives the parts a slightly u-shape.

Tungsten inclusion is the defect that is created by the non-consumable tungsten electrode used during GTAW. To be more specific, tungsten inclusion is when participles from the electrode are found in the weld metal. This is not an acceptable defect, especially for high-quality work. The only way to find it is by internal inspection techniques (Gordon & Robin, 1993).

Lack of fusion and lack of penetration happens when incorrect welding conditions are used and from improper electrode manipulation. Fusion is when the original material surface is fused with filler material. Lack of fusion is caused by excessive travel speed, insufficient current and joint angle. Penetration is referred to the deepness of the weld through the material and lack of penetration can depend on excessive travel speed, low weld current or surface contamination (Gordon & Robin, 1993).

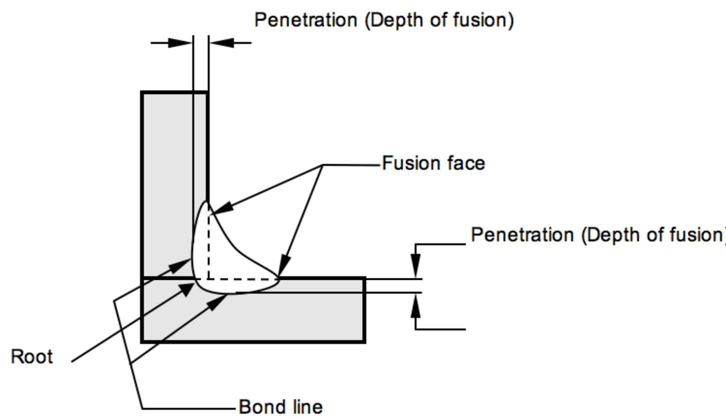

Figure 13 Fusion and Penetration (Internal Document)

3.2.4 Inspection Methods

The need to assure that the produced parts meet the quality standards that have been set during the design phase from the development team as well as the customer is covered by different inspection methods. The inspection methods that do not actually cause any damage to the inspected part are called Non-Destructive Testing (NDT). Examples of NDT are the radiographic (X-rays), the ultrasonic, the liquid penetrant (FPI), the magnetic-particle, the remote visual inspection (RVI) and the low coherence interferometry (Prakash, 2011).

FPI (Fluorescent Penetrant Inspection) is a low cost and simple NDT Method that is used widely in many different industries. As shown at the picture below, FPI is a type of liquid penetrant inspection that a fluorescent dye is applied to a non-porous surface (Wikipedia, 2013).

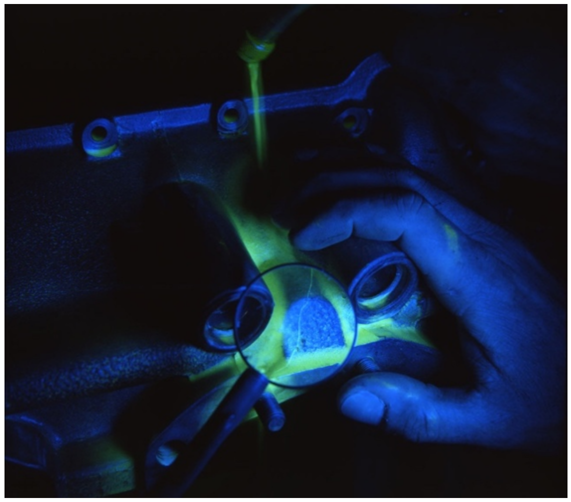

Figure 14 FPI inspection method (http://www.victor-aviation.com/index.php)

Inspections are done in order to make sure that the welding result fulfils the acceptance criteria that are set during the design. These are shown on the drawings of the parts. Not all the parts of a product have the same criteria of acceptance when it comes to welding. For instance, at GAS, for groove welds, there are three different classes that define the requirements for weld dimensions. Class A represents high, Class B represents medium and Class C represents generous requirements for weld dimensions. That means that the critical characteristics are Class A, and the less critical have lower class welds (Internal Documents).

Depending on the different method, the outcome of the weld will distinguish them from each other. There are certain specialised welding methods that may have more discontinuities unique to them, like electron-beam and plasma arc welding.

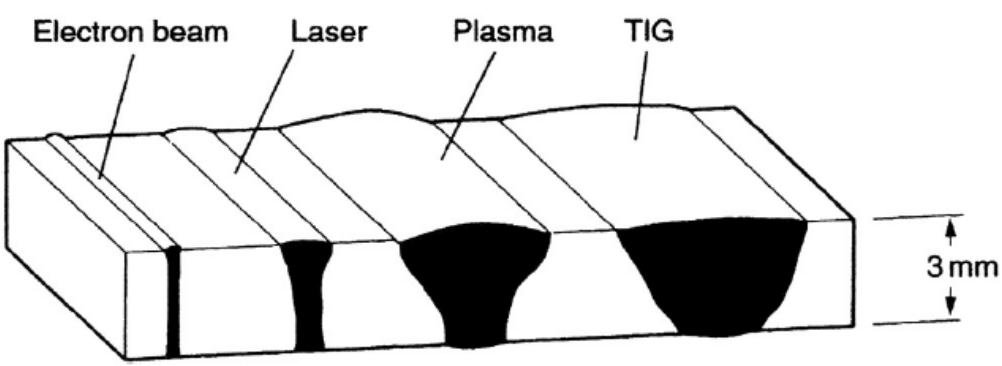

Figure 15 Penetration Profile for the different welding methods (Weman , 2012)

The following table summarises the different welding methods, the material that can be welded and the minimum and maximum thickness of the welded material. This knowledge is acquired from theory. The fact that different handbooks have slightly different information included is an interesting observation for the master thesis students. More tables can be found in Appendices.

Table 1 Summary of Fusion Welding Processes (Olson et al., 1993)

Method	Material	Thickness min	Thickness max	Fusion zone profile
GTAW	All engineering metals except Zn and Be and their alloys	1 mm (0.13 mm min thickness, joint prep. over 3.2 mm)	6 mm	Shallow for single pass
PAW	All engineering metals except Zn and Be and their alloys	(0.13 mm min thickness, joint prep. over 6.4 mm)	Usually up to approx. 1.5 mm	Shallow at low energy end. Deep penetration at high energy end
LBW	All metals except where excessive gas evolution and (or) vaporization occurs	2mm	Up to 10 mm	Shallow at low energy density range. Deep penetration at high energy density range
EBW	All metals except where excessive gas evolution and (or) vaporization occurs	0.5mm	Up to approx. 25 mm normally but may go to 100 mm	Deep penetration

3.3 Robust Design Methodology

Robust design is a systematic effort to achieve insensitivity to noise factors. These efforts are founded on awareness of variation and can be applied in all stages of the product design (Gremyr & Arvidsson, 2008). The history of robust design methodology started when Taguchi first introduced parameter design, which claims that system prototypes are made insensitive to different kinds of noise factors (Taguchi, 1986). According to Arvidsson and Gremyr (2009), Taguchi (1986) proposed a three-step strategy for the development of products. The steps are the system design, the parameter design and tolerance design, with an emphasis on the use of experimental methods in the latter two steps.

Briefly, the system design is the stage in which different concepts and choices of technology are considered at different levels, system and component level. The parameter design is the stage in which the appropriate levels of individual systems parameters are decided. In the tolerance design, the tolerances are set in a way that further minimises the noise. The tolerances of the factors with the greatest influence to the output are narrower. Taguchi (1986) emphasises, however, that this is not the most efficient way to reduce variation caused by noise and that it should be seen as a last resort after parameter design (Arvidsson & Gremyr, 2009).

Full insensitivity to noise factors is not possible in a realistic system, that is why the goal is first to understand variation and the sources of variation. Understanding variation is an important aspect of managing the product design process and it is emphasised by Shewhart (1931, 1939) and later by Deming (1986, 1993). More specifically, understanding variation is an important aspect of engineering knowledge. Sources of variation, also known as noise factors, are not always unwanted. That happens because we want a product to be successful in different environments and for different customer categories (Bergman & Klefsjö, 2010). Driven from the above, it could be stated that "*the objective of robust design methodology is to create insensitivity to existing sources of variation without eliminations of these sources*." (Bergman , de Maré, Lorén , & Svensson , 2009). When designing a system or a product, the need to think about different sources of variation in the concept stage of the product development appears (Bergman & Klefsjö, 2010).

In order for the product design to be considered robust, reliability term needs to be considered, which is the ability of a product to provide the desired and promised function to the customer or user. If the product is not reliable, then it cannot be considered as robust (Bergman , de Maré, Lorén , & Svensson , 2009).

P- Diagram is a visual tool that explains the factors that affect the output of a process (P stands for Product/ Process). It is an illustration of the influence from different factors on the system output (Bergman & Klefsjö, 2010). It includes the functions of signal factors, the design parameters (often denoted as control factors) and the noise factors (also denoted as transfer functions). P-Diagram is an important tool for this thesis, because the mind-set of this work is focused on a process perspective, which is facilitated by the use of P-diagram thinking (Figure 16). This tool is also used, as will be mentioned, in the conceptual framework that was developed by this thesis supervisor, Julia Madrid (2015).

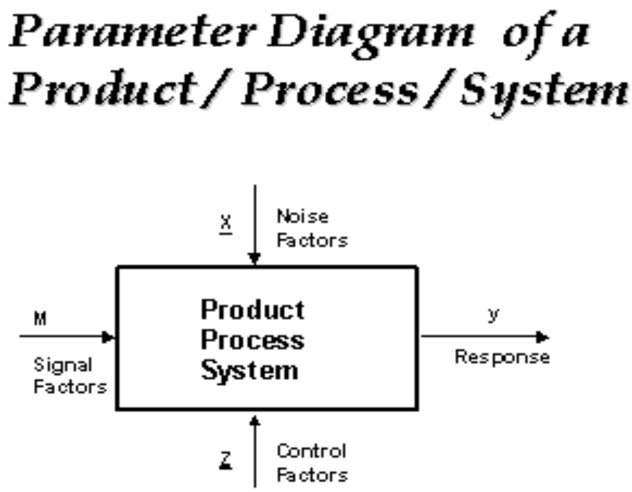

Figure 16 P-diagram illustration, how inputs affect the output of the system (Bergman & Klefsjö, 2010)

A summary of principles of the robust design methodology is following (Bergman & Klefsjö, 2010).

