CHALMERS

DFM - Concept cost evaluation model for fabricated components at Volvo Aero

Master of Science Thesis

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Dedicado a mi abuela,

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Abstract

"Does Volvo Aero reach the target cost? – No, we struggle to reach the target cost; Are there usually problems during production, for instance, rework? – Yes, but it does not only affect production, also design. Loopbacks within a project are common problems, which increase drastically the final product cost." These are critical questions and common answers throughout Volvo Aero´s employees.

The root causes to these problems come from, on the one hand, the fact that Volvo Aero has recently changed the way of manufacturing jet engine´s components. The new production strategy claims for fabricated components instead of large casting and forgings. The idea is to cut-up the components in parts, so that these smaller casting, forgings and sheet metal parts are welded up together afterwards. The main driven force to this change is the possibility of weight reduction. On the other hand, the requirements situation at Volvo Aero is not balanced. That means technical requirements dominate over cost and *producibility*. However, the situation becomes worse since these two root causes reinforce to each other.

The main purpose of this thesis work is to increase the awareness, regarding the current dramatic state, through the whole company. For a mindset change, which deal with these problems, to succeed, a complete commitment from all the employees is necessary.

Therefore, this thesis is divided in two main parts. The first one will cover the company way of thinking, hence presenting the current problems and situation; identifying the drawbacks coming from this new production strategy and proposing a systematic approach to standardize, thus to support the continuous improvement. This systematic approach aims for basing the decisions on facts not on feelings. Within this Systematic approach, the experience will be transferred to a knowledge base and it will not remain just within the wise senior engineers' minds. Design For Manufacturing (DFM), production philosophy, is the key of this project.

The second part is more focus on the set of tools that follows this way of thinking. Through these DFM tools created, this thesis wants to show that a good production requirements break down is necessary in the early beginning of a project; and that it is possible to create a systematic method, which deals with producibility, in order to support the designers' work; however, always having in mind that the engineer intelligence and creativity are irreplaceable.

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.

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Abbreviations

DFM	Desgin For Manufacturing
DFA	Design For Assembly
CE	Concurrent Engineering
SBCE	Set Based Concurrent Engineering
DFSS	Design For Six Sigma
QFD	Quality Function Deployment
TQM	Total Quality Management
HoQ	House of Quality
DSM	Design Structure Matrix
PDSA	Plan Do Study Act
VAC	Volvo Aero Coorporation
VPS	Volvo Production System
OMS	Operational Management System
GDP	Global Development Process
TD&R	Technology Development & Research
CPM	Chief Project Management
TEC	Turbine Exhaust Case
TRF	Turbine Rear Frame
LPT	Lower Pressure Turbine
FBO	Fan Blade Out
GA	Geometry Assurance
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode Effect and Critical Analysis
KC	Key Characteristic
CpK	Corrected Process Capability index
ULSAB	Ultra-Light Steel Auto Body
MRB	Material Review Board
CAM	Computer-Aided Manufacturing
Nx-CAD tool	Siemens Software Computer Aided Design
HVC	Hardware Variability Control
FPI	Fluorescent Penetration Inspection
CMM	Coordinate Measuring Machine
IN-718	Inconel 718
H-282	Haynes 282
CNC	Computer Numerical Control
TIG	Tungsten Inert Gas
SAE	Society of Automotive Engineers
Producibility	The quality or state of being producible

Part I –DFM Way of thinking

Julia Madrid

1 INTRODUCTION

This chapter will explain to the reader the reason of why this work has been initiated. The chapter consists of an introduction of the project background and the current problems regarding producibility at Volvo Aero, but also information of project limitations, aim and goal.

1.1 BACKGROUND-THE NEW STRATEGY

Volvo Aero is designing and manufacturing high precisions jet engines. The company strategy for manufacturing structural components has changed recently, from large forgings and castings to fabrication instead. The basic idea is to use smaller forgings, castings and sheet metal parts or plates which are welded together into its final shape.

There are many reasons that have pushed to this change. Firstly, the higher chance of weight reduction that this new production strategy brings, directly related with the "Make it Light" vision of the company. Secondly, the supplier market situation, where only few suppliers were capable of producing such large components, consequently the purchased cost was really high. In addition the value added to the product increases, the reasons is that all the preparations and joining processes are made in-house.

"Make it Light" vision comes from the fact that one of the most important goals when designing current and future jet engines is to reduce weight and at the same time maintain or improve its performance, strength, durability and safety.

The manufacturing of these different parts are somewhat easier than large precision castings and forgings. However, the number of different parts and the fabrication process to assemble and join all parts together has a significant complexity and many alternatives can be used that will have a large influence on the manufacturing cost; besides the inherent problems coming from joining methods, such as geometrical variation.

1.2 THE COMPANY: VOLVO AERO

Volvo Aero, located in Trollhättan, Sweden, was a subsidiary of AB Volvo, recently sold to the British industry group GKN. In cooperation with the world's leading engine manufacturers, Volvo Aero develop and produce components for aircraft, rocket and gas turbine engines with high technology content *[1]* (see Appendix A- Product Range).

The company's specialization strategy has proven highly successful and more than 90 percent of all new commercial aircraft with more than 100 passengers are equipped with engine components from Volvo Aero. Volvo Aero has been an integral part of the aviation and aerospace industries since it was founded in 1930 *[1]*.

To be less sensitive in the market, since the 70's, Volvo Aero has strategically moved its focus from military to civilian, focusing as well on product development besides the existing manufacturing programs. That means that instead of only receiving drawings from the customer and producing what was on it, Volvo Aero also has the responsibility for the design *[1]*.

Volvo's core values are Quality, Environment and Safety, which are all important aspects in the aviation industries. In addition, Volvo Aero´s mission is focusing on developing lightweight solutions for aircraft engine structures and rotors, including a range of technologies. The motto "Make it light" describes the essence of that mission *[1]*.

1.3 PROBLEM DEFINITION

On the one hand, changing the production strategy from large castings and forgings to fabrication brings a lot of alternatives when it is coming to design work. The complexity of the design creation lies in the fact that many concept alternatives are suitable to fulfill the requirements. Therefore, the selection of the best one is a difficult process. On the other hand, this new manufacturing strategy brings different and more difficult producibility requirements to deal with.

Every company´s production system structure *(Figure 2)* is governed by the company values. Most of them are translated directly from customer voice, others are internal values. Company principles are adapted to satisfy these core values. For instance, Volvo Aero has a product principle named Phi *(Figure 1).* This philosophy describes the importance *"... to balance and optimize between fulfillment of Product Cost, Technical Requirements and Producibility*" *[1]*.

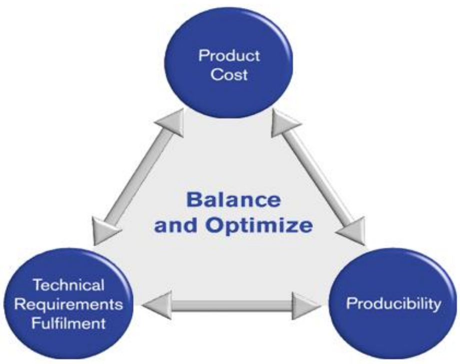

Figure 1 Phi principle

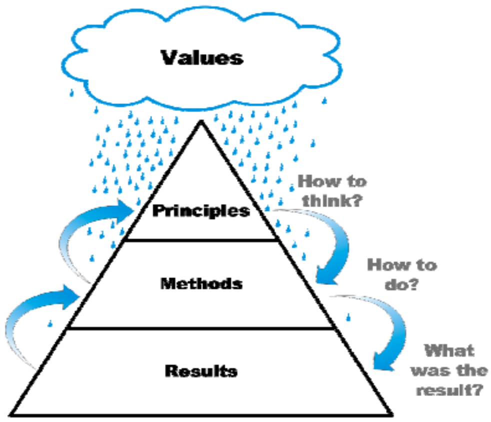

Figure 2 Production system structure

However, regarding the Phi principle, the current reality at Volvo Aero describes a non-balanced situation between Technical Requirements, Cost and Producibility. Giving more importance to Technical Requirements and secondly, Product Cost, moving Producibility to a third plane. Nevertheless, this problem that Volvo Aero presents is not unique. Traditionally, the attitude of designers has been "we design it, you build it", what is termed as the "over-the-wall approach", where the designer is sitting on one side of the wall and throwing designs over the wall to the manufacturing engineers, who then have to deal with the various manufacturing problems arising because they were not involved in the design effort *[2]*.

Nowadays, the manufacture industries have been dealing with this situation, but still it is not enough, or even sometimes, it is not necessary due to the evidence of the production processes combined with long experience achieved during many years of manufacturing the same products. In those cases producibility is not seen as a problem.

At Volvo Aero this non-balanced requirement situation still remains, even became a bigger problem, due to the new production strategy, fabricated components. There are manufacturing processes, such as joining methods, which capabilities are not well known. Also, new aspects arise to deal with, such as geometry assurance.

To solve this situation there are several important points to go through. Mainly, there is a need of Robust Design and a methodology to design and verify the producibility. In addition, the communication between designers and manufacturing engineers in both directions is essential, from the first stage of the product development. There is also a need to detect where knowledge gaps reside and to close them, so that all the process capabilities and design limits are known from an early beginning.

Without communication and knowledge build, problems such as firefights and loopbacks, appears in every project; defining loopbacks as redoing work already completed earlier in the project or reviewing decisions previously made; and firefights as short term fixing problems, thus not understanding the root causes. As a consequence of them, problems are coming over and over again. All of this ends up in the final big project; Volvo Aero has difficulties to reach the target cost.

1.4 AIM AND GOAL

Volvo Aero's new production strategy, fabricated components, brings several problems to deal within production. This situation is heightened by the fact that there is not a balanced requirements situation and that producibility is still a problems' root cause not solved.

Therefore, in order to fulfill the Volvo Aero core values and principles, and to balance and to optimize the requirements, there is a need to create a systematic approach, design methodology, to support the designers work within the product development as well as to improve the knowledge management. This will be based on the Design For Manufacturing (DFM) production "philosophy".

The project is divided in two main parts. The purpose of the first part is to answer to the question "How to think?" *(see Figure 2)*, thus, the objectives are first of all, to define and to analyze the current situation, creating a framework of the big existing problem; Secondly, to define the base for a systematic approach, methodology, to apply during the product development. The second part of the project answers to the question "How to do?" *(see Figure 2),* where some DFM tools are proposed to reach that goal.

This thesis work is an important contribution within the research project called "Design For Manufacturing – cost and robustness in aerospace components manufacturing" funded by VINNOVA (Swedish Agency for Innovation Systems), and the NFFP5 program.

1.5 PROJECT LIMITATIONS

The engineer mind is irreplaceable, everyone should be aware of that. There is no tool or methodology able to substitute an engineer work or thought. But there is a possibility to support this work and to obtain better results. This is the focus of this project.

In addition, it is important to mention the size of the problem presented here and the impossibility to cover all, as well as the limitation coming from the project length.

1.6 PROJECT PLANNING

A Gantt chart was used to follow up the progress of the project, *(See Appendix B)*. This chart was made before starting the project and it was valid as well to plan how the project was going to be performed. Beyond this, periodic formal meetings with supervisors, both from Volvo Aero Corporation and Chalmers University of Technology were made.

The formal meetings, in which an oral presentation was carried out, were made to assure that the project was going on as planned. This also helped to create an overall picture of what had been done so far and what was planned for a next future. It also worked as an information channel towards the supervisors which made them discuss in the process of the project and gave them the possibility to give important input to the project

The Thesis work had the duration of twenty-eight weeks. Within the Gantt chart the activities made during the project are presented, but also the duration for each activity. Nevertheless, some adjustments have been made to the plan in order to adjust to the day by day.

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2 THEORETICAL FRAMEWORK

This chapter summarizes all the theory and theoretical knowledge needed and used within this project. It is a recommended reading for those who are not familiar with Design For Manufacturing methodology or Project Development.

2.1 THE PRODUCBILITY ROLE AND PRODUCTION STRATEGIES

Most successful companies were initially formed around an innovative or superior product design. This trend resulted in a situation where design was considered the most important function and, therefore, received the most attention and resources. Manufacturing was treated as a service organization and it was not expected to make a positive contribution to a company´s success. Japanese success in manufacturing higher quality, lower cost products show the error in this judgment. Unfortunately, large capital investment alone cannot immediately correct problems caused by years of neglect. Improving company´s producibility is a difficult long-term process that requires considerable reserves of both expertise and capital *[3]*.

Producibility is defined as a discipline directed toward achieving design requirements that are compatible with the capabilities and realities of manufacturing. More specifically, producibility is measure of the relative ease of manufacturing a product in terms of cost, quality, lead-time, and technical risk *[3]*. Nowadays the goal is cleared; the entire product development team must understand and assist manufacturing to ensure that a design can be efficiently and quickly produced, so that the final product cost does not dramatically increase. Moreover, when producibility is considered throughout the design process, designs easier to manufacture will result.

To reach this goal, an adequate production methodology and plan should be carried out. The production methodology is the vision and framework for accomplishing long-term corporate goals, while the production planning is the roadmap that identifies the approach and tasks for all critical paths between design, production, and the tasks necessary to ensure a successful transition from design to manufacturing *[3]*. Therefore, the production methodologies will answer to the question “what need to be done”; while the production plan will cover “how to do”, i.e. product development steps or tasks.

The production methodologies represent the philosophical aspect. That means, the company´s mindset, from where all the principles come out. Design For Producibility, often called by other names such as Design For Manufacturing, Design For Assembly, Design For Automation, Design For Robustness, is the philosophy of designing a product so that it can be produced in an extremely efficient and quick manner with highest levels of quality. This philosophy and others, such as lean production or Six Sigma, represent the production strategies. These are the foundation of every production plan.

2.2 DESIGN FOR MANUFACTURING

Design For Manufacturing (DFM) is a philosophy and mind-set in which manufacturing input is used at the earliest stages of design in order to design parts and products that can be produced more easily and more economically. Design For Manufacturing is any aspect of the design process in which the issues involved in manufacturing the designed object are considered explicitly with a view to influence the design. Examples are considerations of tooling costs or time required, processing costs or controllability and variability control, assembly time or costs, human concerns during manufacturing, availability of materials or equipment, and so on. Design for manufacturing occurs or should occur throughout the design process *[4]*.

Decisions made during the early conceptual stages of design have a great effect on subsequent stages. In fact, more than 70 percent of the manufacturing cost of a product is determined at this conceptual stage, yet manufacturing is not involved *[4]*. Companies that have applied DFM have realized substantial benefits. Costs and time-to-market are often cut in half with significant improvements in quality, reliability, serviceability, product line breadth, delivery, customer acceptance, and, in general, competitive posture *[5]*.

The following diagram (Figure 3) shows the sequence of steps during the design process when using DFMA methodologies.

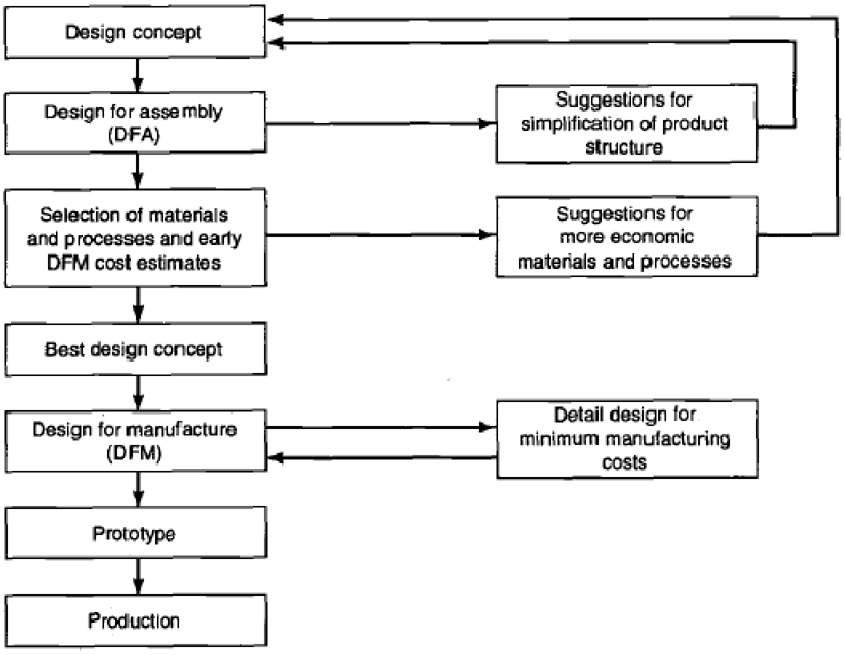


Figure 3 Design process steps using DFMA methodology *[2]*

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 *[2]*.

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. If there 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 worst, 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 and as soon as possible inside the same *[2]*.

Boothroyd and Dewhurst 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 assembly process at the workshop. Knowing the time it takes, it is possible to calculate the assemble costs using standard labor prices *[2]*.

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 redesign. 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 *[2]*.

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 is 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]*.

2.2.1 Responsibilities of design engineer

The responsibilities of design engineers cover all aspects of design. Although functional design is of paramount importance, a design is not completed if it is functional but not easily manufactured. Design engineers have the broad responsibility to produce a design that meets all its objectives: function, durability, appearance and cost. A design engineer cannot be covered under the "*over-the wall approach* by saying "(approach mentioned in previous section). The functional design and the production design are too closely interrelated to be handled separately. Product designers must consider the conditions under which manufacturing will take place, since these conditions affect production capability and costs *[6]*.

2.2.2 Responsibilities of manufacturing engineers

Manufacturing engineers have a dual responsibility. Primarily, they provide the necessary to enable a product to be manufactured. Secondarily, they are responsible to ensure that the design provided to the manufacturing organization is satisfactory from a manufacturability standpoint *[6]*.

It is then, cleared established the need of cooperation between both organisms for a successful DFM application.

