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Design for Manufacturing – Concept cost evaluation model for fabricated components at Volvo Aero

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Abstract

Design for Manufacturing is an engineering methodology that bases its principles in designing products in such a way that they can be manufactured with the machines available and for the desired cost. This methodology is already developed in the literature providing information and guidelines for each manufacturing process, but not for the production of a component that combines several different ones in the flow of operations.

This thesis is the starting point of a research project regarding cost and robustness in the manufacture of aerospace components at Volvo Aero Corporation. First, it was necessary to make an assessment of the current situation in the company, followed by the creation of tools to implement the methodology of Design for Manufacturing.

The design process at Volvo Aero is described and the major gaps and problems identified. Currently, the most critical issue is producibility, because there is lack of information, regarding manufacturability aspects, provided to the designers while they are performing their work in the concept study phase.

In order to deal with this problem, trade-off curves are suggested as a tool to be used in the concept study phase to close the knowledge gaps. A lot of parameters that influence the design are identified and the relation between them is made, to try to see possible parameters to be included in these trade-off curves.

Keywords: Design for Manufacturing, Cost, Volvo Aero Corporation, Producibility, Concept study, Trade-off curves.

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List of abbreviations

CNC	Computer Numerical Control
DFA	Design for Assembly
DFM	Design for Manufacturing
DFSS	Design for Six Sigma
DSM	Design Structure Matrix
EMS	Engineering Method Specialist
FMEA	Failure Mode Effect Analysis
FPI	Fluorescent Penetrant Inspection
GDP	Global Development Process
HIP	Hot Isostatic Pressing
HoQ	House of Quality
IE	Integrating Events
NDT	Non Destructive Testing
OMS	Operational Management System
PD	Product Development
QFD	Quality Function Deployment
SBCE	Set Based Concurrent Engineering
TD	Technology Development
TEC	Turbine Exhaust Case
TIG	Tungsten Inert Gas
TRF	Turbine Rear Frame
TRL	Technology Readiness Levels
ULSAB	Ultra Light Steel Auto Body
VAC	Volvo Aero Corporation
VPS	Volvo Production System

1 Introduction

1.1 Aim and goal

The aim of this Master Thesis was to create some kind of DFM tool that could gather valuable information for the creation and evaluation of concepts to be used by the designers. First, it was necessary to assess the way a concept study is done at VAC, to realize the current situation regarding the use of information from production in the design phase.

1.2 Background

Volvo Aero is a company that designs and manufactures components for high precision jet engines. The strategy is to manufacture these components using fabrication instead of large castings and forgings, so the different smaller parts have to be welded together to build the final shape. This process can be very complex and a lot of different alternatives exist to divide the components in smaller parts and then join them, which influences the final quality and manufacturing cost.

This work is an important contribution within the research project "*Design For Manufacturing – cost and robustness in aerospace components manufacturing*" funded by VINNOVA (Swedish Agency for Innovation Systems), and the NFFP5 program. This project aims to develop new engineering methods to improve manufacturability.

1.3 Problem description

Over the past few years, the way of manufacturing the components at VAC has changed. Before, they were produced by large castings or forgings, while nowadays the strategy is to fabricate these components using small casted, forged or formed parts that are welded together to build the final component.

The main reason for this change was the lack of suppliers that could cast or forge components with a big size. VAC was limited to one or two companies in the whole world that had a dominant position in this business, which meant lack of competitiveness between supplier companies and therefore these components were very expensive to purchase. The manufacturing operations that were done at VAC in those times were mainly machining and inspection of the component to achieve the final dimensions, which did not add a lot of value to the final product.

The new strategy of fabricating the components adds much more value to the component by doing the manufacturing operations inside the facilities of VAC. By splitting up the components in several small parts, the number of suppliers capable of cast, forge or form them increases, making possible to have competition between them, so VAC can purchase these parts for a better price. The flexibility of the supply chain increases, making possible to choose between suppliers and adopt different options and strategies for the variety of components produced. This way, it is easier to rework or repair something, since it is divided in smaller parts and not in one as a whole. Another advantage of this strategy is that, because there are manufacturing processes done in-house such as machining and welding, it is possible to improve them for the manufacture of the components, reducing costs and saving money. Also, fabrication allows the component to be lighter, which is one of the most important issues in the aerospace industry, and especially for VAC, which slogan is *"Make it Light".* Fabrication has great advantages, but it is necessary to have a new way of designing and be aware of the problems that joining processes can bring. A major issue in fabrication is the geometry assurance process, which varies according to the joining processes chosen. The most frequently used joining process is welding, which brings problems related to deformation of the parts when they are welded together. It is necessary to have a robust design to assure that all components will be inside the specified tolerances of the drawings. This can be achieved with knowing the welding processes and have good fixturing systems for the parts. It is also necessary to have accessibility for the areas that will be welded and inspected. Other problem related to welding is the appearance of cracks due to the process itself and also because of the loads that the component has to carry. A final disadvantage of fabrication is the necessity to keep track of the parts, requiring more logistics which increases cost.

There are a lot of ways to divide the components in small parts and to assemble them, which makes fabrication very complex. Concepts are the combination of some engineering decisions regarding a component. A design concept combines the way of splitting up the component in small parts, the manufacturing operations used to produce those parts and the assembly processes to join all of them. So, there are several different combinations that can be done to build up the final component. It is necessary to have some kind of methodologies or tools to evaluate them in order to know which one is the best. DFM is an important philosophy to be applied in this case, to know if the design is producible, if the technical requirements are achievable and to what cost.

1.4 Limitations

This Master Thesis is only focused in the Concept Study phase, which means the earliest phase of the development work. It is also based on hot structures, such as the TEC or TRF depending on the customer, which is a component that has already been produced for different engines using different concepts, so there is information available to study and evaluate the alternatives.

1.5 Structure of the thesis

This thesis work is divided in two parts. The first part of the thesis is related with the way of thinking and working regarding DFM at the company Volvo Aero. The current situation is defined and the problems identified, ending in a systematic approach to be implemented in order to deal with these issues. The second part of the work is related with the creation and implementation of engineering tools regarding the same working methodology in the design phase.

2 Part I

2.1 Introduction

In this first part of the thesis project, an assessment of the current situation at the company is made. The first part of the report is divided in sub chapters that present how such thing was achieved. It starts by the theory that supports the principles related with the project, followed by the methodology used to perform the work, and ends in the results with the subsequent conclusions.

2.2 Literature review

To support and give a base to the work, this sub chapter presents theory related to the project. It consists of The Design Process, Design for Manufacturing and Assembly, Design for Robustness and Set Based Engineering.

2.1.1 The Design Process

The aim of the design process is to understand and know the marketing objectives and transfer that to an input for manufacturing the product that hopefully will give profit to the company. This process involves the participation of cross-functional teams and a lot of communication between the members that contribute to the development of the product *[1]*.

What is done in the design process will be the input for manufacturing and assembly, therefore it is necessary to include requirements from these areas in order to avoid problems in those phases due to bad designs. There are methodologies covering these areas called Design for Manufacturing (DFM) and Design for Assembly (DFA). There are also other issues that designers have to take into consideration during the design process, such as maintenance, service, safety, environment, disposal and so on. These methodologies can be called Design for X (DFX) *[1]*. Another limitation for the design process are the materials that can be used for a specific product, that can be influenced by variables such as temperatures, stresses, etc. So, if design, manufacturing and materials are metaphorically considered as circles, the design of a product has to be located in the overlap of them, as represented in the next figure.

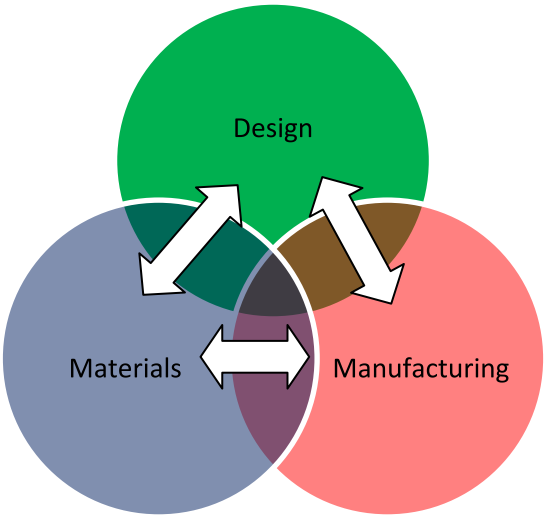


Figure 1: Design space of a product

These three key aspects influence each other, that is why product development is a complex process, being necessary to have methodologies to follow, where there is a lot of iterative steps, until optimization is achieved to develop a product according to the expectations of the customers.

The design process is just one of several steps during the life cycle of a product, but it is where the major decisions are made and the product turns into reality, by a creative process that transforms the market and customer needs in something touchable, always having in mind the subsequent steps that will be influenced by design. The following figure describes better all steps involved in the life cycle of a product.

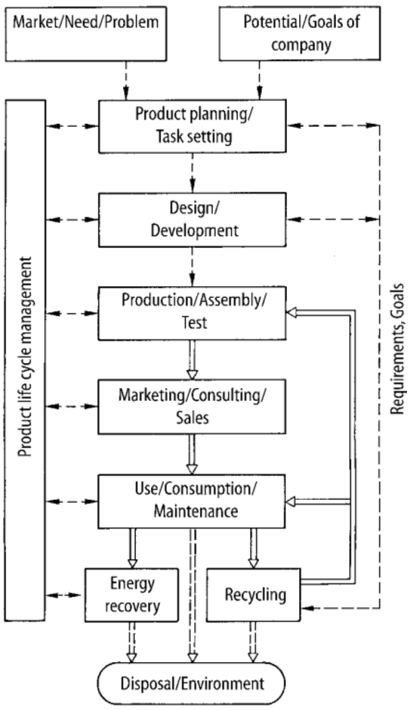


Figure 2: Product life cycle [2]

A project to develop a product must be carried in a standardized way, depending on the type of organization followed by the company. There are three types of project organizations; Functional, Project and Matrix.

A functional structure is the most common type of the three. It is more suitable for small organizations in which the different departments are located close to each other and only provide a small contribution for the project. Each department is specialized in a certain area, having its own functional manager that has the most power and makes the final decisions, rather than the project manager, that only assures the smooth execution of the projects. The role of the functional manager is to prevent conflicts of interest, making it easier to manage the specialists, contributing to a limited authority of the project manager *[3]*.

In a projectized structure, the project manager has the complete control of the project and all the team members report directly to that person. These members come from the different departments, so when the project is finished the team breaks up and disperses. This type of structure drives the company to clone the same resources for each project *[3]*.

A matrix structure is the combination of both structures explained above. Each team member has to report both to the functional manager and the project manager. It is a complex organization more suitable for big companies, where it is necessary good communication and balance in which the power is shared equally. In this type of structure the use of resources and the vertically and horizontally communication are efficient *[3]*. A figure illustrating a matrix structure is presented next.

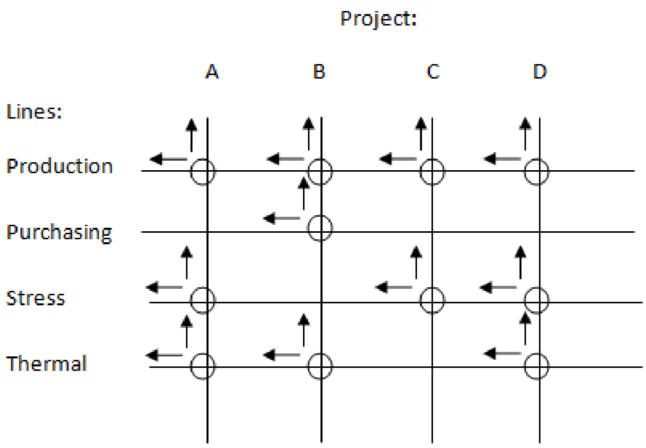


Figure 3: Matrix organization

The product development process starts with a customer or market need. Then, it is necessary to convert those needs into a final product, creating different solutions to fulfill those needs. Nowadays, with short product development times and budgets and the increase of the demand for quality, the design solutions or concepts are limited and most of the times implicit in the customer needs or already existing in the mind of the designers. As a result, these needs are just used as criteria to evaluate the concepts, instead of being the starting point to generate new solutions *[1]*.

It is necessary to have methods to use the customer needs as the initiation of the concept creation phase. The first step is creating a product functional requirement list based on the customer needs. The advantages of focusing in the functional requirements are less complexity and better understanding of the boundaries of the problems that will lead to more creativity and therefore better designs. The next figure shows the steps that must be followed in the design process from the requirements list until the choice of the best concept to be further developed.

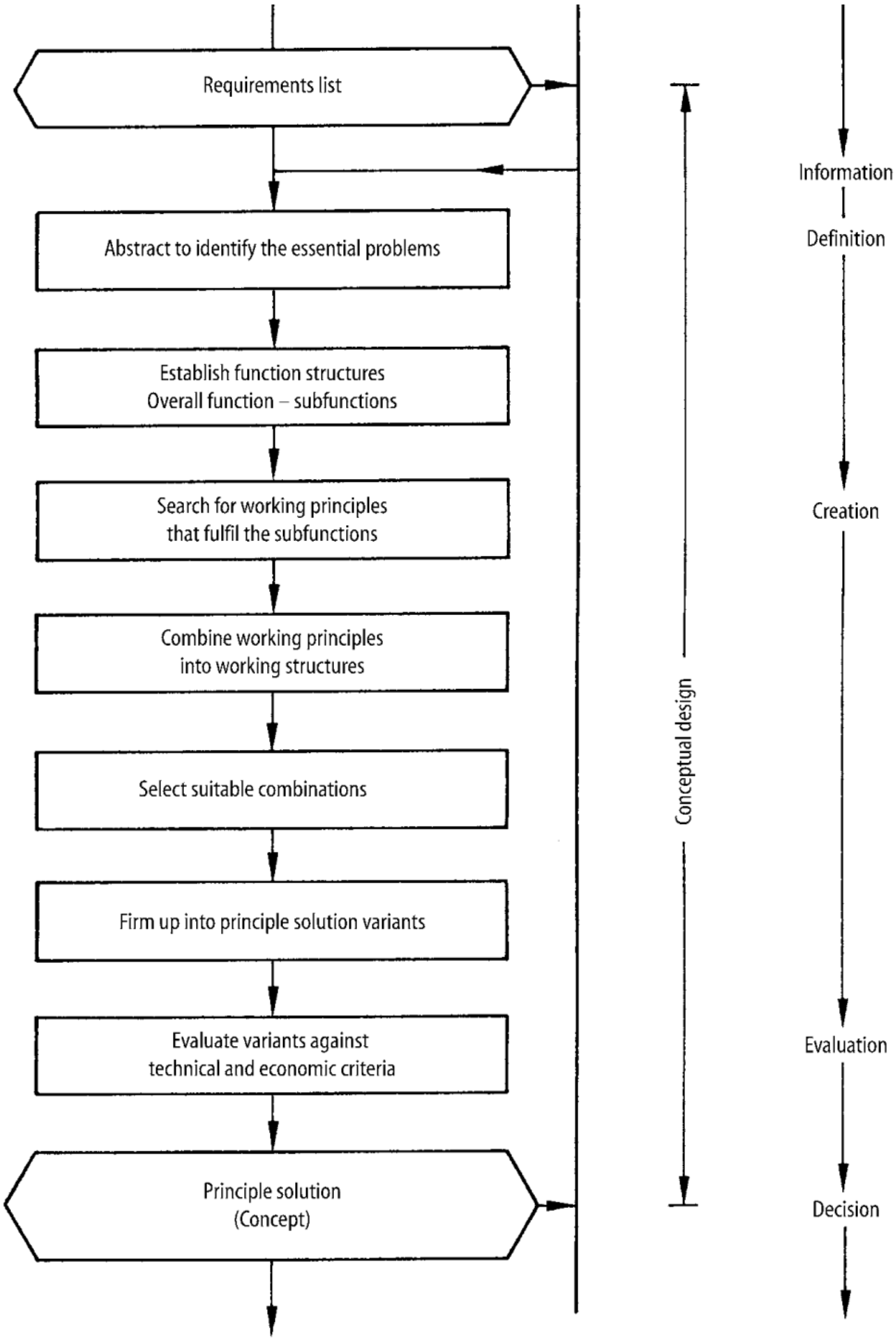


Figure 4: Steps of conceptual design [2]

The concept generation phase is a critical one during product development. There are some tools that help the designers and cross-functional teams to create them. These tools can be divided in individual, to be used when working alone, and group ones, developed to create concepts when there is interaction between several people. Examples of individual tools are checklists, which make the designer think about the concepts related with some metrics using questions to the problem; metaphors, which takes the concept generation to a new reality with the metaphorical transformation that can open the eyes of the designer and bring new ideas for the product always keeping in mind the function of the same; forced random stimulation, which consists of choosing a random object of the daily life and writing the attributes related to this object that will be used to generate ideas about the product the company is trying to develop. Group tools can be brainstorming, where a lot of ideas should come up, with no judgment by others, with the possibility to combine and improve those ideas during the meeting *[1]*.

Cross-functional teams must have some characteristics in order to have a good performance. They should be formed by a small number of members that complement each other in terms of knowledge and skills with a specific target to be achieved, working all together by the same methods and principles to do so. Obviously, meetings are very important to assess what has been done since the last one, because product development work is performed in between meetings. So, when teams gather in meetings, it is a good opportunity to solve problems that appeared and plan the future work. It is important to have in the team people that are able to work independently, that have ideas on their own and a good critical view over the development work, not afraid of presenting a different view and having a different opinion from the others, because in this way different approaches can be explored leading to better solutions and designs. Also, the members should be what is called a T-shape individual. This means they should have a deep knowledge in a certain area, but at the same time open to handle other types of jobs in other specialties. Only this way the team will not have problems with members with lack of commitment to the project or too focused in their area of specialty. The best way to choose the members is by volunteering themselves, because it is necessary to be able to follow what was described before. Working in teams promote the practice of concurrent engineering, so each decision is made taking into account the knowledge of the different areas involved, integrating all the relevant information of those specialties. Concurrent engineering avoids bad designs and objectives that are irrelevant for the customers, developing products that achieve the functionalities specified and that the customers will buy. The decisions made during concurrent engineering will lead to good product functionality, production capability and field-support capability *[1].*

2.2.2 Design for Manufacturing and Assembly

Manufacturing can be defined as a sequence of processes that transform raw material into a final product that has a value for the customer. These processes can be divided in those that change the shape or properties of the material, or those that join and assemble several parts together *[1]*.

These manufacturing processes are chosen during the conceptual design of the product, which means it is necessary that the designers have a good knowledge about them. The design has to be producible by the machines existing at the company or suppliers and also the cost of doing it has to be as low as possible in order to have the highest profit for the company. It is because of these issues that the methodologies DFM and DFA are important to be implemented during the design process.

Product design for manufacture and assemble is, nowadays, known to be a key issue for high productivity in industry. In the past, designers used to have shop courses to learn more about the manufacturing processes available. Meanwhile, this approach was abandoned due to the lack of academic content in the courses and also the increase of technology present in manufacturing and products and time pressure to the designers to do their work, which led to include unnecessary costs in the designs. Latest, another way to implement these methodologies, manufacturing engineers started working concurrently with design teams and DFMA tools started to be available for designers to help them in a manufacturing point of view. The following diagram shows the sequence of steps during the design process when using DFMA methodologies *[4]*.

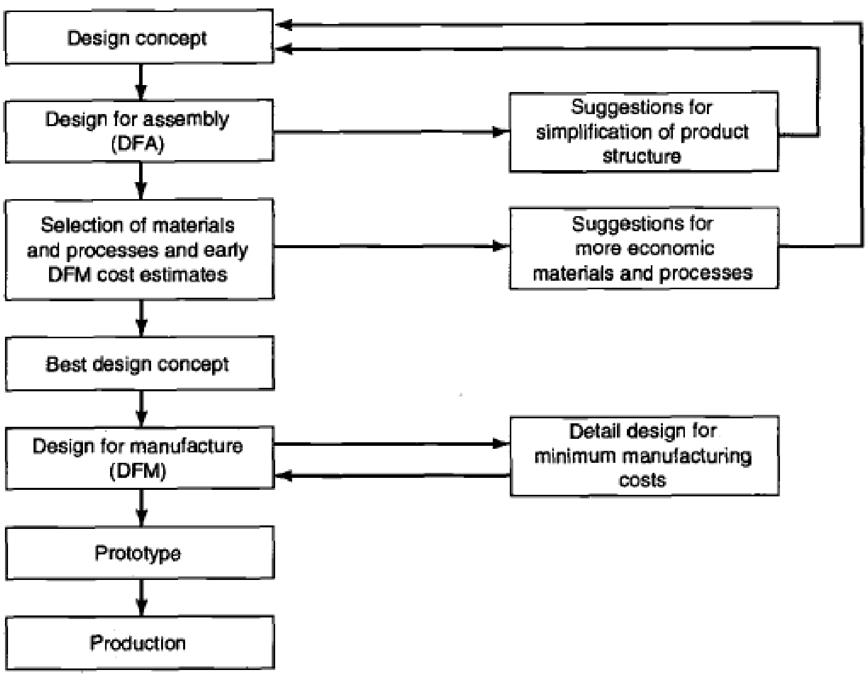


Figure 5: Steps taken in a DFMA study [4]

DFA methodology helps to simplify the product in terms of number of parts, where the desired is to have the minimum possible, also quantifying the time and therefore costs of the assembly process. DFM methodology helps in the selection of materials and manufacturing processes, presenting trade-off decisions to be made for the designs.

If there is not any type of communication between the design teams and manufacturing people, when the drawings are delivered to production, problems will be found in those designs related with manufacturability and design changes will be requested. When there are a lot of changes to be done, the release of the final product will be delayed. Therefore, loopbacks during the design process are not desired, since it makes the company to lose time and consequently money. Also, the later these problems are encountered, the worse, since it becomes more expensive to make the changes, so it is necessary to take into account manufacturing and assembly issues during the design process.

Boothroyd and Dewhurst *[4]* developed a software based on questions, tables and graphics along the years to help analyze designs according to DFM and DFA methodologies. In terms of DFA, this software helps designers reducing number of parts of a product that are unnecessary, by asking several different questions to the designer. It also estimates the total assemble time, taking into consideration the degree of difficulty of all assemble operations, giving then standard times according to industrial experience and university experiments. It is also possible to calculate acquisition and handling times for the parts, which can give an estimate of the overall time for the whole assemble process in the shop. Knowing the time it takes, it is possible to calculate the assemble costs using standard labor prices.

There are other methods to apply DFA, such as the Assemblability Evaluation Method that uses two indices to evaluate a design. One is the assembly-evaluation score which measures the difficulty of assembly, and the other is the assembly-cost ratio to estimate the final cost of the procedure. This method uses symbols to represent the several assembly operations that exist with a correspondent index that shows the ability to assemble. Other method is the Assembly-Oriented Product Design where a rate is given to parts combining the difficulty of assembly and the functional value of that part. The parts with lower rates should be redesigned. The Lucas Method follows three steps, where it is made a functional analysis of the parts, handling and feeding analysis and finally a fitting analysis, receiving scores for each step according to some parameters.

The cost of a part is defined by the manufacturing process selected to create it and the design of the part itself. It is determined by the combinations of the manufacturing methods selected and suitable materials with the design of the part for each processing method and the processability of the part with the correspondent manufacturing process. So, to be able to create good designs with the lowest cost possible, DFM is a very important methodology, since it provides information for the designers about manufacturing methods that help in avoiding making bad choices that later would lead to loopbacks. The challenge is to create valued information that can be used by designers to make decisions in the earliest stages of the development, when the design is not detailed yet. Information regarding cost drivers are the most important thing for each process, since it shows to designers where changes in design can lead to significant cost saves. Also, limitations of the manufacturing methods in terms of sizes, weights, thicknesses, radius and so on are valued information so the designers do not create something that cannot be manufactured by the machines existing in the company or suppliers or it is highly expensive to do it. General design rules and practices can be easily found for several manufacturing processes and also, it is the responsibility of the manufacturing engineers and method specialists of the companies to create documents to provide this kind of information to the designers.

2.2.3 Design for Robustness

This methodology aims to improve the quality of products, reducing the effects of variability that occur during development, manufacturing and usage of them. These sources of variation are the random way of working during development, the different response of people and machines during manufacturing and the different exposure conditions during usage. Therefore it is necessary to design the products so they are insensitive to these sources.

There are some robust design tools such as tolerance design, parameter design and quality loss function. During the design process, these methods can be applied for a low variability during manufacturing. The major problem for the variability in the final product quality is known as tolerance stackup. Tolerance stackup can be critical when more than two parts are assembled together, due to the deviations from the nominal dimensions, even when the parts fall inside the tolerance limits.