- Variation and noise factors are decisive in how the system meets the customer's needs and wants.
- The sensitivity to noise variation is determined by the design and design parameters.
- The way noise factors seem to affect the system is determined in every stage of the system, but the sooner actions are taken, the more effective they are for the system.

3.4 Conceptual framework

The framework named as "*Conceptual framework to assess producibility for fabricated aerospace components*" is a systematic way of thinking when it comes to manufacturing processes. The framework represents how the quality is build-up during different fabrication processes. The holistic view behind the framework is to increase the mind-set of a manufacturing method and how this can be used in future projects to improve quality of the outcome. The drawbacks of using fabrication processes are that they increase the variation on the part because of the step-by-step processing in terms of geometrical variation which effects the quality outcome, however it increases the design freedom. To be able to introduce fabricated design variants, the organisation needs to have a platform strategy for efficiency and to stay competitive on the market. Platform thinking establishes the basic architecture of several products where knowledge and technology are reused. Development of high quality products with large complexity requires a systematic approach. The model increases the understanding on different variation factors that affect the output of the product characteristics (Madrid et al., 2015).

The framework has been developed from several quality tools and theory of systematic thinking. Systematic thinking, or the ability to view things holistically, and see how the various integral parts affect one another is an important element for successful quality improvements (Bergman & Klefsjö, 2010). The conceptual framework has been tested in one organisation using welding as a fabrication process and since it argues for the systematic way of thinking in practice, it should be possible to apply it to any manufacturing process (Madrid et al., 2015). The conceptual framework is comparable to the P-diagram and Cause-and-effect diagram. The model illustrates a transformation process "the box" with different factors as input, influencing the output of the process, control factors and noise factors.

Design and manufacturing teams can control the input, the control factors to some extent and predict the output. On the other hand, noise factors are difficult or expensive to control. By using robust design thinking noise can be minimised. The big *Q* and the little *q* in the model represent controllable design characteristics and uncontrollable parameters. The big *Q* possesses properties that have an important impact on product performance requirement, in contrast, the little *q* gradually affects the product stepwise through the transformation process. The big *Q* is defined as "*those product characteristics that are transformed and that deliver the final quality to the customer"* and the little *q* is defined as "*those parameters that from a manufacturing point of view have an impact in the quality of the manufacturing process"* (Madrid et al., 2015, p. 5).

The model gives an abstract view of how variations are build up through the different process steps (Figure 17). By understanding the variations that exist, the comparison between design concept and producibility is facilitated. In the design phase, they need more information about what cause variation and effect quality if designers can control or minimize variation during construction by using simulations. The design teams can keep cost to a minimum before it reaches the production stage, where it is expensive to make changes regarding producibility (Madrid et al., 2015).

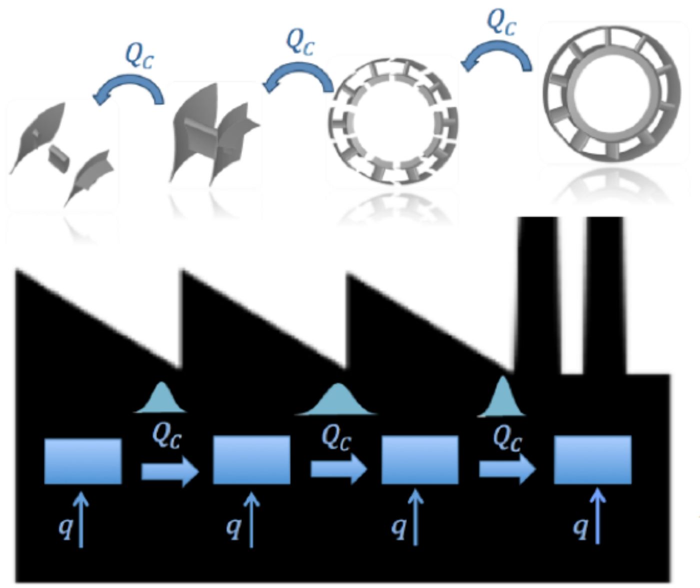

Figure 17 Conceptual framework to assess producibility for fabricated aerospace components (Madrid et al., 2015)

3.5 Design for Manufacturability

Good design practice is a key to success (Carter, 1997). In order to meet customer needs and attain customer satisfaction by designing and manufacturing a quality product and at the same time, improve business performance, the levels of non-conformances and failure costs need to be reduced. Failure costs include rework, scrap, warranty claims, product liability claims and recall (Swift K., 1999).

The development of new products consists of different steps, from the need to the manufacturing of the product that will meet that need. A lot of theories have been developed looking into the product development process. Design for Manufacturability (DFM) is a recommended strategy to follow, which helps companies to create products that can actually be manufactured. It is connected to a methodology that as Jakubowski et al. (2014) mentioned, involves engineers designing with the intention to minimise the production cost and time-to-market without compromising the quality of the produced product. The process of manufacturing and production planning begins when the design is finished. In order to reach a high quality, manufacturable product at a low cost, designers and manufacturers must work cross-functionally (Vallhagen et al., 2013).

"*Selecting the right process and optimising the design to suit the process selected involves a series of decisions which exert considerable influence on the quality and cost of components and assemblies*." (Swift & Booker, 1998, p. 17). A factor to consider when choosing a process can be the maturity of the company's processes. Using Capability Maturity Model (CMM) can lead to a better understanding of the potential strength and weaknesses of the company's processes. To be specific, capability maturity model can help us understand how mature the methods in the company are and at what level they are. i.e. if they are structured and documented, if they are repeatable with consistent results, if they can be managed and adapted to particular projects, if they focus on continually improving process performance through incremental and innovative technological changes or improvements (Wikipedia , 2016).

In products with complex geometry, it is important to investigate the possible risks and difficulties in an early design stage by taking into consideration the manufacturing ability of the designed product (Jakubowski & Peterka , 2014). The level of complexity of products and their components requires scrupulous management in all aspects of the life cycle, and materials are of great importance. Decision making covers different areas and adapts to the life cycle model. A process of reflection is suggested to be used in order to conclude the interrelations of the areas of selection and gain competitive advantage. Decisions can be clustered in three categories, technical, economic and strategic (Albiñana & Vila, 2012).

The technical decisions are the main part of engineering processes and design. There comes the high importance of companies having an efficient system of knowledge management. If technical decisions get combined with economic ones, then the result can be creative, reliable, repeatable and have a short time accessing the market, which are all indicators that raise value of the companies. Finally, through the strategic decisions, the resources for managing the life cycle of the product will be provided (Albiñana & Vila, 2012).

There is a need to rely on a systematic procedure in order to understand the design requirements and fulfil them, because design requirements affect the material when the design is in a phase with a lack of detail or specificity (conceptual design phase). So, the material, the design and the manufacturing process should be chosen by considering many future- vital for quality- criteria (Albiñana & Vila, 2012).

The sooner manufacturing problems are resolved, in the design stage, the lower the cost and the impact to quality, according to Jakubowski & Peterka (2014). As the same source mentioned, by addressing at an early design stage the possible risks can have a great impact on time of delivery and quality of product. There are some design principles that help at the designing phase, so the cost can be reduced and the manufacturing of the product can be easier. Listed by Jakubowski et al. (2014), the rules are: reduce the total number of parts, develop a modular design, use of standard components, design part to be multi-functional, design parts for multi-use, design for ease of fabrication, avoid separate fasteners, minimise assembly direction, maximise compliance, minimise handling. It is believed from the same source that DFM supports a proactive approach of designing products in order to optimise all manufacturing functions (fabrication, assembly, test procurement, shipping, delivery, service, repair) and assure the best possible cost, quality, reliability, regulatory compliance, safety, time to market and customer satisfaction. According to Jakubowski & Peterka (2014), DFM supports the simplification of the product structure.

Design methodologies for manufacturability and assembly reduce the total number of parts and that improves the cost, the reliability and quality of the final product, since it has fewer components. Incompatibility between the chosen material and the manufacturing process that the material will go through can affect decisions made during the design phase about geometry of the product (Albiñana & Vila, 2012).

A technique called "Conformability analysis" (CA) is proposed by Swift et al. (1999), to help the prediction of potential process capability problems when products are manufactured and assembled. CA can be used to evaluate the alternative designs and concepts by project teams or by individuals. Through CA, the problematic areas of the design are highlighted and the failure cost of each design can be calculated. A framework like this is useful, since the connection between a product design and its production quality is complex and cannot be easily amenable to accurate scientific formulation (Swift K., 1999). The framework consists of three main phases, component manufacturing risks analysis, component assembly risk analysis, effects of non-conformance. CA should take place before the detailed design completion and after the concept design start. By communicating the process capability requirements for component characteristics that will occur from CA, the supplier development process can be supported and the supplier will be able to provide validation that the chosen parts will meet the capability requirements (Swift K., 1999).

3.6 Capabilities and Knowledge Management

Improvement of process capabilities requires constant work with continuous improvements according to Slack and Lewis (2015). The two authors emphasise that continuous improvements happen when employees interact between processes, on how to use resources and how to be managed. It is the humans that learn and become better at interacting and handling resources and processes that lead to capability development. The more they learn and understand how to design and run processes and the complexity between them, the better they become at improving operation capabilities. This is a central part of process knowledge. Knowledge does not have one universal definition and have been defined differently between authors as: "*facts, information and skills acquired through experience or education; the theoretical or practical understanding of a subject*" (Slack & Lewis, p. 248). KPMG (1998) defines knowledge as "*business information about customer, processes, products and competitors*", they also state that knowledge can be articulated, through documents, templates, best practices and frameworks.