There are several DFM guidelines to support this philosophy. Always having in mind that these are mere tools, and without a right mindset acquired, the success will never arrive. Examples of these DFM guidelines are as follows *[7]:*

- Reduce the number of parts to minimize the opportunity for a defective part or an assembly error, to decrease the total cost of fabricating and assembling the product, and to improve the chance to automate the process.
- Foolproof the assembly design (poka-yoke) so that the assembly process is unambiguous.
- Design verifiability into the product and its components to provide a natural test or inspection of the item.
- Avoid tight tolerances beyond the natural capability of the manufacturing processes and design in the middle of a part's tolerance range.
- Design "robustness" into products to compensate for uncertainty in the product's manufacturing, testing and use.
- Design for parts orientation and handling to minimize non-value-added manual effort, to avoid ambiguity in orienting and merging parts, and to facilitate automation.
- Design for ease of assembly by utilizing simple patterns of movement and minimizing fastening steps.
- Utilize common parts and materials to facilitate design activities, to minimize the amount of inventory in the system and to standardize handling and assembly operations.
- Design modular products to facilitate assembly with building block components and sub-assemblies.
- Design for ease of servicing the product.

In addition to these guidelines, designers need to understand more about their own company's production system, i.e., its capabilities and limitations, in order to establish company-specific design rules to further guide and optimize their product design to the company's production system. For example, they need to understand the tolerance limitations of certain manufacturing processes, as well as, the company strategies and the company context itself. Moreover, this is very important within the manufacture aircraft industry, since it is a low volume and high variety production, totally different to the car industry production. A clear example regarding the issue just mentioned would be the current Volvo Aero production strategy, addressed in this project, which has the aim of cutting up the component for a later assembly, totally opposite to the first DFM guideline, but still worth strategy.

2.3 LEAN PRODUCTION & SET BASED CONCURRENT ENGINEERING

2.3.1 Lean Production

One of the most popular new strategies in manufacturing is called "lean production". Perfected by Taichi Ohno, this strategy focuses mainly on the elimination of waste in all areas with a focus on inventory, work-in-progress, material handling, cost of quality, labor costs, set-up time, lead-time and worker skills. There are several principles to lean thinking including eliminating waste, standardized work, produce zero defects, and institute one piece flow. This methodology focuses on the Value Stream that is defined as the specific network of activities required designing, ordering and providing a specific product, from concept to delivery to the customer *[8]*. This flow should have no excess steps, stoppages, scrap or backflows. It also emphasizes the complete elimination of *muda* (Japanese term referring waste, i.e. unnecessary tasks, etc.) so that only activities that create value are in the value stream. Timely responses are critical for this methodology to be effective. This provides a way to support value-creating action in the best sequence. Lean thinking provides a way to do more and more with less and less: inventory, human effort, equipment, time, space, while coming closer and closer to providing the customer with exactly what they want *[3]*.

2.3.2 Concurrent Engineering

Concurrent Engineering (CE) is an approach to product development in which multi-disciplinary teams work together from the requirements stage until production. The idea behind it is to ensure that the requirements of all the stakeholders involved in the product development are met. It reduces the number of late changes, time-to-market and cost, as decisions at each stage of the product development are based on the common point of view of people from different disciplines involved *[9]*.

2.3.3 Set-Based Concurrent Engineering

One of the Lean four cornerstones is Set-Based Concurrent Engineering, SBCE.

Set-based concurrent engineering is a method that systematically builds knowledge about multiple design concepts and then successively eliminates concepts, so that the finally decided concept is robust, which reduces the risk of late loops *[10]*.

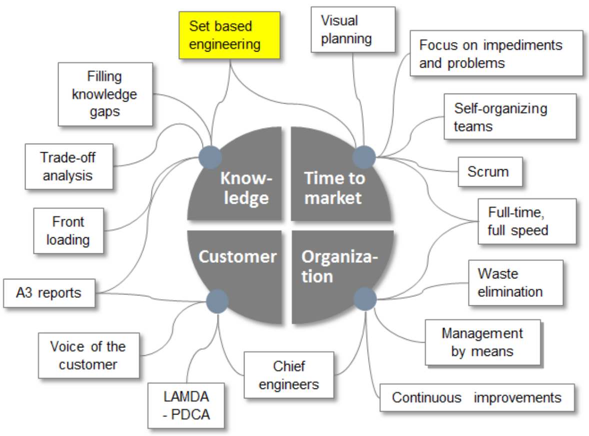


Figure 4 Lean four cornerstones-SBCE

In contrast, the traditionally selection approach, "Point-Based", consists of selecting the "best" concept and making it the winner. This procedure perpetually results in unplanned loopbacks that weave through subsystems and cause all kinds of firefighting, confusion, and costly waste. Products are often late, over-budget, and less than desirable to the customers *[11]*.

	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

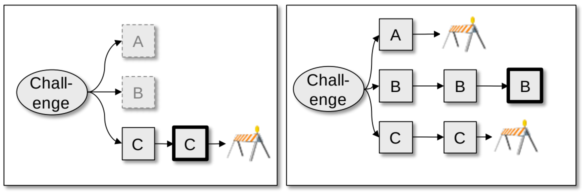


Figure 5 Set based vs. Point base

Therefore, Point-Based is not a suitable approach to deal with these problems. In contrast Set-Based has the *Knowledge building and sharing* as one of the four key principles.

The need of early knowledge built is also motivated by the following graphs, the *Cost of Learning* and *The Designer´s Dilemma*, seen in Figure 6.

Decision making on concepts is challenging due to the limited knowledge and insufficient information available early on in a product development projects, combined with the uncertain and abstract nature of the product concepts considered. While there is more potential to influence the product early in the process, there is less knowledge regarding the design problem. This is the so called The Design Process Paradox *[12]* or The Designer´s Dilemma. This contradiction motivates a knowledge base, and this fact is also fundament by the Cost of Learning curve, which shows that exploring a new idea, i.e., learning, is always lower during an early design phase, due to critical advances or decisions have not been made yet.

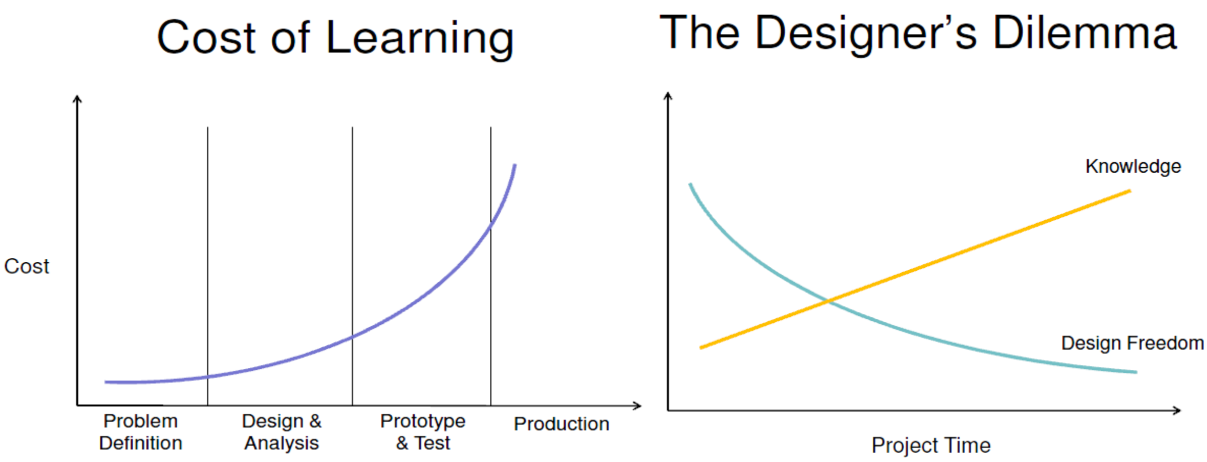


Figure 6 Cost of learning curve & The Designers' Dilemma

The basic Set-Based design rules are summarized as follows:

- As constraints are involved, use a funneling process to reduce the number of feasible designs.
- Focus on keeping the design space as open as possible as long as possible to build knowledge in a systematic way.
- Capture, store and retrieve the knowledge to be used in future designs.

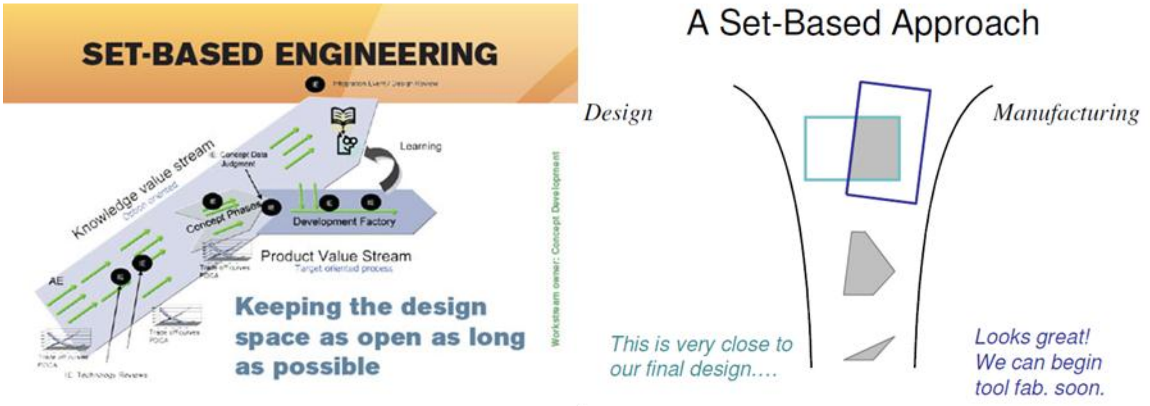


Figure 7 Set Based Concurrent Engineering

A good way to build knowledge and use it as earlier as possible within the project is creating Trade-off curves. These curves describe the limits of performance that are possible with a given design concept in a simple visual way. They typically characterize the relationship between two or more key parameters that relate design decisions to customer interest variables *[13]*, for instance, a trade-off curve can relate weight (customer interest variable) and number of vanes (design decision). The main advantage is that these curves provide reusable knowledge for future product designs.

2.4 QUALITY

The most of the production strategies focus on quality. This is an important aspect to consider within the manufacture industry, since quality concept focuses on customer needs and customer expectations. It can be said that Quality is one of the main core values in every company.

Specific philosophies such as Total Quality Management (TQM) and Six Sigma aim for a continuous improvement of quality. However, as it is said before, the most of the production strategies look for achieving good quality results. Six Sigma is considered a methodology within the holistic and general framework that TQM represents. In Six Sigma, systematic problem solving is emphasized, especially, but not only, when problems occur due to variation in the manufacturing process. The problem solving procedure within Six Sigma is based on an extension of the PDSA (Plan Do Study Act). In order to face the quality problems in the early phase of the product development, during design, rather than solving them in the manufacturing process, design for Six Sigma has been created *[14]*.

The quality of a product is its ability to satisfy, or preferable exceed, the needs and expectations of customers *[14]*. Using this as a basis, Quality Function Deployment, QFD, is a methodology that systematically identifies customer demands on product features and design parameters, translate these demands into product characteristics, and incorporates them into the manufacturing process *[14]*.

Quality Function Deployment is also an excellent methodology for communication and participation. It requires the creation of cross functional groups that meet and work out common concepts, and it provides a common basis necessary for integrated product development *[14]*.

The aim of QFD is to translate the wants and needs of the customers into product and process characteristics by systematically letting the wishes be reflected at every level of the product development process. Without a systematic methodology it is hardly possible to break down the wishes of the customers completely as far as parts of the product and elements in the production process are concerned *[14]*.

Essentially, the QFD methodology can be divided into four phases *[14]*.

Product planning. The wishes of the customer are transferred to properties of the product. At the same time a valuation of these wishes is made, using analyses of the competitors as one source. The final result is an identification of important product properties which will be transferred to the next step of the QFD work. The work is generally carried out and documented in a kind of matrix called "The Quality House".

Product Design. The design concept is chosen that best fulfills the given target values. Parts and components that will be critical for the product are identified and then sub-properties are set in a way corresponding to the product properties in the previous phase. Sub-properties that will be critical are also identifies, to find out where there is a need for further development and research, in order to meet the demands of the market.

Process design. The critical properties are transferred to production operations and their critical parameters are identified. Methodologies for process control and process improvement are determined.

Production design. Production instructions are designed. The operator needs, for instance, exact descriptions of the parts to be measured and the measurements to be observed. Also, instructions must be developed regarding how many units should be measured, how often this should be done and what tools should be used.

2.5 PROJECT ORGANIZATION

The way projects are structured is directly related to the way the project organization is structured, i.e. how people are organized along the product and production development. Therefore, any kind of mindset implementation, for instance DFM implementation will influence both project structure and organization structure in a parallel way.

There are three major organization structures to manage work and people; Functional, Project and Matrix organization.

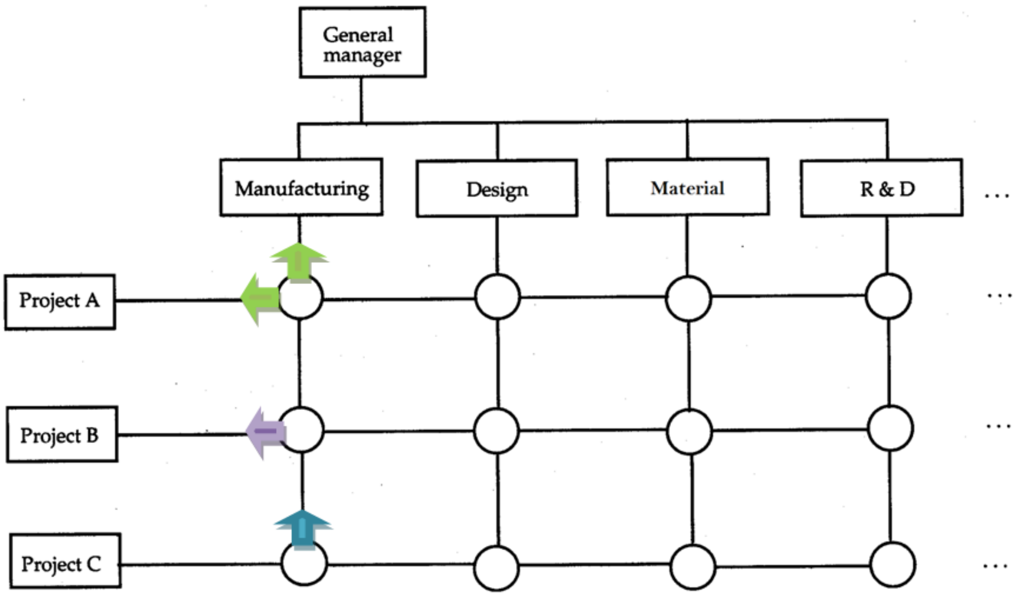


Figure 8 Project Organization structures

2.5.1 Functional Organization

Big organizations used to operate in a silo management structure, where isolated groups of workers in a division would report to a functional manager. Imagine columns on a page with a line manager above each column and a group of workers inside each column under the manager of the division. That means the project would be broken down by functions and each function, or department, would do its own task relatively independently. At the end, those separately solutions would be integrated into one final solution. As these groups operated independently, it was not unique to discover functions replicated in each silo. A member of a functional team will report only to his function department, as it is indicated in the Figure 8 with a blue arrow *[15]*.

Advantages	Disadvantages
Clear authority, since the project managers tend to also be the functional managers.	May not have all the specialist need to work on a project.
No-need to negotiate with other organizations for resources	Team members may have other responsibilities in the functional organization since they may not be needed full-time on a project. They may be assigned to other projects. Consequently that could impact their ability to meet project deadlines
Team members are usually familiar with each other.	
Provides specialization and functional excellence	

Table 1 Functional Organization

2.5.2 Project Organization

In the pure project organization, the project manager is the supreme authority. These are usually large enough projects, carried out in remote locations. In which all the team members implied just report to the specific project. (Purple arrow Figure 8).

Advantages	Disadvantages
Clear authority (same reason as before)	Duplication of resources
Clear focus, since everyone on the team has the project as primary responsibility.	Problems reallocating people when the project is completed.
Full control over resources	Low level of knowledge transfer

Table 2 Project Organization

2.5.3 Matrix Organization

This organization structure facilities the horizontal flow of skills and information. It is use mainly in the management of large projects or product development processes, drawing employees from different functional disciplines for assignment to a team, without removing them from their respective positions.

Employees in a matrix organization report on day to day performance to the project or product manager whose authority flows sideways (horizontally) across departmental boundaries. They also continue to report on their overall performance to the head of their department whose authority flows downwards (vertically) within his or her department. In addition to a multiple command and control structure, a matrix organization necessitates new support mechanisms, organizational culture, and behavior patterns. Developed at the US National Aeronautics & Space Administration (NASA) in association with its suppliers, this structure gets its name from its resemblance to a table (matrix) where every element is included in a row as well as a column (see green arrow in Figure 8) *[16]*.

Advantages	Disadvantages
Efficient utilization of all resources	Strong requirement in communication and cooperation between multiple functional and project managers.
Facilitates information flow	
Team members can communicate with project and functional managers	Conflicts regarding priorities can arise between managers. Consequently there is a need of balancing requirements.
Customer focused	

Table 3 Matrix Organization

2.6 PRODUCT DEVELOPMENT PROCESS

To assure a successful product development, the production strategy chosen (*what to do*) should be implemented by defining a systematic application, i.e. product development steps or tasks (*how to do*), as well as establishing adequate methods of managing people and networking knowledge.

The design process can be divided into the following phases:

1. Requirements Definition
2. Conceptual Design
3. Detailed Design
4. Test and Evaluation
5. Manufacturing

These phases are often overlapped, which is the major objective of Concurrent Engineering, in order to reduce the time needed to develop a product. It requires simultaneous, interactive and inter-disciplinary involvement of design, manufacturing and field support engineers to assure design performance as well as good producibility.

2.6.1 Requirement Definition

The product development task is given to the engineering department by business and sales department. It is necessary to clarify the given task in more detail before starting product development *[17]*.

Therefore, the first phase of the design process is to identify the overall needs of the customer and define the design objectives for the product. Requirement definition is the process of identifying, defining and documenting specific customer needs to develop product requirements for a new product, system or process *[3]*.

Besides satisfying the technical function of the product, other aspects that will constrain the design should be taken into account. These can be classified under the following heading *[17]:*

- *Production* *production facilities and type of production*
- *Safety* *also in the wider sense of reliability and availability*
- *Ergonomics* *human-machines context, also aesthetics*
- *Quality control* *throughout the design and the production process*
- *Assembly* *during and after the production of components*
- *Transport* *inside and outside of the factory*
- *Operation* *intended use, handling*
- *Maintenance* *upkeep, inspection and repair*
- *Expenditure* *costs and schedules*
- *Recycling* *reuse, reconstitution, disposal, final storage.*

The characteristics that can be derived from these constrains are formulated as requirements. Hence they should be treated as guidelines throughout the design process, and be adapted to each phase *[17]*.