2.2.4 Set Based Engineering

The Set-based methodology consists in working with several different design concepts at the same time in parallel that compete with each other, and then successively eliminate them as knowledge is built, leading to a final concept that is robust. The advantages of this methodology are better products and fewer loopbacks in later stages of the product development, reducing the lead time of it.

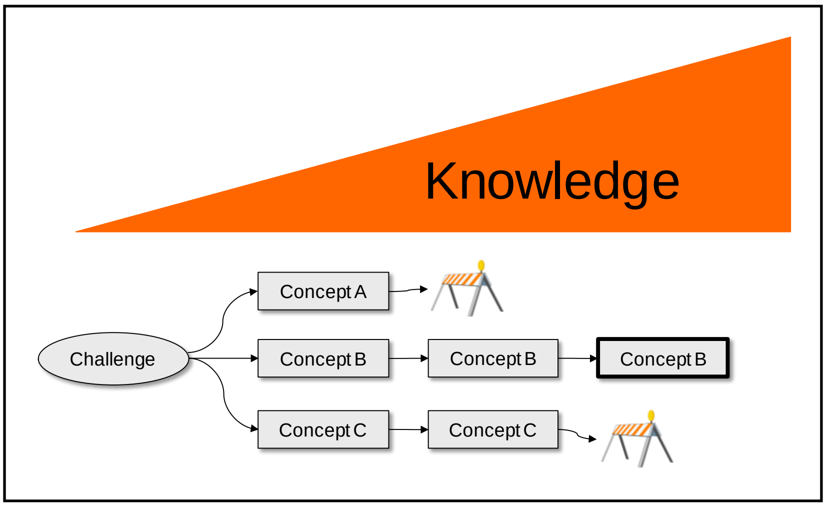


Figure 6: Set based methodology [5]

The cost of making changes in design increases as time goes by in product development phases. Therefore, the design freedom decreases along the way because there is not much room for trying new things due to the costs associated, but the knowledge gets bigger as the projects evolve, which causes a dilemma.

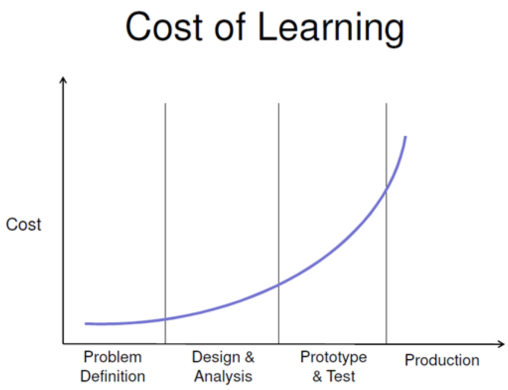


Figure 7: Cost of learning curve [6]

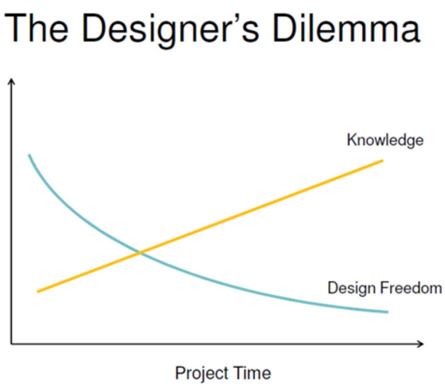


Figure 8: Designer´s dilemma [6]

It is necessary to build knowledge as soon as possible in order to make the right choices for the design. A contrary thinking to SBCE is the point based one, where only one concept is chosen quite early and developed. The main differences are shown next.

	Point based	Set based
Product specifications	Detailed early on	Rough at start. Detailed later
Design decisions	Made early	When knowledge is built up
Testing	Mostly after design	Mostly before design
Time to Market	Long – including loop-backs	Predictable and often shorter
Features		Better spec's and robustness

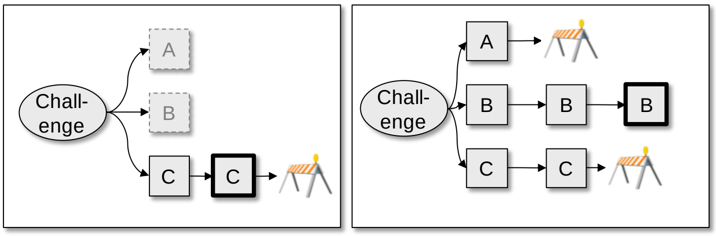


Figure 9: Point based vs Set based [5]

The point based method brings problems in terms of choosing a design that later is discovered that is not good enough or does not work, leading to loopbacks and redesigns. This lack of knowledge can be prevented when applying the set based approach. The main characteristics of it are the development of several concepts at the same time, eliminate them gradually, basing all decisions on facts from analyses, simulations and tests, not on feelings.

To apply this methodology is necessary to know the design limits, by seeing the overlaps between the design possibilities and the manufacturing capabilities. Another important tool are the model trade-offs which are graphics that relate two or more design parameters, where designers can visualize the influence between them and from there make design choices. Since visualization is a very clear tool, since it is easy to understand and to process, trade-off curves have become very helpful for designers to make the right choices. Several concepts can then be developed and explored, until it is necessary to start eliminating some that will not meet the requirements. These decisions are made in Integrating Events (IE), where the concepts that are least likely to meet the requirements are eliminated based on facts. At the beginning, these requirements should be as open as possible and get more specific as time goes by and IE are performed. All these steps must be documented, so knowledge is built and can be reused in later phases of that project or in different ones. The resources used in this methodology are less than in point based, although there are more teams working concurrently in different concepts, because there is not firefighting in the end of the project as represented in the next figure.

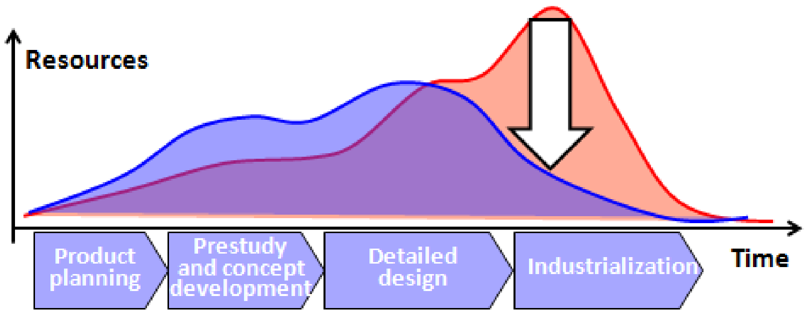


Figure 10: Difference in resources allocation [6]

2.3 Methodology

This first part of the thesis was essentially to understand the way the company works, especially in the design phase. It was important to know which methods and tools are used for the development work, to try to identify the gaps, the needs and the existence of lack of knowledge.

2.3.1 Literature study

This thesis work started with an external literature study (books, thesis and articles) regarding mainly the design process and the influence of DFM and DFA in it, in order to get familiar with the topic of the project. During the development of the thesis, the information studied was mainly internal of the company like guideline documents, design practices, concept books and general technical information.

2.3.2 Volvo intranet

It is a useful tool to start to get to know the company. It provides useful and detailed information regarding the phases of product development according to the standards used at Volvo Group and the way the company is structured with its all different departments.

2.3.3 Unstructured interviews

In order to obtain more knowledge about the situation of the company and the work methodologies, employees of a lot of different areas were interviewed in an unstructured way, which means asking open questions and maintaining a fluent talk and discussion about the topics. This is a good method when the interviewer does not have a lot of knowledge, gaining a deeper understanding in the subject.

2.3.4 Structured interviews

After understanding and having a lot of knowledge about the topic, structured interviews are a good way of interviewing key people that can provide to the interviewer very detailed and specific information about issues considered fundamental for the project. In this type of interview, questions are carefully thought and prepared in advance, so the answers can contribute greatly for the development of the project in the areas being explored.

2.3.5 Benchmarking

A good way to check if the company is going in the right direction and to learn new things to apply is to get in contact with other companies from the same business or not and see the similarities and differences in the methodologies and processes used. For this thesis, four companies were benchmarked providing some input that could be adapted and applied at Volvo Aero. To make a proper comparison, a questionnaire was elaborated and followed during the meetings with these companies. The questionnaire can be found in Appendix A.

2.3.6 Designers questionnaire

A questionnaire was prepared and sent by e-mail to designers that work in hot structures. This questionnaire was composed by 16 questions regarding DFM and concept creation and evaluation. Among these designers were structural, thermal and aerodynamic analysts and also design leaders, so a wide range of different positions were covered to have a more reliable base of answers to be analyzed. This way, their opinions and thoughts could be gathered, in order to identify the lack of knowledge and the areas that need to be improved. The questionnaire can be found in Appendix B.

2.4 Results and discussion

This chapter shows the results of this first part of the thesis, which includes the current situation at the company, benchmarking and the designer´s questionnaire.

2.4.1 Current situation at the company

The information about the current situation was obtained through the interviews made and also by using the intranet of the company.

The interviews started in the beginning of the thesis work. More than 30 people were interviewed in an unstructured or structured way. The summary of these interviews, pointing the people and their job positions, as well as the content of the interview is presented in Appendix C.

These interviews combined with the information obtained in Volvo intranet were a good base for the understanding of the working way at VAC and the possible problems existing there. In the next paragraphs, these findings are reported.

Volvo Aero is a company that designs and manufactures components for jet engines. The area of business is mainly to civil aircraft engines from companies like Pratt&Whitney, Rolls-Royce and General Electric, but there are also some components developed for military engine aircrafts and rockets of the aerospace programs.

This Master Thesis is only focused on the engines built for civil aircrafts. Over the past few years, the size of these engines has increased to produce more thrust while reducing fuel consumption. Nowadays, the engines have two paths for the airflow, one that is used to produce the combustion in the combustion chamber, and other that goes around the core of the engine to produce more thrust in the end of the engine. One engine of this type is shown in the following figure.

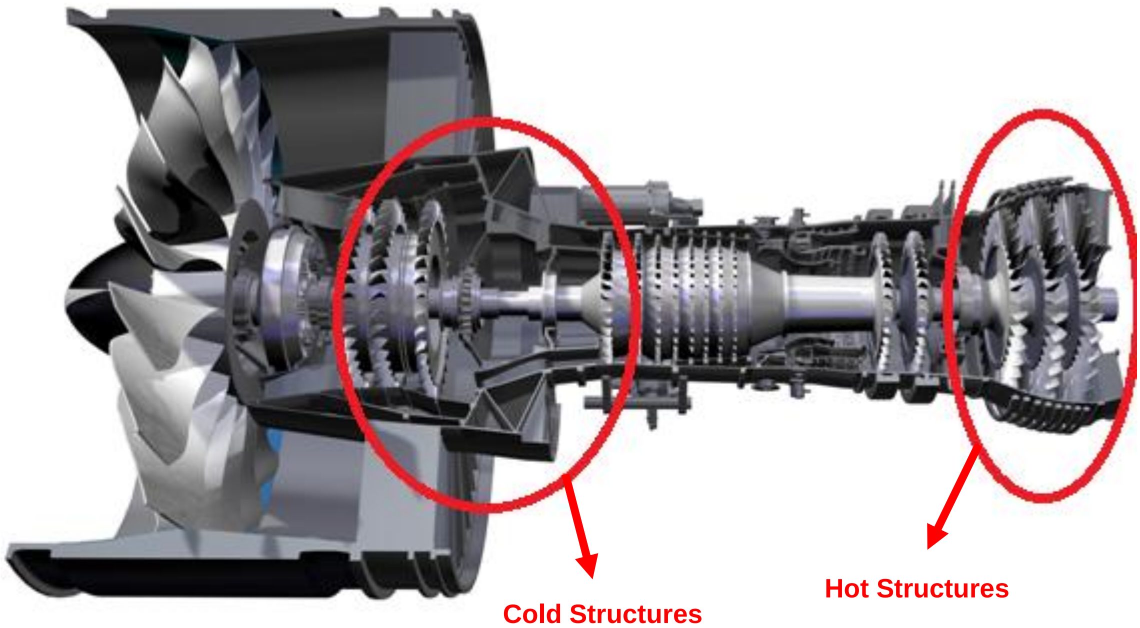


Figure 11: Cold and hot structures in an engine

The engine can be divided in cold structures and hot structures. The cold structures are the ones located before the combustion chamber, and the hot structures the ones after it. Inside VAC, components from both areas are designed and manufactured. There are different requirements for components of the two areas, which is translated in different materials used, therefore influencing the manufacturing operations chosen. One example of a cold structure is the ICC and hot structure the TEC/TRF.

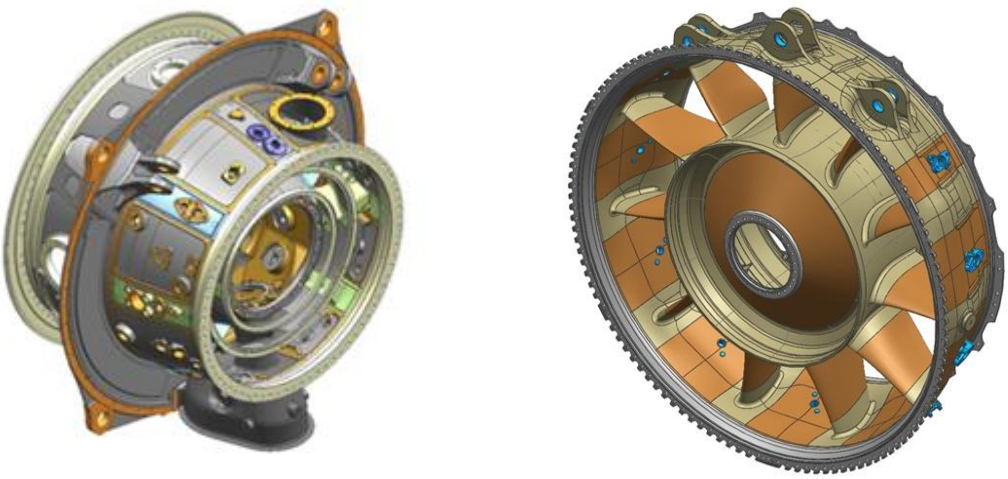


Figure 12: ICC and TEC [7]

The first thing to know about a company is the Mission & Vision. At VAC the mission is *“Specialized for partnership”* where the core competences are the development and manufacturing of components and complex light weight structures. The vision of the company is *“Best Partner”* where is necessary the innovation of customized partnership solutions for a long term *[7]*.

The company is based on a system that is used in all the companies of the Volvo Group. That system is called VPS, Volvo Production System. This system is the base for common principles and practices to achieve operational excellence. It has five principles: Teamwork, Process Stability, Built-in Quality, Just-in Time and Continuous Improvement. These will make sure that the main focus of the company is the customer and it is known what to do in order to create value for them.

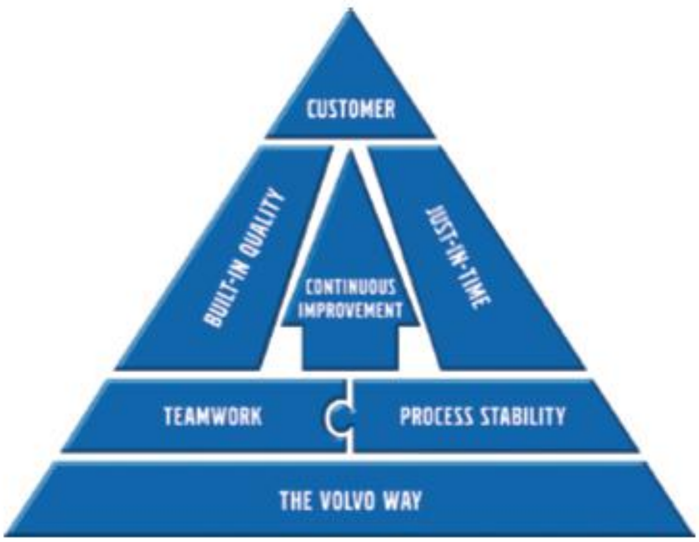


Figure 13: VPS principles [8]

VPS influences the Product Development (PD) in the way that good methodologies and ways of working are established. There is also the opportunity to learn from other companies inside the group and also from other production facilities, taking from there good examples that will lead to improvement *[7]*.

To assure quality in all activities performed by VAC, the company has a tool called Operational Management System (OMS). This quality management system provides the way work should be done by the employees in order to satisfy or even exceed the expectations of their customers, so the vision *"Best Partner"* is achieved. All the different areas of the company are described in OMS as shown in the following figure.

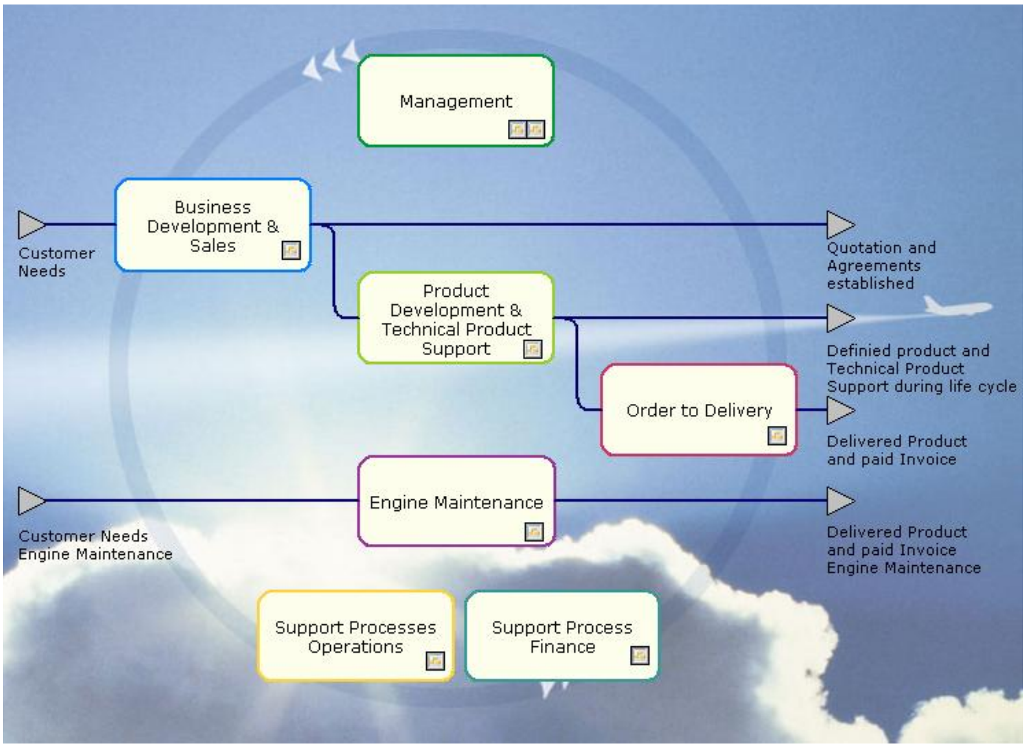


Figure 14: Departments at VAC [7]

Inside PD & Technical Product Support, it is where the products, components, concepts and technologies are developed to meet the requirements of the customers. Two main areas can be distinguished here, the Technology Development (TD) and the PD itself.

The PD phase includes the creation and definition of a product, its manufacturing and production and the use and maintenance of the same. This phase involves some activities and procedures to follow such as: Design and Manufacturing Solutions, Design Verification and Validation, Manufacturing Verification, Sourcing, Serial Production Preparation, Design and Product Quality Assurance, Manage Product Cost, among some others. The PD phase is described in a development logic that is common to all the companies of the Volvo Group called Global Development Process (GDP). The GDP is the result of many years of practical experiences from all the companies of the Volvo Group, so it gathers a well proven systematic and structured way of working in the development phase of a product. It is generic enough to make possible to have the flexibility to fit in every project, no matter its nature or complexity. The fact that is a common base for all projects of all companies has some benefits. It helps the communication and cooperation between common projects, the share of competencies and resources, the use of common tools and finally the share of best practices in the processes. The GDP is divided in six different phases, each one of them with a specific focus in the development work. These phases are initiated and finalized in gates that go from G1 to G8.

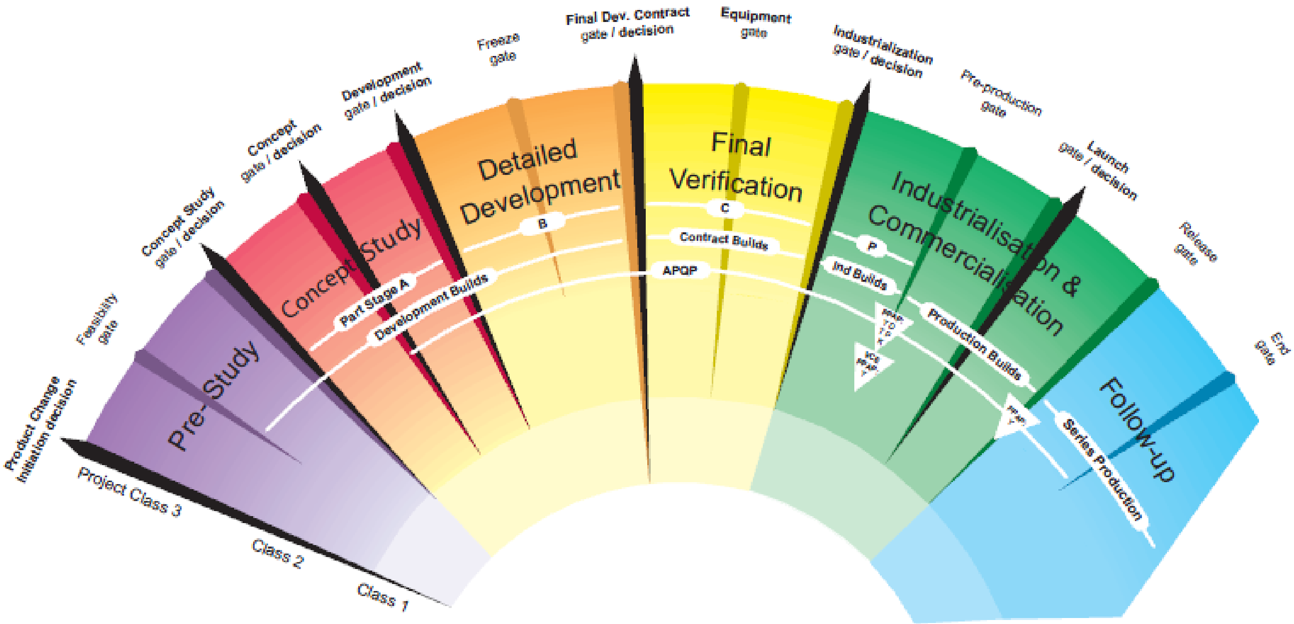


Figure 15: GDP phases [8]

During these different steps, several activities are performed simultaneously in the same one and also during different ones, as can be verified in the following figure.

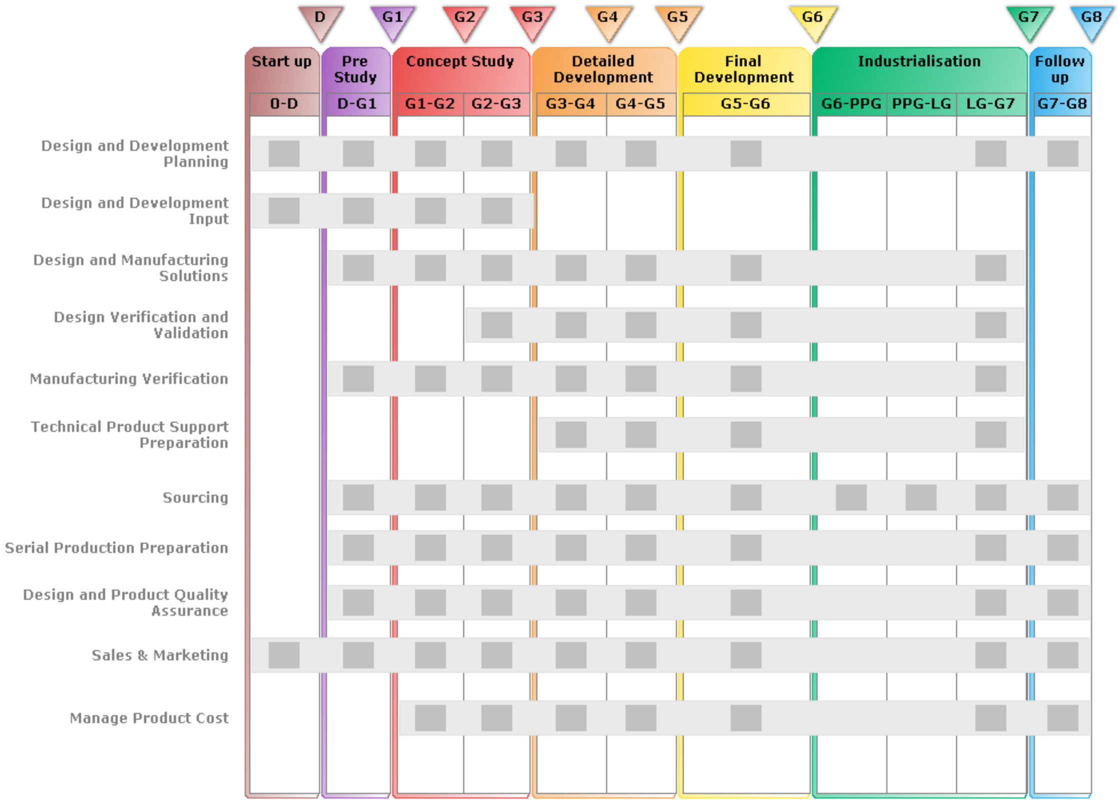


Figure 16: Activities performed in GDP phases [7]

The gates are checkpoints where the Steering Committees of the projects see if the criteria of that gate were met, so it can be closed, and prepare the next one.