The theory states that the view of knowledge management has changed in the perspective that knowledge belongs to the whole organisation, attention must be paid to the knowledge that comes from the blue-collar workers as well. That will lead to actually improving knowledge and increasing productivity so that people will not have to "re-invent the wheel" with every project that begins (Slack & Lewis). Identifying and transferring knowledge through the organisation is well-known to be important. Consequently, it is hard to carry out, due to personnel's own difficulty to process knowledge obtained (Shin et al., 2001). This relates to the users' own access to knowledge, frame of reference and cognitive ability. Hu et al, (1998) argues that the quality of information that individuals transfer into the organisation is crucial, and how they sort out valuable and less valuable knowledge is equally important. Shin et al, (2001) also stresses that knowledge location matters when distributing information between providers and seekers. Normally, individuals are not aware that the information they are seeking for already exists.

3.6.1 Tacit and Explicit Knowledge

Nonaka and Takeuchi (1995) invented the most influential theory about knowledge management; what these two authors did was to divide knowledge into two different kinds, tacit and explicit knowledge. Tacit knowledge is the knowledge that exists in people's heads, which is hard to share with others since it is not documented or externalised. It is the know-how, the mental models, beliefs, perceptions that are not easily visible or expressible. On the other hand, the explicit knowledge is easy to communicate to others, since it is uttered in a defined form and transmitted in formal, organised language. According to Polanyi (1966, 1969), explicit knowledge is always based on tacit knowledge but it is formal and systematic and it is expressed in words and numbers. He also argues that tacit knowledge cannot be written down in a formal language, and be converted to explicit knowledge. More authors share his opinion, for instance, D'Eredita and Barretto (2006), Gourlay (2006), and Ribeiro and Collins (2007). In organisational learning, tacit and explicit knowledge should not be seen as two different characteristics since they compliment each other, and when personnel are learning new tasks their tacit knowledge succeeds their explicit knowledge (Nonaka & Krogh, 2009).

A good visualisation of the conversion of knowledge has been created in the form of a model that is called SECI (Socialisation, Externalisation, Combination, Internalisation). That model was created by Nonaka & Takeuchi (1995). The model is used, given the fact that the imperative need for organisational knowledge creation is known.

Externalisation is what happens when tacit knowledge transforms into explicit knowledge. It is an important step in order to expand knowledge beyond what a single individual knows (Nonaka & Krogh, 2009). Explicit knowledge is easy to share at low cost between two or more individuals and this is called internalisation. It is the stage when through actions, practice and reflections, explicit becomes tacit (Nonaka & Krogh, 2009). Socialisation is the way to circulate tacit knowledge through learning to engage in social activities, like discussions, seminars, participation in social practices under the guidance of people who are more experienced on a topic, or even shadowing, which means to follow someone and learn from what they do (Nonaka & Krogh, 2009). Combination is the knowledge conversion from a type of explicit knowledge to the other, for example the use of databases. The result is the creation of new knowledge that could and should be further communicated (Nonaka & Krogh, 2009).

Table 2 Four Modes of Knowledge Conversion (Nonaka & Takeuchi, 1995)

From/ To	Tacit Knowledge	Explicit Knowledge
Tacit Knowledge	Socialisation	Externalisation
Explicit Knowledge	Internalisation	Combination

3.6.2 Managing Lessons-Learnt

When employees finish projects, the learning they gain will follow them into the next project. These new experiences will only be reached through personal networking. Organisations want to avoid this situation, since the risks of losing knowledge become larger. That is an outcome of people not being able to document and externalise their tacit knowledge, or perhaps sometimes choose what is important to transfer and what is not with subjective criteria. This knowledge is also referred to as lessons-learnt. Lessons-learnt are defined as "*Key project experiences which have a certain general business relevance for future projects"* (Schindler & Eppler, 2003). Knowledge engineering is a methodology that supports the creation of knowledge-based systems and enables reuse of results from earlier projects. It can support engineering design in early stages, by referring to lessons-learnt (Jakubowski & Peterka , 2014).

Frank A. Gulliver also published a method to learn from experience called *Post-Project Appraisal.* This model aims to review the project and examine lessons that can be useful in future projects. This model is also referred to as post-project review and is widely recommended to identify this type of gained knowledge (lessons-learnt) (Goffin et al., 2010). Schindler and Eppler (2003) argue that learning from projects is too important to be left to chance. Williams (2008) believes it is more important to implement critical awareness of learning than following techniques. In the post-project review, team members are sharing knowledge through stories and metaphors to describe their tacit knowledge, leading to deeper level of understanding. Goffin et al, (2010) stress that stories and metaphors help explaining situations that couldn't be articulated. It is the manager's task to understand the stories and take out key points to write down in useful documents as a best practice. In William's (2008) article, it can be read that employees feel like they learn more from post-project review than from formal documentations. But there is no argument that both documentation and human participation and discussions are equally important means to keep the knowledge going from one project to another in an organisation.

4. Results

The findings of this master thesis will be presented in this chapter. The data collection was conducted from internal documents, observation and interviewing personnel at GAS as well as the literature study. The combination of the previously mentioned data collection sources and the structure of all the data constitute the results of this thesis work in a form of a generic flowchart.

From the theory Nonaka and Krogh (2009) stressed that, when developing new projects, employees' tacit knowledge succeeds their explicit knowledge. This also happened when developing the sector. The knowledge the employees had from previous project was taken into account, and any changes that occurred were based on tests. The results that came out from testing different settings were used as a base for negotiations about the different dimensions of the sector. This can be one reason why the involved departments are now sharing the same perspective of critical characteristics, since the result of the sector came from compromises between product and production development and manufacturing, on the contrary to projects that GAS has currently been involved in. During previous projects, the manufacturing perspective was taken into account in a later phase of the project. More specifically, when it was time to start producing and changing at those phases are apparently costlier. That also led to delays and reactive decisions. Driven from all these concerns, the need to create a structured sequence of steps that will complement the decisions made, derived or not from the production platform of Turbine Rear Case product, emerged.

4.1 Flowchart for lessons-learnt management

The thesis students have created a flowchart (Figure 18) that describes the decision making process and identifies the steps where lessons-learnt should be generated and documented. The effort was to include the different stakeholders' perspectives, as has been occurred by interviews and observations. In this flowchart, the product development process is presented in a vertical sequence of steps, without excluding the feedback loops that are suggested to transpire. The feedback loops and connection lines suggest that this is an iterative process between different departments. To be more specific, the red lines in Figure 18 illustrate the overall strategy of the company, the cost considerations and the politics (4.2) that affect the decisions made in different steps of the process. The blue lines illustrate the connections of the documentation to a generic knowledge database (4.6) that is connected to the conceptual design step.

For the creation of this sequence, standard shapes of flowcharting have been used in order to depict the processes and the decision steps in a more globally understood way. The flowchart identifies the areas that documented knowledge is missing. Each step of the flowchart will be analysed in the following chapters, as indicated in the step boxes.

When planning a project for product development, the involved multidisciplinary teams should communicate in an effective way. Those teams are often geographically separated and it is necessary to maintain a structured decision-making. Since during the concept creation, the decisions made are not very detailed (Albiñana & Vila, 2012), but can affect the future product development, the flowchart for lessons-learnt management can assist the decision-making procedure and the documentation management so that the ideas can be visualised for everyone. The flowchart for lessons-learnt management highlights the vitality of including the obtained knowledge from the creation of a new product in a structured way and makes the lessons-learnt available for use to future developments and revisions.

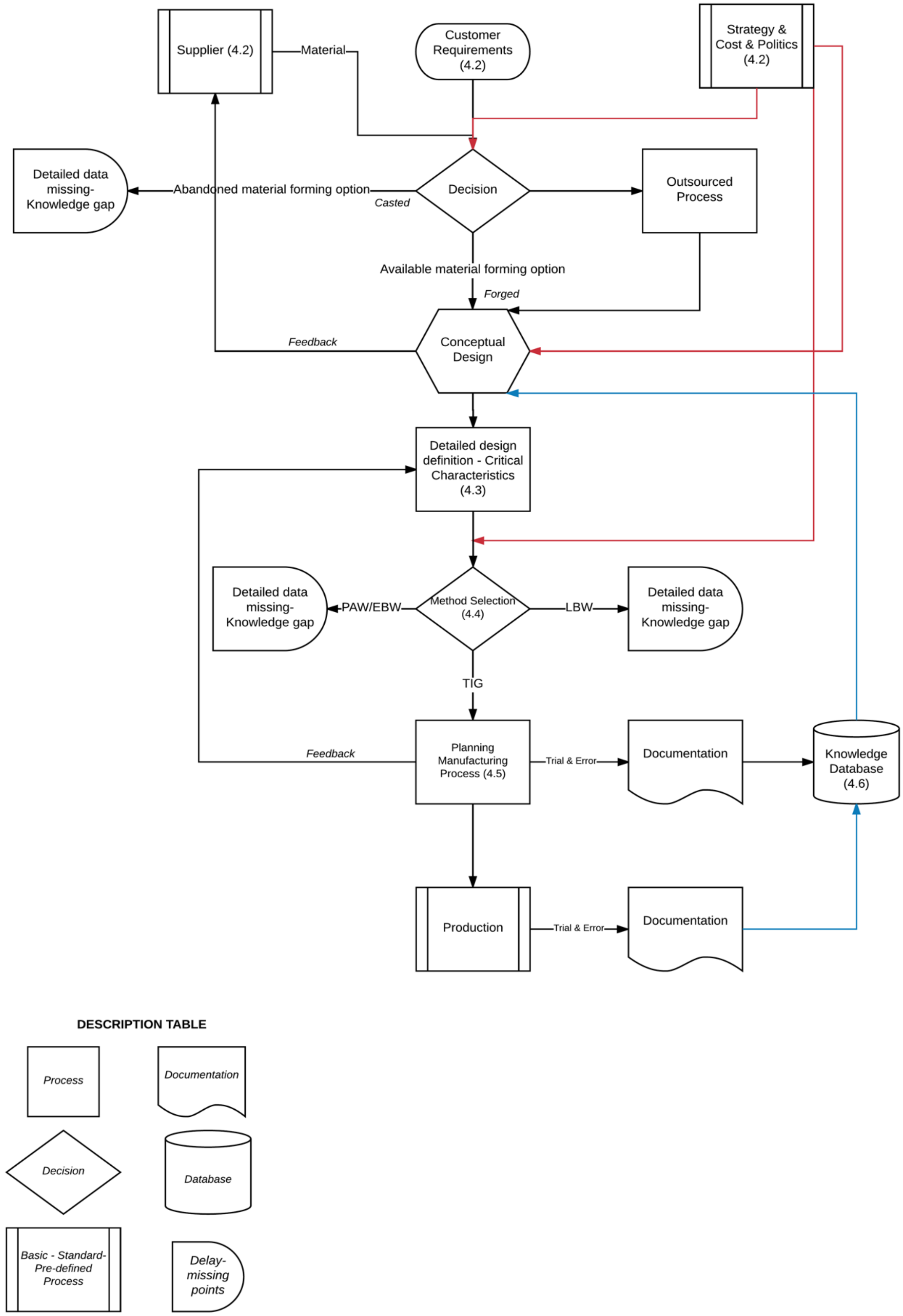

Figure 18 Suggested project development structured decision-making

4.2 Strategy, customers, suppliers and conceptual design

Including the strategy, customers and suppliers into the decision making process of the company's project development is an attempt to integrate management into the manufacturing capabilities and manufacturing processes. These different departments and stakeholders affect the conceptual design of the products and define the product in a low-detailed level at this point.