Although requirements specifications are the final output of the early phase of the product development, modifications and updates will be probably required as the design evolves or new technologies are introduced.

In order to get an optimal and successful result an adequate understanding of the customer´s needs and company´s capabilities is required. Therefore, the Requirements Definition process is a critical point within the product development. Successfully translating customer needs into level requirements is extremely difficult. There are several common pitfalls in this process such as:

- The product requirements should not become too complex and detailed.
- Requirements can be stated in general terms, thus it will be difficult to measure the progress.
- Trying to develop only one set of requirements for all customers.

There are several approaches for knowledge acquisition of customer (external) and Volvo Aero internal needs. The design team should use these methods to insure that the final requirements are representative of the needs. These methods include tools such as House of Quality.

2.6.2 Conceptual Design

The conceptual design process identifies all the design alternatives that could meet the defined requirements; performs trade-off analysis to identify the best approaches to be developed in further detail during next phase; and transforms the product requirements into lower design requirements based on the alternatives selected *[3]*; meaning by lower design requirements, a further detail level of requirements, since the top level is considered as the functional requirement, the most general ones.

It begins when a new product is defined in the requirement definition process and continuous until the final design approach has been identified. Requirements are allocated down to the lowest levels needed and documented during this process. This is the phase where the size of the design team will grow. As more and more specialists are added, effective communication and teamwork become essential *[3]*.

Concept Creation

The first step of the conceptual design is to start identifying potential design solutions to be used in trade-off analysis. Many people are involved in this collaborative effort to insure all possible options are considered. Creativity and innovation must be encouraged not only for design but also manufacturing and other areas *[3]*.

Design is about anticipation. The team anticipates new technologies and styling trends to envision how they might be translated into desired products. The widest possible range of potential solutions should be examined early in the project. In this way, the opportunity is optimized to take advantage of recent advances in technology and new styling trends to avoid being locked into out of date or preconceived solutions *[3]*.

Concept Evaluation

The next step of conceptual design consists of evaluating each of the identified design alternatives. Trade-off studies or techniques examine the different concepts design alternatives and parameters with the purpose of finding a proper requirements fulfillment balance. The trade-off studies should include all-important parameters such as cost, schedule, technical risk, reliability, producibility, quality, and supportability.

Some structured evaluation methods are preferable in the concept development process such as decision matrix (Pugh´s evaluation matrix) or the Analytical Hierarchy Process (AHP)

V-Model

After identifying the alternatives to develop in further detailed, the next step in the conceptual design in to translate the high-level product requirements into lower level design requirements. This is often called requirements allocation *[3]*.

All the design requirements should be measurable and “testable”. That means that each requirement at every level should be defined to allow the evaluation as to whether the design is satisfying the requirement *[3]*. The V-model allows this process of breaking down requirements and testing, as it is shown is the following figure , Figure 9.

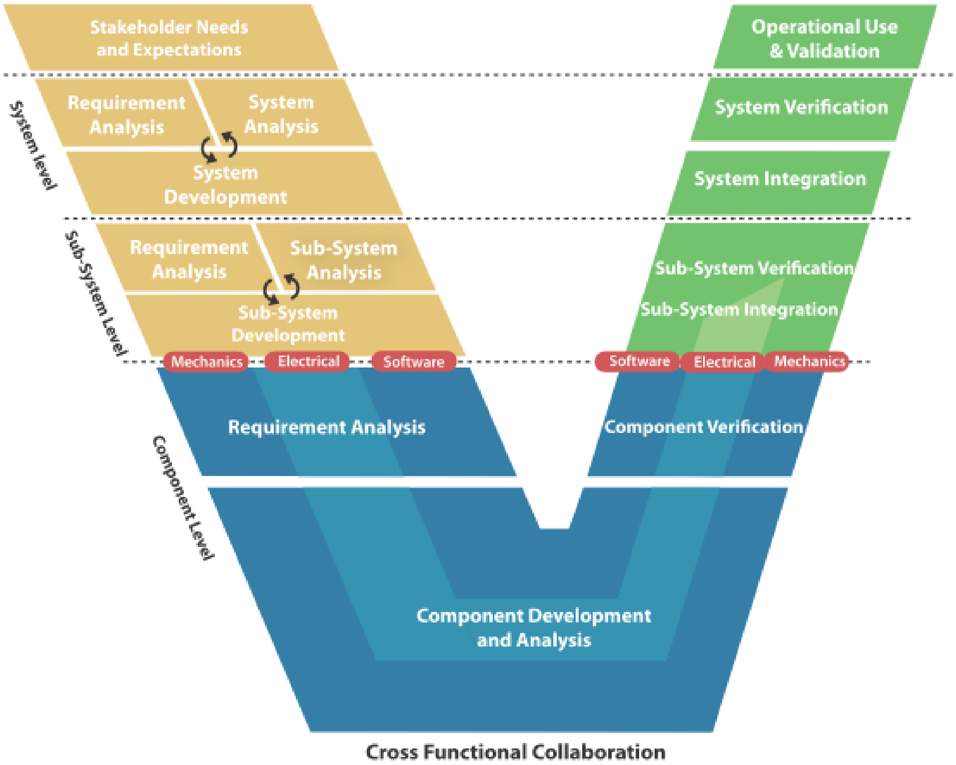


Figure 9 V-model

Within the V-model requirements are translated and distributed in the left leg and solutions integrated in the right leg. The solutions are verified and validated to the corresponding requirements and expectations at the left leg.

2.6.3 Detailed Design

Detailed design is the process of finalizing a product’s design which meets the requirements and design approach defined in the early phases. Critical feedback takes place as the design team develops an initial design, conducts analyses, and uses feedback from design analyses to improve the design. Design analysis uses scientific methods, usually mathematical, to examine design parameters and their interaction with the environment. This is a continuous process until the various analyses indicate that design is ready for testing. During this stage, the product development team may construct prototypes or laboratory working models of the design for testing and evaluation to verify analytic results *[3]*.

2.6.4 Test and Evaluation

Test and evaluation is an integrated series of evaluation leading to the common goal of design improvement and qualification. When a complex system is first designed, the initial product design will probably not meet all the requirements and will probably not be ready for production. Test and evaluation is a “designer’s tool” for identifying and correcting problems, and reducing technical risks. A mature design is defined as one that has been tested, evaluated, and verified prior to production to meet “all” requirements including producibility *[3]*.

2.6.5 Manufacturing

The product development effort does not end when the product is ready for production. Problems found in production require the design team to perform analyses. Additional team efforts continually try to reduce manufacturing costs and improve quality throughout the product’s useful life.

The knowledge gathered during this period is an important and useful input to new projects. Therefore a good knowledge data system should be linked to this phase.

2.7 COST MODELS

Design engineers, manufacturing engineers, and industrial engineers, in analyzing alternative methods for producing a part or a product or performing an individual operation or an entire process, are faced with cost variables that relate to materials, direct labor, indirect labor, special tooling, perishable tools and supplies, utilities and invested capital.

During the production and assembly stages there are relatively few opportunities to reduce those costs. Therefore, it is important to start cost optimization as early as possible since any design changes that have to be made during production are usually very costly. This might prolong the design process, but overall it is more economical than a retrospective drive to reduce costs.

The overall cost of producing a product can be divided into:

- **Direct costs:** those costs that can be allocated directly to a specific cost carrier (e.x. material and labor costs of producing a specific component)
- **Indirect costs:** cannot be allocated directly (e.x. costs of running the storages and illuminating the workshop)
- **Manufacturing cost** is the total of the costs for material and production, including additional costs such as for production tooling and fixtures, and for design, development, models and test as far as they relate to a specific product.

Manufacturing cost therefore consists of variable and fixed costs. For decision making during the design process, however, only variable costs are of interest. This is because they are influenced directly by the designers, for example, by the choice of materials types, production process, thus production times and assembly methods. Of interest, therefore, are the variable manufacturing costs which comprise direct costs and indirect costs *[17]*.

Despite its obvious relevance throughout the product development, cost analysis has not been a focus of the design engineer.

2.8 RISK MANAGEMENT

Most product development problems are result of “unexpected” events. Technical risk is a measure of the level of uncertainty for all of the technical aspects of the development process. Risk management identifies and tries to control this uncertainty found in product development. Experienced designers know there are conditions, requirements, and situations that almost always create problems. Companies that do not study and learn from history are doomed to repeat the same mistakes. An early detection is critical because it is easier and cheaper to make changes early in design *[3]*.

Failure Mode and Effect Analysis (FMEA) is a formalized method for the systematic identification of possible failures and the estimation of the related risks (effects). The main goal is to limit or avoid risk *[17]*.

A Key Characteristic (KC) is a feature of a material, process, or part (includes assemblies) whose variation within the specified tolerance has a significant influence on product fit, performance, service life, or manufacturability. Those should be identified and controlled. This is another way to risk assessment.

2.9 GEOMETRY ASSURANCE AND ROBUSTNESS

The term geometric assurance (GA) covers all the activities aimed at securing that geometric quality is met. Knowing how the product concept and manufacturing processes combine and understanding the origin of the variation are central to geometric assurance work. The opportunity to simulate and visualize variation and tolerance results as well as an efficient use of experience and data from previous solutions are important success factors for increased geometric quality. Robust concepts give a high quality end product, which pays for itself in the form of reduced costs for adjustments, rejections and complaints *[18]*.

Every manufacturing is exposed to variation *(Figure 10)* which means that the nominal value of a manufacturing dimension may not be expected always. The dilemma is that as less variation more cost.

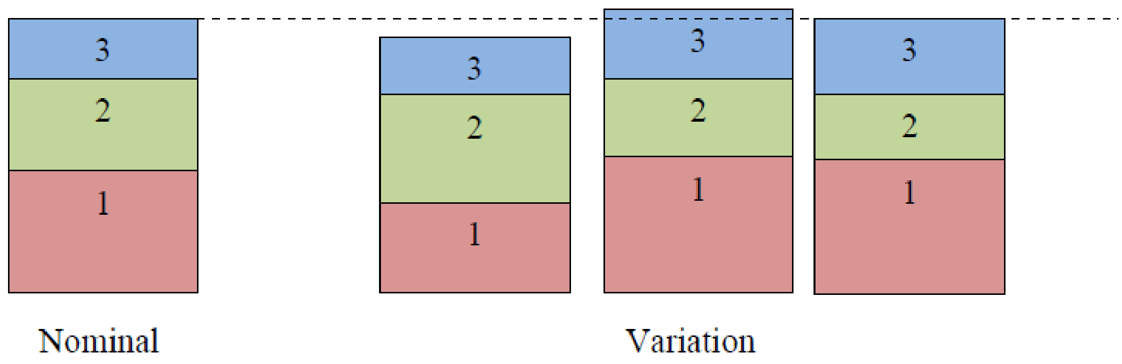


Figure 10 Component in nominal state and state affected by variation

The means of managing variation and securing function, form and assembly, is by assigning tolerances that restrict the permitted variation of a geometrical feature. Properly done, tolerances are allocated in a top-down fashion where overall product constraints are broken down into component constraints and finally into tolerances for individual geometrical features. This is a complex process (figure 11), where function and quality aspects must be balanced against manufacturing constraints and cost aspects *[19]*.

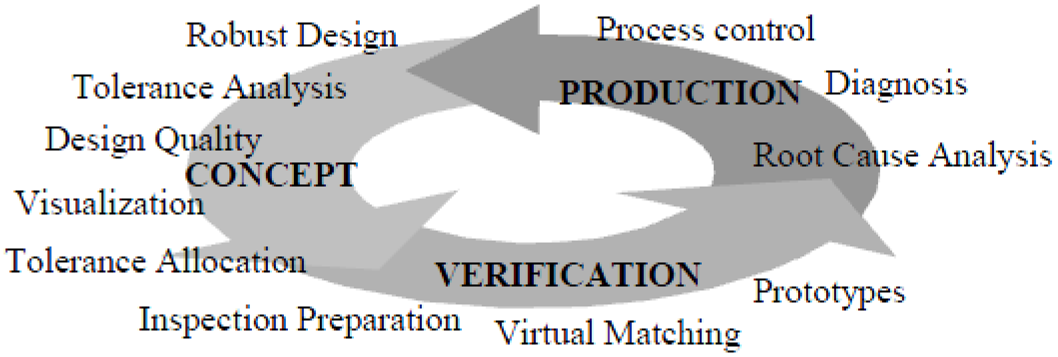


Figure 11 Geometry assurance process for a car industry *[19]*.

In the Concept phase the product and the production concepts are developed. Product concepts are analyzed and optimized to withstand the effects of manufacturing variation, and tested virtually against available production data. In this phase, the concept is optimized with respect to manufacturing robustness and verified against the assumed production system by statistical tolerance analysis. The visual appearance of the product is optimized and product tolerances are allocated down to part level *[19]*.

In the Verification phase and Pre-production phase the product and the production system is physically tested and verified. Adjustments are made to both product and production system to adjust errors and prepare for serial production. In this phase inspection preparation takes place. This is the activity when all inspection strategies and inspection routines are decided *[19]*.

In the Production phase all production process adjustments are completed and the product is in full production. Focus in this phase is to control production and to detect and to correct errors *[19]*.

3 METHOD: Gathering all the necessary information

The first target of this project is based on analyzing the current situation at Volvo Aero and identifying the problems along the product development regarding producibility. Before that, it is necessary a clear definition of what it is understood by producibility. The study of adequate strategies to apply during the design phase, which takes into account the producibility, is directly related to this part.

Therefore, the methodology followed to achieve this first goal basically looks for gathering the necessary information in order to get an understanding of the company and to learn about the product development process and the different strategies beneficial to deal with the producibility problem. This information has been gathered from multiples sources by using different data collection methods such as interviews, observations, literature review, Internet research, Volvo Aero intranet research and benchmarking.

Regarding the second part of the project, basically structured interviews were performed as a data collection method. That information was used for developing the DFM tool. Further information regarding the specific methodology carried out to perform the second part will be present later.

In order to give to the lector a wide sight of the interviews made during this thesis a summary table will be presented at the end of this section.

3.1 LITERATURE REVIEW

A great part of this thesis project has been an external literature study on a wide variety of topics due to the undefined project scope at the beginning of the thesis work. Areas such as Design For Manufacturing, Lean Production, Set Based, Cost Modeling, Concept Selection processes, Risk Management, Knowledge Management, Quality has been covered by going through books, articles, thesis works, videos, websites. The literature study was also conducted internally (Volvo Aero intranet) with company documents, PowerPoints and the Volvo Aero internal website.

3.2 INTERVIEWS

An interview can be organized in different ways. Usually the interviews can be classified in unstructured interviews, half structured interviews and structured interviews.

One mayor advantage of the interview is its adaptability. A skillful interviewer can follow up ideas, probe responses and investigate motives and feelings, which the questionnaire can never do. They way in which a response is made (the tone of voice, facial expression, hesitation, and so on) can provide information that a written response would conceal *[20]*.

3.2.1 <u>Unstructured interview</u>

Within an unstructured interview the person who is leading the interview asks wide open questions allowing the interviewee to answer freely *[21]*.This also gives the person doing the interview a chance to make an attendant question and obtain a deeper understanding in the subject *[21]*. Usually, the unstructured interview takes place as an informal conversation, with the researcher asking follow-up questions in response to statements made by the interviewees *[22]*. This interview method is very good when the person making the interview does not have much knowledge about the subject *[21]*.

Multiple unstructured interviews were conducted from *8-February-2012* to *3-May-2012*. During these two months engineers coming from a wide variety of areas, such as designer engineers, manufacturing engineers, cost engineers, method engineers, verification engineers, project managers, were surveyed. The main goal of these unstructured interviews was, first of all to get an overall insight of Volvo Aero Corporation, how it is structured, which projects they are carrying out, how the people are organized along the projects, which kind of product they are manufacturing, which the customers are, etc.

This type of interview resulted in some irrelevant information, but also allowed evidence to the variables of interest to emerge naturally.

3.2.2 Half structured interviews

Half structured interviews are a combination of the structured interview and the unstructured interview methods. The person making the interview knows in advance the areas of interest and partly what kind of questions are going to be asked. Some knowledge is necessary about the subject area. The questions can be open or specified, and thereby the person being interviewed can answer freely or by specified answers. This gives a better opportunity to ask attendant questions in comparison to the structured interview method *[21]*.

Once having achieved an overall overview of the company, the unstructured interviews allowed make a jump to half structured interviews. The reason is that the project scope was gradually defined and better knowledge about the subject was acquired, due to the information gathered so far.

In addition, interviewed engineers themselves were opening and guiding to more research fronts, which was one of the main factors that contribute to narrow the project scope.

3.2.3 Structured interviews

In a structured interview there are pre-made questions in a predefined order, asked by the one making the interview. The person being interviewed can either answer freely or by specific alternatives. In order to know what areas that should be explored and how to develop the questions so that desired information is obtained, a lot of knowledge is needed. This kind of interview method is usually used on a larger number of people and is often short interviews. An alternative for structured interviews are questionnaires *[21]*.

Structured interviews have been used through two different instruments in order to cover two different purposes. The first developed instrument was a questionnaire, forwarded by email to 20 designer engineers that have been part of the concept development process, with the purpose of detecting knowledge gaps, exploring in a structured way about project phases and organization and getting an insight about which methodologies are used during product development, as well as testing DFM and Set based general knowledge. This questionnaire had both closed-ended questions, which could be answered by checking predetermined answers, and open-ended questions where the participant could answer in their own words. All answers were anonymous and voluntarily. The questionnaire gathered information that could be statistically analyzed.

The second instrument was pre-made questions. Two sets were created to fulfill two different but closely areas. The first set was focus to the manufacturing engineers (method specialist engineers), with the purpose to know in more detail about all manufacturing processes followed in the TEC product (item chosen to focus the analysis of the project and to implement the DFM tool, as it will be explained further within the report) and to detect the cost drivers and their dependencies. The other set of premade questions was directed to operators at the workshop in order to follow step by step all the TEC manufacturing operations.

The complete Designers Questionnaire, first instrument used for these structured interviews, can be found in the Appendix C.