The GDP and VPS interact with each other in order to find the most efficient way to work. With the GDP knowledge is built and with VPS the philosophy of continuous improvement is provided *[8]*.

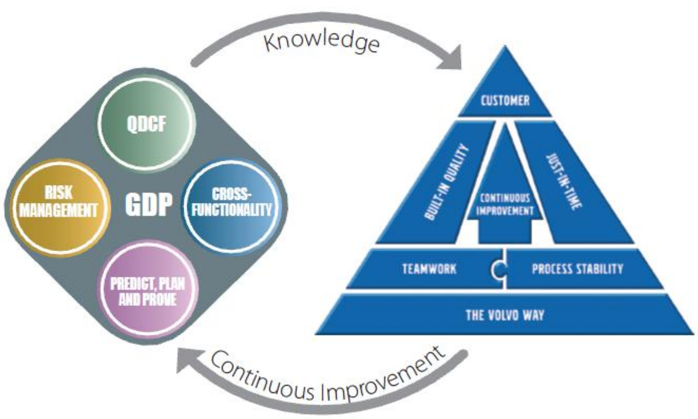


Figure 17: Relation between GDP and VPS [8]

The most important issue is focusing on the customer, because the products are developed for them, so their expectations need to be fulfilled and if possible exceeded. They set requirements for their products that must be achieved. Other stakeholders, set requirements as well, that must be taken into consideration. The V-model shows how these can be broken down into measurable things so a suitable alternative can be developed and chosen (left leg of the model) and then verified and validated according to the initial requirements (right leg).

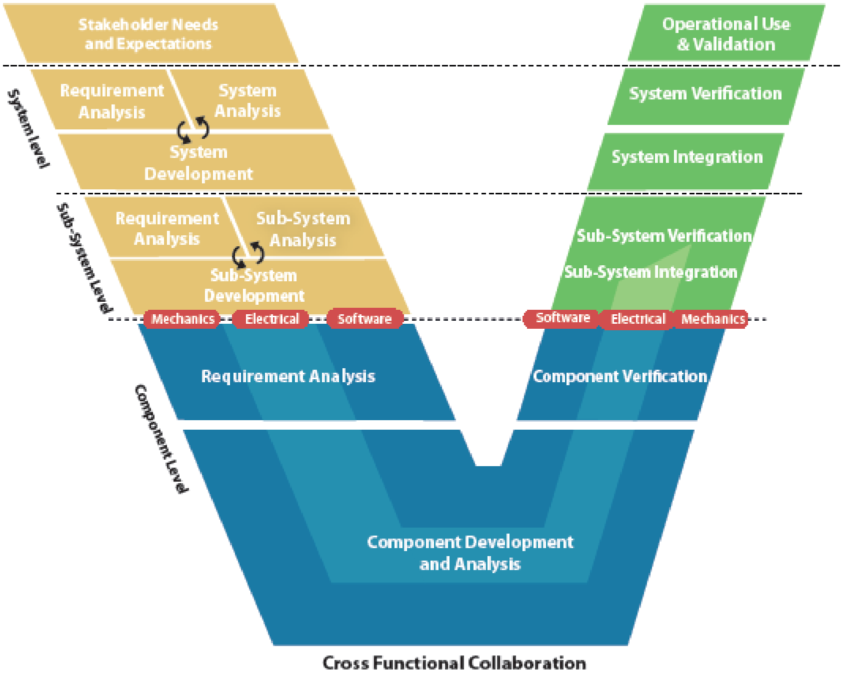


Figure 18: V-model [8]

This process is done cross-functionally, like all successful development work is. It is necessary skilled people from different areas, that working together and communicating towards a common goal will develop the best product possible.

Figure 19: Cross-functional team [8]

Everything done in a project has to meet the targets established. These have to be in accordance with the QDCF principles, which are Quality, Delivery, Cost and Feature. To fulfill these four principles, risk has to be managed along the project to avoid problems in achieving them.

The TD phase happens separately to the PD phase. In TD the pressure of a time limit is not verified. This phase is very important in order to keep bringing technology innovations that can be used later in PD projects. These researches are done outside PD phase to reduce the risk of failure of the technologies during this time that would lead to high costs and delays. During TD, there is a scale to measure the maturity of a certain technology called Technology Readiness Levels (TRL). It is necessary that a technology has reached level 6 to be possible to use it during PD projects.

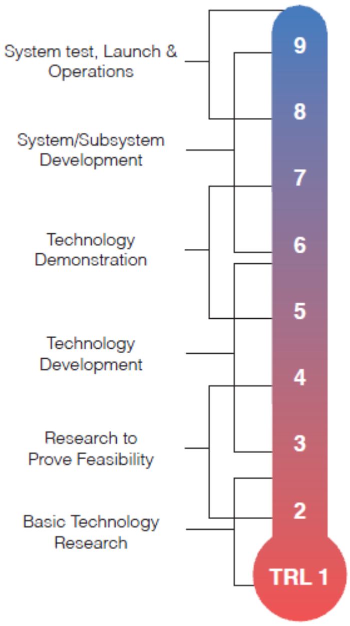


Figure 20: Technology Readiness Levels [8]

The development of a new product starts in the Concept Study phase. It is in this phase that the concepts are generated and evaluated, so one is chosen for detailed development. The generation of concepts occurs in a brainstorming session with people from many different areas. From this meeting, around 20 concepts can be generated that most of them are combined together to form 4 or 5 concepts. These concepts are developed and studied in terms of stresses, aerodynamics, temperatures and cost. The next step is evaluating the concepts in order to choose which concept will be developed further in more detail. For this purpose, it is used a selection matrix combined with risk analysis. At VAC, the type of selection matrix used is a Pugh Matrix, where the different concepts are compared in a subjective way with each other regarding some criteria that is based on the initial requirements of the project. These criteria receive weights according to their importance and then each concept gets a value in each criteria that will result in the final rate of that concept.

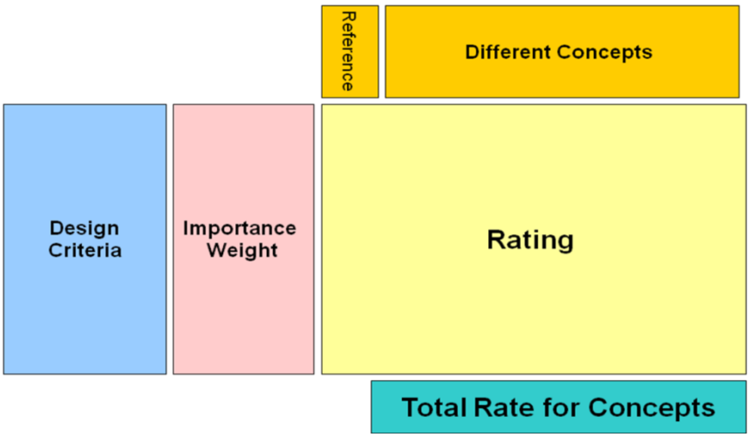


Figure 21: Pugh Matrix [9]

There are not any production requirements breakdown used as criteria for the ranking of the different concepts in these Pugh Matrixes. Normally, it only exists one row that takes producibility into consideration, which is not enough to assess the concepts in a manufacturing point of view.

For the risk analysis, a FMEA is performed, where risks related with design or production, depending on the type of analysis, are identified for each concept. These risks are graded in their level of severity and probability. Finally, the project team makes a decision of the best concept based on these two tools. These results are documented and presented in the Concept Book. This book summarizes all the design work that was done for a certain project, where design and manufacture choices are documented.

Other important documents to consult during the concept work are the design and production platforms. These documents compile methods and processes that are already proven to be efficient, so it is a good practice to base the work according to them.

Since it is in the earliest stage of the product development that the most critical decisions are made, it is comprehensible that it should be in this phase that more resources (money, people, etc) are used. The ideal would be to develop lots of knowledge during TD phase, so only good and proven concepts, ideas and technologies should be carried and used during the earliest phases of PD. This way of working follows the principles of SBCE methodology, which theoretically is the more reliable way of working.

The cross-functional teams that develop the concepts have a manufacturing engineer present to take care of producibility issues as soon as possible. It is not the only way DFM is applied at VAC since there are some recently created tools to help designers. Some processes have guidelines and design practices available for designers, giving advices and limitations about the processes, so the designers are aware of them and do not exceed them. Also, a tool showing the capabilities of turning operation was developed in another Master Thesis and checklists for casting and welding creating by their method specialists have been implemented in the CAD software used at VAC.

Regarding cost, it is the responsibility of cost engineers to verify if the concepts are inside the limits, which means not exceeding the target cost. This assessment is based in rough estimations done by method specialists that can lead to errors, so there is a necessity of having more accurate cost predictions. Most of the times, the target cost is not reached, so more efforts should be done to try to solve this problem. A new cost model introduced only at TD so far is the ULSAB model, which comes from the automotive industry and it has been modified to be applied at Volvo Aero. This model is a cost breakdown, that shows every single detail of an operation that has a cost associated to it and the person responsible for this model gives values to these parameters to achieve the final cost of the manufacturing process. This model requires more use and tests during PD to check its accuracy and reliability to be used in that phase.

In every project it is necessary to try to balance the future product between three important aspects: technical requirements, cost and producibility.

Figure 22: Requirements [7]

Over the years, technical requirements have always been the most important one, not caring a lot with producibility, which brought problems in production. So, the reality of the figure above is the following at VAC.

Figure 23: Unbalanced requirements situation

Producibility is a complex term that can have multiple meanings, but in this context can be defined as how good is a design in meeting the production requirements. Therefore, these requirements from production have to be set to designers from an early beginning of the design phase, so they are considered and producibility can become a requirement as important as the others.

After getting to know all this information, it was necessary to narrow the scope of the Master Thesis, since the initial description of the project was very wide and vague. It was decided to limit the project to hot structures such as the TEC due to the several different projects already existing of this component. It was also decided that this project should aim to create a tool to be used by designers in their work at the earliest stages of PD, which means the Concept Study phase, where both design and manufacturing are working concurrently and there is the opportunity to apply DFM to support the work in progress.

2.4.2 Benchmarking

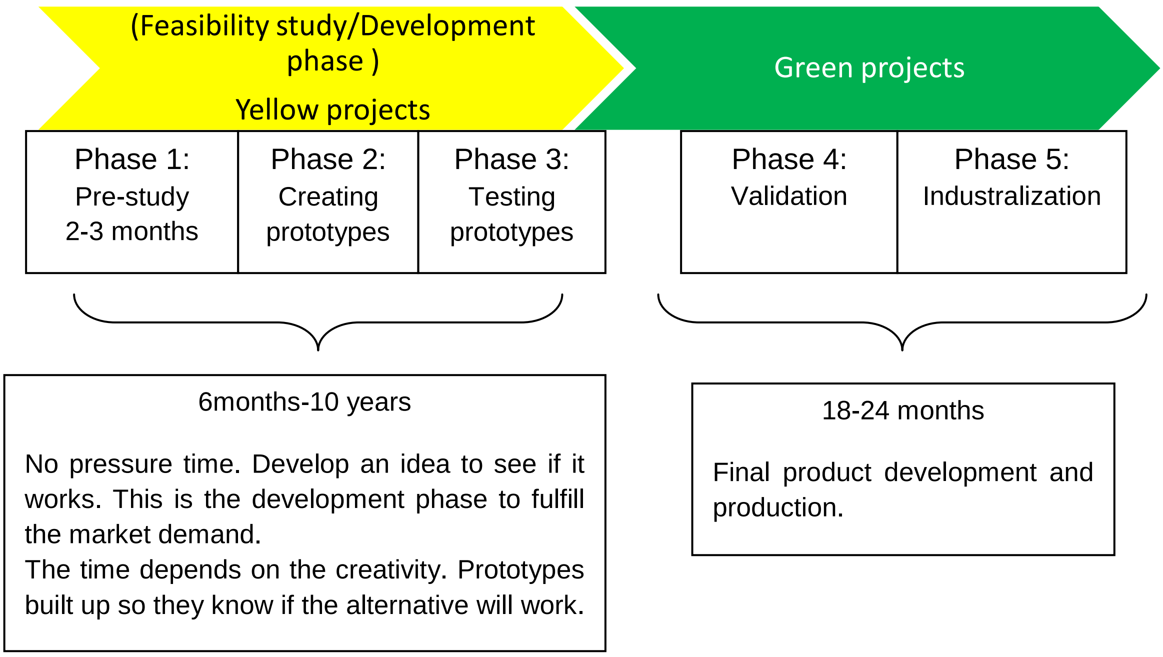
The results and analysis of the benchmarking to other companies is presented with the comparison between them for general topics and not for every single of the 18 questions presented in the questionnaire, since some of the questions were not asked or answered by them and it would be a very extensive analysis and probably with some irrelevant parts.

The companies benchmarked were SKF and Volvo GTT located in Göteborg, Scania in Södertalje and SAAB Aerospace in Linköping. For the three first companies, the meetings took place at their headquarters, while the meeting with SAAB Aerospace was done through videoconference.

The type of project structure followed at Scania is a matrix one. Since it is a quite big company, this type of organization is the more suitable to be efficient in their processes and projects.

Regarding concept work, SKF has some contribution from method specialist, besides designers of course. At Volvo GTT, the concept work is based in requirements set in the beginning by stakeholders such as manufacturing, design and at SAAB Aerospace it is done by concurrent engineering using cross-functional teams. Finally, at Scania, the matrix organization allows that people from different departments are present in the concept work, balancing this way all the requirements from the different areas.

The product development phases are quite similar from SKF in comparison with VAC. They also have a TD phase where TRL levels are used as gate system in that phase. In product development, there are technical gates, where the pre-study that corresponds to Concept Study at GDP takes about 3 months, the detailed design 1 to 2 years and the validation 0.5 to 3 years. Then the industrialization phase is the next one, ending in production for many years. At Volvo GTT it is used the GDP system since it is a company of the Volvo Group. Only technologies with TRL 6 can be approved to be used in product development, and this phase can take up to 46 months. At SAAB Aerospace there is a similar system as the GDP, and the concept study takes up to 3 months. At Scania, the system of developing a project is different. It is divided in yellow and green projects, where the yellow phase is similar to the TD at VAC, but further developed. In the end of this phase, if the project is feasible it moves forward to the green phase. This system is represented in the following image.



The investment in resources and intelligence should be focused in the following phases according to the companies:

Table 1: Investment of resources

	Technology Development	Concept Study	Detailed Development	Final Development	Industrialisation
SKF	x	x			x
Volvo GTT		x			
SAAB Aerospace	x	x			
Scania	x	x			

It is consensual that the more amount of resources should be added in the beginning of the projects, where the most important decisions are made. The two companies of Volvo Group focus more on the concept study phase, while the other companies benchmarked consider TD as the most important phase.

For the concept creation, the companies use the following knowledge as the starting point:

Table 2: Concept creation knowledge

	SKF	Volvo GTT	SAAB Aerospace	Scania
Platforms		X		X
Benchmarking		x	X	X
Technical specifications(cust req)	X	x	X	X
Previous projects	x	x	X	X
Technology Development period	x	x	X	X
Guideline/Principles	x	x	X	X
Experience	x	x	X	X
Production knowledge based	x	x	X	X
Courses (trainee)			X	X
Market	X			X
Standardized methods				X

Volvo GTT has similar platforms as the ones used at VAC. Besides having design and production platforms, they also have platforms for assembly. The assembly is performed using like a fishbone line, where different modules are assembled in their stations, being combined together in the main line.

At Volvo GTT they also have architectural and modules guidelines to support the design phase. At Scania, the platforms are a bit different, since they are present in the modules. They also have a list of 59 items of assembly principles to be used by designers. The table above shows that the knowledge used by the companies is similar, happening the same at VAC as confirmed in the designers´ questionnaire.

The concept creation starts with a brainstorming session with a team of experts in different areas at SKF. They use DFSS toolboxes, using principles and guidelines. One example of something they use is QFD. At Volvo GTT, all the team members are aware of the list of project requirements from the stakeholders and from there several concepts can be developed in parallel or they just try to make variations from already existing ones. Scania bases their concepts in trying to combine the different modules existing to fulfill the customer needs and requirements.

For concept evaluation and selection, SKF, Volvo GTT and Scania use Pugh Matrixes to do select the best concept to develop further. SKF usually evaluates the concepts using customer requirements as criteria and also parameters like robustness, maturity, cost and risk analysis. In Volvo GTT they discuss in group which is the most important factor of decision according to the project and at Scania they base the comparison on cost, time and quality. SAAB Aerospace evaluates their concepts according to cost and weight, since these two are the only parameters their customers care about. So, there is not any difference in the tool used compared with what is done nowadays at VAC, although the technical requirements are the most important criteria in the company.

The term “producibility” does not have a clear definition in those companies. At SKF it can be seen as related with cost, trying to manufacture more with the same resources. It can be also related with process control, capabilities and robustness. At SAAB, the idea is also that it is connected with cost.

Regarding the methodology of SBCE, it is not in use at SKF, although they had heard about it. Some things are documented, especially the good ones, but they are not reused in later projects. At Volvo GTT, they also know about this methodology, but they do not use it. There is not a good communication and there is no data available for creation of trade-off curves for example. SAAB thinks this methodology is not good for their type of work, since they sometimes have projects with 800 requirements, so they say it is impossible to have trade-off curves about them. They also choose one concept quite early to optimize based on cost and weight. At Scania, this methodology is unknown, although trade-off curves are used, not for design purposes but for manufacturing decisions.

Cost assessments are taken care of since the beginning of the project at SKF. Cost models from materials, suppliers and production are used and a lot of people is consulted to make the assessment of a new concept, which is really difficult. It is easier and more accurate the result when the concept is just a variation of one that already exists. In Volvo GTT the cost is just taken care after concept development, which is the job of cost engineers to do rough estimations and quotations for purchased parts. At SAAB they use their cost models since the beginning since it is one of the most important parameters for their concept. Since cost is one of the steering parameters at Scania, the assessments also start in the beginning of the project. They use a cost calculation system, but their assessments usually are not good, which is something they want to improve.

DFM is not applied at SKF. They do not have any methods or guidelines, since they think it is not necessary to have it. They use the same processes for a very long time and they are highly specialized in 3 products, so they already know about what the limitations are and what can be produced. DFM is implicit in everybody´s mind and new designers take production courses and training. The capabilities of the processes are documented but not reported to designers. Since Volvo GTT has more assembly than manufacturing, they have a defined structure for the assembly sequence in their line. Manufacturing people are present in all stages of the product development, since the initial requirements they set until the end of the project, so it is still based on experience and talking. The aim at SAAB Aerospace in this moment is to implement DFM. They have been using cross-functional teams with manufacturing people involved, but it is not enough. It is necessary to have tools and methodologies. They already have simple design guidelines that they adapted from A SAE course and they also use DFM handbooks. Scania also has more assembly. They have been using DFA, creating a list of 59 items. Regarding manufacturing, there is a lot of interaction between people of design and production, and sometimes they take courses in each other departments. Capabilities are known but not reported to designers, since they think they do not understand them.

SKF is very developed using Lean methodology, with weekly meetings in a room where problems can be visualized. This way everybody involved is aware of them and try to solve as a team.

Volvo GTT uses a table like the following one to visualize which requirements are not fulfilled yet.

Table 3: Requirements fulfillment visualization example

	Requirements	Fulfillment	Status
Cycle time	-4%	+2%	**Red**
Weight	-100kg	-110kg	**Green**
Cost	-5%	+1%	**Red**

This is also a good way to see which are the problems to solve and work in order to achieve that.

2.4.3 Designers questionnaire

The questionnaire was sent to all designers working in hot structures and 11 of them answered to it. The answers and analysis to the questionnaire present in Appendix B are presented in the next pages.

1.

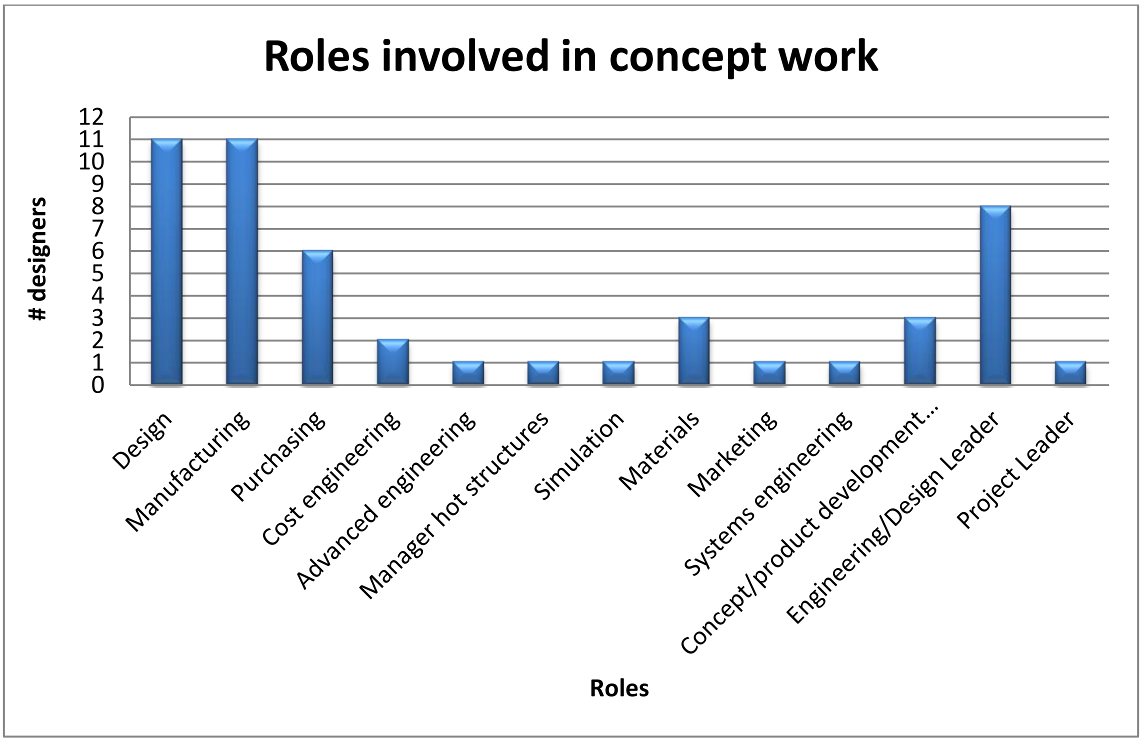


Figure 24: Roles involved in concept work

Concept work is done by a cross-functional team. All designers answered that people from Design and Manufacturing are always present in this work. It is a good result since this is the

first important step to apply DFM in a company. There are other roles mentioned by some designers, which always depend in the projects they have been involved. The role of purchasing engineers, which is also very important for DFM, is only mentioned by approximately half of the designers, probably because some refer to them as being part of manufacturing people. Design group encompasses aero, structural, thermal and definition areas. Since this was an open question, some roles only have one or a few designers pointing to them. It should be taken into consideration that probably the majority of the designers only pointed the most obvious roles and not a detail description of the roles present in the concept work.
One opinion of a designer is that the choice of the members of the team does not depend on roles, but on experience and skills. This opinion can be partly true, but it is always necessary to have specialized people from each area, for a good assessment of the work.

2. The next figure shows in which phases the designers have been working in the different projects they have participated.