4.2.1 Strategic capability

Every made choice needs to follow the company's strategy. If some choice sounds good but is not preferred, there is a reason why the company chooses the alternative. Cost is an important factor that defines most of the choices. As mentioned, manufacturing can manufacture almost everything, but the cost is a crucial restriction that needs to be thought through. Additionally, if the company's strategy has endorsed manufacturing processes such as fabrication against casting, it is wiser to follow it for the overall benefit of the products.

What is understood by the company's strategy is that a platform thinking is introduced, so most of the developed products should be a part of this platform for all the advantages that a platform offers. That extends to similarity of parts, but also similarity on the production methods. Another strategic and cost related choice is to make the majority of parts in-house and use less outsourcing. That will add value inside the company, the cost is reduced and the company has a better control over the produced parts. The avoidance of outsourcing gives automatically the advantage of proximity, so if something needs extra adjustment or rework, the machines will not be at a different site or country. That can explain, for instance, the fact that they currently outsource just the vane of the H-sector.

What is more, it is useful for the company as a whole to clarify and make known the responsibilities of each department. If the different departments have a clear picture of not only theirs but also the other departments' responsibilities, it will be easier to address any issue to the appropriate department and handle the situation with the help of the experts.

4.2.2 Customer

As far as the customer is concerned, interviews taught the students that customers might change the "requirements" frequently during the product design process. In addition to this fact, the design department cooperates closely with the customers and depending the needs and the details or the dimensions of the product, they suggest designs to customers. These facts make clear the need for the design to plan ahead and design in less detail at the beginning of the process, but also, to have a good understanding of what can be produced and what the capability of the company is at the current point. If these qualifications are met from the design department, the company will not just accept the customer suggestions without knowing if it is manufacturable at a specific cost. All in all, there is a need to adapt customer requirements to the production strategy.

4.2.3 Supplier

When deciding and designing the manufacturing processes, the company should take into account the customers, for the above mentioned reasons, but also the suppliers, who are equally important with the customers. To be more specific, the company's suppliers must be trustworthy, perhaps have the same producing philosophy with GAS and also, be the most "value-for-money" choice that is able to adapt to the parts' correct tolerances.

It is a fact that when the production runs out of materials (raw materials, shielding gas, filler material), the cost is increased. Therefore, the choice of the proper suppliers, and preferably multiple suppliers, is important for the actual function of the production. It is the students' belief that the suppliers should be partly included in the design and production processes, because they indirectly affect the outcome and support the product development procedure, and a closer cooperation could result in a better control of the process and the design choices.

It would be preferable if the supplier could also adopt a robust, three-point target system for the incoming parts, so that the robust result and the best fit could be reached.

4.2.4 Conceptual Design

The design is an important step of the product development, since the characteristics of the product, the drawings and the conditions for a robust target system are created at this stage. Also, the geometries, the weld interfaces, the materials, everything that will play a role at a later stage is decided here. The aim is to bring the knowledge from manufacturing earlier on the system by feedback and documentation and integrate it in the design.

The cooperation of the design department with customers and suppliers should be a close one. Design is supposed to have a close cooperation with the customers, with the suppliers, but the most durable one is with the manufacturing. Design and manufacturing should be merged not only by having a good communication and feedback though, but also by being co-located and have the discussions together and raise arguments for different decisions simultaneously.

After the general characteristics of the products are designed and decided, the knowledge of the process in general and more specifically welding capabilities of the company will be of use. The sequence of the processes, the processes and the process characteristics will be based on that knowledge. Decisions must be made and the manufacturing involvement is vital.

The lessons-learnt from the design perspective are the ones that fulfil the customer requirements, are able to be met by the supplier and follow the company's strategy and goals. Since the material is chosen and the method is implied by the material's choice and the technology maturity, then the manufacturing process parameters are decided. An important factor that affects the decision of the method choice is the capacity of the available machines in the company as well. Functions such as aerodynamics, stress sturdiness and weight requirements must be met according to the customers' needs.

In detail, when looking at the H-sector of the specific product, the stress should be led away from the highly loaded areas, in particular the leading edge, thicker material should not be designed close to the weld interfaces in order to avoid the risk of heat sinking, and the position of the inner and outer stand-up should be parallel in all three directions, in order to avoid twisting after the welding process. Given the design needs and the welding capabilities, the manufacturing takes over and uses the lessons-learnt.

4.3 Sector's critical characteristics

According to literature, the product development and the planning of the production are two parallel actions. That means that cross-functional work is important because it will help the integration of manufacturing aspects from concept development to the detailed design. That is a safe way to check if the production goals are met. The product performance is strongly related to the process capabilities (Vallhagen et al., 2013).

For that reason, the research team interviewed experts from the design department who focus more on the functionality of the product, but also, experts from the manufacturing department who deal with the manufacturability and producibility of the designed product. The first step for the research team was to ask the experts from both sides which are the most critical characteristics of the H-Sector at the specific TRC. Critical characteristics must be identified in order to choose the appropriate strategy to control and improve the outcome of the process (Bergman et al., 2009). Both design and manufacturing agreed on the critical characteristics, which are the thickness of the vane, the width of the vane, the radius of the vane at the leading edge and the height of the stand-up (the position of the horizontal welds). The height of the stand-up can differ between the inner and outer component. The vanes do not have the same thickness since their functions differ as described in theory.

The following table (Table 3) helps to visualise the above-mentioned data and to compare the functional perspective with the manufacturing perspective for each critical characteristic. It also includes the current values of those characteristics. The current values occur by trading-off the functionality needs and the manufacturing needs. When the arrow is upwards, it means that the value should be as high as possible and when the arrow is downwards, it means that the value should be as low as possible. In case of a circle, the value does not affect the specific area of consideration.

Table 3 Critical Characteristics from Design & Manufacturing Perspective, Current Values

			Areas of consideration/ Functional Perspective			
	Critical Characteristics	Current Value	Aero	Stress	Weight	Manufacturing
Vane	Thickness, T_{vane}	$T_{vane} = X_1$mm	o	↑ close to the welds ↓ in the middle	↓	determines the choice of welding method
		$T_{vane} = X_2$mm	o	↑ close to the welds ↓ in the middle	↓	determines the choice of welding method
	Width, W_{vane}	$W_{vane} = X_3$ mm	↓	o	o	↑
	Radius, $R_{L.E.vane}$	$R_{L.E.vane} = X_4$mm	↓	↑	o	↑
Stand-up	Height, H_{case}	$H_{case} = X_5$mm	o	↓	↓	↑
	Height, H_{hub}	$H_{hub} = X_5$mm	o	↓	↓	↑

Moving from the design to the manufacturing perspective, it is obvious that there are important trade-offs compared to the functionality areas of consideration. The current values of the characteristics have been chosen by combining the customer needs, the functional perspective and the manufacturability of it. The on-going project has been a good example of cross-functional work between different departments and that brings the output a step closer to the ideal combination of design and manufacturing sides.

Starting with the design perspective, there are three main areas of consideration when designing the component of the TRC. The aerodynamic, the stress and the weight of the product. The behaviour of each critical characteristic was defined in order to facilitate the purpose of the area. From the aerodynamics' point of view, the thickness of the vane and the height of stand-up do not affect the outcome. The thickness does not affect the air flow and the position of the horizontal welds at the point where the stand-up is joined with the vane are parallel to the airflow, so the height is indifferent from that perspective. However, the width and the radius of the vane should be as low values as possible. The justification is that the sharper the vane, the more aerodynamic result will occur. If the vane is too wide, the pressure loss will be increased and that will have an impact on the performance of the engine.

Moving on to stress and especially mechanical loads, the results show that the width of the vane does not interfere with the functionality of the part. The thickness of the vane is directly related to the stresses. The ideal thickness should be of higher value close to the sensitive area where the welds are, but lower value when moving away from the welds. Stress-wise, the value of the vane width does not affect the outcome. The radius of the vane in combination with the thickness at the leading edge makes the assembly more stable and the welding result more robust, so the radius' value should be as high as possible. The stress will decrease with a larger radius.

From a weight perspective, it is logically assumed that the thinner the vane is, the less the sector will weight. Additionally, the sheet metal is lighter than the forged metal of the outer and inner part of the H-sector. The vane is made by sheet metal. That explains why the height of stand-ups should be as short as possible, so that the sheet material will be more and the total weight will be reduced. The width of the vane and the radius of the leading edge are two critical characteristics assumed not to affect the weight of the H-Sector.

The discussion of the data collected from the manufacturing perspective about the key characteristics of the H-Sector is following. To begin with, the thickness of the vane defines the welding method that can be used, while the radius and the width of the vane defines if the welding is going to be robust single pass. It is preferable to have a wider vane as possible so that the transition from one side to the other to be smoother and at the same time, without having starts and stops at the leading edge, which is the most critical and highly loaded part of the vane. The width of the vane is also important for inspection reasons. If FPI is possible with the given width, then less cracks will be assumed during the grown analysis or when doing the simulations and a more realistic scenario will be calculated.