3.2.4 Observations

Observations typically involve recording behaviors or conditions in an environment that are relevant to the research propositions *[23]*. Understanding the complexities associated with an environment may best be attained through observation. Sometimes structured interviews may be biased but the emotional involvement of the interviewee with the topic. Observations permit the researcher to reach his or her own understanding. Observations also allow the researcher to collect data on routines activities that may never be discussed in structured or unstructured interviews. However, observations can also unintentionally affect the behavior or response of the participants, since they know they are being observed *[22]*.

3.3 BENCHMARKING

Benchmarking is the process of identifying, sharing, understanding, learning from and adapting outstanding or best practices from organizations anywhere in the world in the quest for continuous improvement and breakthroughs *[24]*.

Although there are different benchmarking models to follow, such as XEROX benchmarking model, pioneer in this discipline and AT&T model or ALCOA model, all of them commonly describe similar phases, which are:

- Phase1- Planning
- Phase 2- Analysis
- Phase3- Integration
- Phase 4-Action

Within these phases each model develops its own steps adapted to the different company needs.

Regarding this project, a benchmarking practice has been developed to deal with Volvo Aero context. Having in mind the project time limitation and the wide project area covered, a light benchmarking model has been selected, in order to detect mainly which methodologies have been applied in other companies to face producibility problems. As well as observing other important points such as knowledge management, types of project structure and project organizations.

This comparison practice has been performed with four important and successful companies, which are SKF Group, Volvo Group Trucks Technology, Saab Aerospace and Scania. All of them belong to the transport manufacture industry, as Volvo Aero does. It should be pointed out that not always the best strategy is choosing companies from the same sector, but due to time limitation this was the quickest way to obtain comparable results.

During the *Phase 1 – Planning*, the areas to cover and the companies to benchmark with were selected. It was not an easy process since the project scope has not been completely defined by then. In fact, benchmarking helped partly to define the project´s scope. A questionnaire was created in order to gather the necessary information. The questions were developed, firstly by using a brainstorm method, and after those results were screened and defined. The purpose of questionnaire was mainly to make aware the interviewee about what kind of questions he was going to find, so he could prepare in advance, as well as to drive the interview to the areas of Volvo Aero interest. These interviews were carried out through live meetings with relevant employees at each company domains, which allows not only to interview, also to see the *Genba* (lean manufacturing term to define the real place, that means the workshop), where solutions and problem can easily visualized.

This questionnaire can be found in Appendix D. Following phases are integrated along this report.

3.4 LIMITATIONS OF METHODOLOGY

The subjectivity and the own perception clearly influence the results of these analysis methods. Moreover, though the objective of these interviews and surveys was to cover all areas required to fulfill the project´s goals, not everyone has been contacted within the Company or externally, existing the possibility of missing some important and critical information for the project performance.

Interviews activities and observations have not been thoroughly reported within this document. However, a summary of the unstructured interviews as well as the questionnaire answers and benchmarking survey answers are documented and can serve as references. The results and conclusions are more important than the detailed documentation itself.

Specifically, the language has been a limitation since several documents and sides within Volvo Aero intranet are not translated to English yet. There is also the fact the English is not the mother tongue of any of the people involved in this project, what could has end up in missed or misunderstood information gathered.

Other problem was the number of questionnaire answers from designers, 11 over 20 replied. The problem resides on the most of them were working on the final phase of an important project. Even so, the results are quite analyzable.

3.5 INTERVIEWS AND BECHMARKING SUMMARY

This table summarizes the entire interview period. More than 40 employees have been taking part of this procedure.

METHOD: GATHERING INFORMATION	INTERVIEWEE
Unstructured and Half structured interviews ***(8th February 2012 – 3th May 2012)***	25 employees with different roles and backgrounds. *Their names are company confidential and cannot be published in this report due to Intellectual Property Rights for GKN.*
Designers Questionnaire ***(May 2012)***	11 designers working during concept phase. *Their names are company confidential and cannot be published in this report due to Intellectual Property Rights for GKN.*
Engineer Method Specialist Structured interviews ***(11th April 2012 – 25th June 2012)***	9 Engineer Method Specialist related to the operations: • Casting • Forging • Sheet metal forming • Welding • Heat treatment • Inspection methods 2 engineers working with tooling and 1 engineer working with geometry assurance. *Their names are company confidential and cannot be published in this report due to Intellectual Property Rights for GKN.*
Benchmarking ***(27th April 2012 – 24th May 2012)***	SKF Volvo Group Trucks Technology Saab Aerospace Scania

Table 4 Interviews and Benchmarking summary

Note that the interviews to Engineer Method Specialist (EMS) have the purpose of supporting the Part II of the project. Even though, they were useful to complete the framework of the current situation.

4 ANALYSIS AND RESULTS

The following chapter describes the results and information gathered during the thesis work regarding *Part I*. The current state description at Volvo Aero is the outcome of the unstructured and half structured interviews performed, complemented with some information from the structured interviews. This represents an overall view of the company as well as an introduction to the company problems related with producibility.

Moreover, the Designers and Benchmarking Questionnaires help to describe a detailed framework of the situation due to more focused results are achieved through them.

4.1 ANALYSIS OF THE CURRENT STATE

There is a need to clarify the meaning of producibility, since this term is the key of the project. Therefore, this will be the starting point of this chapter. The current state at Volvo Aero has been defined by developing the most important topics regarding the project. Therefore the exact answers during unstructured interviews are not presented here, but there is summary containing the people interviewed and the main ideas (see Appendix E).

4.1.1 Producibility Definition

Producibility is not a real word, it cannot be found in a dictionary. Instead, producibility is an auxiliary term to describe an abstract concept. Several definitions made by different authors regarding this term can be found:

By "Producibility" the interpretation is a collective term for capabilities and restraints that determine to what extent the product can be produced in a robust and efficient way in serial production [25].

Producibility— relative eases of producing an item that meets engineering, quality and affordability requirements [26].

Producibility — The term refers only to the ease of manufacture parts and components rather than assemblies them [27].

Still this term is rather wide in meaning. *How producible is a design?* The answer to this question can be addressed from different points of view such as quality, robustness, capability, or cost. It is considered, within this project, that a producible design will be that one which fulfills the production requirements. Therefore, the goal will be to create a systematic approach that defines and meets those requirements with the design, from an early beginning.

Some of the Volvo Aero main methodologies and principles are presented now in order to analyze the content, what those principles aim for and which are the real current outcomes.

4.1.2 The Volvo Way

In the same way that Toyota Motor Corporation developed its own production system, basing their principles on lean philosophy and putting behind the traditional mass production system, Volvo Group also developed the Volvo Production System VPS in 2004, thus continuing the learnings of previous leaders in the industry.

VPS is a customer-driven, people-oriented, unifying system that serves as the source of common principles and practices to help the employees achieve operational excellence by having a common understanding on what to do to create value for customers *[1]*.

An organization where everyone continuously improve quality, delivery and productivity, in everything we do.

Figure 12 VPS Vision

The Volvo way is its foundation, which advocates for a set of principles and values such as team work, continuous improvement, customer focus and empowerment or for instance, the 3 cornerstone values, quality, safety and environment.

This new way of thinking requires of a change through overall company, which still is a challenge. Moreover, Volvo Aero Corporation has to deal with the implementation of new production strategy idea, fabricated components.

4.1.3 The Real Balance Requirements Principle

The objective of the product philosophy named Phi *(Figure 1)*, as it was explained in the introduction section of this report, defends a requirement balance, in which the three most important requirements, producibility, cost and technical function are given the same weight. But the reality does not describe this situation *(Figure 13)*. Instead, producibility requirements are not having enough consideration as technical requirements, and this unbalanced situation can be found out due to the problems that arise during production and the impossibility to reach the target cost.

Figure 13 Non-balanced Requirements situation

4.1.4 Constraining the Project Scope

The scope of this project focuses on creating a systematic approach to deal with producibility problems within product development process. This is an extended scope that needs to be constrained due to time limitation. The interviews´ progress was helping to delimit the project. It is important now to explain this result since it will influence the results exposed below since they are constrained by the project scope.

Volvo Aero Corporation mainly works with two big different product families, concerning civilian aircraft products. The so called Cold Structures and Hot Structures (see Appendix A). Within a jet engine all the components before the combustion place are named cold structures and the components after that are the hot structures, terminology used by Volvo Aero. This project focuses on the hot structures, specifically in the Turbine Exhaust Case component, TEC.

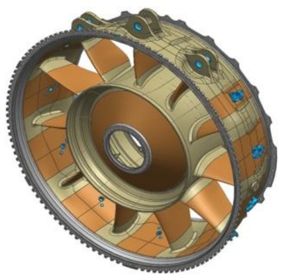


Figure 14 TEC

Moreover, only steel components will be considered. That means material composite field, currently in research, would take part of future thesis works.

Regarding the stage where the systematic approach can be applied and the role of the user, several options were raised. For instance, either using the DFM approach within Technology Development & Research department in order to start the design work with high level maturity concepts or helping to the Business & Sales area in order to get a feasible target cost. Finally this project focuses on concept phase, trying to support the design engineer’s work, in order to deal with producibility from an early point within the product development process. This concept phase is explained within the next section.

4.1.5 The Product Development Process (GDP)

In order to live up to Volvo Aero vision "Best Partner" the company must have quality work from all employees, which lies in the workers´ responsibility. The Operational Management System (OMS) is an important tool for employees to get an understanding of what Volvo Aero does, how it is done and how all the pieces and processes fit together. Having a true understanding of the employees' interactions with each other and each other's working processes will help Volvo Aero reach their goals the best way possible *[1]*.

In OMS a description of the Global Development Process (GDP) can be found, which describes the Volvo Aero development process. The Global Development Process is a model sharing a common value base and a common project tool box for the Product Development projects within Volvo Aero. It also consists of a maximum set of gates and Project Decision Points as well as a high level set of common gate criteria *[28]*.

The GDP is divided into six phases, each of which is intended to indicate a certain focus in the project work. These phases start and end at various gates.

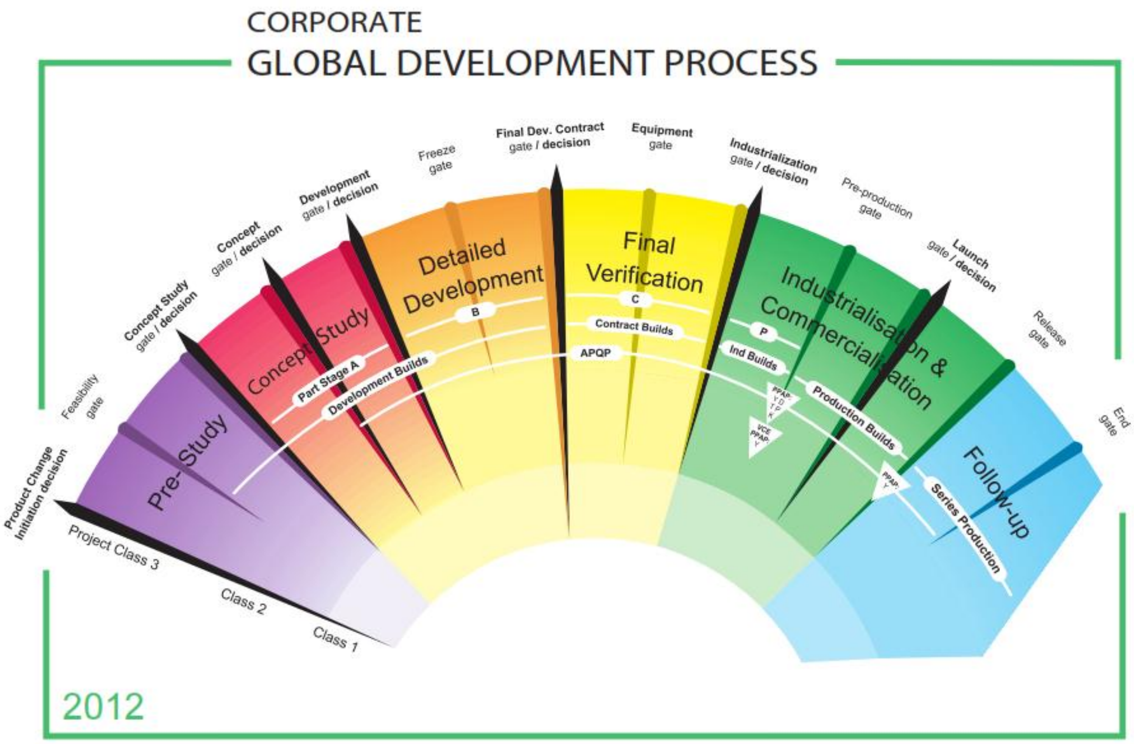


Figure 15 GDP Global Development Process *[28]*

These six phases can be found similarly in any company product development process. Instead, they way to go through them, the loopbacks and the outcomes clearly differ.

Only the early phases, subject of this study, are described. The main purpose of the pre-study and concept phase is to investigate, create and evaluate different realization alternatives. What is to be investigated and the goal of the investigation shall be stated in the Pre-study decision. Moreover, Requirement specification is delivered in that pre-study phase. During concept phase different concept alternatives are identified and evaluated to meet the requirement previously specified. This phase is divided into two equal parts with CG (Concept Gate) in the middle. The main purpose up to CG is to review a selected number of concepts and to decide on, preferably, one of them before opening the CG.

A number of steps describing the way to proceed along the concept work at Volvo Aero has been found out thanks to information gathered during interviews and they are presented here. Even though there is not an standard way to proceed and the different steps within the concept work might vary depending on the project and on the people involved.

A project does not start from point zero, there is always a base of information composed by experience, knowledge, customer specifications, old projects, platforms (considering platforms as a collection of processes and knowledge that are shared by a set of products) , all of that influence the design possibilities from an early beginning. Starting from this information base, a brainstorm method is carried out by the cross functional team, which end up in different solutions, in some cases up to 20. This is a creative phase, but still it is constrained by experience and feelings, which guides the creation to the “best considered” alternative from the start, when likely it will not be the best solution. The cross functional team is composed with people from different areas such as aero, thermal, stress, production. And the alternatives from this brainstorm are usually focused to improve just one requirement, for instance the safety or the weight, always related to technical aspects and not to producibility.

The next step would be to combine those different alternatives ending up in 4 or 6 possible concepts, which are evaluated in a Pugh matrix. At this moment the design solutions start to meet requirements. The documentation of the concept work starts from this point, the information is reported in the so called Concept Book. Later, by accomplishing the scoring matrix, 2 or 1 best concepts are selected to be developed in further detail (which would represent the Concept Gate).

The evaluation parameters within the concept matrix are basically functional and technical requirements. Manufacturing requirements are not break down into subrequirements. The matrix below, Figure 16, is part of the Pugh evaluation matrix, where can be proved that production requirements are not break down. Only the requirements MRB-s and Ramp-up period (MRB, Material Review Board and Ramp up,preparation for serial production), which are not very close to manufacturing processes specifications.

Evaluation criteria							Concept name 1		
		Risk of NOT meeting FETT						1	
Requirements which can be traded	Group Weight	Requirements broken down	Weight (1-10)	Relative weight total sum = 100	Target information	Target value	Information	Valuation [1 to 5]	Score
Business case	30								125
		Material cost	10	17,6				5	88
		Manufacturing cost	1	1,8				3	5
		Development cost	3	5,3				3	16
		Tooling	3	5,3				3	16
Technical requirements	20								93
		Life	5	5,3		1000,0		5	26
		Weight	5	5,3		70 kg	Weight 55 kg	5	26
		Wear, tear and corrosion	5	5,3				4	21
		Aero performance	3	3,2				5	16
		Repairability	1	1,1				3	3
Manufacturing/Producibility	20								90
		MRB-s	5	10,0				4	40
		Ramp-up period	5	10,0				5	50
Development/Risk/Quality	20								32
		TRL-level of technologies	5	5,3				3	16
		Quality on delivered parts	5	5,3				3	16
		Required validation	4	4,2				4	17
		Component test	5	5,3				5	26
Alignment with strategy	10								45
		Fit VAC fabrication strategy	5	4,5				5	23
		Widening supplier base	1	0,9				0	0
		Product platforms	5	4,5				5	23
Sum	100								385

Figure 16 Pugh Matrix - Concept evaluation and selection

After the requirements specification is done, a verification discussion to check if the design alternatives fulfill the requirements is carried out, following the V-model (Figure 9). Even within this evaluation, production requirements are not described in detail as they should be.

A fragment of the verification matrix it is also taken with the purpose to show this fact. The producibility requirements regarding the different manufacturing operations are compiled within a general requirement "Manufacturing processes need acceptance criteria".

Manufacturing step	Material	Mechanical properties according to design data base	Material is according to spec (including defects)	Manufacturing processes meets the acceptance criteria	Dimensional accuracy	Weight assumptions fulfilled?	Surface properties
Hub Casting	17-4PH - cast	3	4	0	4	4	3

Figure 17 Verification matrix fragment

The remaining phases within the product development process such as detail design, industrialization and follow-up are not described in this study. Nevertheless, it is important to mention the Technology Development period, where new technologies and methods are researched and developed. This period works parallel to any project. The objective is to research into new technologies, based upon previous market studies, and to develop these, presenting the possibility to release the ultimate products, processes or technologies with a high maturity level, so as not to have any problems during the production period. Figure 18 shows how this process should work ideally. But the real results such as concepts found in latest phases that do not fulfill the maturity criteria, prove that this "Technology ready for implementation" process is not made properly.