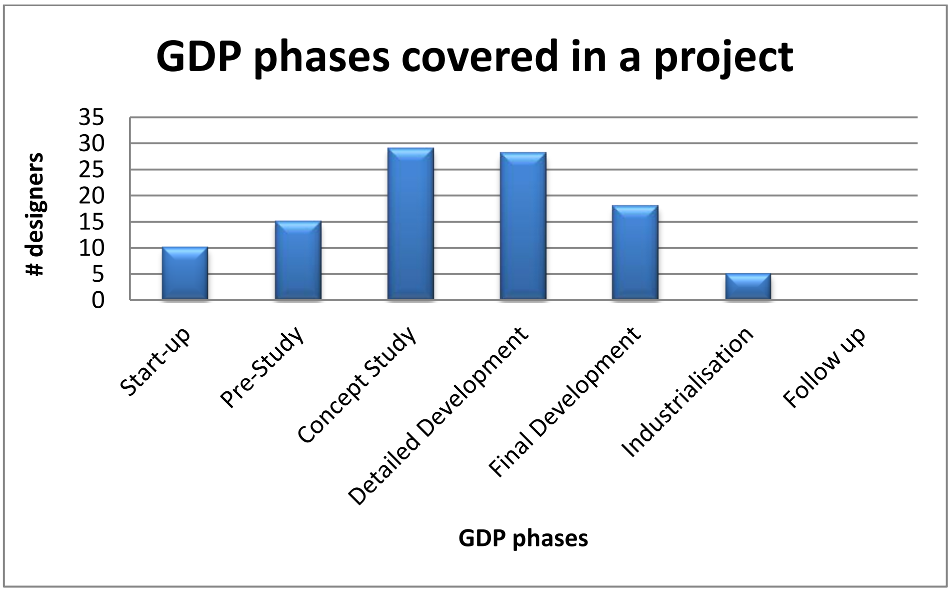


Figure 25: GDP phases covered in a project

Since the Start-up and Pre-Study phase do not cover the actual design work, since it is more related with planning and preparation of the project, the analysis will only consider the other phases. It can be seen that the number of people working decreases as the projects progresses, which is the best way of working because of the learning cost curve shown in figure 7.

The main effort should be done in the beginning of the project when it is easy and cheap to make changes to the design. As the project goes forward to Detail and Final Development, it becomes more costly to make changes, therefore it is necessary to have as much knowledge as possible during the Concept Study phase. So, it is logical to have the majority of the resources in the beginning of a project.

Another graphic can be drawn from the answers to this question.

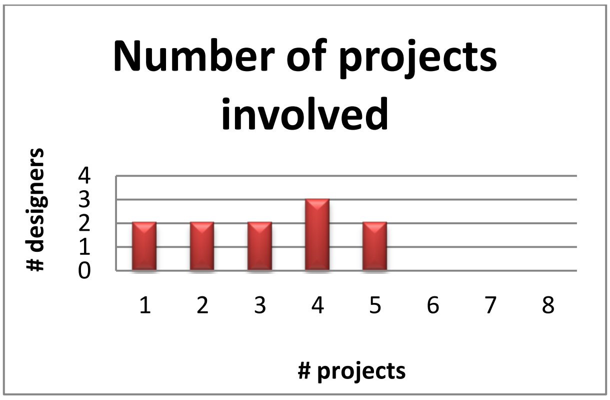


Figure 26: Number of projects involved

It represents the experience of the designers at VAC. It shows that there is a mixture of experienced and new people in the company.

3.

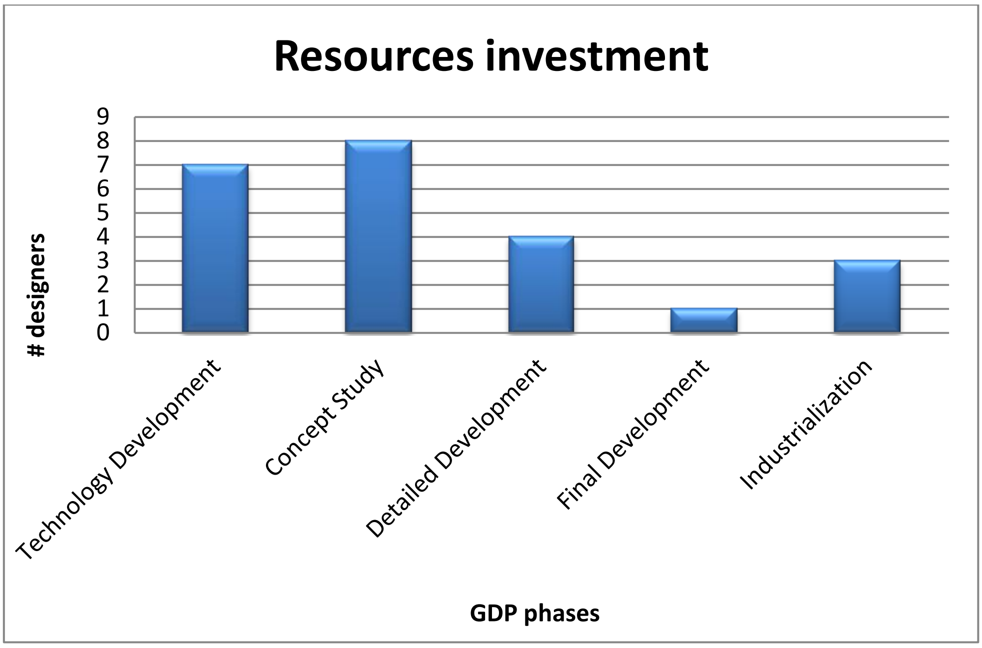


Figure 27: Resources investment

The designers at VAC have a good understanding where the resources should be allocated wisely. Comparing again with the cost learning curve, it is good if there are more resources in the beginning of the projects to avoid late changes that are highly costly. Also, from SBCE theory, the more knowledge the better, therefore Technology Development is very important in studying and developing ideas to make them usable during projects.

4.

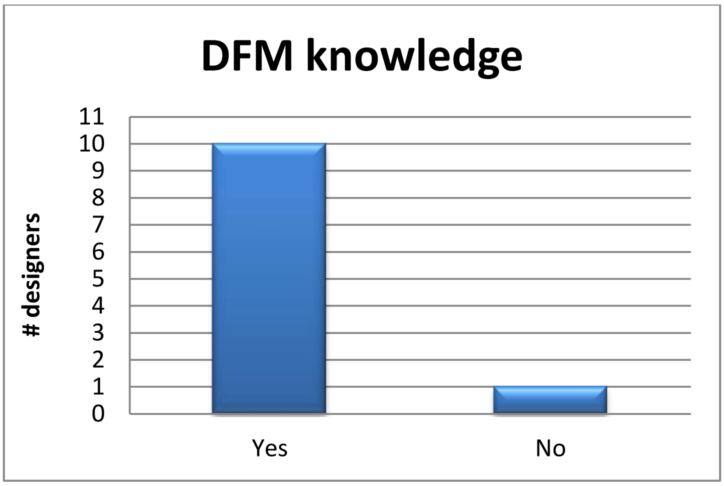


Figure 28: DFM knowledge

The huge majority of the designers knows what DFM is and presents the following sentences as advantages of this methodology:

- Minimize rework
- Avoid poor cost predictions
- Right balance between producibility, cost and requirements
- Decisions based on knowledge data and early tests, rather than guesses from experts
- Reduced cost
- Producible design
- Minimize quantity and severity of problems in production
- Time and money saved in the producibility phase
- Good and fast tool to select manufacturing solutions and details such that a low cost production design be developed
- More likely to find the best way when evaluating and comparing different manufacturing methods in a team

These opinions of VAC designers match with the advantages described in the theory presented in literature.

5.

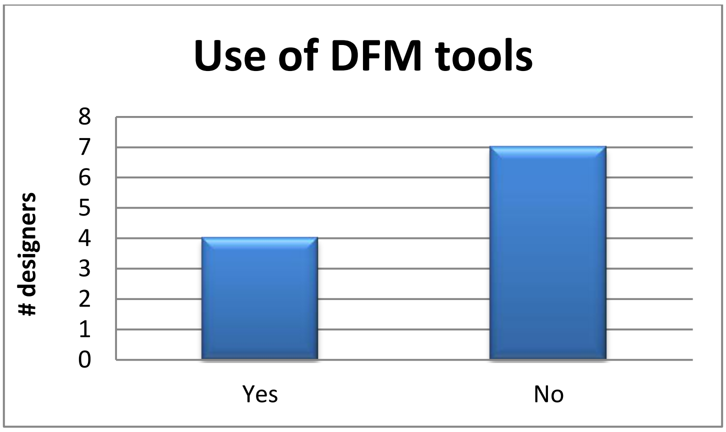


Figure 29: Use of DFM tools

The majority have never used a DFM tool to help in their work. From those who have, the tool used was the cooperation of the manufacturing people included in the cross-functional teams and one designer uses his own evaluation matrix. The use of DFM at VAC is still very dependent on the people and communication, not existing a global DFM tool that encompasses manufacturing methods. According to one designer, there is missing data and unawareness of DFM methods in order to do such thing.

6. As seen in the following graphic, the majority of designers consider that they do not have enough information for their work.

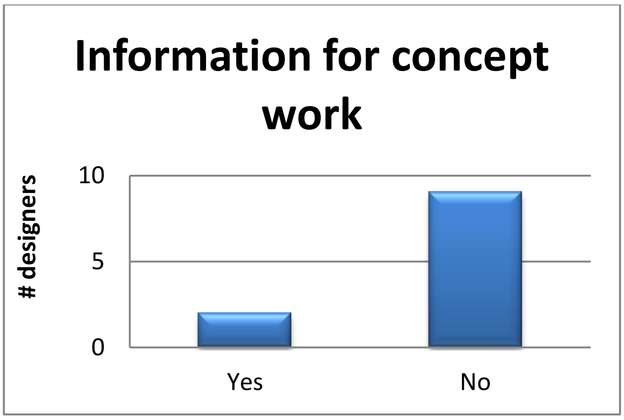


Figure 30: Information for concept work

There is missing information from suppliers, method specialists, production people, cost specialists and customers, being the suppliers and cost specialists the ones that designers more times referred as having lack of knowledge in their field.

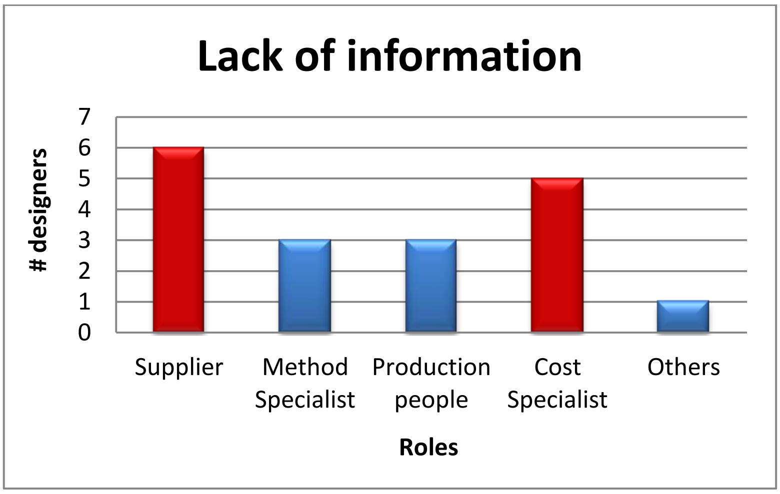


Figure 31: Lack of information

7. Almost all designers that answered the questionnaire know about the Set-Based Engineering methodology.

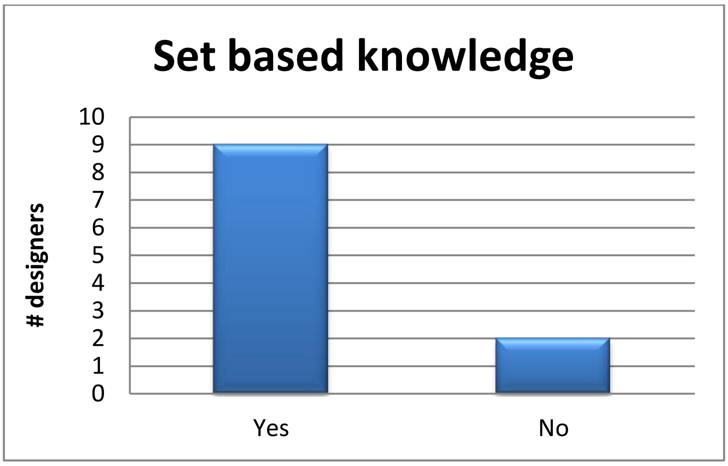


Figure 32: Set based knowledge

8. The knowledge used for creating concepts is the following.

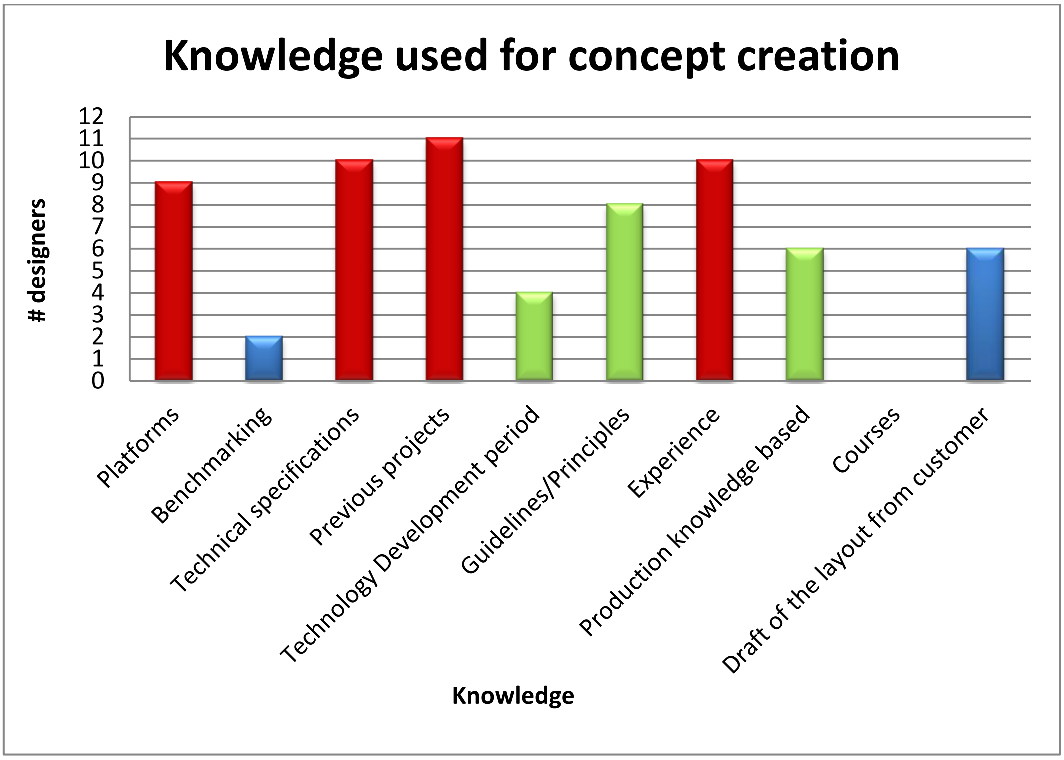


Figure 33: Knowledge used for concept creation

For the concept creation, designers use a lot of things as base to do it. The things more referred were previous projects, designer´s experience, technical specifications and platforms. The platforms used are the TEC/TRF design and production platform and the guidelines are the design practices provided by method specialists, the ones presented in Volvo intranet system or just general verbal information from the experienced people. Basing new concepts in previous projects and experience creates a concept that works, but limits the creativity and an outstanding design is difficult to achieve. Knowledge based information as Technology Development period, guidelines/principles and production knowledge should be more used.

9. The following figure shows the processes which capabilities or design limits are known by the designers.

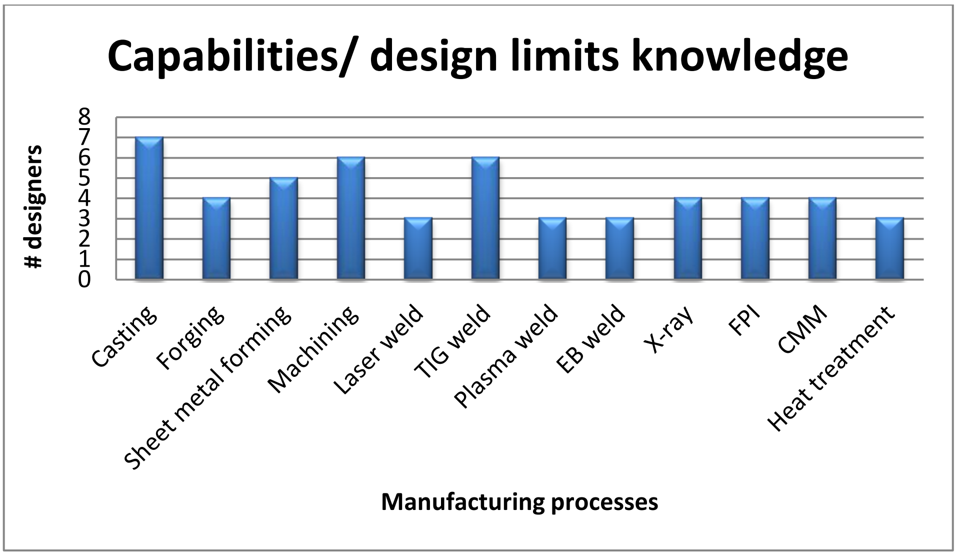


Figure 34: Capabilities/design limits knowledge

According to the designer´s opinion, there is a some knowledge about casting, machining and TIG welding. Since the three processes are critical for the manufacture of the components, it is important that the capabilities of them are known. It is also important to point that most of designers do not know the design limits of the other types of welding and forging, which can bring problems since they are critical operations as well.

The designers considered that there is lack of knowledge or need to improve in these areas:

- Knowledge curves are missing from most of the processes, i.e. the limits of the process at combinations within a given solution range, because the prefect parameters described in the guidelines almost never can be applied.
- Some unawareness from experts regarding the limits of the processes and method application range tests or work is not being developed.
- The transfer of knowledge from research and technology development into the production environment is missing.
- Lack of methodology in unveiling key process quality elements and characteristics.
- Crack size detection using X-ray and FPI
- Review and summarize of the DP in terms of important design features such as roughness, form, thickness, profile, weld heights, min radius
- Laser welding, plasma welding, EB welding, X-ray, FPI
- Know how to ask about details
- Basically there is a lack of knowledge in all processes, especially machining.
- Just known some bits and pieces of capabilities and design limits.

- There are “guidelines” for most of the processes, but the exact design limits aren’t known, because designers are constantly pushing the limits
- Learn more about forging and sheet metal forming, as well as laser and plasma welding
- Processes for new materials
- Sub processes such as etching and high speed machining
- Effect of rework in material properties

10. Some designers skipped this question, probably because they do not know the answer to it. The results from the others are shown in this graphic.

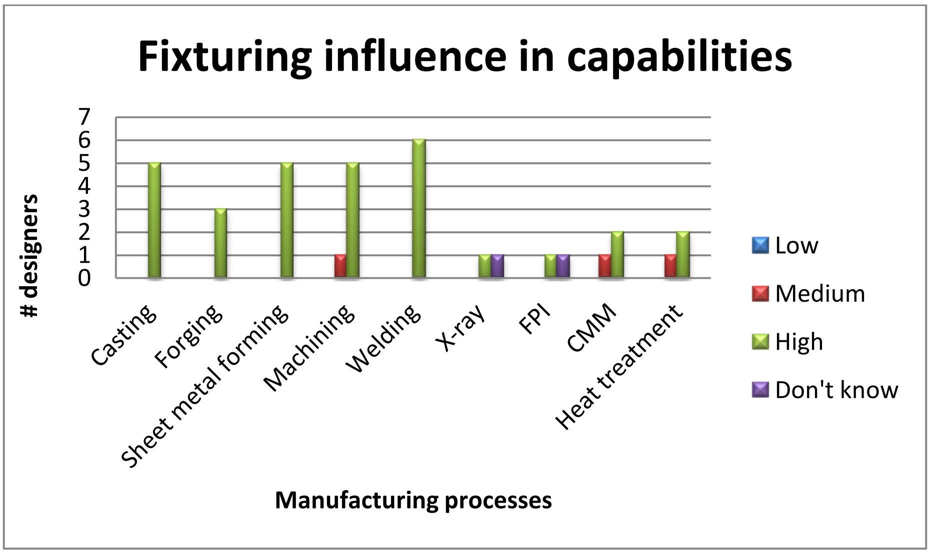


Figure 35: Fixturing influence in capabilities

Designers think that fixturing have high influence in capabilities of machining and welding, and also for the three purchased operations. It is known that both machining and welding require fixtures to hold the parts to perform the operations, so its quality is very important for the final result.

11.

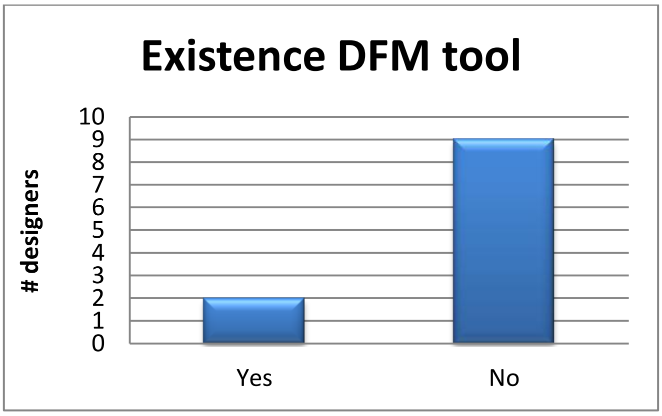


Figure 36: Existence of DFM tool

The existence of the DFM tool about tolerances and capabilities in turning that was developed in a Master Thesis is unknown for the majority of the designers. So, it is not surprising that nobody uses this tool in their job, because they do not know about the existence or they do not need to perform their work.

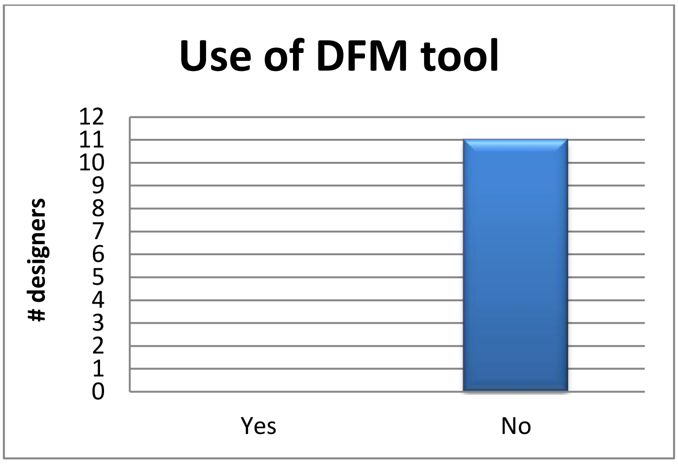


Figure 37: Use of DFM tool

12. Another DFM tool existing is a checklist for welding and casting developed in house and implemented in the NX software that some designers work with. Only one of them uses it, maybe because their work does not require the use of the software or simply because they do not want or think it is not good enough.

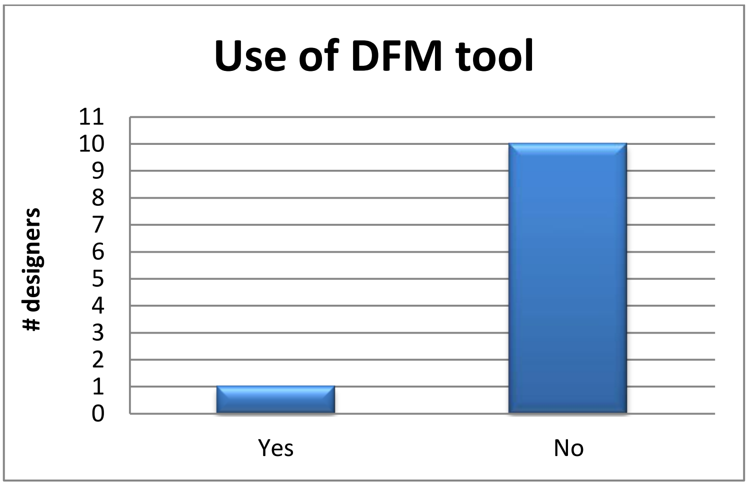


Figure 38: Use of DFM tool

13. Most of people did not answer this question. Probably they do not know what routing means. The ones that did gave the following answer:

- Parallel with concept splits
- Early
- It is constantly evolving
- Brief routing in start-up phase. Developed and detailed in later phases

14. Designers opinion differs a lot when concerns in how many gates of the GDP cost assessments are done. The answers go from just one gate to all gates as seen following.