The radius of the vane, as explained, cannot be narrow in order to allow good welding torch movement and assure a complete weld pass. Another reason is that if the vane is narrow, there is a lot of heat concentration at the same points and that affects the microstructure of the material. The stand-up height has to be enough to meet the manufacturing needs for accessibility and producibility. In that case, the heat of the operation will not cause any tilting or bending on the inner and outer part of the H-Sector. The weld torch should preferably be perpendicular to the work piece. As a consequence, the higher the stand-up, the better the accessibility of the welding equipment.

4.4 Welding methods characteristics

At this point, it is necessary to present the data that the company has structured so far for the welding methods, and are derived from theory. The summary of those is included in the following table (Table 4). This thesis scope and focus is on TIG welding method, at the H-Sector level.

It is obvious from the table that according to theory and internal documents' information, when using TIG, the weldable thickness is between 0.4mm to 3.0mm. Even if it deforms the part because of the high heat input, TIG is consider a stable and cost-effective solution. It offers a good accessibility to the weld interface, but not on very narrow radiuses and it is not sensitive to closed joints. Similar details for the rest of the methods are included in the table. However, there was a need to zoom into the H-Sector more and combine the geometrical characteristics of the part with the potential strengths of the welding method.

Table 4 Welding methods information at H-sector and TRC-assy level

	Material thickness (mm)	Deformation (amount of heat input)	Benefits	Limitations	H-sector stage	TRC-Assy stage
TIG	0.4-3.0	High	Stable process, cheap, applicable for most situations	Low speed as thickness reach 3 (mm), high heat input	Preferably used as the method have good accessibility. Limited accessibility at sharp turns. Not sensitive to closed joints	Suitable method but very limited in terms of thickness.
PAW	2.5-8.0	High/Medium	Keyhole mode assures full penetration, faster than TIG, less sensitive to variations in weld distance	Sensitive to angular variations toward joint, sensitive for oxidation when welding Ni-based materials (shielding gas required), more parameters to control not suitable at 2-3 mm	Preferably used as the method have good accessibility (slightly less than TIG). Limited accessibility at sharp turns. Inclusions tend to form in closed joints	Suitable at this stage due to many axial welds (i.e. no closed joints). Cannot weld the thickest sections of a TRC.
LBW	2.0-8.0	Medium/Low	Faster than TIG, small heat input, thin and thick sections	Expensive, weld spatter is common, pores are said to be common, smoke and metal vapour disturbs the process	Fairly new method to the company and development left to be done before considering this method at this stage. Possible to use though	Preferably used at this stage. Wide range of thickness are welded for which laser becomes a competitive candidate
EBW	0.5-34	Low	High speed, very small heat input, thin and very thick sections, clean environment (vacuum), beam control	Requirements on set-up (e.g. gaps), expensive, weld spatter is common	Not feasible for H-sector stage due to high volume of sectors and cost	Preferably used on very thick joints for which other methods cannot be employed

4.5 Planning the manufacturing process

In a process, there are different parameters that affect the end result. The thesis students have assumed that the combination of the parameter settings is the base that defines the expected outcome of the product. Customer requirements and quality-needs must be fulfilled. It was understood from the beginning that there are relations between the robot welding sequence and the output. The remaining question was how much knowledge the operators had about this relation and if this knowledge was a lesson-learnt. From analysing the parameters, the researchers also wanted to understand the relationship between the welding settings, the design of the product and lastly, the output characteristics. The outputs are referred to the weld bead shape, weld defects, and weld dimension and deformation of the joint bead.

A ranked picture of the most important welding parameters is presented (Table 5). As the most important factors with the highest level of importance as 10 and lowest as 1, the welding current and welding speed in combination with the arc voltage will result in full penetration. If the operators must choose between not having full penetration or having other welding defects, they prefer to have full penetration. The reason behind this is that other defects can be reworked to reach the wanted outcome, but if full penetration is not achieved, the parts need to be re-made.

Table 5 Ranking of the most important factors of the robot welding characteristics

Robot Welding Characteristics	Level of Importance
Weld Current	10
Weld Speed	10
Arc Voltage	9
Electrode Stick-out	8
Height of welding tool	7
Wire Feed Speed	6
Wire Diameter	5
Torch Position	4
Electrode Angle	3
Electrode Diameter	2
Gas Flow Rate	1
Shielding Gas	1

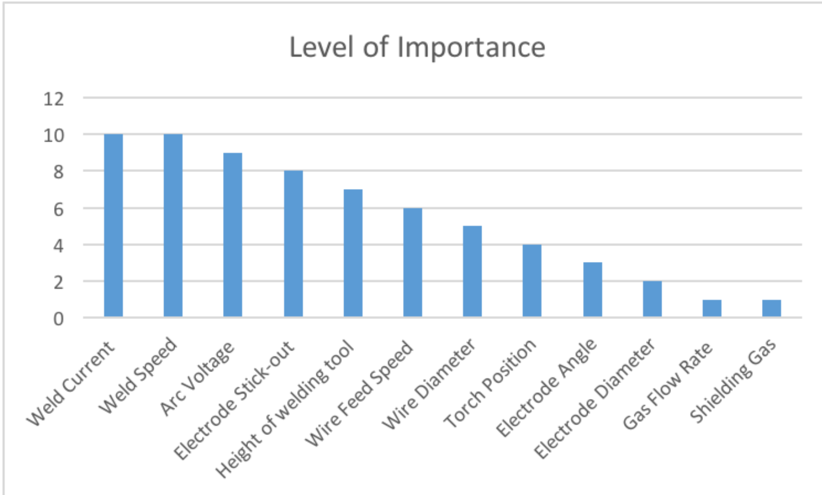

Figure 19 The weld current and welding speed in combination with the arc voltage are the characteristics that if controlled will result in full penetration.

When staring a welding operation, the first thing to take into consideration are the weld current, in combination with the welding speed (Figure 19). When designing the welding process, the welding engineer prioritises to achieve full penetration of the weld. To increase the weld speed, the weld current needs to be increased to achieve full penetration. Full penetration is dependent on the weld speed. When welding in thicker materials, the weld speed needs to be decreased and the weld current increased, to have a fully penetrated weld. One of the respondents from the manufacturing engineer department explained it like this: "*If the weld speed is increased and still use the same wire speed, the weld will become colder, which will lead to difficulties in achieving full penetration. The outcome of not fulfilling full penetration is that the weld height on the topside will be too high and this affects the airflow in a negative way*".

Using a thinner diameter of filler material leads to increased weld speed, because less time is needed to heat up the filler material. The combination of the heat and filler material needs to be balanced, otherwise a drop effect of the filler material will occur. That leads to unwanted quality defects of the weld bead shape. On the contrary, when using a thicker diameter of filler material, more material needs to be heated. The filler material and the incoming parts are made of the same alloy material. The characteristic of this material is the heat persistence and the high viscosity[3]. The thickness used at GAS for the sheet metal and for the filler material diameter is standard, according to what is available on the market. In that way, GAS avoids customised dimensions in tooling and materials in order to keep the cost as low as possible.

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[3] Viscosity is the state of being thick, sticky and semi-fluid in consistency, due to internal friction.

Many of the weld settings can be referred back to fundamental physics knowledge. When calculating the arc voltage, the Ohm's law can be used. Increasing the weld current leads to increased arc voltage, and when increasing the arc voltage, the arc length is also increased. The distance between the electrode tip and the work piece is increased. If manufacturing engineers do not increase the arc length and only increase the heat input, the weld pool will become too wide and they will not be able to control the weld shape, which will lead to irregular geometry and weld shrinkage. An increased arc will also increase the resistance (Ω) in the arc length and more weld current is needed. A decreased arc length will give a more robust end result using TIG.

Before final welding of the sector, the robot will tack weld the part in an irregular pattern to spread out the heat and reduce twisting in the material, which is also done to reduce deformation. According to welding engineers' know-how: *"The longer the tack-welds, the less resistance in the material occurs, due to better capacity of the ions to pass through more material down to earthling grounds"*.

The weld torch has many functions that affect the final weld outcome (Figure 20). The accessibility to the weld interface will first be taking into consideration. The accessibility considerations help manufacturing engineers to decide the ingoing parameters. According to the process engineers, the different positions that the torch can access are around the x-axis, ± 5° from the nominal position. The y-axis angle should not change, since it will affect the height of the arc and the parameter settings. The z-axis movement will not affect the weld outcome in a negative way.

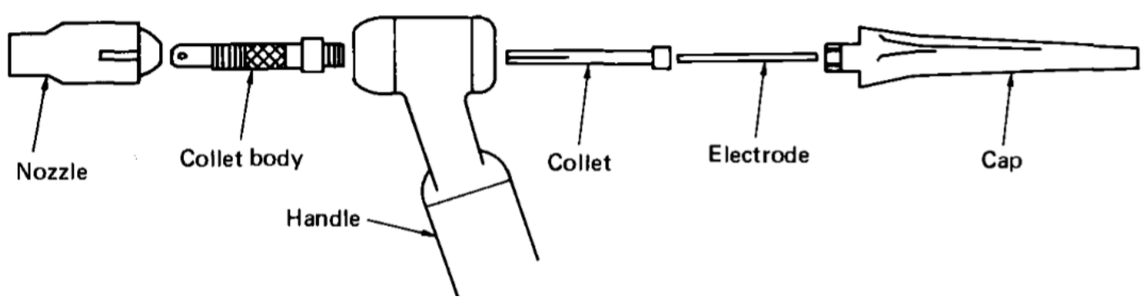

Figure 20 Key components of Welding Torch (Hicken et al., 1993)

The torch distance from the filler material cannot be too long, since distance is dependent on the arc voltage. Increased distance will lead to problems with full penetration. The distance between the electrode tip and the filler material is X mm and this is know-how acquired from the new robot cell that GAS is using. Process engineers should be familiarised with the proper melting point.