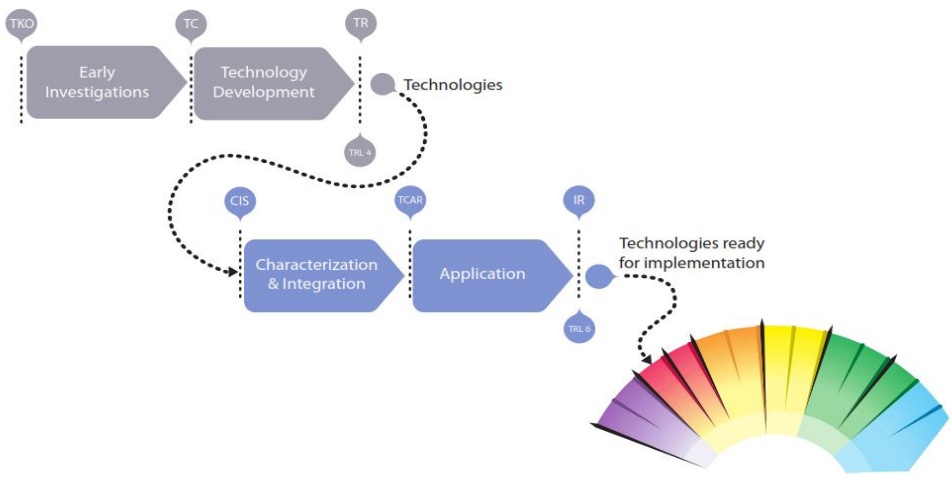
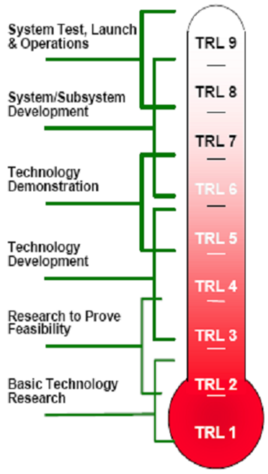


Figure 18 Technologies implementation within a project

4.1.6 TRL Technology Readiness Levels

The primary focus of the Global Technology Development Process is to identify, foster and deliver mature technologies ready for application in the product development projects. The objective is to identify knowledge gaps and to develop needed knowledge before Concept Decision. Introducing premature technologies in new product development projects will ultimately generate cost overruns and schedule delays. Consequently, all affected organizations need to carefully assess the maturity of the technologies under development and identify the potential consequences on the product projects. In order to assess the technology maturity, the “Technology Readiness Levels” scale is used. The general directive is that the technology has demonstrated a “proof of concept in a laboratory environment” (TRL4) at the Technology Ready (TR) gate, and that the technology has been demonstrated in the targeted product/process environment (TRL 6) at the Implementation Ready (IR) gate before product development project Concept Gate (CG) approval *[28]*.That ia means the design to cross the GDP gates has to fulfill the cirterion TRL≥6.



9 - System proven through successful mission operations
8 – System completed and qualified through test and demonstration
7 - System prototype demonstration in an operational product/process environment
6 – System/subsystem model or prototype demonstration in a relevant product/process environment
5 - Component and/or breadboard validation in relevant environment
4 – Component and/or breadboard validation in laboratory environment
3 – Analytical and experimental critical function and/or characteristic proof of concept
2 - Technology concept and/or application formulated
1 - Basic principles observed and reported

Figure 19 Technology Readiness Levels [29]

However, the reality brings unexpected problems such as changes in laws or legislations, which makes a technology not to have the required TRL level. Sometimes it is found a concept that does not fulfill the TRL criteria, because the concept has been promoted through the phases with not enough mature level. Those problems delay the project.

4.1.7 Supplier Involvement

The suppliers have an important role within product development. The operations made in-house at VAC are pre-joining preparation operations (basically machining and deburring), joining operations, some heat treatments and inspection (all of these are operations related to the product of study, TEC). The casting, forging and sheet metal parts are purchased. Since a large part of the solution is created by suppliers, clear cross functional processes including suppliers to support fact based decisions in product development, are required. By including supplier early, knowledge and innovation increase in the projects.

The current problem at VAC regarding supplier involvement is the late supplier selection. At the early stage it is difficult to select a supplier since there is not detailed information, there are not decision made yet. The unknown supplier also influences the cost assessment of the concept alternatives, thus , the cost estimation.

4.1.8 Project Organization

The product development at Volvo Aero Corporation is organized in projects. Every project has a Chief Project Manager (CPM) who manages the project and reports to the Steering Committee *(Figure 20)*. The project gets resources from functional departments in a line organization. Different disciplines are represented in the projects depending on needs and resources and can vary throughout the project. The Steering Committee supports and supervises the project management and approves the Project Management Team including the CPM *[28]*.

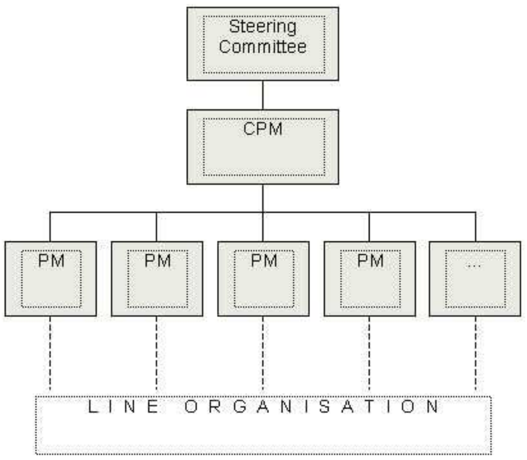


Figure 20 Project Management Team

4.1.9 Cooperation between Product Development and Production Development

The Volvo Aero Corporation structure describes the connection between the three main organisms within a project. Business Development & Sales, Product Development and Production Development. The cooperation between them is fundamental for a project to success, which means to reach the target cost.

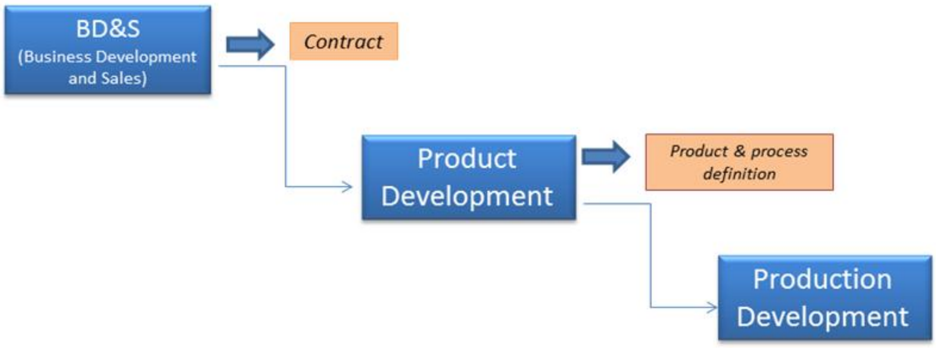


Figure 21 Volvo Aero Coorporation Structure

Communication problems and the difficulties to reach the target cost are the most common comments got from the interviews.

Cost Assessment

The cost estimations made during the business case do not usually meet the final product cost, which is in fact the real big problem. There are several reasons to explain this.

On the one hand, before a project starts, the people responsible for the business case negotiate with the customer to end up in a contract. At this time the project target cost is established. The business people make their estimation based on old projects and using some technical support but there is not a direct cooperation, in none of the directions, between them and the cost engineers responsible for the cost assessment during the product development. *Is the target cost bad estimated? Should Volvo Aero invest more resources to come out with a more accurate value for the target cost?*

On the other hand, there is the cost assessment carried out during the product development, which is focused on meeting the target cost, within a 10% of error margin, and minimizing the final cost result as much as possible. The cost engineers are usually responsible to perform this task; they analyze and evaluate the different design alternatives, starting this assessment in an early concept phase. A very rough estimation is made at the beginning due to lack of detailed information. Within this assessment, cost engineers compare the estimation with the target cost and develop an action plan to look for risks and potentials in order to find any possibility to reduce the product cost. *Is everyone aware of the cost while creating and selecting a design alternative? Is the cost considered as a result or as a steering parameter? How accurate should these cost assessments be?*

Finally, during the first production period, problems such a rework and firefights arise, increasing drastically the product cost or forcing loopbacks to design which is really costly. This happens as a consequence of a not enough first robust design, result of poor communication between Production Development and Product Development. The learning curve shows how this product cost gets closer to the target cost at the time of production progresses, reason of that is the experience acquired along the time. At Volvo Aero the manufacturing time of a specific project usually lasts 20 or 30 years, Figure 22.

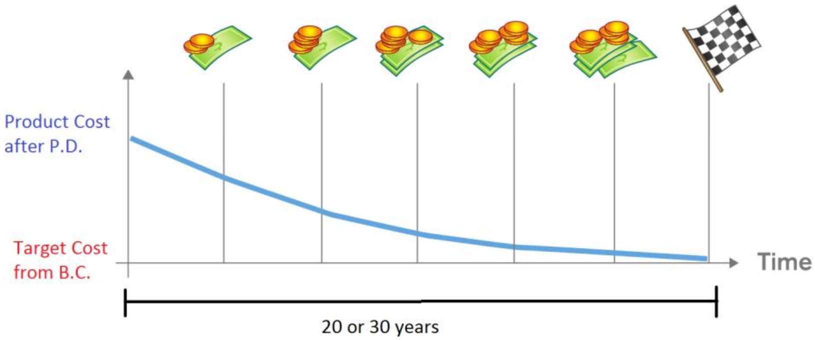


Figure 22 Learning curve *[28]*

Figure 22 shows, on the one hand that the real product cost after the product development process is higher than the target cost, estimated by people from Busines case. On the other hand, these two values aprox as the project time progress. The reality at VAC confirms that the product cost curve (blue line) never reachs the target cost.

Currently there is a person at Volvo Aero working on a cost model in order to consider cost as an steering parameter and not just as a result, i.e. as a limit to conclude if the concept is above or below the allowed cost. This model is taken from the automotive industry, the so called ULSAB model (Ultra Light Steel Atutomotive Body), which aims for the cost break down so it is easier to detect the weakest points, where cost value can be improved.

VAC tools

Every methodology has a set of tools which help with its implementation. These tools can bring benefits within the short term, but they cannot be overrated, since without a change of mind throughout the company, the methodology implementation will never success. The aim is to look for the long term benefits.

In Volvo Aero Corporation some tools to deal with the production problems have been already developed. The purpose is to increase the cooperation between Product Development and Production Development, i.e. between designers and manufacturing engineers. These are called the VAC tools.

The first tools are two checklists, implemented in the NX, CAD software, for the manufacturing methods, casting and welding. All the production capabilities and the database, acquired from all the production experience, are interpreted by method specialists and the results are implemented in digital checklists, so that the information flow from manufacturing engineers is improved. This system helps the designer to limit the design from a manufacturing perspective without the need of contacting personally the method specialist. But these constraints are basic, i.e. it is a really rough design limitation. Therefore, these checklists are more focused for inexperienced designers; it is a way to keep the knowledge.

The other tool, created by a Master Thesis student, is an excel tool that compiles all the turning operation capabilities with the objective to provide, as a result, the possible tolerances that can be achieved during the process having as input the product diameter. This tool could be considered within the CAM, Compute-Aided Manufacturing area.

Platforms

Platforms are another way to create knowledge base, platforms are standards. At Volvo Aero there are Product and Production Platforms. Regarding the last one, the purpose is trying to share a bunch of production methods for all the components, so that it is easier to predict the cost. All the methods described in this Platform are considered mature enough, with a high TRL level, so there is not risk of implementation. It also describes the current industry structure, important to know during the design period.

Even though, there are some inconveniences detected during the interviews regarding these platforms. Some employees believe that those limited the creativity. Also that is a need for other platform areas such a purchasing or technology development, with the purpose to standardize. Moreover, some problems usually appear during late phases within product development, problems related with technologies that do not fulfill a TRL level higher than 6, maybe because new legislations or a no-good previous TRL checked.

4.1.10 Risk Management

To run a project is to actively manage risk. During the course of a project, as the committed costs increase, risks need to be actively managed and mitigated to avoid problems. Project Risk Management is in its essence the early and proactive identification and mitigation of risks and ultimately increases the likelihood of requirements fulfillment *(GDP Pocket Guide 2012).*

To assess the risks at VAC, a risk tool FMECA is performed. Failure Mode Effects and Criticality Analysis (FMECA) is the most important risk analysis tool, which based on functional requirements, addresses failure modes and failure events with mitigation and verification activities. The objective of the FMECA is to assimilate and asses any failure mode related to a novel design. Its first purpose is the early identification of all catastrophic and critical failures in order to eliminate or minimize them through early design adaptation; along project advancement the FMECA becomes a planning and recording file of risk reduction activities while the later issues comprise the documentation of the actual status of the risks (throughout the life of the product).

Therefore, the FMECA is initiated at the early concept phase, and has to be a living document throughout the product development to analyze the design changes, changes of loads (external and internal) and changes of Technical Requirements Specification or other prerequisites *[30]*.

4.1.11 Geometry Assurance

Geometry Assurance got an important role due to the change of production strategy to fabricated components, as it was previously mentioned. Volvo Aero Corporation is investing a lot of resources within this area, since the influence into the production results is critical.

To achieve a good geometry assurance, measurements have to be taken from an early beginning. A good target system, which defines how the part is located, is the main cause for good geometry assurance results. The target system of a part is created during the design phase; consequently high requirements will come from this stakeholder, the Geometry Assurance. There is a guideline which defines the basic principles to achieve a good target system design.

The geometry variation is mainly coming from fixturing and joining operations. Therefore, the target system of a part is not the only important aspect, the tooling system become important and it also influences the cost.

4.2 DESIGNERS' QUESTIONNAIRE ANALYSIS

All the answers from the Designers questionnaire are analyzed and presented in this report (Appendix F). Within this section how the analysis has been made is explained for a deep understanding of the lector.

The Designers Questionnaire is divided in four main parts. The first one covers the project organization and structure. The second part is related with DFM and the two final parts focus on the

Concept Creation and Concept Evaluation and Selection, since this thesis project is applied to the Concept phase within the product development process. The purpose of these four main divisions is to cover in detail the targets of the project following a structured way.

One of the objectives of the first part is to find out how the project organization is made and which are the roles of the persons, who form the cross functional teams during the concept work. Moreover, the objective of identifying how the resources (time, money, intelligence, knowledge…) are allocated along the product development and how this distribution should be done in the designers' opinion.

The DFM part tries to identify the knowledge about this subject within designers and also to detect the use of the current DFM tools. The information flow between the different stakeholders is also analyzed.

Regarding the Concept Creation part, the purpose is to detect the knowledge used to perform this task as well as the knowledge gaps. For the last part, Concept selection, the cost assessment is studied.

4.3 BENCHMARKING ANALYSIS

During the benchmarking process a relevant employee from each company has been interviewed by using pre-made set of questions as a guide. Therefore the answers are more open than forwarding a detailed questionnaire. Consequently their analysis will be different. Instead of presenting the answers in detail to every single question from every company, a summary containing the main results will be offered.

As it was done with the Designers Questionnaire, the Benchmarking set of questions is divided in the same four parts. This similarity has the purpose to gather results from the same specific area in order to compare them afterwards.

The companies benchmarked have been SKF, Volvo GTT, Saab Aerospace and Scania as it was mentioned previously.

The limitations founded during the benchmarking analysis, mostly within the concept phase are related to the fact the Volvo Aero production differs from Volvo GTT production, which is mainly based on assembly system; from SKF, which have been manufacturing the same component for many years; from Scania production, which is based in modules. Therefore the Concept work has different objectives and it will be performed in a different way depending on the company.

4.3.1 Project Organization and Structure

It is difficult to classify the **project organization** of a company regarding the following types: functional, project organization or matrix organization, since usually the real structure is a mix of them. Scania stands out regarding project organization since they work through a pure matrix type. They use it as a way to balance the requirements since every function representative claims for they own area interest within a project. Volvo GTT has similar organization as Volvo Aero, since both companies belonged to the Volvo Group. This organization is closer to a project type, as it is shown in the following scheme. But it is not a pure project organization since there is always feedback to the functional areas. SKF presents analogous organization as the just mentioned, where people from different areas are working and reporting to the project manager.

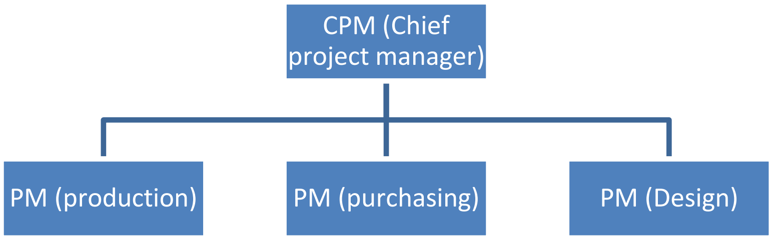


Figure 23 Project Organization at Volvo Group

All the companies work in **cross functional teams** from an early stage. At SKF, those teams have not production roles involved at the beginning; in addition, there is a change of people within the team as phases are passed. This lack of production stakeholder within the cross functional team at an early start is directly related with the no-need of DFM methodology within SKF, as it will be explained afterwards.

Every company has a **system development process** quite similar to the GDP. The main differences come from SKF and Scania. SKF presents a development process based on technical readiness gates (Figure 24), so that when the pre-study phase arrives they ensure a good maturity concept creation based on previous research.

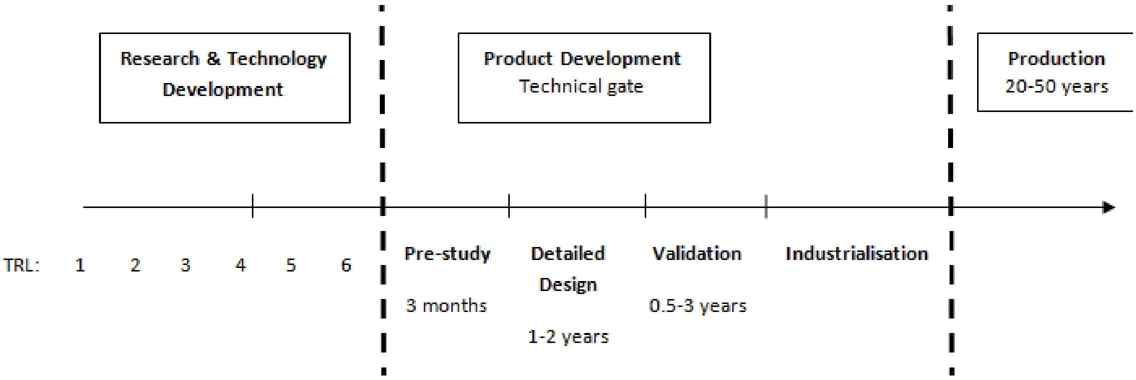


Figure 24 SKF System Development Process- Technical gates

Scania development process matchs with their modularization methodology, (see Figure 25). The so called “green projects” are small projects focus on releasing an specific item or module to the market. The feasibility of this idea is previuos checked and developed during the “Yellow projects”. During this Feasibility study period loopbacks are allowed, not the same situation within “Green projects”, where time lead and cost are critical.