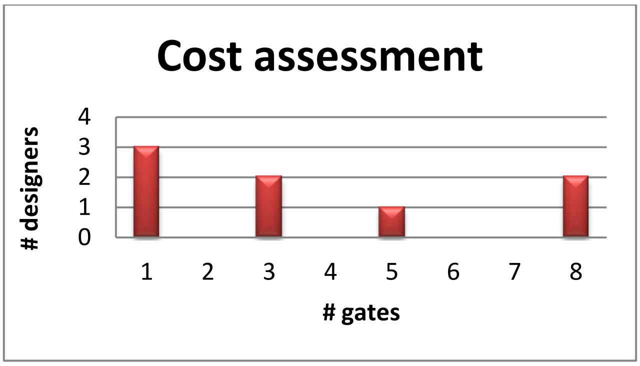


Figure 39: Cost assessment

About in which gate these assessments are done, the results of the interview were the following:

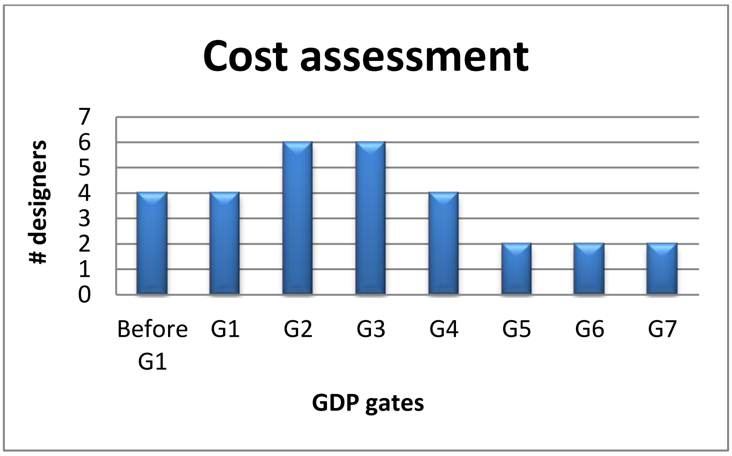


Figure 40: Cost assessment

Designers say the cost assessments are done early in the project, with the majority agreeing that at gate G2 and G3 (during Concept Study phase) it is performed.

According to the designers, the people involved in these cost assessments are the ones that compose the project team, like project manager, design, production, manufacturing and purchasing leaders, process specialists and cost engineers. Some also said that because the assessments are constantly evolving, different people participate along that time.

15. The majority of designers considered cost as steering parameter for their work. Some answered both, that cost is a result and also a steering parameter.

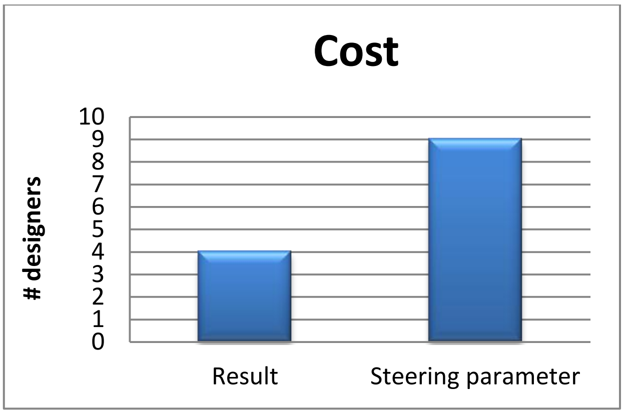


Figure 41: Cost

If cost is a steering parameter, not only cost assessments have to be done regularly, but mainly the designers have to be aware of cost drivers and have a good knowledge about the manufacturing processes, so DFM is very important for this.

16. The cost drivers pointed by the designers were the following:

- Poor quality
- Extensive fixturing
- Machining of very complex shapes
- Lack of multiple sourcing from purchasing
- Welding
- Material
- Cycle time
- Delivery capacity of suppliers
- Purchasing components
- Fabrication, complexity, many parts and processes
- Design requirement fulfillment
- Late changes in design phase
- Design adjustments on frozen concepts due to change in technical requirements
- Design without considering cost of manufacturing processes
- Machining
- Welding, unless robot makes possible to have low distortion
- Optimistic (wrong) early process capability assessments
- Suppliers, not aware of requirements. Spend more time with them discussing ideas from technical side and how to reduce cost
- NDT
- Low volumes, better large volumes with customized cells, tools and machines

2.5 Conclusions and suggestions

2.5.1 Conclusions from benchmarking

In all the companies benchmarked there are always manufacturing people present in the concept work. Although DFM is not very well implemented, without the use of almost any tools or guidelines, at least, this presence is a help to deal with manufacturing issues in the earliest stages of concept development.

The time spent in concept study is the shortest compared to all other phases, although it is the most important phase, where the critical decisions are made. Therefore, designers consider that this should be the phase where more resources should be spent in order to make the right decisions. The designers at VAC have the same opinion as it can be seen in their questionnaire. The technology development phase is crucial, not only to increase maturity of new technologies and research in new areas, but also to create useful knowledge that can be directly applied in the concepts while developing them in the concept study phase.

These companies do not use SBCE. It is known that designers at VAC already have knowledge about this methodology, so it could be interesting to start applying at the company, in order to compare the results with these companies that do not use it.

Documentation of knowledge is sometimes done in these companies, although is seldom used for later projects. Also information regarding manufacturing and production is almost never available for designers.

Like at VAC, the cost assessments done in these companies have their problems and most of the times never reach the target cost.

A summary of the benchmarking interviews and its most important content is presented in the next table.

Table 4: Benchmarking summary

Company	Resources allocation	Methodologies	DFM	Concept evaluation	Key evaluation parameters
SKF	Technology Development	DFSS and Lean	No	Pugh Matrix to select the best	Cost
Volvo GTT	Concept Study	DFA	Manufacturing people present from the beginning. Manufacturig requirements as stakeholder	Pugh Matrix or +/- to select the best	Different parameters depending on the project
SAAB Aerospace	Technology Development	Design to cost, Variation management	Implementing guidelines for designers from SAE course. DFM handbooks. Involved in 2 research projects	One concept based on cost and weight	Cost and weight
Scania	Feasibility Studies (Technology Development)	Modularization, Lean and DFA	No	Pugh Matrix	Cost, time, quality

2.5.2 Conclusions from designers questionnaire

From the questionnaire, it can be concluded that DFM has some implementation inside VAC. It is mainly through the presence of a manufacturing engineer that this methodology is implemented, which means that is based on people and their experience and not on a systematic knowledge based way. Although there are already some DFM tools available for designers, they do not use them mostly because they are unaware of their existence. So, it is necessary to introduce these tools to the designers and if possible give them training on how to use those tools.

Rely DFM just on the presence of people with knowledge and skills is not enough, as seen in the results of the designers questionnaire, since there is still lack of information regarding most of the manufacturing processes. Manufacturing engineers cannot be all the time assisting the design work and also they are not experts in all manufacturing operations. Therefore, there is the necessity of a methodology to be implemented that encourages the build of knowledge and the creation of systematic approaches for the creation and evaluation of concepts.

The designers showed a good understanding of the advantages of DFM implementation and where more resources should be allocated. Moreover, the majority knows the SBCE methodology, which can make it easier the implementation of this way of working in the company. Nevertheless, there are still s high amount of resources working in later stages of the product development, such as in Detail Development and Final Development phases.

Finally, cost assessment is an area to be further investigated and developed. There are not homogeneous answers between the designers about when it is done and it is known that the estimations done of manufacturing costs are never good. Again, DFM could provide tools that help making better cost predictions.

2.5.3 Suggestions

To end this first part of the thesis, some suggestions are done in order to deal with the problems found, specially producibility. These suggestions can be used to create a systematic approach based on DFM methodology, to be implemented during the development work of a component.

First of all, the project organization should be a matrix one, like Scania uses. Since VAC is a big company, in which the projects involve a lot of people from different areas of expertise, the matrix structure makes easier to balance all the requirements from those departments, since the team members have to report both for the functional and project manager. This way, the most important requirements from each division would be always taken into consideration for every single project.

During the phase of setting all the requirements, the production ones should be really specific and breakdown. This step can include the use of DFM tools that increase the awareness of having to deal with manufacturing issues from an early beginning.

The evaluation and selection of concepts should not be based in opinions and feelings, as it is when using a Pugh Matrix. Instead of a selection, this process should consist on the elimination of the worse concepts gradually in time, based on SBCE. Production requirements should be used as one of the criteria to base these decisions, as well as other important criteria based in facts.

Finally, more resources should be allocated in TD. Besides developing new technologies, which is the current goal of this phase, objective ideas and proven concepts should be developed here, so when a new project would start, the right decisions would be made in the early phases, which are becoming shorter and shorter in time, avoiding loopbacks and firefights in later stages.

3 Part II

3.1 Introduction

The second part of this Master Thesis project is the case implementation. It aims to create ordinary tools to be implemented at VAC, which take into account the manufacturing aspects that are currently missing during the design task.

Tools and principles are the foundation of every methodology in order to fulfill the company core values. The DFM tools are a good help to implement DFM methodology and achieve profitable results, but they are not enough by themselves. The engineer work is the fundamental part of this puzzle. Consequently, for a company to succeed with DFM, the engineer mind should think in DFM while performing the work and also make use of the tools as a valuable help.

3.2 Literature review

This sub chapter presents some theory that gives the base to the development of the DFM tools, such as trade-off curves, Design Structure Matrix and Quality Function Deployment/ House of Quality.

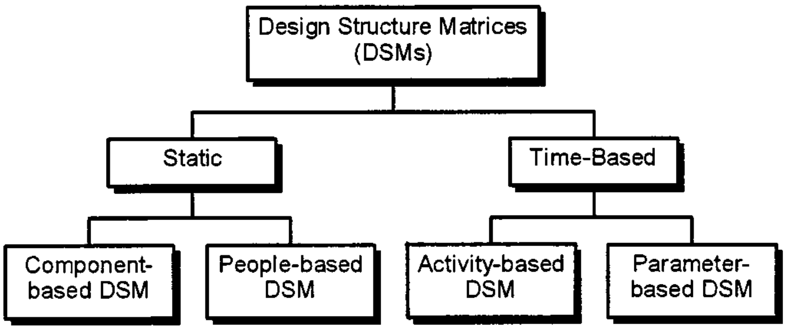
3.2.1 Trade-off curves

Trade-off curves are used as a tool of SBCE. Trade-off analysis is a way to provide information and knowledge to the design team before any work or result is obtained. Knowledge gaps are closed by the existence of trade-off curves, since the designers have the necessary information to establish the design limits from an early beginning. These curves are basically the correlation between key parameters, which can be either technical or manufacturing requirements. The main advantage is the visualization, since it is easier to understand how two parameters behave in respect to each other following a curve than searching numbers within a table. Therefore, trade-off curves´ main goal during the concept work would be to support the designers´ creations or decisions and to guide them to achieve a producible result. During concept work the need is to know where the design limits are referring certain aspects in order not to start with a wrong concept from the beginning.

3.2.2 Design Structure Matrix

The Design Structure Matrix, also known as dependency structure matrix, dependency source matrix and dependency structure method, is a general method for representing and analyzing system models in a variety of application areas. A DSM is a square matrix, meaning that it has an equal number of rows and columns, which shows relationships between elements in a system. Since the behavior and value of many systems is largely determined by interactions between its constituent elements, DSM has become increasingly useful and important in recent years.

There is no pre-defined DSM that is helpful for any problem that needs to be structured. Rather, DSM needs to be adapted to the kinds of elements and relations that prevail in the system in focus. Basically, the type of elements and dependencies need to be defined as precisely as possible to obtain the information structure for the DSM. There are four common classification of DSM matrix. However, any other type of DSM is possible, too.



DSM data types	Representation	Applications
Component-based (Product)	Component relationships	System architecting, engineering and design
People-based (Organization)	Organizational unit relationships	Organizational design, interface management, team integration
Activity-based (Process)	Activity input/output relationships	Process improvement, project scheduling, iteration management, information flow management
Parameter-based (low-level Process)	Design parameter relationships	Low level activity sequencing and process construction, sequencing design decisions

Figure 42: Types of DSM [10],[11]

Therefore, the next step is identifying which kind of elements are going to be analyzed in the matrix, because the use of the matrix and the results´ interpretation will vary depending on the type of elements.

Once the elements are introduced in the matrix, having the same elements in the rows and the columns, it is time to start establishing dependencies between them.

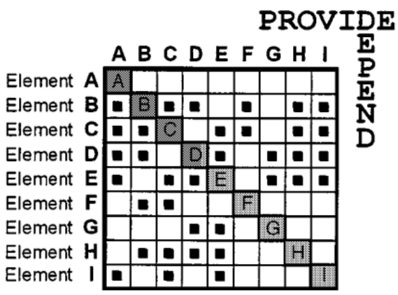


Figure 43: Example of a DSM [10]

Every mark represents the relationship between a pair of parameters.

Once the matrix is completed, the next step is the matrix manipulation. There are different ways of DSM manipulation.

- Partition or sequencing
- Tearing
- Banding
- Clustering

These are different ways to manipulate the matrix but with shared objectives, like identifying groups of parameters that are independent of others.

3.2.3 Quality Function Deployment/ House of Quality

The aim of QFD is to provide methods to achieve design excellence that will be verified in subsystems, parts of components and manufacturing processes. The starting point of any QFD project is the customer requirements, those that describe the component functionality. These requirements are then converted into technical specifications like load distribution, temperature, etc. This stage is referred to as House of Quality. The QFD process involves three more phases, which are the following:

- Product planning (HoQ)
- Product design
- Process planning
- Process control

A chart (matrix) represents each phase of the QFD process. The complete QFD process requires at least four houses to be built that extend throughout the entire system's development life-cycle, with each house representing a QFD phase.

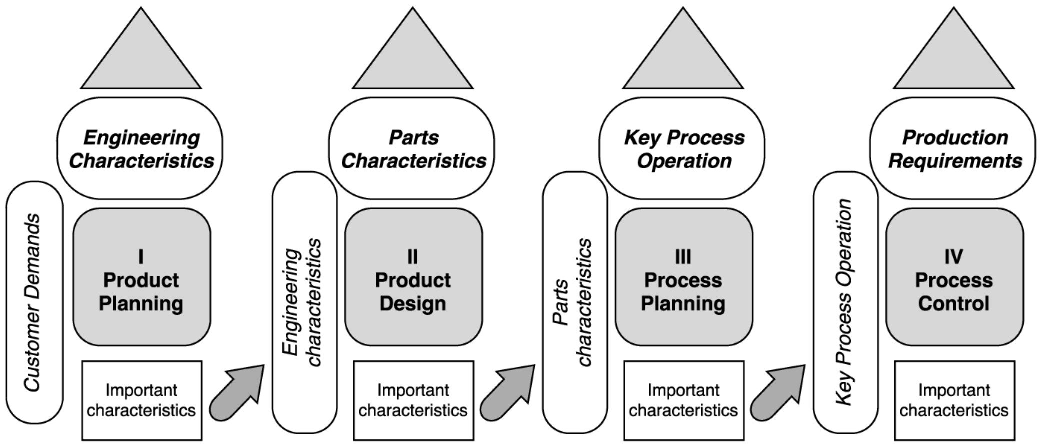


Figure 44: Four phases of QFD [12]

3.3 Methodology

The second part of the project was the creation of tools to be used and possibly further developed in the design teams at VAC. This section presents the explanation of how things were done to get the results achieved.

3.3.1 Trade-off curves

To begin the second part of the thesis, the idea was to create trade-off curves. After the interview with Dr. Durward Sobek from Chalmers, it was decided that the creation of trade-off curves would be a good way to carry on the project and that it could be a useful tool for designers.

The following steps compose the trade-off curves creation.

1. Identify parameters
2. Data collection
3. Analysis data
4. Create the relationships

The parameters chosen were cost drivers from mainly manufacturing operations, since everything can be transferred to cost. This is a way to deal with producibility since the most important cost drivers come from the production period. By detecting the requirements from design and production that are sensible to cost, some useful dependencies can be established. After that, the most significant relationships can be used to create trade-off curves, since it would be very difficult to create them between all the possible parameter couple combinations. Having from an early beginning the relationship between the main cost drivers is a quick way to find the design limits and make right decisions.

Due to the time limitation of this project, only the first step of identifying parameters was performed.

3.3.2 Cost map

In order to identify the cost drivers the first step was to create a cost map. This map was based on the content of interviews mostly to the method specialists and on the definition of each manufacturing process. By using the brainstorm method and some visualization techniques, a big number of cost drivers raised. The complexity of this cost map and the huge difficulties to find out the existing relationships between those cost drives led to make use of some methods to deal with complex systems. Therefore, in order to structure all these parameters, a Design Structure Matrix was chosen.

3.3.3 Design Structure Matrix

Due to the complexity of the studied case, having a lot of cost drivers to analyze, it was necessary to create a systematic approach to compare these parameters. Firstly, the task was defining in detail every parameter, so that there was no ambiguity. Secondly, it was necessary to clarify a method to create dependencies, so every group of parameters was treated in the same way and level, therefore, achieving a fair comparison. Finally it was possible to enter the marks in the matrix. Every mark represents the relationship between a pair of parameters.

The matrix creation has been performed with the help of a software called ProjectDSM 1.0, which allows to establish and to justify dependencies at the same time. The software also automatically manipulates the matrix, giving then the final result.

The final step would be to identify which are the suitable parameters to create trade-off curves. Due to the big task that this implies and the impossibility to carry it out within the project´s time, only some suggestions of trade-off curves will be addressed within Future Work section.

3.3.4 Houses of Quality

As it was mentioned above, there was no time to proceed with the realization of the trade-off curves. However, some other results and conclusions such as critical cost drivers could be used to perform some kind of Houses of Quality.

Three different HoQ were created. The first one follows the theory, being the first phase of QFD. The requirements are distinguished between functional and technical and they are described for the component in study, the TEC. In the second HoQ, production requirements are presented and integrated with the manufacturing processes of the component. For the three purchased operations, these requirements are evaluated in detail in order to see advantages and disadvantages. Finally, the third HoQ differs from the theory. The idea of this project was to integrate QFD methodology to translate the customer requirements into design requirements that take care of the producibility. That means, instead of creating a HoQ for each phase along the project, these successions of HoQ should be integrated and developed during the concept phase, so that manufacturing operations and production requirements are already defined from an early beginning. By performing this kind of HoQ the design would be able to fulfill the production requirements from an early beginning and a balance between technical requirements, cost and producibility would be achieved.

3.3.5 DFM tool

The last part of the project contains a real case implementation. The idea was to transfer all the production requirements and the producibility drivers to the flow of operation of the TEC, specifically from the GP7000 project. In order to create this tool a data collection process at the workshop, following every step of the TEC flow of operation was performed.

3.4 Results and discussion

3.4.1 Cost Map

As explained before, the first step in order to create trade-off curves is to identify cost drivers that later could be used for them. These cost drivers come from the manufacturing processes and have influence in design decisions. Consequently, it is necessary to have a good description of the manufacturing operations and identify the critical characteristics that have impact in the design process. So, the processes are described in the next pages, referring the cost drivers of each.

Materials

The material characteristics suitable for TEC performance should fulfill certain technical requirements coming from functionality aspects. For instance, to support fatigue due to load case and the high temperature that the airflow brings, the material should have the enough strength and temperature resistance. On the other hand, the manufacturing process also gives requirements to the material, such as proper welding characteristics, especially its resistance to postweld cracking. Therefore, manufacturing operations will influence in the material selection, as well.

The materials to fabricate the TEC/TRF considered in this project are IN-718 and H-282.

IN-718 (INCONEL alloy 718)

The nickel alloy 718 is a precipitation hardenable nickel-chromium alloy used at -423° to 1300°F. It combines high strength in the aged condition with good corrosion resistance and weldability.

H-282

HAYNES 282 is a new strengthened superalloy developed for high temperature structural applications, especially those in aero and land-based gas turbine engines. The principal features of this superalloy, besides the excellent high temperature strength (within a range of 1200 to 1700°F), are thermal stability, weldability and easily fabricated.

The materials mentioned above fulfill both, technical and manufacturing requirements. But there are some important differences. The main difference, which will drive the material selection, is the temperature range. For those applications where there is a need to support over 1300°F IN718 is not valid, and it is forced to choose H-282. On the other hand, H-282 is slightly harder to form at elevated temperature compared with Alloy 718, and the result to cast H282 does not achieve the mechanical properties expected from the material; thus, the only possible purchased operations for H-282 are forging and sheet metal forming.

Casting

Investment casting, often called lost wax casting, is regarded as a precision casting process to produce near-net-shaped parts from almost any alloy. Although its history lies to a great extent in the production of art, the most common use of investment casting in more recent history has been the production of components requiring complex, often thin-wall castings. The industrial process is suitable for manufacturing of complex aircraft engine components. The main advantage of the investment casting process is the possibility to create complex geometries including but not limited to hollow structures, complex 3D shapes, etc *[13]*.

The investment casting process begins with fabrication of a pattern with the same basic geometrical shape as the finished cast part. Patterns are normally made of investment casting wax that is injected into a metal wax injection die. Once a wax pattern is produced, it is assembled with other wax components to form a metal delivery system, called the gate and runner system. The entire wax assembly is then dipped in a ceramic slurry, covered with a sand stucco, and allowed to dry. The dipping and stuccoing process is repeated until a shell of up to 20mm is applied. Once the ceramic has dried, the entire assembly is placed in a steam autoclave to remove most of the wax. After autoclaving, the remaining amount of wax that soaked into the ceramic shell is burned out in a furnace. At this point, all of the residual pattern and gating material is removed, and the ceramic mold remains. The mold is then preheated to a specific temperature and filled with molten metal, creating the metal casting. Once the casting has cooled sufficiently, the mold shell is chipped away from the casting. Next, the gates and runners are cut from the casting, and final post-processing (sandblasting, machining) is done to finish the casting. After these processes the part goes thru the required thermal process cycles, such as HIP and heat treatment. The final operations include NDT inspection, such as visual, FPI and X-ray) and dimensional inspection to guarantee conformance to drawing requirements *[13].*

Many process factors affect the final quality of an investment cast product. These factors include mainly but not exclusively process parameters: type of wax, wax injection temperature and pressure, die temperature, mold properties such as slurry and stucco composition, number of coats applied, firing temperature, pouring temperature, rate of cooling, design configuration, etc *[13].*

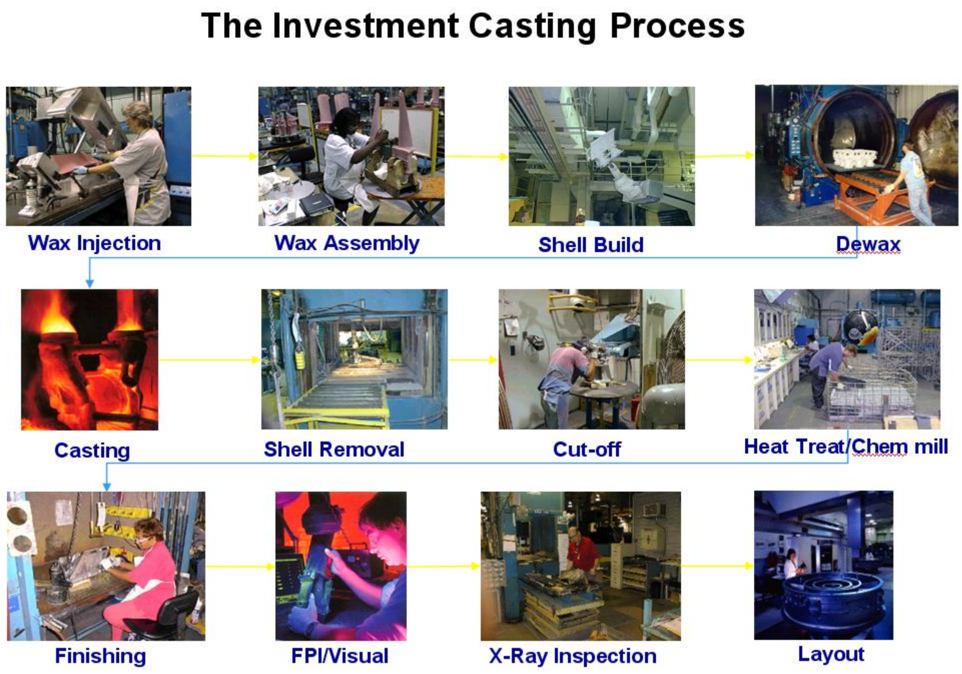


Figure 45: Casting process [13]

A generic description of when it is optimum to use castings would be very complex since many factors impact the selection. The influence that the operations have in design can be summarized in what is called cost drivers. In the casting process these cost drivers can be related with the suppliers or with the process itself. Supplier cooperation and delivery capacity of the suppliers are the cost drivers related with the firsts. When there is a good cooperation, errors and changes can be avoided, reducing the cost, and also delays in the delivery of the parts increase the time of the manufacture and therefore the cost. In the process, cost drivers for the designers are thickness, size, weight, material and stress areas. Although it is a good process for complex shapes, sometimes some geometries can be problematic to create. Also, some casted materials do not achieve the desired properties and therefore have to be done by other operation such as the H-282. Knowing that other operations give better strength to the components, designers have to take that into consideration when choosing the manufacturing processes depending on the stress areas.