In the robot cell, manufacturing engineers have minimized the torch size due to the height of the stand-up part that challenges accessibility. The electrode is minimised from 2.4 mm, which consequently reduced the weld current range that the electrode could handle. Moreover, the gas coup is smaller and this was chosen as a solution in order to have full accessibility to the upper and the lower weld interface. The electrode is surrounded by a gas coup to protect the melted material from contamination. At GAS, they are welding in a closed area filled with shielding gas to help protecting the weld bead shape. Engineers claimed that with the given welding method and the current technology, the size of the stand-up height cannot be reduced further.

The weld torch holds the electrode (Figure 21). The length of the electrode that is apparent is called stick-out distance, and that is an important factor for the process as well. Specifically, the sharper the electrode tip is, the more precise the flow of ions will be towards the work piece. Nevertheless, the distance between the tool and the work piece is much more important. Suppliers offer a variety of electrode sizes to customer with a diameter from 1.0 mm to 3.2 mm. The higher the diameter of the electrode, the higher power source it can handle. The dependency of the weld current and the electrode size became even clearer from the interviews, when the engineers mentioned: "*When using an electrode diameter of 1.6 mm and weld current of 170A, the electrode will be destroyed and will emit tungsten in the weld bead. However, this can only be discovered in the X-ray inspection in the form of white dots*".

Figure 21 The tip of the electrode is ground to a length L=1.5-2 times the diameter (D) (Weman , 2012)

The angle of the electrode used in GAS has become a standard one of 30 degrees. The reasoning behind the standardisation is that a sharp angle will result in a wider weld diameter and a wide angle will produce better penetration. Therefore, the chosen angle is a result of trading-off the two characteristics and choosing the best according to the expected outcome (Figure 22). That is why the degrees of the angle are chosen for the specific robot from the manufacturing engineers in order to give the desired result.

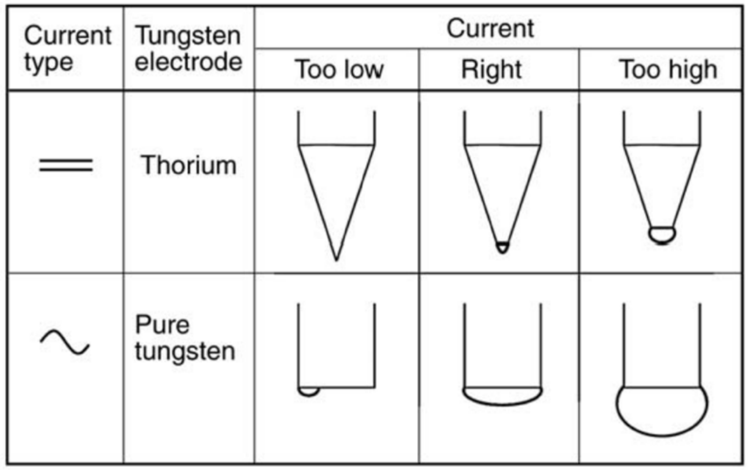

Figure 22 TIG electrode tips, showing the effects of too high or too low welding current in relation to the electrode diameter (Weman , 2012)

In manufacturing, they have defined a welding sequence and they simultaneously control the welding speed by increasing or decreasing depending on the point of the vane. Consequently, they need to adjust the welding current and voltage because of the vane's shape. That is a lesson-learnt from testing different welding sequences before deciding the current combination. When tack welding two parts to fit them together, an effort to spread out the heat as much as possible takes place. The reason this is necessary is because they are trying to reduce the heat input and deformation in the material.

To achieve an acceptable quality of the cosmetic weld when moving over the joint weld bead, the appropriate move is in a U-shape or a circle-shape movement. In that way, the proper drop off effect from the filler material will happen in the centre of the weld bead shape and that will not affect the final weld shape. Manufacturing operators start welding the concave side first since it will give a smoother transaction to the convex side. The heat accumulation on the material also affects the welding process and this also connected with the welded material. Depending on how fast or slow the material cools down, the weld current and distance might need to change in order to achieve the welding shape that is expected. All in all, the awareness of the material is always a significant factor.

Another difference between forged and casted materials is when it comes to the final heat treatment. Forged material has, according to GAS studies, shown to have smaller pores than casted material, which will lead to fewer variations in the size of the pores that have a significant effect on the products' result. Manufacturing engineers support the forged material use as one of the most important factor that leads to a robust end-result.

4.6 Learnings from on-going projects

After the conducted interviews and observations, a follow-up interview with people from manufacturing took place. The topic of this interview was to rank and prioritise the factors and the characteristics that from their perspective are considered as the most important to maintain or the most crucial to introduce. The answers came up as know-how or lessons-learnt from previous and current projects and, in students' opinion, are valuable to take into consideration in future projects, when designing new products.

The "Wish List" (Figure 23), as the employees named it, starts with first prioritising a "robust target system". That means, according to them, that a robust platform should be designed in order to simplify the current and the following operations. Less manual work and adjustment at set-up should be a result of the robust target system. The procedure should be repeatable, the assembling in the fixture should be fast and effective, and a three-point target system should be applied in all the incoming parts. That is a suggestion that might raise the purchasing cost but might decrease the cost of the part production as a whole.

Robust, as defined earlier, is a system that does not allow many variations. It can also be conceived as a stable system. In order to achieve that, there is a need to introduce mistake-proof steps in the production. A suggestion from the manufacturing that according to them is necessary to introduce is a Poka-yoke[4] system when assembling the H-sector. Some parts when doing the tack-welding assembly, look very similar, and you can realise their difference after their tack-welding is done, because of mismatch that appears. In order to avoid a mistake like that, engineers suggest that a differentiating indication could be added on the geometry of the parts, in other words a mark or a signal, so the assembly of wrong parts can be avoided, that will help avoiding any human factor problems. According to the engineers, if a mistake happens once, the possibility of happening again is high. If the system has no opportunities for human factor mistakes by its design, then the problems of this nature will be eliminated.

The second priority is to keep the three-side machining, because the result of it is less variation in mismatch, welding gap and thickness. That fact will also enhance the output of the sub-sector assembly and will accommodate the following operations in a better way. Three-side machining can result in correct positioning of parts, it eliminates variations that occurred during the manufacturing process and leads to less thickness variation at the weld interface.

Thirdly, the manufacturing desires the best accessibility to welding interface and that can be a result of the parts' geometries and dimensions. Additionally, ellipse geometries should be avoided, because the ideal welding interface is as straight as possible. After accessing the welding interface in the best possible way and by avoiding "problematic" geometries, the

[4] Poka-Yoke is a terminology derived from Lean manufacturing and means "mistake-proofing" in Japanese. Its purpose is to eliminate human factors mistakes that might occur. (Liker & Meier, 2006)

weldability of the parts is the next thing the manufacturing engineers prefer. That has to do with the materials they use. So far, the weldability is better to forged materials than to castings. A consideration is also to remove filler material and avoid cosmetic welds.

Last mentioned priority in the manufacturing list of factors to preserve is the inspectability and the class of the welds that are set by the design. If the class weld is low, then the mandatory inspections will be less and the cost will also decrease. A close cooperation is needed between design and manufacturing in order to decide the best weld class for each point so inspectability will be better and the parts will be following much closely the drawing requirements without extra costs.

At this point, it is worth mentioning that other important factors came up during interviews, however, they did not conform with the viewpoint of this thesis work and these were not design factors, so after screening them, they are not included in the priority list.

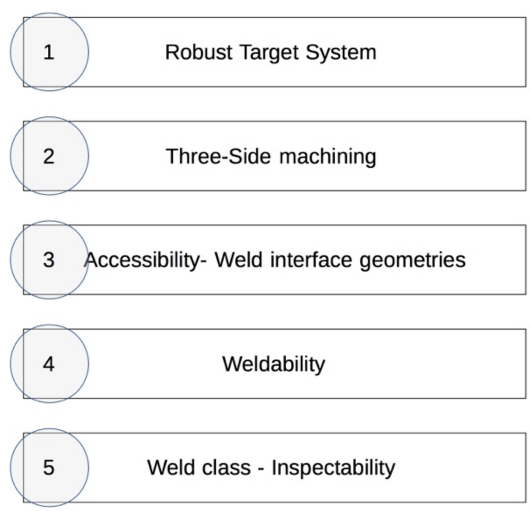

Figure 23 Ranking priority of important factors to maintain to future projects

Documenting all this knowledge, the outcomes of the test and simulations, the creative ideas, is of paramount importance for the continuous improvement of the company and the quality of its products. Knowledge and lessons-learnt need to be communicated and shared within the company, but notably used as well. There are two steps to manage this. The first is to have people that were involved into previous projects to participate in new ones. The second is to document and update a knowledge database that is accessible from the involved in design, production and manufacturing people and be done after every trial and error test, a new idea tested, a new simulation and all those ideas that did not work in practice.

The documentation is not necessarily supposed to be an official, hard to follow document. It can be simple and effective so that it can become popular both among those that are updating it as well as among those who use it when making decisions. A suggestion of this thesis is to structure a lessons-learnt flowchart that includes knowledge from different perspectives combined and indicates the sequence and the factors that affect each decision. Only by seeing from the beginning the procedure of product manufacturing as a whole, can someone fully perceive the needs and interrelations for decision making and method choosing.

By observing the data that were available to the thesis students, the following extrapolation was drawn (Figure 24). Taking for example a specific dimension on the product that is considered important to study, thickness of the welded material, the observation was the following. From the literature, the thickness that is weldable with TIG is between a specific range value. When looking into the internal documents, the same dimension's value was defined between a narrower range of numbers. So, according to the company, TIG can weld a smaller range of thicknesses. The internal documents concern the ability of the TIG method in general, without specifying it according to a geometry of a product. So, it was observed that the numbers get even narrower when they look into a specific weld interface and geometry, not just an axial weld. This occurrence has been observed with different characteristics.