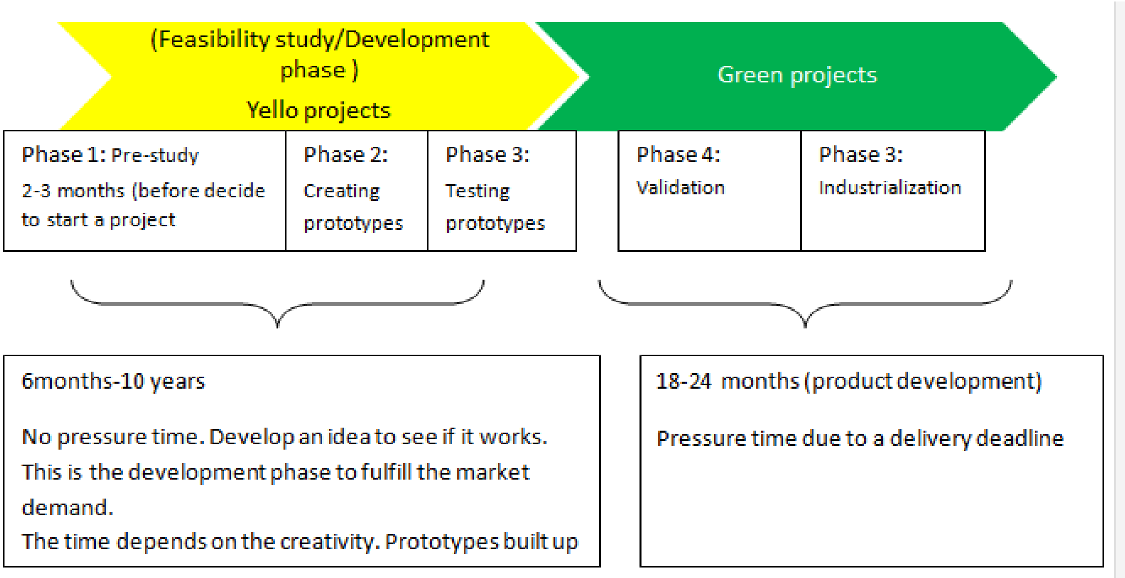


Figure 25 Scania development process

Regarding **resources investment**, the answer to the question *"In which phase within the product development do you invest more intelligence?"* is presented in the following table.

Table 5 Resources invesment-benchmarking

Company	Resources investment	Observations
SKF	Technology Development	
Volvo GTT	Concept Development	Due to firefights the project gets longer at the end
Saab Aerospace	Technology Development	
Scania	Technology Development	

4.3.2 Concept Creation

In order to find out the **knowledge base** of the different companies some questions have been asked with the following results, shown in Table 6.

Table 6 Knowledge used at the starting point of a project- Benchmarking

	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

The term **platform** differs from company to company but the concept, which advocated for standardized methods, remains. For instance, Volvo GTT has platforms for assembly. In Scania they call platforms to the modules but still they have standardized methods for both product and production development, based on the modular system. SKF platforms refer to the different groups of items, no related with the Volvo Aero platform concept. However, SKF has been using the same production methods during long time, so indeed they make use of platforms in an implicitly way.

Regarding the standardized methods the next question would be, *do these established ways to proceed limit the **creativity** while creating concepts alternatives?* For SKF the experience gives the impression about what it can be produce and what cannot, thus it is difficult for them done something out of the ordinary, at the same time they do not have the need. Volvo GTT basically makes variations to old projects in order to get a more improved design, so the creativity does not play a big role here. In contrast, for Scania, creativity is fundamental to continuously combine and develop the modules, but the design is not totally free, the modules still create a limited box. The concept creation task is usually supported by some **tools**; the following table shows the results.

Table 7 Methodologies used during Concept Creation- Benchmarking

Company	Main ideas / methods within Concept Creation
SFK	DfSS toolboxes, guidelines, checklists (QFD as example). Team of experts brainstorming.
Volvo GTT	DFM trend, trying to integrate parts as much as possible to eliminate assemblies.
Saab Aerospace	Fundamentally, making variations of existing concepts. Sometimes several concepts created to be developed in parallel.
Scania	Module methodology. They get the customer needs and the requirements and they try to figure it out how the modules combination can fulfill those req.

4.3.3 Concept evaluation and selection

For the concept evaluation task, the **Pugh matrix** clearly dominates. The **key parameters** to evaluate concepts from the different companies' point of view are presented below, see Table 8.

Table 8 Concept evaluation tools and key parameters considered within evaluation- Benchmarking

Company	Tools/ Methods within Concept Evaluation	Key parameters
SFK	Pugh matrix	Robustness, maturity, risk analysis, cost, cycle time.
Volvo GTT	Pugh matrix	The important factors are chosen as a group exercise within each project.
Saab Aerospace	One concept based on cost and weight	Cost and weight.
Scania	Pugh matrix	Time, Cost Quality

In order to research on **Set Based methodology** knowledge that companies have and its application during the concept "selection" process, some questions have been made, obtaining the following results, Table 9. It is important to point out that all of them use the traditionally selection approach “Point-Based” since the “best concept” is selected from the Pugh Matrix assessment and this is the concept chosen to develop in further detail.

Table 9 Set Based - Benchmarking

Company	Knowledge about SET BASED	Use of SET BASED	Comments related with SETB BASED
SFK	Yes	No	Concept elimination is not reported.
Volvo GTT	Yes	No	No good at set based for the moment. There is not data to create trade-off curves, lack of documentation.
Saab Aerospace	Yes	No	Trade off curves are really tough due to there are about 800 requirements.
Scania	No	No	Use of manufacturing trade-off curves.

The **cost assessment** is an important evaluation for all the companies. And still this is a problem that remains. The cost evaluation during the concept creation is still a competence from how experienced or smart the designers are. Even if the cost is considered as a steering parameter, in the most of the cases it is treated as a result during the concept work. The cost drivers are competence of production people.

Before getting into the DFM topic, it is necessary to know the companies´ opinion about **producibility** as a key parameter. Based on the answers, it could be said that producbility is still a term with a wide range of meanings. For SKF, the producibility challenge is producing more with the same resources, aspect quite related to lean production principles, methodology they are based on. Producibility could be considered as robustness and it is difficult to be measured, still it can be related with production volume, tooling, cost and Cpk. Within SKF they aim for statistics process control, keeping the capabilities variation during production rather low, by using Poka Yoke tools, therefore this improves the DFM aspect since it is easier to fix the design within the production capabilities. Saab Aerospace also uses Hardware Variability Control (HVC). In Scania they deal with producibility regarding assembly, and in their opinion the CpK shows is the design is not feasible but does not indicate if there is a better design alternative.

4.3.4 DFM

SKF does not make use of the DFM philosophy, they are really good at Lean but they do not need to implement the DFM mindset since they have been producing the same products for many years, so they have a good knowledge about what can be produced, even though this knowledge is still based on experience. Their systematic approach used for the concept phase comes from DfSS strategy. Although, design guidelines regarding producibility do not exist; there are some design rules for specific product, but not a general systematic approach to proceed. Even tough, during the T&RD period TRL gates are used, which can be considered as producibility checkpoints.

Volvo GTT is basically making assemblies; they have a systematic way to carry out this task by following a fishbone structure, Figure 26.

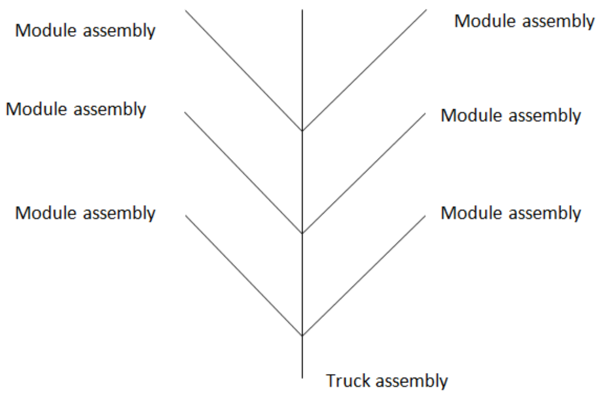


Figure 26 Fishbone structure- to systematize the assembly procedure

The only standardized step for the concept work is gathering all the stakeholder's´ requirements at the beginning of each project.

Saab Aerospace is currently researching in DFM methodology. From their experience, cross functional team are not enough; there is a need to implement the mindset throughout the company. Tools and a systematic way are necessary.

Scania is closer to DFA methodology (since 2008). Although DFM is not implemented officially, it is presented in the people mind. DFM tools cannot substitute the engineers´ involvement but can help to discuss, it is more a matter of interacting people. In Scania sometimes designers and manufacturing engineers changes roles in order to visualize the task of the other. Another DFM tool is the 59 items list, which contains design rules.

Knowledge based is one fundamental part of DFM, therefore it is important to know how the benchmarked companies deal with this issue. SFK is not good at knowledge base, but for the moment this has not been a big problem since experienced designers know what can be produced. There is an information feedback, regarding capabilities or problems detected, from production to design development, but there are not measurements done afterwards. Consequently there is not benefit result from this feedback. That means that the fact of reporting or documenting is not enough, it is also necessary to make a good reuse of this knowledge. Another SKF´s problem is that negative experiences are not reported and only the final result is reported, but the White book, used to report really bad results. In order to close the knowledge gap the Process Development department is working on trade-off curves.

Volvo GTT does neither have a good process for documenting. They based on people, experience and talks.

Saab Aerospace is very interested in this topic, they used 3D models both at the workshop and at the design department, models that are update every day, so it is a way to create continuously communication. They also aim for empowerment with people at the workshop. In their opinion general guidelines are easy to write but not to use.

Finally in Scania, capabilities are reported in production but there is not a good feedback to design.

So far, this is the complete analysis of the benchmarking process. In the following table a summary with the main results is presented, Table 10. Volvo Aero has been included in this benchmarking-results summary table, for a better comparison.

Table 10 Benchmarking Results 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
Volvo Aero	Concept Study	Quality, DFM	Research for better implementation	Pugh Matrix to select the best	Technical requirements

Some interesting observations out the questionnaire answers have been gathered, analyzed and reported below.

4.3.5 OBSERVATIONS

SKF:

- Before implementing the TRL gates system, the technology maturity and the obtained results were based on the engineer´s opinions and feelings but not in facts, which brought problems afterwards.

- Supplier cooperation is very important. There is a need to improve the purchasing task in order to find more suppliers.
- The Lean room, this is a way to make the whole company, including people from all the projects and all the functions, to be aware of the problems. It is a good way of visualization through weekly meetings all together in the same room and updating the project status. There is not possibility to hide problems; they are visualized and transparent to all.

Volvo GTT:

- They claim for a right requirement balance by having stakeholders from all the different functions.
- They are doing well at breaking down requirements from complete product level to detail level. A good understanding of requirements will allow to identify the key characteristic to consider while designing. All the departments take part of the requirement specification phase. An example about how the evaluate these requirements is shown in the following table.

Table 11 Volvo GTT-Requirements evaluation

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

- However, there are problems to translate manufacturing costs to requirements, and the cost is a very important stakeholder.

SAAB Aerospace:

- Regarding requirement management. There is a data base for product requirements but not for manufacturing requirements. However, they collect the key characteristics of the product and they measure them in production.

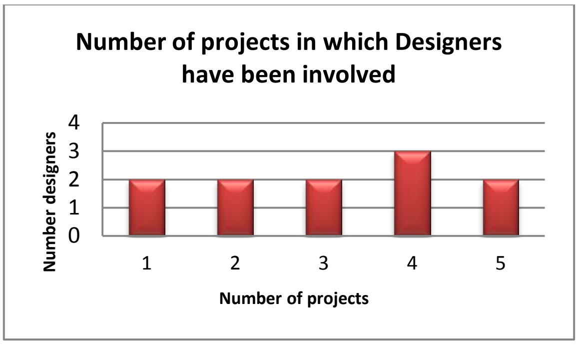
5 CONCLUSIONS AND SUGGESTIONS

At the beginning of this chapter some specific conclusions from Designers Questionnaire and Benchmarking are reported. Based on those conclusions and the entire previous analysis and results a systematic approach to follow during the concept work is presented, as well as some general conclusions.

5.1 CONCLUSIONS FROM DESGINERS QUESTIONNAIRE

The results and conclusions achieved from the Designers Questionnaire are not totally accurate, since the number of questionnaires filled was eleven out of twenty. However, useful outcome has been achieved.

The aircraft manufacture industry presents a big inconvenient to success in philosophies' implementation. The types of products to manufacture are defined as low volume and high variety products. Usually the manufacturing periods take many years and the lengths of the projects are huge. The bad consequence is that employees that have been working at VAC for years take part only of few projects; or some new employees are entering to work in the middle of the project development. This can be reflected in the following graph, where the maximum number of projects an interviewee took part of was 5. For instance, 2 designers were involved in just one project and the same number in two projects.

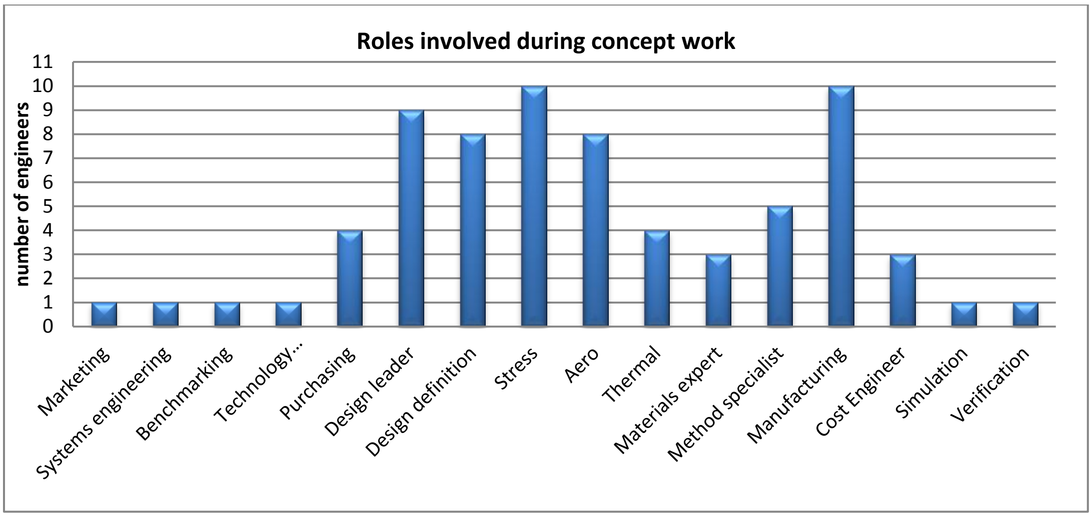


Graph 1 Number of projects in which designers have been involved

The problem that comes out is the lack of opportunities to learn from previous mistakes and the long period needed to see the benefits of the methodology implanted. Even so, it is possible the change. Moreover, the need of a systematic approach increases due to this reason.

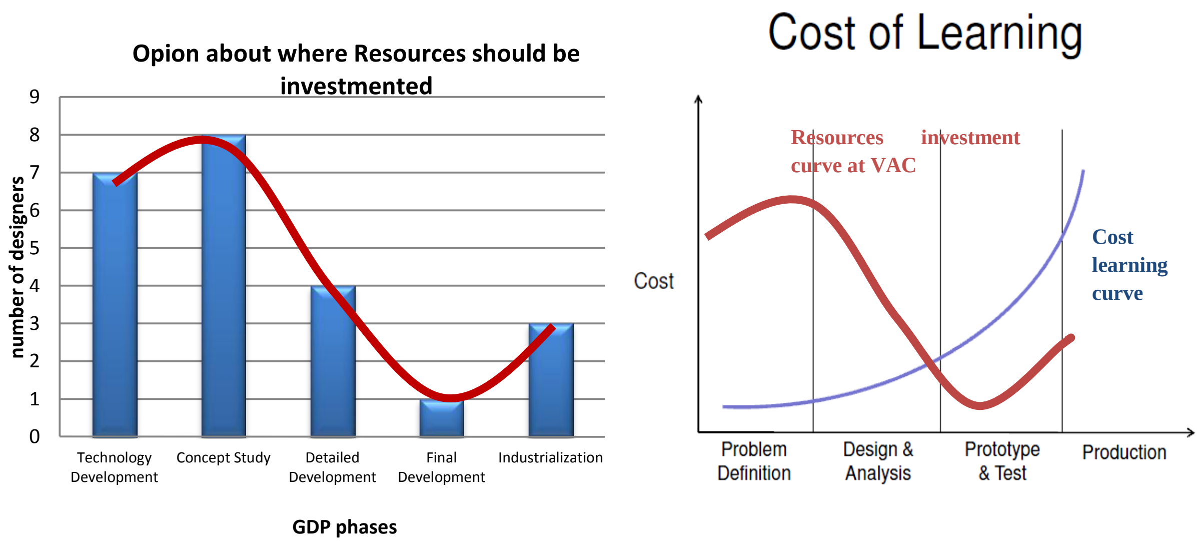
5.1.1 Project Organization and Structure

There is still the need to emphasize the manufacturing engineer role. Looking at the following graph the conclusion obtained is that the design areas such as aerodynamic, stress and thermal are given more importance than the production and cost areas. Although the manufacturing column has the same high, the manufacturing requirements are not break down as it is done with the design requirements; hence this ends up in no-producible designs. This is one of the reasons of no-balanced requirements.

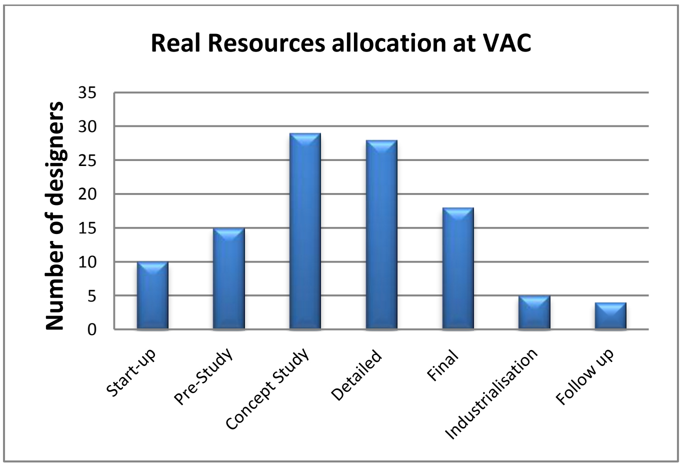


Graph 2 Roles involved during concept work

Regarding the resources investment, a comparison of the answers gathered with the theory can be done, Graph 3. The graphic shows the employees' opinion regarding how the resources should be allocated. Looking at the learning curve the best option is to invest all the knowledge, people and intelligence at the beginning of the project. Therefore the employees are aware of this. But, *is this really what happens?* Looking at the third graph, Graph 4, it can be seen that people are working in concept study but still many resources are spend during final phases.