Forging and Sheet metal forming

In both types of processes, the surfaces of the deforming metal and the tools are in contact, and friction between them may have a major influence on material flow.

Types of forging**:**

- Closed-die forging with flash
- Closed-die forging without flash
- Coining

- Electro-upsetting
- Forward extrusion forging
- Backward extrusion forging
- Hobbing
- Isothermal forging
- Nosing
- Open-die forging
- Rotary (orbital) forging
- Precision forging
- Metal powder forging
- Radial forging
- Upsetting

In forging the input material is in billet form and the surface-to-volume ratio in the formed part increases considerably under the action of largely compressive loading.

Features:

- The deforming material or workpiece undergoes large plastic (permanent) deformation, resulting in an appreciable change in shape or cross section
- The portion of the workpiece undergoing plastic deformation is generally much larger than the portion undergoing elastic deformation; therefore, elastic recovery after deformation is negligible

Close-die forging is the shaping of hot metal completely within the walls or cavities of two dies that come together to enclose the workpiece on all sides.

With the use of closed dies, complex shapes and heavy reductions can be made in hot metal within closer dimensional tolerances that are usually feasible with open dies. Closed-die forgings are usually designed to require minimal subsequent machining. Close-die forging is adaptable to low-volume or high-volume production. In addition to producing final, or nearly final, metal shapes, closed-die forging allows control of grain flow direction, and it often improves mechanical properties in the longitudinal direction of the workpiece.

The forgings produced in closed-dies can range from few grams to several tons. The maximum size that can be produced is limited only by the available handling and forging equipment.

Complex nonsymmetrical shapes that require a minimum number of operations for completion can be produced by closed-die forging. In addition, the process can be used in combination with other processes to produce parts having greater complexity or closer tolerances than are possible by forging alone.

A material must satisfy two basic requirements. First, the material strength (flow stress) must be low so that die pressures are kept within the capabilities of practical die materials and constructions and, second, the forgeability of the material must allow the required amount of deformation without failure. By convention, closed-die forging refers to hot working.

The flow of the metal is influenced by the part or die geometry. Most of times, several operations are necessary to achieve gradual flow of the material from the initial simple shape to the final shape, much more complex.

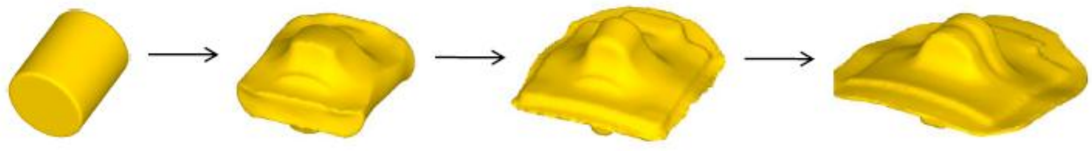


Figure 46: Steps of forging process [14]

To build a TEC, two different materials are used in VAC, In 718 and H 282. Both of them satisfy the requirements explained above and therefore can be forged.

The typical parts of the TEC that can be forged are the shrouds and the hubs, due to their complexity and strength required.

Ring rolling is a forming process suitable for the manufacture of circular parts. It usually requires less input of raw material than the alternative forming methods and it is suitable for the production of any volumes desired.

This process consists of placing the circular part to be formed between a driven roll and a static mandrel. The friction between the rotating roll and the ring makes it rotate, and the radial force decreases the cross-section of the ring, which leads to the increase of the diameter of the same. The cross section of the ring can have multiple shapes, not only rectangular.

This process is suitable to manufacture the flanges of the TEC, due to the circular shape that they have. These parts have lots of holes, that when produced by forging do not create any susceptible areas of having cracks.

To forge nickel-base alloys such as In718 and H282, it is necessary to have powerful equipment, since these alloys were developed to resist deformation at high temperature. It is necessary to heat up the material before forging, and then the several reductions should be uniform to avoid duplex grain structure. Finally the parts should be air cooled.

The cost drivers of the process are basically the same as for casting. Supplier cooperation and delivery capacity related with suppliers, and related with the process there is complexity, size, weight and net shape. Although complex shapes can be created with near net shape properties, there is always the necessity of performing a machining operation to remove the excess of material, while with the process of casting it is not. The increase of cost is largely influenced by the amount of machining necessary to do.

Types of sheet metal forming:

Bending and straight flanging:

- Brake bending
- Roll bending

Surface contouring of sheet:

- Contour stretch forming (stretch forming)
- Androforming
- Age forming
- Creep forming
- Die-quench forming
- Bulging
- Vacuum forming

Linear contouring:

- Linear stretch forming (stretch forming)
- Linear roll forming (roll forming)

Deep recessing and flanging:

- Spinning (and roller flanging)
- Deep drawing
- Rubber-pad forming
- Marform process
- Rubber-diaphragm hydroforming (fluid cell forming or fluid forming)

Shallow recessing:

- Dimpling
- Drop hammer forming
- Electromagnetic forming
- Explosive forming
- Joggling

In sheet metal forming a piece of sheet metal is plastically deformed by tensile loads into a 3D shape, often without significant changes in sheet thickness or surface characteristics.
Features:

- The workpiece is a sheet or a part fabricated from a sheet
- The deformation usually causes significant changes in the shape, but not the cross-sectional area, of the sheet
- In some cases, the magnitudes of the plastic and elastic deformations are comparable; therefore, elastic recovery or springback may be significant

Inside the group of the sheet metal forming, there are a lot different processes. They can be divided in cold forming or hot forming. Cold forming processes are more stable than hot ones, because to these last there is the necessity to control temperature and oxidation. Several of them, individually or in combination, can be used to manufacture some parts that compose the TEC, such as the vanes or cases. Some of the processes are described next:

In deep drawing process, a sheet of metal is constrained in the sides, while the central part of the sheet is pressed down into the opening of the die to form the desired shape. It is necessary that the machine provides a hold-down force for the sides so they do not wrinkle and a punch force to deform the sheet. The presses to perform this operation can be mechanical or hydraulic, being the last ones preferred because of better control of punch travel. Deep drawing can process sheets produced by both hot and cold-rolled, so basically all metals can be formed with this operation without rupture due to low ductility. During the process, the thickness of the sheet does not change substantially, so the final surface area of the formed part has approximately the same area as the initial sheet.

In stretch forming process the sheet is formed against a form block with the shape desired, while the workpiece is in tension. The material is stretched a little beyond its yield point, enough to plastically deform and keep permanently the shape of the form block. This process allows creating almost all shapes that can be formed using other forming operations. This is a common forming process in the aerospace industry for materials like steel, nickel, aluminum and titanium alloys. This process requires little forces compared to the other conventional forming methods, can reduce material costs, increased hardness, reduced springback, low residual stresses and has a low cost form block. This process is not suitable for progressive operations and the surface finish can be changed because of the contact with the form block.

The mechanical properties of the sheet do not change along the process, they are already determined when the sheet is hot rolled. The two materials used for the TEC have identical forming capabilities at room temperature. Their ductility makes them suitable to be produced by sheet metal forming.

Forming is more suitable for producing sheet shape parts such as the vanes of the TEC, due to the low complexity and high strength required for those parts.

The cost drivers in this operation are supplier cooperation and delivery capacity because it is not done in-house. In the process itself, thickness, complexity, size and weight are the parameters designers have to take into better consideration.

Fixturing

This operation is not a manufacturing process in the sense that something physical is done to the component, but is critical for the success of operations such as machining and welding. Fixturing consists in positioning the part to be worked in a support device called fixture. These fixtures are unique for each part, since they are built to accommodate that particular part. The parts are clamped to the fixtures in what is called the target or datum system. These systems can be seen in the pictures below.

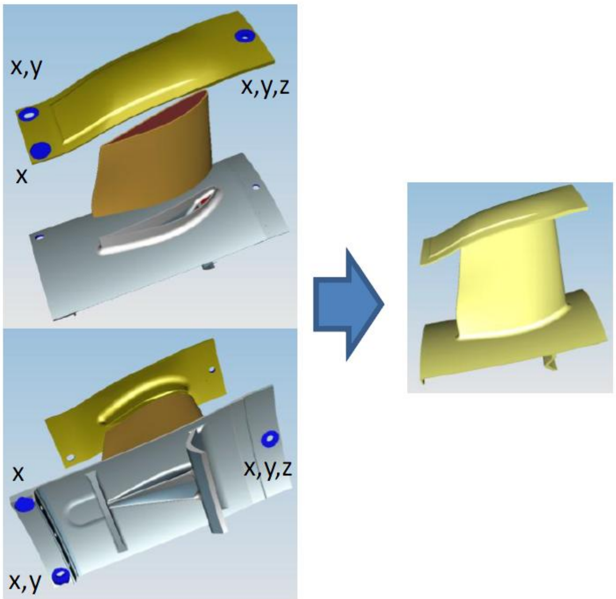


Figure 47: Target systems [15]

The datum system and the fixture are critical for the final quality of the process in which it is implemented. They have to be as good as possible, considering the design limitations, so the process is robust, with low variability.

For the TEC manufacturing sequence, fixturing is present before the machining of the single parts that come from suppliers and during the welding operation of the parts to form sectors and the sectors together to build the final component.

The cost drivers for this operation are size, weight and number of parts, influencing the shape and design of the fixture. The accessibility is also important since the fixturing operation can be really complex. Finally the quality of target system and of the tool/fixture will determine the final quality of manufacturing operation associated.

Machining

Machining is considered a subtractive manufacturing operation where cutting tools operated by machines remove the excess of material until the desired geometry or shape is achieved. Three major operations can be distinguished inside machining; turning, drilling and milling. In the turning operation, a cutting tool works on a rotating workpiece, removing material. Drilling consists in making holes using a rotating cutting tool, and finally milling also uses a rotating tool but to remove material of a surface.

The basic common characteristic of a machining process is the use of a cutting tool on the part to be worked, removing chips of material. It is necessary to have a relative motion between the tool and the part, achieved by a primary motion called cutting speed and a secondary called feed. The combination of these motions with the shape of the tool and the penetration on the part, machine it to the desired final geometry.

The cutting tool is made of material harder than the one of the workpiece and is composed of several sharp cutting edges that separate the chips from the original part. The tools can have only one cutting edge or several.

Normally, machining operations have two stages. In the first one, large amount of material is removed as fast as possible until a shape close to the desired is achieved. High depths and feeds are used with low cutting speeds. Then, the finishing cuts are done with high cutting speeds, but low feeds and depths to achieve the final dimensions with the right tolerances and surface finish. Nowadays, the machining operations are performed in CNC machines, which are computerized ones, where the operator only has to place the part with the fixture inside the machine, being the motion of the cutting tool controlled by the computer.

In the TEC manufacturing operations, machining is performed to prepare the edges that will be welded in the single parts and in the sectors. It is also done as one of the last operations, after heat treatment, to correct the distortions that may happen, giving the final dimensions to the component.

The cost drivers of this operation are thickness that can lead to vibration problems while machining, accessibility for the cutting tool to remove the material and number of parts to be machined.

Joining method

The joining method used for the TEC built is welding. Welding joins the materials, generally, by melting them and adding a filler to create a weld pool of molten material. When it cools and solidifies, a strong joint exists, becoming only one part. The energy source to create the heat to melt the materials varies according to the type of welding, existing electric arc, flame, laser, friction and so on.

At VAC, there are four types of welding, TIG, plasma, laser and EB welding. It is necessary to weld the single parts together to form the sectors and then weld them to obtain the final circular component. Before the weld itself, tack weld is done manually to fix the parts together. For the GP7000 project, all the welds are performed with plasma, except one small weld done at the curvature of the regular sectors, which is performed by TIG for quality reasons.

Tack welding

Tack weld is defined as weld spots made to hold parts in proper alignment until the final welds are made. This is a manual procedure, requiring some adjustments done by the welder in the parts and fixtures to assure the correct alignment of them.

TIG welding

TIG stands for tungsten inert gas, and this process is also known as gas tungsten arc welding (GTAW).The melting temperature necessary to weld materials in the TIG process is obtained by maintaining an arc between a tungsten alloy electrode and the workpiece. This process is characterized by the use of a nonconsumable tungsten electrode, an inert gas and a separate filler material.

Plasma welding

Plasma welding is similar to TIG, also using a tungsten electrode, but uses a plasma gas to create the arc. This process is automatic due to the fact that the arc is more concentrated than in TIG, being harder to control. It is faster and it can be used in a bigger range of thicknesses than TIG.

The welding process has great impact in design decisions, since the different concepts have much different necessities in terms of welding. The cost drivers of this operation are the stress areas, since the welds are able to have cracks, so it is better not locate them near areas that support high stresses. Also, thickness and accessibility are important factors to choose types of welding. Parameters like welding continuity, number of welds, length of welds, weld gap and level of distortion imparted, are critical for the choice of which weld type to use and have great influence in the final cost of the manufacturing process.

Heat treatment

There is a standard heat treatment method for almost every alloy. In the case of the TEC fabrication, only the super alloys In 718 and H-282 will be considered, as it is explained above.

The heat treatment process for INCONEL alloy 718 and HAYNES 282 are rather similar. This fact gives certain flexibility to the concept and design generation since it would be possible to build up a TEC concept alternative using the combination of both materials, which will be heat treatment at the same time during one of the last manufacturing stages.

The heat treatment operation for both superalloys is specified as solution annealed and precipitation hardened. The purpose of the first step, solution annealed, is reducing hardness and increase softness, ductility to facilitate machining, to relieve stresses after welding and to prepare for age hardening. In contrast, the superalloy is hardened afterwards, by the precipitation of secondary phases into the metal matrix to achieve a full strength of the material.

The heat treatment parameters such as temperature, time, heating rate, cooling rate will come indicated from the following stakeholders and in the following order.

1. Customer indications
2. Drawing indications
3. Standard indications (SAE international standard)
4. Instructions (internal indications)

Contradictions between the indications will be solved by following the hierarchical order, listed above.

Within the whole TEC production process, heat treatment is the final operation, besides the final inspection. Therefore, this operation is made when the assy is completed and the purpose is to fulfill the mechanical properties. Only a little of machining is left afterwards to correct the distortion imparted in the component by the treatment.

In some cases, intermediate heat treatments are performed during the welding operation to decrease the stress built up due to that joining process. This extra operation is not desirable due to it increases highly the cost result.

As regards to this project, intermediate heat treatment will not be considered for analysis.

Considering the heat treatment as a rework operation, when it is performed after the final inspection and after welding rework, the most of the times is a local heat treatment in order not to increase so much the rework cost.

Finally for the heat treatment process to achieve good capabilities there is a need of process and quality control, basically supervision of process conditions. In a typical heat treatment operation, a component is moved into a furnace, heated according to a time temperature program, cooled, and finally moved out of the furnace. The temperature and frequently the atmosphere must be controlled. To control the temperature cycle thermocouples are used. The furnaces are qualified according to the production demand.

The cost drivers of this process that can influence in the design are size and material. The size of the component will influence which furnace is chosen, so the component fits inside. The furnaces have different performances and therefore the cost varies. The choice of material influences the parameters set in the furnaces such as heating and cooling rates.

Inspection methods

There are several inspections methods performed during the manufacturing sequence to check the quality of the TEC. These inspections are the following:

- X-ray
- FPI
- CMM
- GOM
- Visual inspection

X-ray

X-ray is a type of radiation produced by electrons at high velocity hitting a metal surface in a vacuum tube. It is used by having a source of x-ray beams in one side of the part to inspect and a film on the other side.

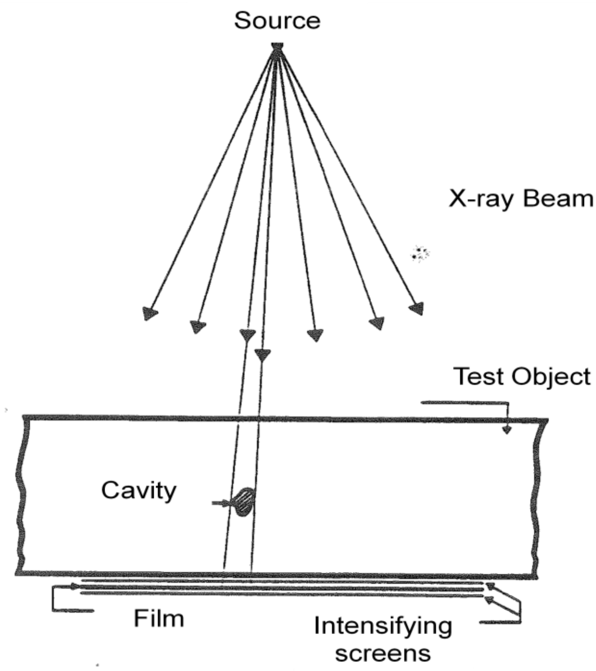


Figure 48: X-ray procedure [16]

The areas that have more density receive more radiation, which will get darker in the image captured by the film.

X-ray is used to find mainly internal volumetric discontinuities such as:

- Porosity
- Heavy inclusions
- Light inclusions
- Cracks
- Underfill (welds)
- Lack of penetration (welds)
- Lack of fusion (welds)
- Cavity (castings)
- Shrinkage (castings)

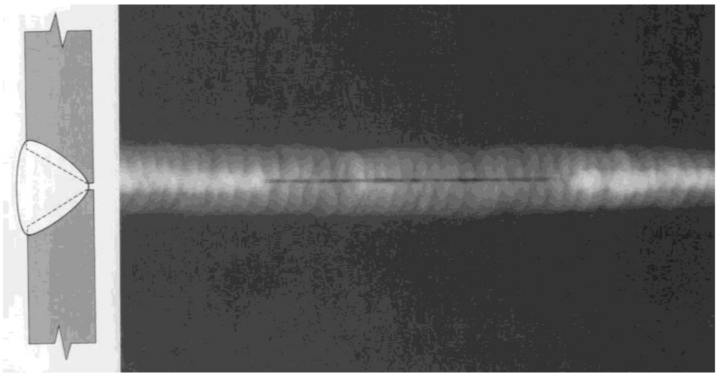


Figure 49: Weld discontinuity [16]

For the TEC, the x-ray is performed to inspect the welds. In the manufacturing sequence of the GP7000, it is done when the whole TEC is already welded together. This operation used to be done also after the individual sectors were welded, but this step was eliminated because it is more efficient to do it only in the end. It is also done when the component requires rework, in the areas that those additional operations were performed.

FPI

FPI stands for Fluorescent Penetrant Inspection, which is a surface inspection method to locate discontinuities in metallic materials. The method consists in applying a fluorescent liquid that penetrates in the flaws and defects of the surface. The excess of liquid is then removed from the surface and a developer applied to emphasize the defects. Finally with a UV light, the component is inspected, that shows the cracks. A very important step of this process is cleaning, both before and after the inspections takes place.

For the GP7000 project of the TEC this type of inspection is done only for the vanes as single parts, being also performed for the sectors after the single parts are welded together.

CMM

CMM stands for Coordinate Measuring Machine, which is a device to measure the geometrical dimensions of an object. This machine works by using a probe that is connected to a moving axis of the machine that measures the geometry of the part. The machine can be either man or computer controlled and also there are a lot of different kind of probes such as mechanical, optical or laser for example.

For the TEC, this operation is only done when the whole single parts have been welded together and the component is already built, in the particular case of the GP7000.

GOM

GOM is also a measuring inspection method like CMM. In this machine, the parts are photographed several times to build a CAD model in the computer that is therefore compared with the original CAD model drew by the designers. The final result are the deviations in all the parts compared to the nominal drawing.

In the GP7000 TEC project, this operation is performed after the single parts are welded together to build the sectors.

Visual inspection

Visual inspection is performed by operators to check with their own eyes and some measuring instruments some basic distances and radius.

In the TEC for the GP7000 it is performed for the individual parts before they are welded together and also after when the sectors are built.

The cost drivers for the inspection methods are thickness, accessibility and level of automation. An inspection that has to go through the part and the machine has to access some locations make thickness and accessibility cost drivers. Also, if the method is manual or automatic will have an impact on the final cost.

Finally, there are cost drivers transversal to all the manufacturing processes. In a general way, the industrial structure limits the processes that can be chosen to manufacture a component. Also, the lead time of a process or a purchased operation is something to take into account as costly. Specific of each process, maturity, capability, level of automation and cycle time are important cost drivers that have major influence in the design process, finishing with the rework hours, which is the result of the unexpected bad quality of a process.

3.4.2 Design Structure Matrix

The elements introduced in the DSM are the cost drivers presented in the previous section. In order to establish dependencies between them, to see possible relations to create trade-off curves, it is necessary to have these parameters very well defined, so there are not any doubts of their meaning. First of all, these parameters were divided in six different groups to make easier to distinguish them. The groups and parameters of each are presented next.

- Project features
  - Industrial structure
  - Lead time
- Purchasing requirements
  - Supplier cooperation
  - Delivery capacity
- Customer requirements
  - Size (volume)
  - Stress areas
  - Weight
  - Material
- Design
  - Quality of target system
  - Thickness
  - Number of parts
  - Complexity
  - Accessibility
- Features belonging to operations
  - Number of welds
  - Length of welds
  - Tool/Fixture quality
  - Net shape
  - Capability
  - Level of automation
  - Cycle time
  - Level of distortion imparted
  - Maturity
  - Rework hours
  - Welding continuity
  - Weld gap
- Operations
  - Casting
  - Forging
  - Sheet metal forming

- Machining
- Fixturing
- Welding
- X-Ray
- FPI
- CMM
- Heat treatment

The next step was to give clear definitions for each of the 35 parameters, which are presented in the Appendix D.

To create fair and homogeneous dependencies through all the parameters, it was necessary to have a method to make these relations between the groups. Some relations are obvious, but others require justifications of the possibility to have dependencies between the groups or single parameters. Therefore, these were created to make clearer the DSM. They can be found in Appendix E.

Finally, the Design Structure Matrix could be filled in by choosing which parameters influence each other, according to the knowledge acquired from the method specialists. The software automatically does the partition of the matrix, which goal is to rearrange the matrix, in order to get groups of parameters that are separated from the others. The final result of the DSM is presented in the next figure.

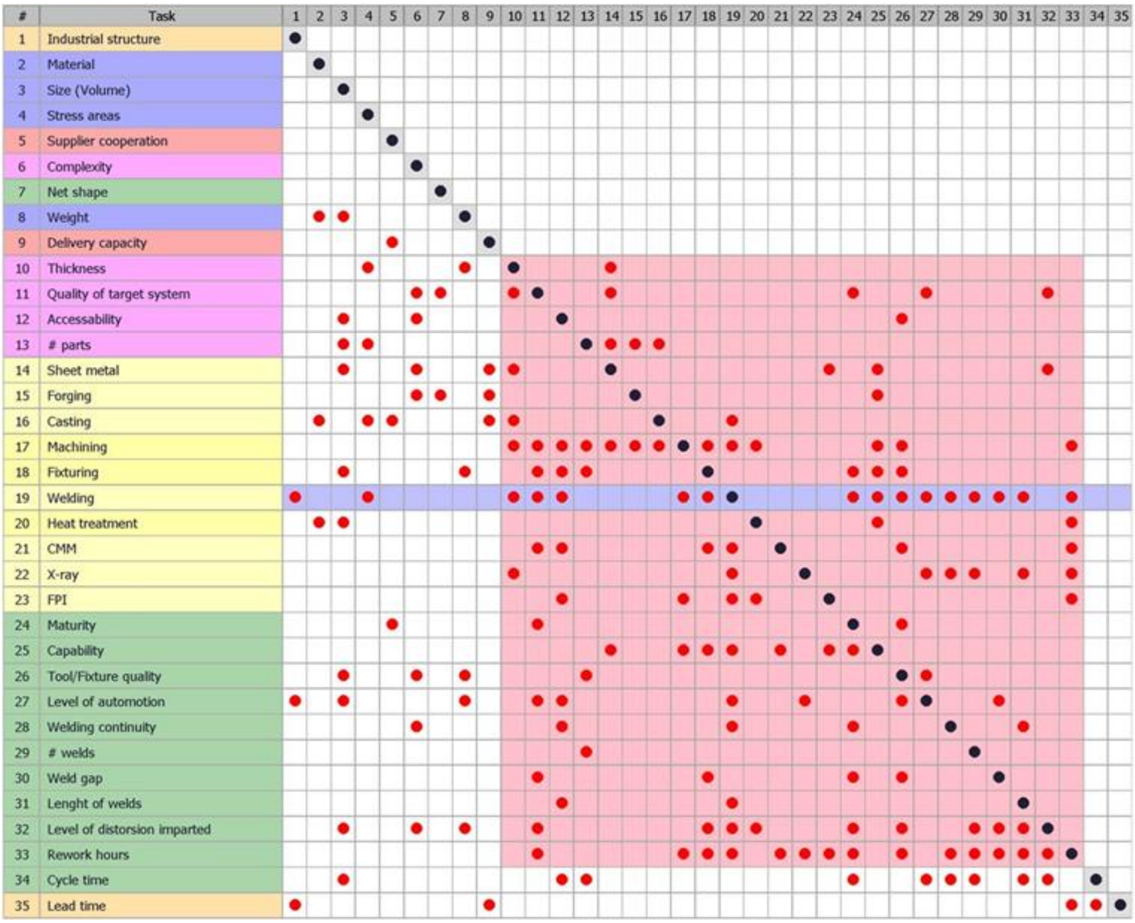


Figure 50: DSM after manipulation

Each red spot represents that the parameter of that column influences the parameter of that row. As it can be seen, a lot of dependencies between these parameters where found (more than 150), so explaining and justifying every single one of them would be a long and exhausting process, probably without major interest. Therefore, only the dependencies that influence operations were justified and such explanations can be found in Appendix F.