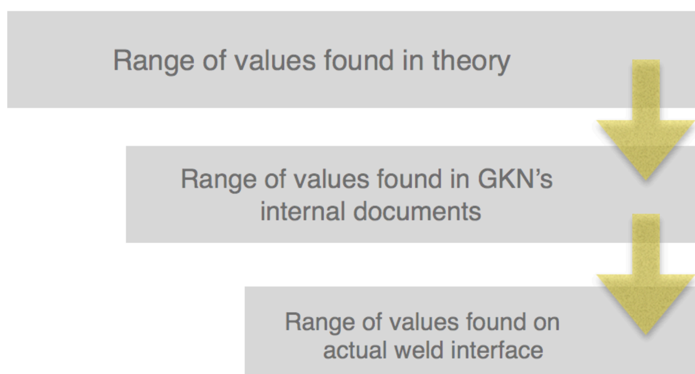

Figure 24 Schematic representation of different values from different sources

For that reason, understanding but also defining welding capability becomes such a crucial analysis. Because, there lies the proof that a welding method can be generally used under different circumstances, but the more we zoom into the interface and complicate the welding area by actually considering a product and not just the method, the stricter and narrower the value ranges become. Welding capability can be explained as the ability of the welding method to produce a specific product with specific requirements and give the expected high-quality outcome. Welding capability, therefore, is not about the ability of the welding method to weld in general, but it actually gets a more vital meaning when different interfaces with different challenging-to-weld areas come into the picture. Factors like equipment and experience of the operators should not be excluded either.

5. Discussions

In this chapter, after processing the results mentioned previously, the master thesis is completed by concluding and answering the research questions that were set at the beginning of the report.

5.1 Research Question 1

What are the product's critical characteristics that should be documented and considered in future project;

i. *From the functional perspective?*
ii. *From the manufacturing perspective?*

In order to answer this research question, first, we have to describe how the company identified and reached a common consensus of which the product's critical characteristics are. Then, these characteristics will be presented. To begin with, it seems that both functional and manufacturing perspectives currently agree about the critical characteristics of the H-sector for the specific project under study. In previous projects, this was not the case, as the departments lacked collaboration. However, according to the interview with one of the managers, the collaboration could have been even better between the departments, even in the current project. The fact that knowledge created within other products that the company produced was not taken into account in a large scale was also mentioned in the interviews. On the contrary, the success of the project, according to the interviews, was based more on hard work and choices made based on common sense.

In addition, new tests and simulations took place with the purpose to understand how the product would act in different situations of the production and where compensations had to be made in order to achieve a good outcome. Every tolerance that has been set to the drawing has been a trade-off between the departments. One interesting quote narrated by manufacturing engineers to the students was: "*Why does the design team always have to put the start and stop position of the weld in the most critical area of the sector?*". This is one reason why a good documentation needs to be frequently updated, and departments that are working together should have a good communication and understanding for each other's work tasks.

As mentioned in Chapter 4.3, the most critical characteristics of the vane are the radius of the vane at the leading edge, the width of the vane, the thickness of the vane and the height of the stand-up. The vane is the central part of the sector, where the inner and outer parts are welded together. The positions of the welds are put in the most strategic position from a cost perspective, but for manufacturing perspective, the most strategic position would be in the centre of the vane where only one weld had to be made. To position the weld in the centre of the vane would likely not occur, since machining time needs to be added and costlier material to be purchased. For the moment, the vane is a cost-effective product and strategically outsourced. At this point, it is worth mentioning that each department might have recognised additional product characteristics as important from their perspective. However, the thesis students decided to focus on the common ones, those that have been mentioned from both the functionality and manufacturing perspective, because these are the ones that have been traded-off in order to decide the current values.

When both the functional and manufacturing needs are shared, the trade-off between dimensions becomes easier. According to manufacturing employees, they can produce anything, but the question is more about cost and time. And if the functional department is aware of the dimensions that cannot be too narrow, faster decision can be made to fulfil customer requirement in accordance with the price range. We believe that the most critical characteristic are still the ones affecting the functional perspective like aero, stress and weight. And if these dimensions can be relaxed to improve producibility and at the same time not affect the product's final performance, there is no point of keeping tight requirement. Especially in products with complicated geometries, the repeatability of the process decreases when the tolerances are too narrow. The tolerances GAS is using today in their manufacturing are a trade-off between the departments' perspectives. The combination of functional requirements and dimensions of the product has been given to achieve as good critical areas as possible from both the functional and manufacturing perspective.

5.2 Research Question 2

What are the factors that should be prioritised as important for future use, from the knowledge that the company already obtains?

The manufacturing employees argue for a better “robust target system” as a first priority to improve the new platform. If the noise factors can be controlled by introducing a “robust target system” for both the company’s and the supplier’s incoming products, then the process will be more stable and repeatable. Supplementary benefits that can be achieved with introducing a “robust target system” is that operators do not need to add a lot of manual work that increases geometrical variation as well as cost.

It is inevitable that while welding, geometrical variation is added-on in every production step to the final step. To compensate for the geometrical variations, GAS has introduced three-side machining, during which, the extra material is removed from three different axes in order to also compensate for deformations and bring the product closer to its nominal position. Three-side machining, therefore, is included at the factors that help the process and should be kept in future projects. This is beneficial when welding, because of less thickness variation. Also, when constraining a part in order to weld it, both constraining and welding add loads to the part. As a result, it is expected to have geometrical variation and deviation from the nominal position. With machining, the parts are better controlled geometrically and the variation is decreased.

Moreover, accessibility is mentioned as an important factor. Combined with the weld interfaces, manufacturing suggests that the parts should be designed with as many “straight-line” geometries as possible, avoiding ellipse geometries. Accessibility of the welding equipment when welding is correlated to the result of the weld. With the intention to have an easy accessibility, the location of the welds is decided. Needless to say that depending on the welding method and welding equipment, the design should consider that the weld interface needs to be accessed without the need from manufacturing to create customised tools. Customised tools can increase the cost of the equipment and the total cost of the product. Problems can also be created from the low availability of customised tools, since the supplier does not maintain stocked customised tools and delays can occur.

The choice of the method which joins the two parts is directly related to the quality of the welding outcome. If the two parts have been produced by different manufacturing techniques (i.e. casting and forging), that will lead to a lot of variation and quality issues. If this must be achieved, then a lot of machining to prepare the weld interface should take place to compensate the different behaviour of the two parts to heat input from the welding. That is the reason why it is not recommended to weld two different parts that are produced by different manufacturing techniques. According to that statement, weldability of the parts is considered as the next most important factor to include when designing the future projects.

High precisions on the right tolerances are needed to achieve a good weld. Less robust welding methods are in need for better target systems. When it comes to the aerospace industry, even 0.1 mm makes a difference in the welding process. That is the reason why the next important factor is the weld class and the inspectability of the designed parts. When tolerances are unnecessarily higher in the drawing, that makes parts hard to manufacture in tolerances. Consequently, the tolerances and the weld class that is given to each part of the product should be well discussed and arguments about its severity should be raised. Additionally, if the weld class is high, the need of inspection on the part is doubtless. According to manufacturing, it would be preferable to inspect only the parts that are important to be inspected and not the whole product, since that would add cost and time to the production, and the weld classes that are usually in need for inspection are A and B.

5.3 Research Question 3

How can the welding capability knowledge be used in the product development process?

The product development process is the whole chain from the appearance of a need or a problem to the production of a product that meets that need or solves that problem. In the case of the

Turbine Exhaust Case, which is a highly functionality-driven product produced by fabricating parts, the welding is reckoned as a main procedure. The more the available welding capabilities within the company get acknowledged, the better and higher quality results in lower cost will be produced.

During this thesis, a difference between the theory and the practice on what can be welded and how, has been observed. Moreover, there are a lot of knowledge gaps in Welding methods' books. When designing a product and a process, it is not enough to know the theory that explains the welding method choice, because there is a difference between theory and the actual weld interface. When technology meets the actual product, a lot can change from theory because geometry difficulties are added to the equation. The goal is, therefore, to understand the welding capabilities and the welding potentials of the given technology and allow for manufacturability when designing the product.

Documentation is an important aspect to ponder during every step of the product development. By documenting not only the successful and plausible ideas, but also the unsuccessful ones, lessons-learnt stay into the company and repeating the same experimentations in current or future projects is avoided. Feedback and information flow from the manufacturing and production to design and vice versa is another vital step to an effective product development process. Manufacturing and design need to work closely to each other in order to succeed in recognising probable mistakes early in the product development, when the cost for changes is lower and the quality of the product is not compromised.

For all the above mentioned reasons, this is why the flowchart for lessons-learnt management can enable the use of the existing welding capability knowledge in the product development process.

6. Recommendations

In this chapter, the master thesis students are making some recommendations according to the time perspective that these can be applied. There are three categories, short-, mid- and long-term recommendations for future work and future improvements. After working on this thesis, the students have some suggestions for future academic work that belonged to this thesis delimitations or that were ideas born after gaining knowledge about the company.

6.1 Short-term Recommendations

A short-term suggestion that will purvey the knowledge inside the company and between projects is the best possible use of the database system. Starting with some observations made by employees and the master thesis students, concerning the use of internal database on SAP, an improvement that could be made is suggested. On SAP, the internal documents are uploaded, updated and approved by the stakeholders of every project, depending on the type of the document. The knowledge of the company is documented in that system, so the better it can get and the better access people can have, the more knowledge will be circulated in the company. The documents should not belong strictly to the department that created them, especially those that concern general knowledge. Secondly, the documents should include the role of people that issued them, the position in the company and not just the name of the issuer. That could enhance the knowledge spread, since it will make the contacting these people easier. People might leave the company or change departments in the company, and stop being responsible for a document. That can be improved by introducing the role of people, because in any given change of position, the document will follow the person in charge of it, and not the other way around.

A following recommendation would be to unify the terminology of the product and product parts in the company, so that people refer to the same or similar project parts by the same name. This might sound simple, but there are a lot of confusions created by the multiple naming of the same thing that belongs to different projects. This need is magnified more since the company introduced the platform thinking. The names of products and procedures should be common within the company.