Graph 3 Comparison: Resources investment at VAC & Cost of Learning curve.



Graph 4 GDP phases covered by employees in a project

5.1.2 DFM

Although there is a general knowledge about what Design For Manufacturing is and stands for, there are huge problems related with producibility. The main reason is that it is not enough by knowing the theory. Lip service to DFM is not sufficient. There must be a process of awareness, a change of way of thinking from the top of the company until the lowest point within the hierarchical pyramid of roles. And this is not done yet, the proof of that is the no existence of any systematic approach which deals with DFM principles. Moreover the only DFM tools at VAC either are not in use or are unknown. Only two of the total interviewee knew about the checklist integrated within the CAD program. Non-interviewee knew about the DFM tool for turning operation. Moreover nobody used any of them.

On the other hand, the concept of DFM tool is wrong for some of the designers, which implies an inconvenient for a proper DFM implementation. The purpose of this project will try to deal with that awareness problem.

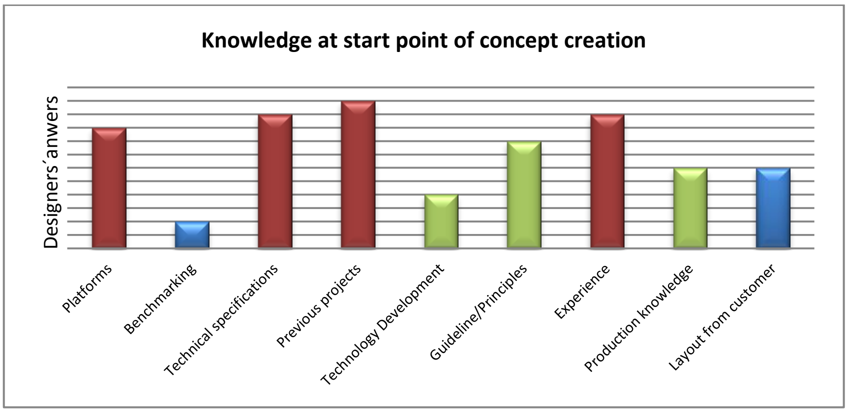
For those people who consider have made use of DFM tools, the answers were as follows.

Table 12 DFM tools used by designers

DFM tool / method	Number of Answers
Platform	**1**
Common sense and lessons learned	**1**
Cross functional teams (including manufacturing expert)	**3**
Pugh Matrix	**1**

5.1.3 Creation of Concepts

There is a need to improve the knowledge base. The designers should not support their actions in experience, feelings or opinions, because not all of them have the same skills. As it is shown in Graph 5, experience is still a high knowledge source at the starting point of a project, while standards such as Guidelines and Principles are not so used. Neither the production knowledge has an important role.

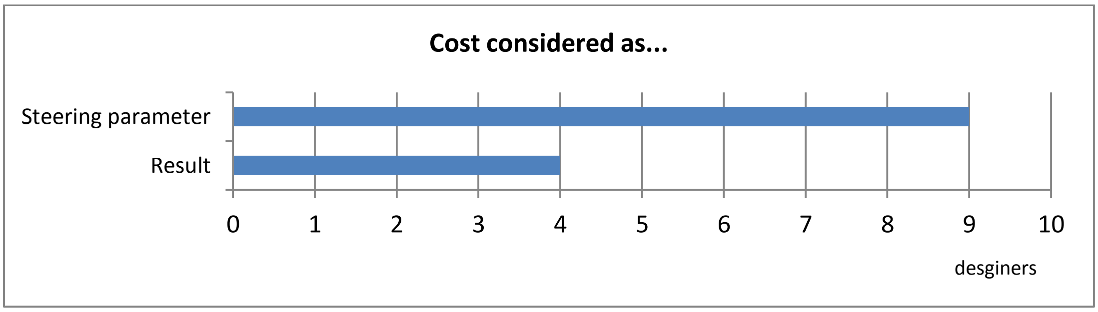


Graph 5 Knowledge used at the beginning of a project

Therefore designers do not start with a good based of information. Moreover they do not receive either enough information while performing the concept task. Designers are missing information from suppliers, method specialists, production people and cost specialists. Specifically there is a lack of knowledge regarding production capabilities. The most critical process is welding.

5.1.4 Concept Cost Evaluation and Selection

At Volvo Aero the cost is considered as a result, when it should be a steering parameter as most of the interviewee agree.



Graph 6 Designers 'opinions about how cost should be considered

Therefore if they are aware that cost should be steered, *why Volvo Aero does not reached the target cost?*

5.2 CONCLUSIONS FROM BENCHMARKING

Regarding DFM methodology, none of the companies benchmarked were a model to follow. But a lot of important conclusions and aspects can be taken from them in order to implement at VAC. It is also important to point out the fact that not finding any solutions regarding DFM is also useful information. Obviously, DFM is still a handicap within the transport manufacture industry.

Regarding project organization and resources allocation, the best project organization to deal with the requirements balance is the matrix organization.

As it was already known it is better to invest resources at the beginning of a project than at the end, so that loopbacks and over cost products can be avoided. However, the new idea taken from benchmarking aims for investing knowledge, intelligence, people, money and time during the *Technology Development and Research* stage instead of investing at the early concept development as it was previously though. Consequently, when it is time to start with concept creation all the new ideas are already proven during that feasible study period and the project lead time is reduced drastically.

For the Requirement specifications task and its verification, an evaluation matrix can be added, as the following one.

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

Figure 27 Requirements Specification matrix

5.3 GENERAL CONCLUSIONS AND SUGGESTIONS

The final section of this first part presents all the conclusions achieved, as well as a systematic approach suggested in order to deal with producibility during the concept development. Conclusions that are got thanks to the analysis and results obtained during almost five months, in addition to the experienced acquired, which allows a better understanding of the field.

The project´s objective claims for solving the root cause of the producibility problems. That means the purpose indeed will be to create a fair and optimized balance of the requirements. Due to producibility could be defined as "how good is a design at meeting the production requirements", in order to achieve this goal, a systematic approach, which defines and meets production requirements with the early concept design, will be proposed.

One more time there is a need to clarify that results are not accurate due to projects limitations, and these conclusions and suggestions should be taken as an idea to improve the awareness more than as a final result to implement directly in the work.

5.3.1 Conclusions and Suggestions for specific aspects

First of all some single conclusions and suggestions will be given in order to improve some specific aspects of the company, so that the new proposal concept development process can be presented based on those previous improved areas.

The most difficult idea to implement, but the one which would bring the best results is to invest resources within **Technology Development and Research period**. This is a difficult challange since there is a need to first standardize certain aspects within the project development. This big improvement need to be based on something stable, so once a systematic approach for the product development has been achieved it is time to start, to modify the TD&R mission. The idea would be to keep on researching in future market demands and innovate technologies but at the same time to create a group that focuses on developing new ideas to apply directly to specific concept design. Therefore once a project starts the maturity of the concept alternatives considered is rather high avoiding then loopbacks and firefights during production. To conclude, Technology Development and Research period should be consider as a feasibility development phase where the new concepts ideas are proven.

In order to improve the DFM concept, hence increasing the awareness that a change to DFM mindset should be addressed, a **DFM tool idea** is presented. This DFM tool is developed to support the product development process and to improve communication with manufacturing so that the design will fulfill the production requirements. This needed flow of information can be assessed following different paths or loops. In the next image three loops with different targets are shown.

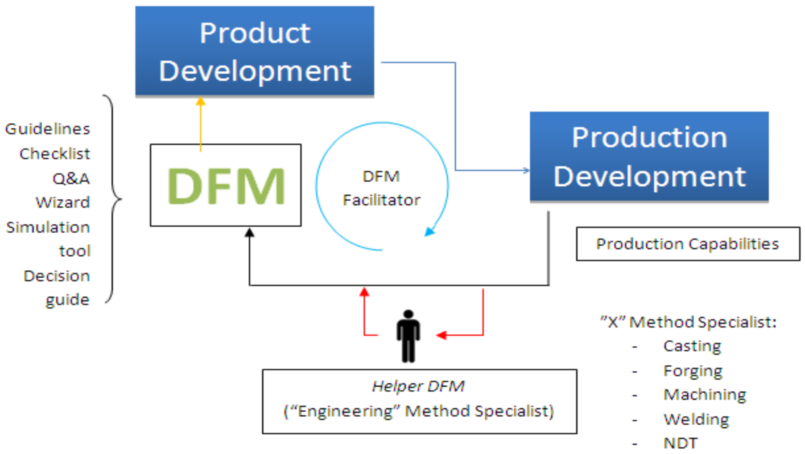


Figure 28 DFM tool idea

First loop (*red loop in the figure 28*): This loop represents the communication from method specialists to designers. The "X" method specialist, for instance, the welding method specialist, interprets the data base within production and provides information to the designers. Since this person cannot take part all the time in the product development process, helping the designer, some DFM tools can be created. Currently at VAC there exist checklists for welding and casting to keep the method specialist knowledge in some way so that the inexperience designers can make use of it. However, the Designers Questionnaire analysis indicates that these tools have not being used. There is a need to promote the use of these tools. And there is a need to create new DFM tools to help within this loop.

Second loop (orange loop): There is also a person supporting the DFM philosophy but working in parallel with the DFM tools. The difference is that this person has a general knowledge about manufacturing to support the designer decisions; instead the DFM tool is located to an individual process. Usually this manufacturing engineer is located with the designer team.

Third loop (*blue loop*): The "DFM facilitator" figure is a new creation. This person takes part of this loop trying to achieve the whole communication process. Not only from method specialist to designer, also in the opposite direction. This is the most complete and global task since the purpose of the "DFM facilitator" is to compile all the method specialist knowledge and share with all the cross-functional team. The main purpose of this project is to develop this loop.

The flows of information structure will help during product development to deal with some of the current problems. Moreover, the conviction of the DFM tools benefits is the key for Design For Manufacturing methodology implementation.

Platforms, as the same way as the checklists do, are a way to create flow of information from production to design. There is a need to improve these platforms, both concept and application. Here there are some new areas proposed to develop platforms and complete a balance requirement.

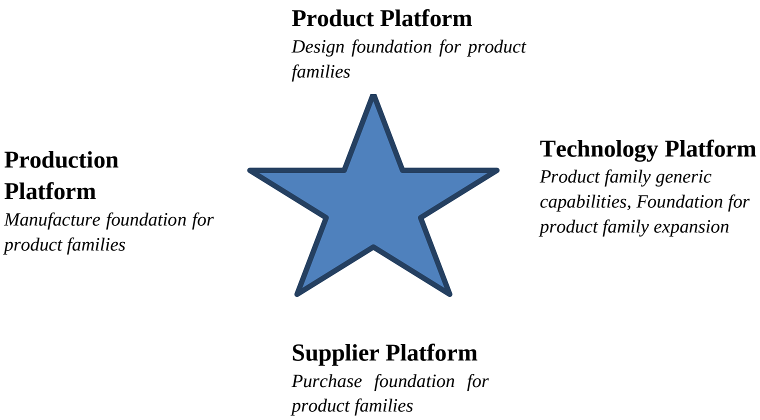


Figure 29 Platforms proposal for balancing requirements

Another suggested aspect to improve would be the **employee empowerment**. On the one hand, in order to success with DFM implementation every single person within the company has to take part of the change, from the highest level to the lowest level of the pyramid. On the other hand, this is a way to level the designer role with the manufacture engineer role, since operators and engineers in the workshop are given more responsibility, so that they feel involved enough within the process to discuss with designers.

5.3.2 Proposal Concept Development Process

Improving those aspects mentioned before will help to success with DFM implementation, but there is also a need to define a systematic approach to proceed. There are not tools or methods to substitute the engineer work, experience and intelligence. But there are structured ways to proceed that help to create standards as a base for the continuous improvement.

It is interesting to briefly remember the current concept work, before presenting the **proposal concept development process**. A scheme description is presented. Note that this a general way to proceed but in reality the concept work is not always perform like this, it varies from project to project.

1. Brainstorm→ 20 concepts
2. Combination of 20 concepts → 6 concepts
3. Pugh matrix → selection of 2 or 1 “best” concepts

Requirement Specification

The first task before starting the concept work is the *Requirement Specification*. It is really important to perform well this part in order not to take the wrong direction from the beginning. A better Requirements break down should be performed. In other to achieve that, the first aspect to modify is the top level requirements; there is a need to difference between functional requirements and technical requirements. Currently there is a trend to start from technical requirements not looking at the root, the functional requirements. This fact influences directly the concept creation. That means looking only at the technical requirements, obviating the function, constrains the creativity and the possibility to create new different concepts that still could fulfill the function requirements. In contrast, it is easier to create new concepts when the function is visualized.

Moreover, production requirements should be develop within this phase so that they can be incorporated during concept creation and evaluation phase. Finally, regarding the requirement verification phase, the V-model is a good approach, but a quick matrix evaluation, as the used at Volvo GTT, can be incorporated, Figure 30. This would be a good way to set up targets, to quick visualize the fulfillment status of the requirements and to start earlier the verification phase.

	Requirements	Fulfillment	Status
Cycle time	-4%	+2%	**Red**
Weight	-100kg	-110kg	**Green**
Cost	-5%	+1%	**Red**
Break down Production Requirements	….	…..	**RED**

Figure 30 Requirement Specification-evaluation matrix proposed

The second part of this project, Part II, will develop a series of Houses of Quality in order to achieve a good Requirement Specification. Starting from functional requirements and incorporating production requirements as well.

Project Organization

The best *project organization* to create a good requirements balance is the matrix organization, as long as every area, such as purchasing, costing, manufacturing, is included. This organization will help also to increase the knowledge along the different projects and within the different functional areas. Fortunately, the corporate organizational structure will become more horizontal by using this matrix since it will increase workers empowerment, the decentralization and team-based activity. In order to achieve the excellence organization and to fulfill all the demands and requirements there should be some responsible of Key Characteristics, apart from the function responsible and the project responsible. These key characteristics could be requirements not covered within the different function departments. Therefore there is a need to have a person responsible to assure the fulfillment of these features and requirements. This new role brings to the organization matrix a third dimension.

Supplier Involvement

Purchasing, based on the interviews and questionnaires results, is an area for improvement. This stakeholder is missing within the cross-functional activities. Some *Supplier Involvement* steps are:

- ✓ Involve suppliers as soon as possible to increase innovation and knowledge.
- ✓ Evaluate supplier capabilities and select the right suppliers.
- ✓ Align expectations and requirements with suppliers.
- ✓ Develop product project with selected suppliers.

By sharing knowledge and information the compnay aligns expectations and creates trust and commitment.

Set-Based Approach

Once every stakeholder has a representative within the cross functional team, it is time to start the concept development process. The *new concept phase* based its principles on Set-Based approach. This brings basically two ideas. Regarding with the concept evaluation phase, the first idea is down eliminating instead of down selecting. That means it is better to eliminate the concepts progressively than selecting the best one and make it the winner, when there could have been better considerable options. The goal is to remove quite early those concepts that will not fulfill the requirements, and keep on developing the rest until the next checking point, where some old concepts will not fulfill the specifications again. Hence the process will continue while eliminating concepts and developing the rest until reach a rather high level of concept maturity. The second idea took from Set-Based approach is that all these eliminations will be based on facts, not only on feeling, opinions or experience. And they should be reported.

This is a way to build up the knowledge. There is always the possibility to consider an already deleted alternative, if some requirements have changed, since the elimination causes are reported.

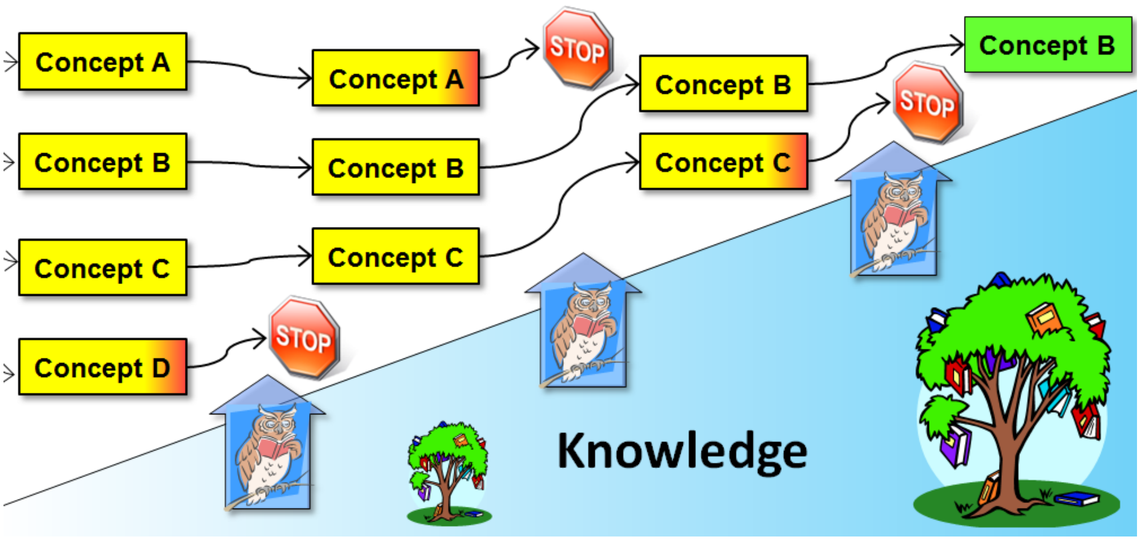


Figure 31 Set Based approach

The drawback coming from this way to proceed is the need to invest more resources at the beginning, the concept phase will be longer and more intelligence and knowledge should be invest on it. However, this is a false drawback since by using this approach there will be no possibilities for loopbacks and firefights which really increase the project lead time. Therefore, set-based approach is an advantage looking at the cost learning curve (see Figure 32), where the cheapest period to invest resources is in the early beginning.