If, for example, it is wanted to know which parameters influence casting, all the red marks in that row mean that the parameters of those columns give information to the casting operation. On the other hand, if it is wanted to know which parameters casting influences, the casting column has to be checked, and all the red marks belonging to the parameters of those rows are influenced by casting.

3.4.3 First House of Quality

In a HoQ the customer needs are transferred to product properties. This is what was done in this first House of Quality. The functional requirements were set as well as the technical requirements that correspond to the functional requirements. The requirements are the following:

Functional Requirements

- Possible to install the engine within the aircraft by holding the TEC in the nacelle envelope.
- Assure a system for an easy transportation during the engine installation process.
- The TEC configuration should fit within certain engine envelope without affecting the installation of the engine into the aircraft or having impact on partner interfaces.
- Provide oil system requirements.
- Provide load paths for thrust, mounts and internal load paths to bearings.
- Assure a TEC configuration which supports the Fan Blade Out, FBO.
- Provide primary gas path, coming from the LPT to the TEC.
- Fulfill the durability requirements.
- Fulfill environmental requirements (for instance, oxidation, corrosion, erosion).

Technical Requirements

- Provide rear engine mounts including a failsafe mount.
- Provide rear hoisting points on engine, i.e. ground handling mounts.
- Provide oil supply, scavenge and scupper drain tube.
- Fulfill limit and ultimate strength requirements in components.
- Maintain the structural stiffness of the component
- Fulfill aerodynamic design requirements.
- Fulfill life requirements.
- Fulfill temperature requirements (aircraft operated within a certain temperature range).

These requirements are based in information gathered from interviews with people at VAC and also from several different documents of the company. This case was difficult to differentiate both requirements, since the customer voice that gives the functional requirements already has a lot of technical aspects involved. In order to distinguish them, the functional requirements answer to the question “what”, while the technical requirements answer to the question “how”.

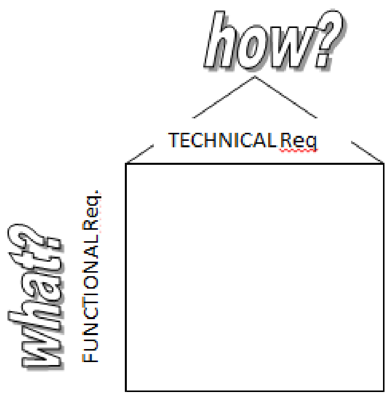


Figure 51: House of Quality

The importance of doing this is that it is really important to start the concept creation looking at functional requirements instead of technical ones, in order that creativity for the creation is not constrained.

3.4.4 Second House of Quality

The second HoQ created is based on the information obtained from DSM. The most critical requirements that influence the manufacturing operations were identified and used to perform this matrix. These requirements were the ones that had more number of red marks in the rows of the manufacturing operations.

These requirements are evaluated against the different operations. There are two types of evaluations. For the purchased operations, they are evaluated using the code ++, + and - , which means that the manufacturing method fulfills the requirement very good, good or bad, respectively. The evaluation of the rest of the operations is just done using a mark if the requirement influences that manufacturing operation and needs to be taken into account. The final matrix is shown in the next figure.

Requirements			Manufacturing Methods									
			Casting	Forging	Sheet Metal Forming	Machining	Fixturing	Welding	Heat Treatment	Inspection: CMM	Inspection: X-ray	Inspection: FPI
Design (customer req.)	Material	In-718	+	+	+				x			
Design (customer req.)	Material	H-282	-	+	+				x			
Design (customer req.)	Size		+	+	-		x		x			
Design (customer req.)	Stress Areas		-	++	++			x				
Design (customer req.)	Weight						x					
Design/Manuf	Complexity		++	+	-							
Design/Manuf	Thickness		-	+	-	x		x				
Manuf	Accesability					x	x	x		x		x
Manuf	#Parts/#welds					x	x	x			x	
Tooling	Target system quality		+	++	-	x	x	x		x		
Tooling	Tool quality					x	x	x		x		

Figure 52: Second House of Quality

The evaluation done matching the requirements with the purchased operations is used and included in the matrix of the third HoQ.

3.4.5 Third House of Quality

Two different projects of TEC, with different concepts used were chosen to the base of the creation of the third HoQ. The projects chosen were the GP7000 and the PW1000. In the Excel sheet created each part of that concept was assessed regarding important parameters such as strength, complexity and thickness for the purchased operation chosen to manufacture that part in that project. Other parameters like the material, the temperature that must be tolerated, the loads applied and the weight of the part are also present in this sheet.

The study of the loads distribution in the single parts of the TEC was not based on any finite element software. It was based more or less on intuition and some assumptions were made to do it. Some single parts are not considered in this study such as flanges, cone of the hub and generic standard parts and bosses. Also, it is only considered the loads transmitted to the mounts by the airplane, having the same value for the three of them, without considering any angles of projection that would lead to have shear stresses in the vanes of the sides.

For the GP7000 project, the component is split up in 3 mount sectors, composed of one shroud mount, one vane and one hub each, and 10 regular sectors, composed of one shroud, one case, one vane and one hub each. If all of them would carry the same amount of load, it would be approximately 7,7% each sector. Since it is known that the mount sectors are the ones that will carry the majority of the loads, it was considered that they would carry around 3 times more than that, 65-70% of the total loads. Also, knowing that the 3 shroud mounts are the single parts that are in direct contact with the points where the loads are applied, it was considered that they would carry around 50% of the total. The loads are transmitted then to the vanes and finally to the hub, decreasing gradually its value. With all these knowledge and assumptions it was considered that the shroud mounts would carry 15% of the loads each, the vanes 5% each and the hub 2% each.

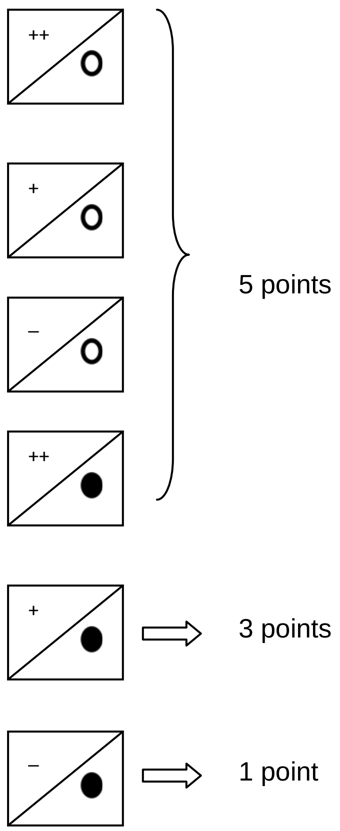
For the regular sectors, it was considered that they would carry half of the loads compared if they were all equal. Knowing that the loads are transmitted in the circular areas (shroud and hub) and are in contact with those parts from the mount sectors, it was considered that the shrouds would carry 1% each, the cases 1% each, the hubs also 1% each and the vanes 0,5% each.

For the PW1000 project, the split up concept is different from the GP7000. This TEC is composed by 1 mount sector, 8 regular sectors, 9 outer cases and a circular hub. The mount sector is composed by one shroud with 3 mounts and 3 vanes are welded to it. The regular sectors have one shroud and one vane each, being connected to each other and to the mount sector by the 9 outer cases. For the loads distribution, the same type of thinking from the GP7000 project was applied here. Therefore, the shroud mount was considered to carry 50% of the loads and the vanes of the mount sector 5% each. The shrouds of the regular sectors and the outer cases were considered to carry 1% each, the vanes of the regular sectors 0,5% each and finally the whole hub 14%.

When a House of Quality is performed, it is necessary to choose some weighting factors to give to the parameters, to distinguish between high, moderate and low relationships. There is not a scientific base to justify which scale should be used in a specific situation, depending only on the judgment of the people that are doing it, to choose one that they think is the most appropriate and fair for the evaluation.

However, there are some scales that are used most of the times in the HoQ, being the most common the 9(high)-3(medium)-1(low) scale. Sometimes the 5-3-1 or the 4-2-1 are also used. The 9-3-1 shows more dramatically the difference between the highs and the lows, while the other two are more even in terms of the punctuation difference between high, medium and low.

In this HoQ, there are some parameters (strength, complexity and thickness) related with purchased operations which are weighted with the ++(very good)/+(good)/-(bad) scale, according to the characteristics of the manufacturing process. The HoQ is performed by relating each part of the component with these parameters of the manufacturing process that produces it, with a full dot (strong relation) or empty dot (weak relation). Then, for each part, a ranking number is given, by summing the correlations of the 3 parameters according to the following scale:



The scale chosen for these correlations was the 5-3-1, in which there is a higher step from low to medium relations, than from medium to high. It was intended to emphasize when there is a problem or difficulties related with a parameter for a specific process, rather than showing when a process is optimum for a parameter, because with more or less difficulty the parts can be manufactured with all the purchased operations, depending mostly on cost and producibility. The weight 5 is given for all the correlations when there is a weak relation (empty dot) because that parameter will not have importance and influence in the manufacturing process for that part.

Then, the result obtained is multiplied for a weighting factor regarding cost and producibility. These parameters are graded with ++(very good)/+(good)/-(bad) for each manufacturing process. Regarding cost, the grade will vary depending on the thickness parameter, because when a part does not have major variations in the thickness, it is cheaper to produce it by sheet metal forming than by casting and the opposite is true too. So, the following table applies for this case:

	Cost	
Thickness	Casting	Sheet metal forming
●	++	+
○	+	++

The weighting scale chosen was the 4-2-1, which has a balanced step between high, medium and low, opposing to the 9-3-1 scale that dramatically highlights the very good relations giving a very high ranking. This way, a ranking number for cost and producibility is obtained for each part of the component.

Knowing this, now it is possible to compare, regarding cost and producibility, different manufacturing processes to produce the same part and know and decide in a rough way which one is the best. The highest value cost and producibility have, means a cheaper and more producible part.

A ranking value can also be given to the sectors and to the whole component. For the sectors, the ranking value of each part that composes it is summed and then divided by the number of parts that the sector has. Finally, for the whole component, it is summed the values of each sector that the component has, dividing for their number. This way, it is also possible to make in a rough way an overall comparison in terms of cost and producibility between different concepts for the choice of the purchased manufacturing operations of a component.

Both sheets are presented in the next two figures.

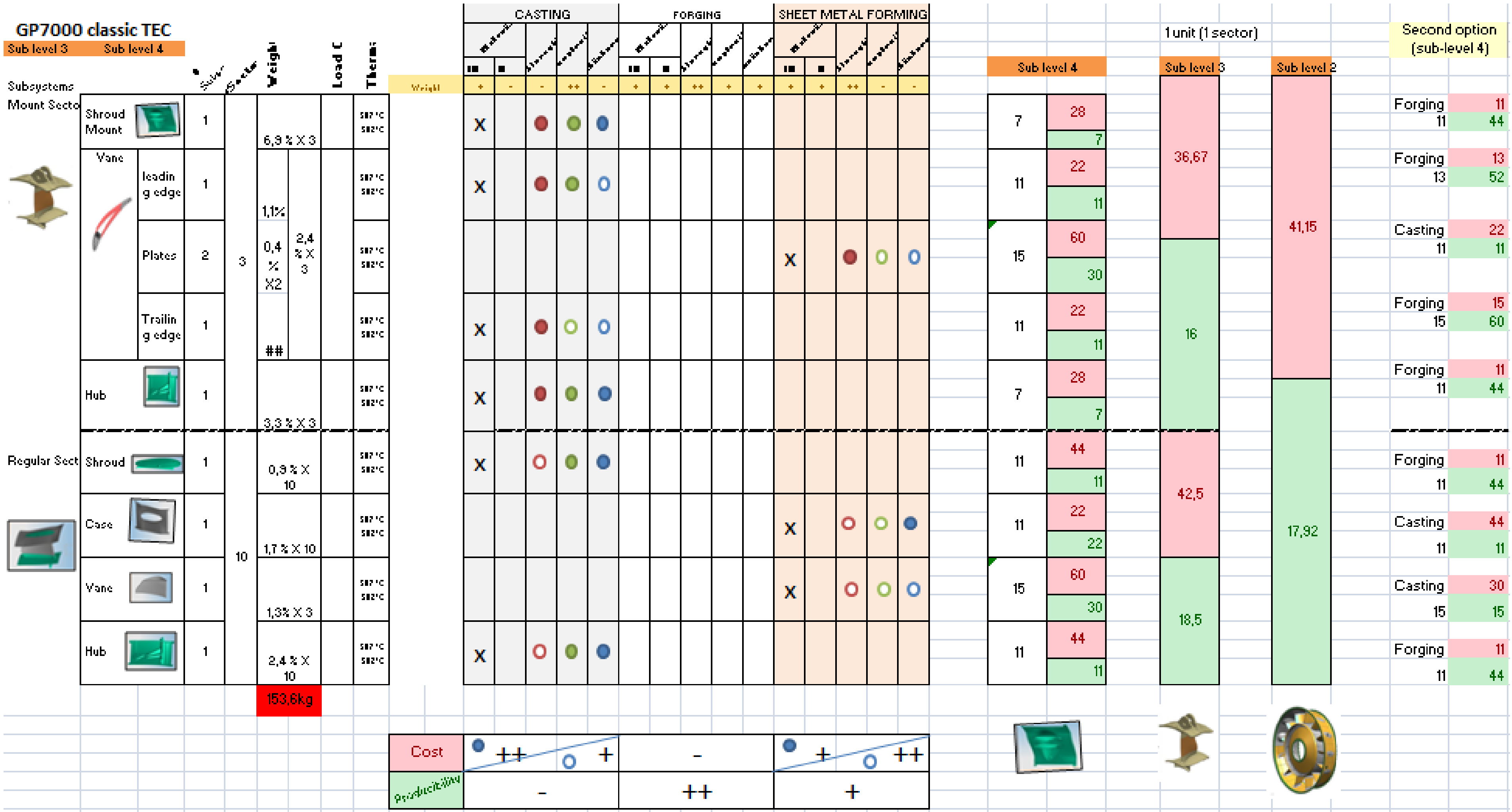


Figure 53: Third House of Quality (GP7000)

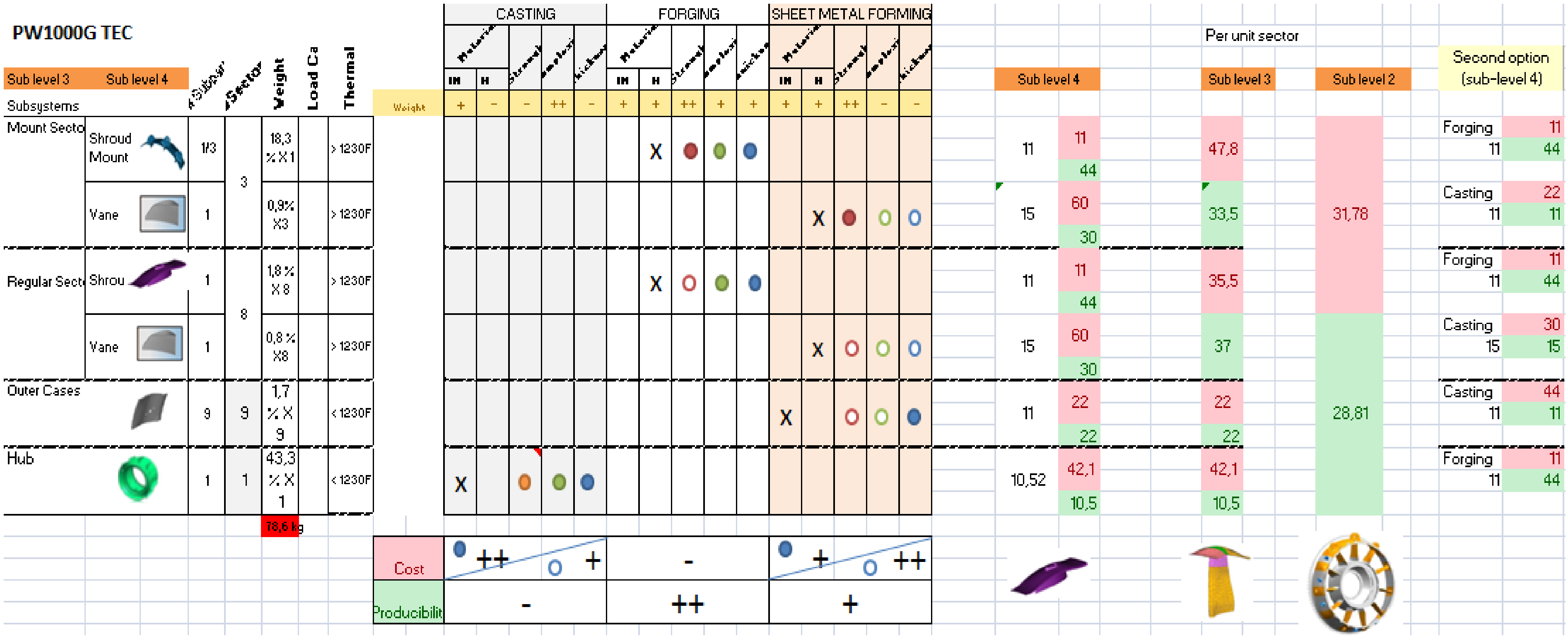


Figure 54: Third House of Quality (PW1000)

In these, below the heading sub level 4, the numbers in the white boxes represent the value obtained by the weighting factors, in pink the value for the cost and in green the value for producibility. Below the headings sub level 3 and sub level 2 it is presented the value of the sectors or final component for the cost and producibility too. In the last column it is done an assessment with an alternative manufacturing operation for that specific part, being possible to compare in relative terms cost and producibility for different manufacturing operation for a part and decide, based on those subjective values, which one to choose.

The results show that none of the alternative option gives a better value in both cost and producibility. In most of the cases, one parameter gives a better result, but the other is worst. This happens mostly when the option is between casting or forging, since the casting process is cheaper than forging, but the last one is more producible, since it almost never brings future problems in the manufacturing process like casting does. Therefore, it is always a difficult choice to do between these two operations, so more detailed information is necessary than just assess them with subjective values, in order to make the right choice.

Comparing the final results of each project, it shows that the GP7000 project was better in terms of cost but had a worst producibility value than the PW1000, regarding the purchased operations. It is mainly due to the fact that the GP7000 project has a lot of casted parts, while the PW1000 project is composed by some parts done by forging because of the type of material used. It is not possible to say which concept is better, since this assessment is only done for the purchased operations, so it would be necessary to do something similar with the rest of the manufacturing operations used, to have a global value of cost and producibility of the whole concept.

3.4.6 DFM tool

For the creation of this kind of DFM tool, the flow of operations of the GP7000 project was investigated and followed. This was only done for the manufacturing of sub level 4 and 3, which means for the operations of single parts and sectors, due to time limitation. The result is presented in the next figures.

SUB-LEVEL 4		
Shroud Mount		1
Vane	leading edge	1
	Plates	2
	Trailing edge	1
Hub Mount		1
Shroud		1
Case		1
Vane		1
Hub		1

Operation name		Casting	Sheet Metal	Machining	Deburring	Cleaning	FPI	Cleaning	Final Inspection
Set-up time	h			0,16					
Time per piece **Shroud** Mount	h			0,8	0,5	0,42			0,1
Time per piece **Vane** Mount	h				3	0,42			0,1
Time per piece **Hub** Mount	h			0,8	0,5	0,42			0,1
Total time	h			**1,76**	**4**	**1,26**	**0**	**0**	**0,3**
Time per piece **Shroud** Reg	h			1	0,5	0,42			0,1
Time per piece **Case** Reg	h			0,5	0,5	0,42			0,1
Time per piece **Vane** Reg	h				2,5	0,42	0,5	0,42	0,1
Time per piece **Hub** Reg	h			0,7	0,7	0,42			0,1
Total time	h			**2,36**	**4,2**	**1,68**	**0,5**	**0,42**	**0,4**
Measurable (effect producibility)		Size (cm3)	Size (mm3)	Lenght of edges (mm)	Lenght of edges (mm)	Pieces at the same time	Pieces at the same	Pieces at the same	Pieces at the same time
Shroud Mount		1271,5		429	429	8-10	40	8-10	1
Vane Mount		456,9			429+557=**986**				
Hub Mount		613,3		557	557				
Shroud Reg		150,0				8-10	40	8-10	1
Case Reg			310,0	429	429				
Vane Reg			243,5		429+557=**986**				
Hub Reg		449,0		557	557				

Figure 55: DFM tool sub-level 4

SUB-LEVEL 3		
Mount Sector	3
Regular Sector	10

Operation name		Tack weld	Welding	GOM	Cleaning	FPI	Machining	Deburring	Cleaning	Final Inspection
Set-up time	h	0,50	0,30				0,30			
Time per sector Mount sector	h	1,20	**1,00**	0,80	0,42	1,50	1,70	0,70	0,42	1,50
Time per sector Regular sector	h	2,20	**3,50**	0,80	0,42	1,50	1,70	0,70	0,42	1,50
Total time	h	32,10	41,90	10,40	5,46	19,50	26,00	9,10	5,46	19,50
Measurable (effect producibility)		No of points	Lenght of welds (mm)		Sectors at the same time	Sectors at the same time	Length of edges (mm)	Length of edges (mm)	Sectors at the same time	Sectors at the same time
Mount Sector (total)		12	429+557=**986**		6	1-8	402x2+401x2+76x2=**1758**	402x2+401x2+76x2=**1758**	6	1
Regular sector (total)		27	429+557=**986**		6	1-8	402x2+401x2+76x2=**1758**	402x2+401x2+76x2=**1758**	6	1

Figure 56: DFM tool sub-level 3

For sub level 4 the sequence of operations at VAC is machining, deburring, cleaning, FPI, cleaning and final inspection. In the machining operation, the parts except the vanes are machined in some edges in order to make easier the welding operation, followed by deburring where the vanes have a long process time, especially the one of the mount sector since it is necessary to make a 45º cut in it to prepare for the weld. For these two operations a parameter that can affect producibility is the length of the edges worked. Cleaning is the next step, where a good number of parts are put together inside the machines and take the same time to wash all of them. Sometimes, after this, by indication of the suppliers or by someone responsible for quality at VAC, it is necessary to inspect by FPI the parts, which has happened with the regular vanes. When this happens it is necessary to clean them again after. Finally the parts are visual inspected by operators, where distances, width and radius are checked part by part, which takes approximately the same time for all of them.

For sub level 3 the flow of operations is welding, GOM, cleaning, FPI, machining, deburring, cleaning and final inspection. First it is necessary to do tack welding where the set up time is quite high due to the necessity of putting the parts in the fixture and adjust it so they are in the right position. The regular sectors take more time than the mount ones because there are more weld spots to do. After that, the parts are welded together by plasma and it is necessary to do a manual TIG weld in a place of the regular sectors, which increases the time of operation. This is considered an extra operation for the regular sectors because with plasma in that area, the quality is not as good as it should be. An example of a parameter that influences the producibility in the welding operation is the length of the welds. The next procedures are inspect the sectors by GOM, clean them and then inspect by FPI which takes the same time for both types of sectors. Then, the preparation for the welding of the sectors together to build the component starts by machining and deburring some edges, taking the same time for both sectors. After they are cleaned with the same process done in sub level 3, and finally another visual inspection is performed by an operator to check basically the same parameters as before individually.

This tool is very process-oriented, that shows the necessary amount of processing, the difficulties and the required amount of time/cost. The process that really stands out from the others in terms of time spent is, without a doubt, all the welding process, from the tack welding to the plasma welding.