When departments have different locations, the communication and daily updates are lacking behind. On a daily base research, design and manufacturing teams are working with improvements on their own. What the students have experienced from observations in the production is that there is no structured way to document and share different test that are made from time to time with the aim to improve the processes. And contributions from different departments' knowledge are hindered. For example, in the manufacturing, they were trying to weld the vane with no filler material. They had specially machined the vane and hub with filler material on the outside to exclude filler material and benefit the process by reducing cost, material and set-up adjustments. The test was not proved to be as efficient as they had thought. The purpose was to eliminate the usage of filler material, which they achieved, but they did not achieve the weld result they wanted, due to the need of a cosmetic weld around the leading edge. Since they still needed to do the cosmetic weld, there was no obvious reason to increase the cost of the machining process when the cost for filler material was not reduced. That is a very descriptive example of knowledge that is not documented and tests are not made known to the people who actually work on research and development. That fact is not the fault of people, but the system's fault that has not predicted a method to keep the knowledge and ideas communicated, and that can be a short-term suggestion for improvement.

Better exchange of human resources, departments that are collaborating should visit each others' workstations, to understand problems in a good way and the different challenges the work tasks contain. By only sharing stories partly does not increase the awareness of new ideas and occurred problems. Close collaboration in cross-functional teams, and if possible, sharing the same location when working on ideas will boost communication and will improve results.

Lastly, a short-term suggestion has come up from discussions with employees. Cost is a determinant that affects all decisions and is always present to every choice made. After all, as manufacturing mentioned, they can manufacture anything, but the cost is what defines the final choice. Top management therefore considers the total cost. Manufacturing also considers the cost and the time they add when they have long lead times and products to be reworked. The suggestion, on balance, is to revisit the idea of a total cost analysis in order to reconsider if the choices made are the less cost-adding ones. Moreover, a better understanding will be reached concerning the choices between casting or forging, in-house production or outsource processes, material and welding technique.

6.2 Mid-term Recommendations

The design of the process should be continuously improved. GAS, currently reckons machining as a time-consuming process, but it is widely used in order to compensate geometrical variations after welding. If improvements of weld deformation can be anticipated, the compensation could be handled from the beginning, instead of being added to the product and than machined back to nominal position. From talking to managers at the production, too much time is spent on the H-sector, and questioning if this is necessary since they machine the whole 360-assy at the end.

Knowing the capabilities of the company's welding processes is a very important step. In order to achieve that, the students suggest that a table be created, including the four available welding methods of the company. The table will include the technological maturity and the knowledge level of the company, rather than the theoretical background knowledge of each method. By reflecting on the methods' potentials, the company can decide, for example, what is the best practice of single pass weld for TIG, PAW, LBW and EBW. A check sheet created by interviews of employees can be of help, so that the knowledge and the knowledge gaps can be identified. If so, further research and tests can be planned in order to fill in the knowledge gaps

Another recommendation that might need time to be implemented is the development of the SAP system. The solution could be to add more filters when looking for documents in that database system. The only way to search for documents currently, is by knowing the code number of the document. It would be preferable if the potential to search for "Reports" or for documents that concern a specific project by using the name of the project. In that way, information about issues around the product platform or the test that have been conducted, or even about current academic or research work can be promulgated within the organisation faster and more effectively.

Finally, a way to support the inspections after welding together the sector parts should be introduced. So far, operators trust their instincts and do the visual inspections by using their experience. If that could be standardised, or if some tools and standards could be introduced, then the procedure would be more predictable and more secure, not to mention that the decisions made would be better recorded and controlled.

6.3 Long-term Recommendations

Since the research centre and the production are not located close to each other, they should make sure that the equipment that is used in both has similar capacity and identical characteristics. Given the fact that what is tested in the research and technology centre should be introduced in the future at the actual production, the production plan should be accurately researched, by having the same equipment and standardising from beforehand the processes that will take place in there. Even the investment on equipment should follow that logic. Research, design and manufacturing should work as one group, together, and ideally have psychical proximity in order to discuss and solve everything at the moment an issue is raised. In other words, cross-functional working philosophy is necessary, but not only theoretically and when it comes to feedback.

Nowadays, GAS is confident with using TIG as a production technique as much as possible. The reason is because the technology is more matured, the people are more experienced and the method is more stable, cost less and it produces a robust result. The suggestion to the company from the students' behalf is to try to develop technological maturity to the rest of the welding methods in order to increase the company's production flexibility. If the choice made is clearly based on which is the best method to produce and not which method is more technologically advanced within the company, the results will be more adaptable and the production more agile. A method to research future steps in context of the H-sector is to see if it can be produced with laser. Laser produces a thinner single pass weld and less heat input to the sector, which leads to less deformation. One tricky part of introducing laser of the H-sector is welding around the leading edge, since laser is a much faster process, hence the achievement of full penetration is harder. Full penetration using laser might be achieved by reducing power of the weld process while passing from the leading edge, but this needs to be researched further. Laser has difficulties as a method when welding from thick-to-thin and back to thick material, but since the vane has a standard, uniform thickness, the step of increasing and decreasing the power of the laser weld is a possible solution.

Needless to say, as a concluding suggestion, that the company should be precise and accurate when negotiating for the new investments on equipment. The crucial factor is to specify clearly what the expected needs of GAS are and what the company wants to produce with the new equipment. In that way, the internal tool suppliers and operators will not need to rework or adjust the equipment that is supplied from external sources. Things must be done right from the beginning. It always takes time to learn how the new equipment works and there is no need of extra time consumed to adjust the fundamental functions of what is bought.

6.4 Suggested future academic work

Suggestions that concern the future academic work can be extracted from this thesis, likewise. First of all, similar studies can be conducted on the final assembly of the product that is done by using a different welding method. If lessons-learnt can be documented from this process as well, the welding capability of the company will be more broadly defined.

Secondly, it would be useful to introduce quantitative data and adjust them into the conceptual framework by Madrid et al. (2015), in order to quantify the amount of influence each factor has to the output of the process, and how these factors affect the total product production. In that way, the connections and correlations between factors and characteristics would be more clear.

Thirdly, the lessons learnt that were found for the current project should be introduced in the SAP system in the form of report so that people of the future projects have access. The knowledge is not produced only in the latest project of the company, however. That bears the need to document more lessons-learnt from other projects, communicate them and identify where the knowledge was created, under what circumstances and when.

A question raised is how the different welding methods can be combined as a sequence and what the impacts of that combination are for the product. Since every welding method has the different heat input or different width result, it is interesting to find out what happens when different sequential processes use different methods and what advantages can be brought by this various choice of methods in the same product. That could be answered with simulations and test, both in vitro as well as in reality.

One of this thesis' results is the flowchart that can accompany the platform document as an appendix, not to mention the thinking when a new project is developed, or a current project is revised. However, it would be strongly recommended for future academic work to research the areas that data are missing from and develop the flowchart to more directions so that the welding capability knowledge can be more complete.

7. Conclusions

This thesis is about welding capability analysis and identification of knowledge gaps and lessons-learnt during the product development of the Turbine Rear Case sub-sectors. As the title of the thesis implies, lessons-learnt and knowledge from trial-and-error procedures exist in the company. The challenge is that all this above-mentioned knowledge is not documented in a proper way or in an accessible place for all the involved parts to reach. That has as a result that resources, sometimes, are invested in trying the same ideas with the same parameters more than once. The first step of every case like this should be to identify the topic to be researched, which in this case is welding, understand the capabilities of it and later identify the knowledge gaps and categorise or codify the lessons-learnt.

During conducting the thesis work, the students identified knowledge gaps concerning the welding methods both in theory and in company's internal documents. Needless to say that access to internal documents and searching for information in the internal database system was also a hindered activity. When addressing this difficulty to the right people, information reached the students and problems were solved. That can be reflected not only to students, but also to people involved in projects of product development or product and process improvement.

With regard to that point, the importance of frequent and consistent documentation is highlighted. In that way, a common thinking will be spread and when a project is developed to a product, all the generated knowledge will be available for the people that are involved into it. Thus, the product will be better control and the important factors from the functional and manufacturing perspective will be taken into account.

Moving to another conclusion, the company needs mature processes and welding methods in order to be flexible to select the most cost-effective solution to produce every product. The company should invest resources in understanding the methods' capabilities, although there is an influence by the policy towards using fabrication methods and concentrating on TIG and LBW.

In conclusion, cross- functional teams are mandatory in order to reassure that the project outcome will be of specific quality and cost. The better communication the design and manufacturing departments have, the more the products will be designed right from the beginning. That is a condition that can minimise the cost during the product development process. Close collaboration should exist between all the stakeholders. The strategy of the company should be clear to everyone, and based on that, decisions and project developments should be made if and when each department's needs are shared and argued. Cross-functional teams between departments but also between old and new projects in combination with documentation will certainly maintain the created knowledge of the successful and unsuccessful projects early in every conceptual design.

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9. Appendix

9.1 Summary of Fusion Welding Processes

Table 6 Summary of Fusion Welding Processes (Olson, Siewert, Liu, & Edwards, 1993)

	GTAW	PAW	LBW	EBW
Part Assembly				
Thickness	Min 0.2 mm	Less than 6 mm (thickness keyhole 20 mm)		
Single pass	Max 5 mm			
Multiple pass	Max > 6 mm			
Unequal thickness	Difficult			
Current				
Type	Alternating or Direct Current (Straight polarity)	Direct current; electrode negative	None	Direct current
Volts	60-150			10-200 kV
Amperes	100-500	Below 120 A		0.5-10 kW
Production				
Welding rate	0.2–1.5 m/min	120-1000 mm/min		
Operation	All			

Table 7 Summary of Fusion Welding Processes (Kalpakjian & Schmid, 2003)

	GTAW	PAW	LBW	EBW
Part Assembly				
Thickness		Less than 6 mm (thickness keyhole 20 mm)	Up to 25 mm	150 mm
Single pass				
Multiple pass				
Unequal thickness				
Current				
Type	Alternating or Direct Current	Direct current; electrode	None	Direct current

		negative		
Volts	8 kW - 20 kW		100 kW	100 kW
Amperes	Dc 200 A, Ac 500 A	Below 100 A		
Production				
Welding rate		120-1000 mm/min	From 2.5 m/min to as high as 80 m/min for thin material.	12 m/min
Operation				

9.2 Table of figures