3.5 Conclusions

Mainly the objective of this second part was to point out the importance of the production requirements integration in the design phase, so that producibility is taken into account from the beginning, as well as showing the possibility to perform this by using certain tools that help the purpose.

Nevertheless, due to time and experience limitations it was not possible to create something with really valuable results that can bring major advantages and improvements for the designers in their work. It is important then to look at the results from a concept point of view and to take the main idea, understand what these tools really aim for, which is increasing producibility.

Every manufacturing process has a lot of parameters that can influence them in terms of producibility. The design process must take into consideration all of these complex relations in order to avoid later problems during production that will cause delays and loss of money.

The DSM result can be a good material to be introduced to new people at VAC, especially designers, so they have an idea of the complexity of production parameters that influence each other and affect design.

Looking at the matrix after being manipulated, it is not possible to identify separate groups of dependencies that could make some parameters independent from the others. The red marks are spread through most of the matrix, showing that the parameters are much connected with each other, representing a highly complex system. This way, it was not possible to separate the parameters in groups with high dependencies with each other that perhaps could lead to create trade-off curves between them. Maybe, an interesting idea could be to repeat this type of work but restraining the parameters used, since in this one the parameters cover all the manufacturing processes of the flow of operations. Using less parameters and focusing on one process for example could be worth it to see what the result would be like. Anyway, some trade-off curves can still be made, relating some of these parameters that are logically connected, which are referred in the section Future Work.

Nevertheless, there is some information that can be learned from the DSM. In the area above the diagonal, the red marks represent loopbacks, where three important lessons can be learned. There is the necessity of involving information from the purchased operations in the design phase, welding and fixturing are the processes that bring more problems and firefights and finally there is lack of information in the design regarding the capabilities of most of the manufacturing processes.

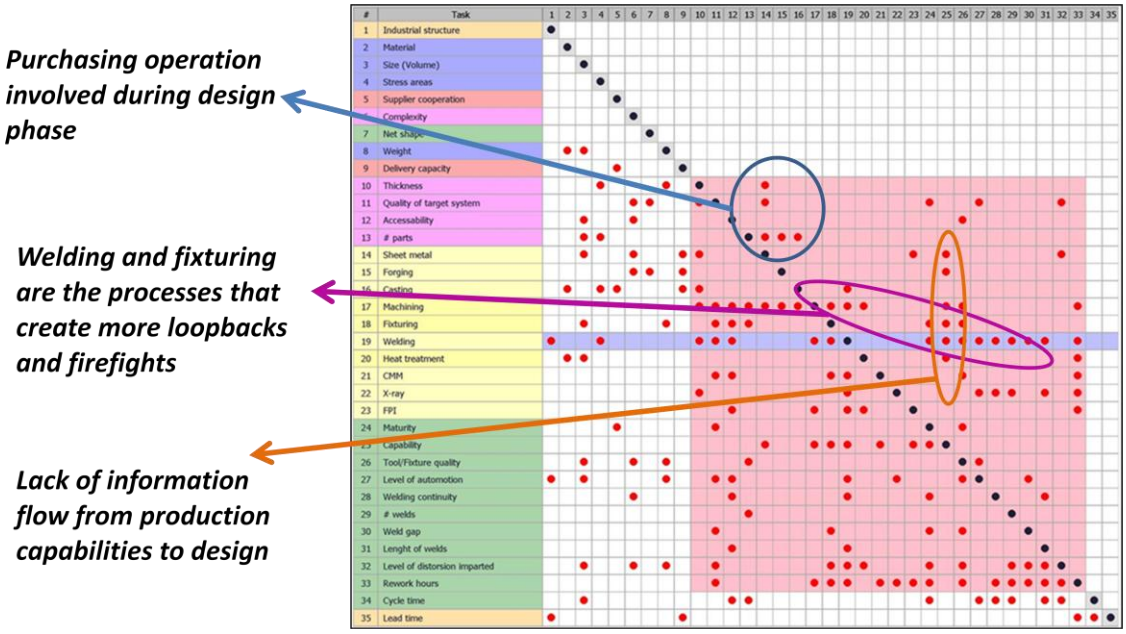


Figure 57: DSM conclusions

The DFM tool with the flow of operations of the GP7000 shows an important manufacturing issue, which is the cycle time of each operation. Since the data was collected in the workshop with the operators, these can be a good input for designers to have a better notion of the reality, since the times presented in documentation of the design phase sometimes have great discrepancy with the ones that happen in the workshop. This way, cycle times for upcoming projects can be better estimated. Also, these times can be used as one of the inputs of the ULSAB cost model, which could lead to better cost estimations since the beginning of the project. With the model, different operations for the same ending could be compared in terms of final cost, which would lead to save money.

4 Future work

Trade-off curves can be really important and useful, and are a key tool in SBCE. Although the DSM did not show groups of parameters independent of each other, there are some parameters which relation are obvious and could be interesting to make trade-off curves with them, such as length of welds with the level of distortion imparted in the part.

This work would start in step 2 of creating trade-off curves, collecting data of the behavior between these parameters. The data collection can be done using historical data, part and production simulations, prototypes and theoretical analysis. After that, the data has to be analyzed to understand the behavior of the parameters with each other and finally create that relationship in a graphic.

Also, reducing the number of parameters and focusing only in some areas could be a work of interest to be carried out.

The third HoQ could be completed with the rest of the more important manufacturing operations present in a usual flow of operations. In this way, an overall value for cost and producibility could be achieved for a certain concept, giving the opportunity to compare with others and see in a rough way which would be better.

Regarding the DFM tool, it could be completed with the last sub level of manufacturing, where the different sectors are welded together and final inspections are performed. It would be a good asset, so the general picture of cycle times of the flow of operations would be given as an input to the ULSAB model.

Also, the same kind of tool should be performed for the PW1000 project, so both projects could be compared and the best decisions from each learnt in order to apply in new projects.

A lot more investigation should be done in this field. Experienced engineers, both from design and manufacture areas, can provide a valuable input for the creation of really useful tools, since they are the ones with the technical knowledge and are also aware of the gaps and problems in achieving a producible design.

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Appendix A

Benchmarking - Questionnaire

Master Thesis Project: "Design For Manufacturing – Concept cost evaluation model for fabricated components at Volvo Aero".

Introduction

The Master Thesis project is regarding DFM philosophy, the purpose is to develop a DFM tool to support the designer work at the early stage of the concept development, creating a systematic approach to evaluate the different concept alternatives from a producible and cost point of view.

1. Could you describe with a scheme the project organization? Identify within this scheme who is involved in the concept work.

2. Could you describe the time line of the product development? Within this time line, how long does the whole product development take? And the Concept Study or Concept work?

3. In which phase within the product development do you invest more intelligence? Considering the Technology Development period (where new technologies and methods are researched and developed) as well.

Concept Creation (within concept study phase)

Keyword: Platform – it is a set of methods or ways to proceed which have been already proven, thus they have a high maturity level.

4. Which knowledge do you use when creating concepts at the starting point of a new project?

☐ Platforms ☐ Benchmarking ☐ Technical specifications

☐ Previous projects ☐ Technology Development period ☐ Guidelines / Principles

☐ Experience ☐ Production knowledge based ☐ Courses

☐ Others: ____

5. What kind of platforms do you have?

☐ Production ☐ Design/Product

☐ Supplier/Purchasing ☐ Others: ________________________________

6. Do the platforms limit the creativity during concept generation and dismiss the functional requirements of the product?

7. How is the concept creation done? In how many different concept alternatives do you end up at the beginning?

8. In which stage is the routing done for the concepts? Which are the main driving forces to choose the flow of operations?

Concept Evaluation and Selection (within concept study phase)

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9. Do you use any method/tool, practice or guideline for the evaluation and comparison of concepts? Which ones?

10. Which are the key parameters to evaluate the concepts? And the most important?

11. Considering producibility as a key parameter, how is it measured at the early phase and in later stages?

12. Do you know what "Set Based Engineering" is? Yes ☐ No ☐

13. How many concepts do you develop forwards (in more detail) and when do you select the best one?

14. When do you start making cost assessment of the concepts and how is it made?

DFM

---

15. How is the DFM philosophy applied at the company?

16. How do you make use of production knowledge in every phase? Therefore, how is the communication and the feedback between designers, production people and manufacturing people?

17. Do the designers use DFM tools? Which ones?

18. Do you have a systematic approach for the concept work/study?

Appendix B

Designers Questionnaire

This questionnaire turns to employees at Volvo Aero Corporation that have been working with concept development of Hot Structures (TEC/TRF). If there is a question you do not understand, or cannot answer, please skip it. The results will be analyzed in a Master Thesis.

Introduction

The Master Thesis project is regarding DFM philosophy. The purpose is to develop a DFM tool to support the designer work at the early stage of the concept development, creating a systematic approach to help in the evaluation of the different concept alternatives from a producible and cost point of view. The project will be focus on Hot Structures (TEC, TRF).

---

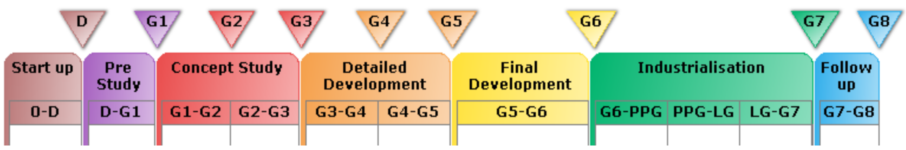
1. Identify the roles of the persons who are involved in the concept work at Volvo Aero.

____

____

2. Which projects have you been involved in? What roles have you performed within the project? Which phases in the GDP system did you cover?

Project: Role:



________ ________

________ ________

________ ________

________ ________

3. In which of these phases do you think more resources (time, money, intelligence, knowledge…) should have been invested? Consider also the Technology Development period (where new technologies and methods are researched and developed).

☐ Technology Development ☐ Concept Study

☐ Detailed Development ☐ Final Development ☐ Industrialization

DFM

4. Do you know what Design For Manufacturing (DFM) is? Yes ☐ No ☐

If the answer is yes, could you describe the advantages of this methodology in the design work?

____

____

5. Have you ever used any DFM tool or method to support your work? Yes ☐ No ☐

If Yes, please specify which Tools/methods:____

6. Do you get sufficient amount of information (from supplier/method specialist/ production people) for the concept generating task? Yes ☐ No ☐

   If No, which information is missing from?

   ☐ Supplier ☐ Method Specialist ☐ Production people

   ☐ Cost Specialist ☐ Other:__________

7. Do you know what Set Based Concurrent Engineering (SBCE) is? Yes ☐ No ☐

Creation of Concepts

8. Which knowledge do you use when creating concepts along the concept study phase?

   ☐ Platforms** ☐ Benchmarking ☐ Technical specifications

   ☐ Previous projects ☐ Technology Development period ☐ Guidelines / Principles **

   ☐ Experience ☐ Production knowledge based ☐ Courses

   ☐ Draft of the layout from customer ☐ Others: ___________________

*** if you ticked this box please specify the kind of platform/guideline/principle*

____

____

9. Select the processes of which you know the capabilities or design limits.

Purchased processes: ☐ Casting ☐ Forging ☐ Sheet metal forming

Preparation processes: ☐ Machining

Joining processes: ☐ Laser weld ☐ TIG weld ☐ Plasma weld ☐ EB welding

Inspection processes: ☐ X-ray ☐ FPI ☐ CMM measuring

Others: ☐ Heat treatment

Could you suggest where there is a lack of knowledge or need to improve the knowledge from the processes above (or additional ones)?

____

____

10. In which processes (from the ones above) does the quality of the fixturing (i.e. tool design and target system) influence the capabilities? *(write the process)* And how much? *(make a cross)*

	Quantify influence			
Processes	Low	Medium	High	I don't know

11. Here at Volvo Aero there is a DFM tool that provides, as a result, the possible tolerances to be achieved in turning operation.

    -Do you know about the existence of this tool? Yes ☐ No ☐

    -Do you use it in your work? Yes ☐ No ☐

12. Other existing DFM tools are the checklist for welding and casting implemented in the NX software. Do you make use of them? Yes ☐ No ☐

13. When is the routing created within the concept development phase?

____

Concept/Cost evaluation and selection

14. When is cost assessment made? *(referring to project gates)*

    ☐ Before G1 ☐ G1 ☐G2 ☐G3 ☐G4 ☐G5 ☐G6 ☐G7

    Who is involved? ____

    What disciplines are involved? ____

15. Do you consider the cost as a result or as a steering parameter? ☐ Result

    ☐ Steering parameter

16. In your opinion, which are the main cost drivers?

    ____

    ____

Appendix C

Name	Job position/ Area	Content of interview
Mats Högström and Anders Lundquist	Manufacturing engineers	Change of production way, production platform
Johan Lööf	Geometry Assurance	Importance of fixtures and target systems in welding, influence of geometry assurance in design
Ola Isaksson	Product development	Basic company structure, concept of DFM
Olof Lewin	Manufacturing engineer (technology development)	Company history, jet engines, problems to reach the target cost, systematic concept selection process
Malin Kämpe	Product development	DFM tool
Sören Knuts	Risk Analysis	FMEA , TRL
Henk de Ridder and Viktor Carlender	Process verification leaders	Balance of cost, producibility and technical requirements, communication between designers and method specialists, problems with the production platforms, necessity of better cost assessments
Anders Sjunnesson	Technology management (technology development)	Time line of technology development, product development and manufacturing, necessity of investing more intelligence at the beginning to select the right concept
Henrik Amnell	Design team leader (cold structures)	Important people to contact related with the project
Malin Norlander and Ola Isaksson	Project management for knowledge based engineering	VAC tools
Markus Nymark	Programmer in CAD software	Checklist of casting and welding created by method specialists for NX software
Tor Wendel	Volvo Trucks	Suggestions for benchmarking method, DFM implementation, set based engineering
Peter Martensson	Risk analysis	P-FMEA

Fredrik Kullenberg	Product design leader	Common design space between processes
Håkan Jakobsson and Anders Lundquist	Manufacturing engineers	Production platform for hot structures
Karin Skogh	Cost engineer	Cost breakdown, rough estimations from method specialists, target cost
Frank Lindevall	ULSAB model specialist	Detailed cost breakdown in ULSAB model
Susanna Hägglund	Bussiness	Cost estimations based on old projects
Fredrik Vikström	Casting specialist	Casting process
Johan Tholérus	Forging specialist	Forging process
Dan Gustafsson	Designer (Definition leader)	Cross-functional teams, design process
Lars-Ola Normak	Designer	Systematic approach for design, producibility vs cost
Jörgen Karlsson and Magnus Vägermark	Tooling designers	Target systems
Fredrik Wänman	Systems engineer	Set based concurrent engineering
Håkan Linnån	Quality auditor	Functional requirements, key characteristics
Dr. Durward Sobek	Professor at Chalmers	Set based concurrent engineering, trade-off curves
Jerry Isoaho	Welding specialist	Welding process
Tommi Vilkman, Stein Gulbrandsen and Lars Lindström	Inspection methods specialists	X-ray and FPI processes
Peter Hammarbo	Heat treatment specialist	Heat treatment process
Fredrik Niklasson and Lars-Erik Brattström	Sheet metal forming specialists	Sheet metal forming process

Appendix D

Project features

Industrial structure: The structure to support in house production, including equipment, foundations for machines, transportation, structures, etc. It does not have any relation with the suppliers and it only influences the operations done in house. It is the current workshop situation so nothing can influence the industrial structure.

Lead time: Represents time from the beginning until the end of a process. Lead time of a project starts when the first pre-studies and negotiations are done until the component starts being produced for use. Lead time of a supplier process is the time since the part is ordered until it is received.

Customer requirements

Size (volume): It is the size of the parts or assemblies at the moment of doing a specific operation. This covers if it is possible to produce this size or not regarding the operation.

Weight: It is the weight of the parts or assemblies at the moment of doing a specific operation. This covers if it is possible to produce this weight or not regarding the operation.

Material (temperature): Options are In718 and H282, which depends on the thermal case required by the customer. The dependencies for this parameter are related when it is not possible to do the operation for any of the two types of materials.

Stress areas (loadcase): Regions of the component subjected to flight service loads. There will be relations when a good strength cannot be achieved.

Operations

All the operations were already described in detail in the section Analysis and Results of the Part II of the thesis.

Features belonging to operations

Cycle time: Time necessary for the realization of a process, from set up the machine, accomplish the operation and finally remove the part from the machine. It will be influenced by parameters that increase the time.

Level of automation: The level of automation characterizes the degree of human and computer intervention in a task, having several different levels from totally manual to fully automate. Only considered for the processes in house.

Maturity: (or TRL level) Maturity relates to the degree of optimization of a process. Again is only considered for the processes in-house when it is difficult to achieve TRL 6.

Capability: Process capability is the ability to produce the output inside the specification limits. This parameter shows the variation of a process.

Net shape: This term refers to how close from the final component geometry it is after an operation is done.

Level of distortion imparted: It refers to the distortion caused by heat due to an operation performed in a part.

Tool/Fixture quality: The quality is related to its robust construction and repeatability, which means the different parts produced being as similar as possible. Another important issue is that it doesn´t vibrate during operations and it is easy to repair when there is a failure or wear. It can be also measured by the interaction with operators, necessary to be easy to use and safe. Only considered for processes in house and it is critical for the success of the process.

Number of welds: It is how many lines of welds the component has in order to join the different parts. It is not influenced by the continuity of the welding process, one weld can be done in just one operation if possible to weld continuously or in several if necessary to start/stop the operation.

Lenght of welds: Distance between the start and end of the welding line.

Weld gap: Distance between the parts to be joined together when they are positioned in the fixture to have a good root penetration.

Reworks hours: Time spent doing additional operations to correct defects in the component originated by manufacturing processes. Considered when there is a high probability that rework will happen.

Welding continuity: It also refers to the start-stop areas. It is the ability of a welding operation to weld without stopping. The stops may bring welding defects, such as cracks.

Design

Number of parts: How many individual parts are joined together to fabricate the final component.

Thickness: Distance through a part or component.

Accessibility: The ability to reach all the locations of a component with a machine or device, required to perform some operations. Considered only for operations in house, not for purchased operations where this parameter may also be required.

Quality of target system: In machining and welding processes, target systems are used to clamp the parts to the fixture. A good quality refers to have small distortion or geometrical variation after these operations are performed. These are created during the purchased parts operations, having different qualities depending on the operation chosen.

Complexity: Complexity can be defined as cavities, features, transitions and interfaces.

Purchasing requirements

Delivery capacity: It is related if the supplier can deliver all the parts ordered on time established or how late some parts will be delivered to the company. Considered for those purchased operations where there is a problem to deliver them on time.

Supplier cooperation: How good is the supplier collaborating with VAC to reach the best purchasing, i.e. optimizing process and reducing cost. Considered when there is a bad communication between the EMS of the purchased operation and the suppliers of the same.

Appendix E

The industrial structure can influence the in-house operations when the machines existing in the company constraint the operations to be chosen. This relation is considered when there is the aim to change the industrial structure to have better results.

The delivery capacity of a purchased operation is important to know if it is possible to manufacture and receive the parts by that operation in the time established. This relation is considered in the DSM when there are problems with delays.

The design parameters present in the DSM can have major influence in the operations. These relations are considered when it is not possible to select one of the purchased operations wanted because of that parameter, or it has to be changed so the process can be used, and also when it is a critical parameter to accomplish one of the in-house operations.

Regarding features belonging to operations, different parameters can have different types of relations. Capability is influenced by the operations when they are not reported to the designers. The opposite relation, i.e. capability influences the operations when these are not good enough for what is wanted to be manufactured in that process, resulting in parts that are outside the limits of acceptance. Level of automation is considered to influence operations when it can be increased, even if the company is not considering it necessary or worth doing it. The operations influence level of automation when it is desired to change the level by increasing it. Rework is probably the most complex case to establish dependencies. It is influenced by everything that if done with bad quality will require rework, such as some operations in-house, welding and fixturing parameters, etc. In the other hand, rework will influence the operations that are necessary to be performed in order to correct what is wrong.

There will also be dependencies between the operations. A downstream operation will be influenced by an upstream one, when problems may appear downstream because of that previous process.

Operations are not influenced by for example inspection and level of automation because this dependency is not direct, since the influence is eventually to rework and then from rework to the operations.

The rest of the dependencies, generally happen when the value of one parameter changes because of the other, does not matter if the influence is positive or negative.

Appendix F

Sheet metal forming

FPI: Difficulty to inspect some areas of the vanes, most of the times manufactured by sheet metal forming

Capability: Some lack of knowledge in some processes like cold forming

Level of distortion imparted: Welding simulations can show the distortion in the parts after the operation, which can be compensated previously adapting the forming process

Size (Volume): Certain sizes are difficult to form

Thickness: Thick parts are difficult and sometimes impossible to produce

Complexity: Impossible to produce very complex parts

Delivery capacity: Sometimes there are problems with late deliveries

Casting

Welding: Casting has a bad weldability, which will bring problems for casted parts while welding like defects and cracks

Stress areas: Casted parts bare less strength than forged or formed ones, which can be a problem for areas that have to support lots of loads

Material: It is not possible to cast H-282

Thickness: Sometimes is difficult to cast parts with some thicknesses, especially thin ones due to the casting process itself

Supplier cooperation: There are some communication problems with the suppliers

Delivery capacity: Sometimes there are problems with late deliveries

Forging

Capability: Some lack of knowledge for this process

Net shape: Final result of the process far from final geometry, which requires a lot of machining to be done

Complexity: Very complex parts are difficult to achieve with this process

Delivery capacity: Sometimes there are problems with late deliveries

Fixturing

Maturity: Researching in geometry variance, to optimize this process to achieve better results

Capability: Difficulty to achieve a good fixturing

Tool/Fixture quality: Quality of the process itself

Weight: Difficulty to create fixtures to support some weights

Size (Volume): Difficulty to create fixtures for some sizes

Accessibility: Necessary a good access to clamp the parts in the fixture

Quality of target system: Target system is crucial for the fixturing process

Number of parts: Changes the complexity of the fixture

Machining

Casting: Can be the previous operation

Forging: Can be the previous operation

Sheet metal forming: Can be the previous operation

Welding: The parts are machined as a preparation for the welding process

Heat treatment: Can be the previous operation

Fixturing: It is critical for the final result of machining

Capability: Not known for the whole machines

Tool/Fixture quality: Since the fixturing operation is critical for the success of machining, the quality of the fixture has its influence

Rework hours: It is one of the operations performed when there is rework

Thickness: Can have an influence in vibration during machining

Accessibility: Necessary access for the tools to work the piece

Quality of target system: Since the fixturing operation is critical for the success of machining, the quality of the target system has its influence

Number of parts: This number will influence the number of machining operations to be performed

Welding

Industrial structure: Change of the structure with the introduction of laser welding

Machining: Can be the previous operation

Fixturing: It is critical for the success of the welding operation

Level of automation: The level of automation of the process can be increased

Maturity: Problems achieving TRL 6, especially for laser

Capability: Lack of knowledge in this area

Tool/Fixture quality: Since the fixturing operation is critical for the success of welding, the quality of the fixture has its influence

Number of welds: Affects how many times the operation has to be done

Length of welds: Influences the welding procedure

Weld gap: Critical for the success of the welding operation

Rework hours: It is one of the operations performed when there is rework

Welding continuity: Better for the operation of welds can be done without start/stopping

Stress areas: Welds are weak points subjected to cracking, so they should be placed in areas of low stresses

Thickness: Thickness influences the choice of type of welding and affects the final result of the same

Accessibility: Necessary access for the weld machine to reach the welding locations in the parts

Quality of target systems: Since the fixturing operation is critical for the success of welding, the quality of the target system has its influence

Heat treatment

Capability: Related with the location of thermocouples

Rework hours: is one of the operations performed when there is rework

Material: Parameters of the process dependent from the material used

Size (Volume): Influences the oven to be used

X-ray

Welding: Can be the previous operation

Level of automation: The level can be increased

Number of welds: Influences the number of x-rays to be taken

Length of welds: Influences the number of films to be used

Rework hours: Defects detected by this and also is used as an extra operation when there is rework

Welding continuity: Inspection of the star/stop areas

Thickness: Difficulty to perform x-ray in thick parts

FPI

Machining: Can create defects in the surface that are discovered by FPI

Welding: Can create defects in the surface that are discovered by FPI

Heat treatment: Cracks can be produced during this operation and come to the surface and detected by FPI

Rework hours: Defects detected by this and also is used as an extra operation when there is rework

Accessibility: Necessary access to spray the parts

CMM

Welding: Can be the previous operation

Fixturing: Necessary a stable setup to measure the component

Tool/Fixture quality: Necessary a stable setup to measure the component

Rework hours: Defects detected by this and also is used as an extra operation when there is rework

Accessibility: Necessary access for the probe to check the parts

Quality of target system: Necessary a stable setup to measure the component