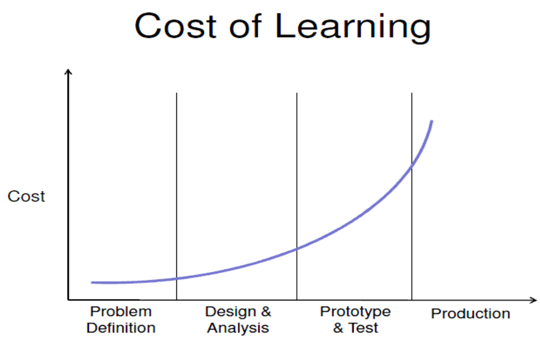


Figure 32 Cost of learning curve

Another way to build up knowledge will be proposed in the second part of this project. It is about trade-off curves, used to solve the lack of knowledge regarding process capabilities.

Finally the implementation of this Set-Based approach into the current stage implies to modify the Pugh Matrix. First of all because it is a Point-based approach, where the “best imaginable” concept is selected; and secondly because this matrix does not include a production requirements break down.

Cost Drivers

In order to *steer the cost and the producibility*, two systems can be created. Regarding cost, apart from some particular cost responsible, every single person taking part of the project should steer the cost. To help with this task the critical *cost drivers* can be identified and included in the requirements. This is what it will be exposed in the second part of the project.

The system to steer producibility is basically the current system based on *TRL levels*. However, this system should be more restrictive and start earlier during the Technology Development phase.

Knowledge management

To conclude, parallel to this new concept development process and structured documentation development process should be carried out. It is a way of knowledge management. Starting the documentation from an early beginning and reporting every action by using facts.

Part II - DFM-tool

Julia Madrid

6 IMPLEMENTATION CASE: BACKGROUND

The second part of this Master Thesis project is the case implementation. Once the current state and problems at Volvo Aero regarding producibility have been exposed and analyzed by creating a big framework; and after proposing some conclusions and suggestions about systematic ways to deal with producibility (big base for a future research work); this last part of the project shows the possibility to create ordinary tools to implement day by day 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´s core values. The DFM tools are a good help to implement DFM methodology and to 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 success with DFM, the engineers´ mind should think in DFM while performing their work, and also engineers should make use of the tools as a supplement help.

Within the research and gathering information period, two interviews were critical to drive this thesis to the implementation case. The first person interviewed was a Volvo Aero employee (name cannot be published due to *Intellectual Property Rights* for GKN, working with IS/IT and Process Development at Volvo Aero. The second person was a remarkable professor coming from Montana State University, Dr Durward K. Sobek, experienced researcher in Lean Production for fifteen years. Important feedback and publications from professor Sobek was used to perform this thesis. Thanks to these meetings the second part project´s scope was defined. The primary goal consisted of creating trade-off curves in order to build up early knowledge. This first idea then evolved to others such as Quality Function Deployment tools, as it will be shown.

Figure 33 Dr Durward K. Sobek

7 IMPLEMENTATION CASE: METHODOLOGY

In this section is presented the methodology of the second parts. All the steps to create the different DFM tools proposed.

7.1 TRADE-OFF CURVES

In order to deal with knowledge gaps, there are several methods to build knowledge. These methods/tools provide standards to support continuous improvement towards producible designs.

Trade-off analysis is a way to provide information and knowledge to the design team previous any work or result is obtained. Knowledge gaps are closed by creating trade-off curves, since the designers have the necessary information to establish the design limits from an early beginning. These curves are basically correlation between key parameters; those parameters can be either technical requirements or manufacturing requirements. The main advantage is the visualization; it is easier to understand how two parameters behave in correlation 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 basically is to know where the design limits are, in order not to start with a wrong concept from the beginning.

The idea would be to create Trade-off curves by using the main cost drivers. This is a way to deal with producibility since the most important cost drivers come from the production period. By detecting those requirements from design and production that are sensible to cost, some useful dependencies can been established. After that, just the most significantly relationships will be used to create trade-off curves, since it would be very difficult to create curves between all the possible parameter couple combinations.

Having from an early beginning the correlation between the main cost drivers is a quick way to find the design limits and influence decisions.

To create trade-off curves some resources can be used such as historical data, part simulations, production simulation, prototypes and analysis. From the opportunities and the limitations of this project, only historical data and analysis will be used. The following steps will compose the trade-off curves creation.

Steps:
1. Identify cost drivers
2. Data collection
3. Analysis data
4. Find relationships

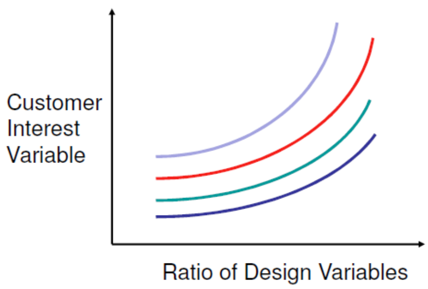


Figure 34 Trade off curves- creation steps

7.2 COST MAP & DSM

In order to identify the cost drivers the first step was to create a cost map. Some interviews to method specialists as well as to operators at the workshop were performed in order to detect cost drivers coming from production and design. This information was completed with the already acquired knowledge from previous interviews. 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.

The Design Structure Matrix (DSM - also known as the 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 (i.e., it has an equal number of rows and columns) that shows relationships between elements in a system. Since the behavior and value of many systems is largely determined by interactions between its constituent elements, DSMs have become increasingly useful and important in recent years.

There is no pre-defined DSM that is helpful for any problem that is 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 the elements and dependencies needs 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.

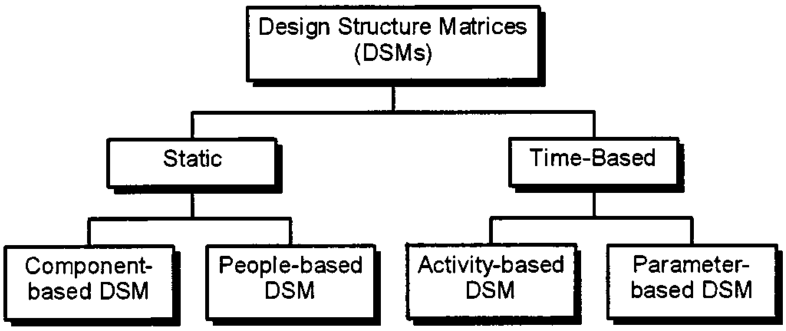


Figure 35 DSM classification

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 36 DSM data types

Therefore, the next step will be to identify which kind of elements would like to be analyzed in the matrix, because the use of the matrix and the results´ interpretation will vary depending on the type of elements. There is also important to have cleared the application in order not to lose the goal of the matrix.

Once the elements are introduced in the matrix, having the same elements in the row and the column, as it is shown in the example (Figure 37), it is time to start establishing dependencies between them.

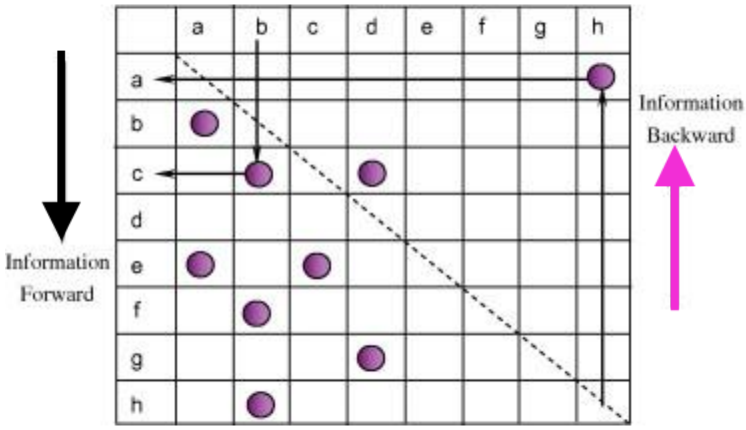


Figure 37 DSM matrix & information flows

Off-diagonal cell marks indicate the interactions (i.e., dependency, information flow) between parameters. The matrix entry (*i*, *j*) is filled with a mark if there is an interaction between elements *i* and *j* and empty otherwise.

Due to the complexity of the studied case, having 35 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, achieving therefore, a fair comparison. Finally it was possible to enter the marks in the matrix. Every mark represents the relationship between a pair of parameters. These loopbacks are represented by the marks situated above the diagonal, the information backward.

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

- Partioning or sequencing a DSM
- Tearing a DSM
- Banding a DSM
- Clustering

These different ways to analyze the matrix shared objectives. One of them is to identify groups of parameters that are independent of others. Moreover, the main objective for time–based parameters is trying to end up in a triangular matrix, so loopbacks in time can be identified.

The matrix creation has been performed with the help of software, called ProjectDSM 1.0 *(http://www.projectdsm.com/)*. Which allows to establish and to justify dependencies at the same time; and after that, it 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.

7.3 VAC HoQ

As it was mentioned above, the trade-off curves realization will be keep for future work. However, some other results and conclusions can be addressed based on the DSM´s outcomes. For instance, critical cost drivers were identified to perform a series of Houses of Quality.

The House of Quality is the kernel of QFD. The detailed theory regarding QFD methodology and HoQ can be found in previous section. Here, a brief summary about the four phases of QFD methodology will be present, in order to explain the work carried out.

The starting point of any QFD project is the customer requirements, often referred to as the non-measurable, i.e., those requirements that describe the component functionality. These requirements are then converted into technical specifications like ``load distribution, temperature, etc.''. This stage is referred to as the engineering characteristics or measurables. The QFD process involves four phases:

1. Product planning: house of quality.
2. Product design: parts deployment.
3. Process planning.
4. Process control (quality control charts).

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 (Figure 38), with each house representing a QFD phase. Indeed the real HoQ is the matrix representing the first phase.

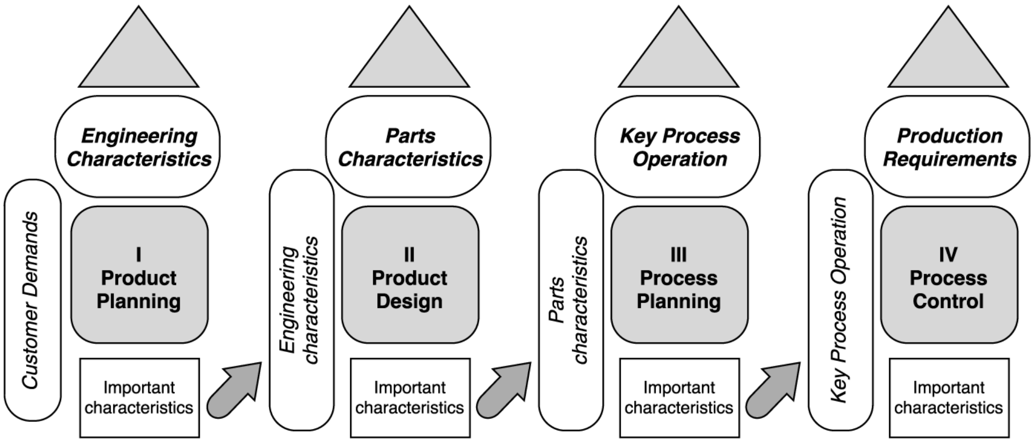


Figure 38 The four phases of QFD methodology

Besides the theory, the idea of this project will be to integrate QFD methodology to translate the customer requirements into design requirements that take into consideration producibility. That means, instead of creating a HoQ for each phase along the project, these successions of HoQ will be integrated and developed during the concept phase, so that process operations and production requirements are already defined from an early beginning. By performing these *VAC Houses of Quality* the design will be able to fulfill the production requirements from an early beginning and the Requirements principle will be balanced.

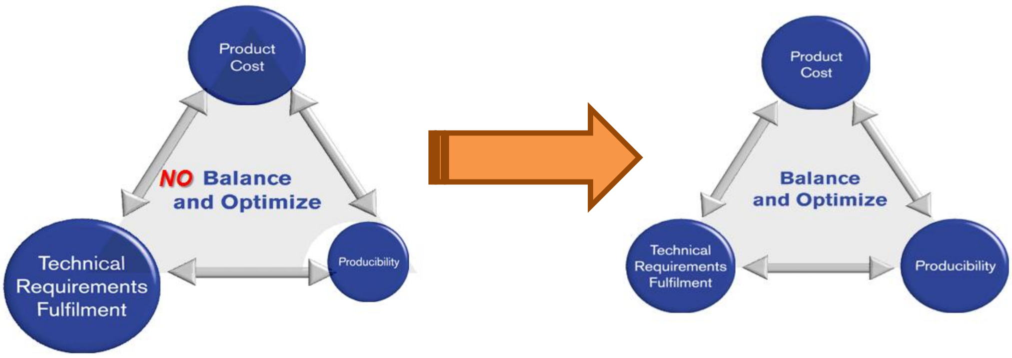


Figure 39 Non-balanced requirement situation

7.1 DFM TOOL

The last part of the project contains the real implementation case, where project´s analysis and conclusion are applied. The idea is to transfer all the production requirements and the producibility drivers gotten from the *VAC Houses of Quality* to the flow of operation of the TEC, specifically TEC from **project X** (*The original project´s name is company confidential and cannot be published in this report due to Intellectual Property Rights for GKN).*

In order to create this tool a data collection process at the workshop, following every step of the TEC flow of operation was performed.

7.2 LIMITATIONS OF THE TOOLS

Mainly the objective of this second part is to point out the importance of the production requirements integration in every matrix evaluation, so that producibility is taken into account from the beginning, as well as, showing the possibility to perform this by using either a systematic approach or certain tools that help the purpose.

Nevertheless, due to time and experience limitations it has not been possible to create a tool that brings feasible results. It is important then to interpret the result from a conceptual point of view, and to take the main idea, i.e., what these tools really aim for, which is, increasing producibility. And not looking into detail the results obtained, which are not fair values.

It is also necessary to mention that a lot of assumptions have been made in order to be able to create these tools due to the project´s limitations already mentioned.

8 ANALYSIS AND RESULTS

Within this section the DFM tools created are presented. These tools are applied to the TEC component, specifically the one that belongs to *project X*.

As it was mentioned in the methodology, the first step is to come out with the so called, cost drivers. These are requirements either from design or production that are sensible to cost. These will be the parameters used to create trade-off curves.

8.1 COST DRIVERS IDENTIFICATION

In order to perform the cost drivers´ identification task, a deep understanding of the TEC flow of operations was necessary. Below, it is presented a brief description of the main operations, which took part of the tool development, so that the critical characteristics, that have impact in the design process, can be identified.

The first assumption was to consider that the performance temperature range is the only factor that influences the material selection. Therefore, material is considered as the first choice within the flow of operations.

8.1.1 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 Material A and Material B, both super alloys. No composite materials will be considered. *The materials´ specifications and names are company confidential and cannot be published in this report due to Intellectual Property Rights for GKN.*

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

Now it is time for the purchased operations, where the supplier involvement is the most important factor. These are casting, forging and sheet metal forming.

8.1.2 Casting

There are several casting processes, however, within this section only the current casting process used to manufacture TEC component, investment casting, is presented.

Investment casting, often called lost wax casting, is regarded as a precision casting process to produce near-net-shaped parts from almost any alloy. 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.

There is no need to explain in detail the process steps, since it is a purchased operation and within this project only basic parameters that are influenced by casting will be considered. However, it would be necessary for a future work a further analysis of the purchased operations. Even though, the following image describes the steps within the casting process.

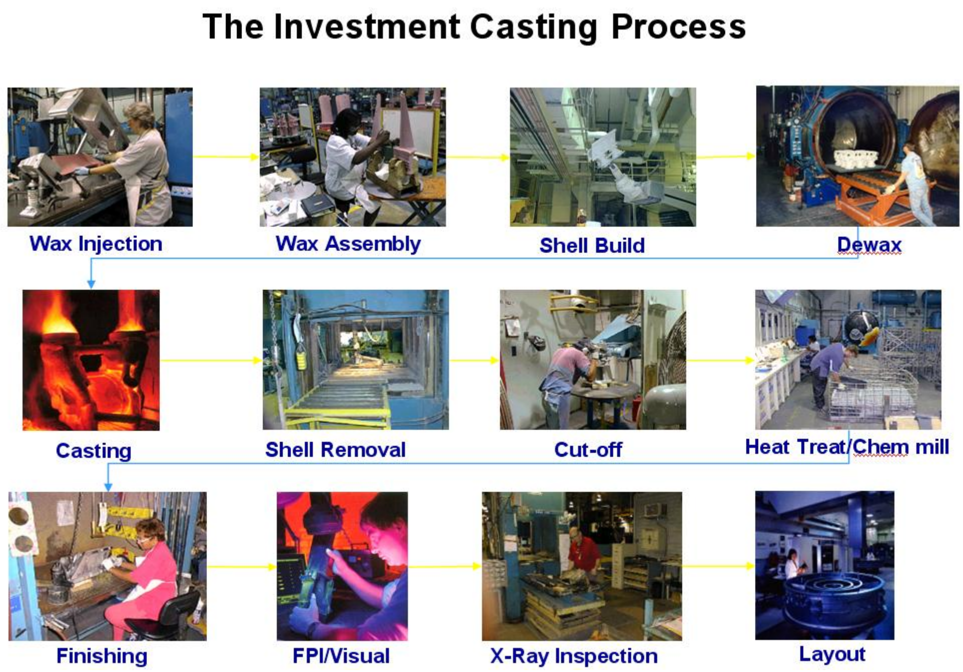


Figure 40 Steps of The Invesment Casting process

Casting, as a manufacturing operation, brings a cost. Therefore all the parameters that influence the performance of this operation would vary the cost result. The process itself and those parameters are considered as cost drivers.

A generic description of when it is optimal to use castings would be very complex since many factors impact the selection. In the casting process these cost drivers can be related with the supplier´s aspect or with the process performance. Supplier cooperation and supplier delivery capacity are the cost drivers related with the first. When there is a good cooperation, errors and changes can be avoided, reducing the cost. In contrast, delays in parts delivery increase the time of the manufacture, hence cost.

Regarding the process performance, 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. In addition, some casted materials do not achieve the desired properties, for instance Material B, as it was mentioned beofre. Consequently, other operation should be selected to form that material. Finally, knowing that other forming operations give better strength to the components than casting, designers have to take that stress areas into consideration when choosing the manufacturing forming processes.

8.1.3 Forging

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

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 *[37]*.
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

Closed-die forging

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 41 Forging process

To build a TEC, two different materials are used in VAC, Material A and Material B. 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

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 super alloys such as Material A and Material B, 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 are 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.

8.1.4 Sheet Metal Forming

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 *[37]*.

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:

Deep drawing

In this 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.

Stretch forming

In this 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.

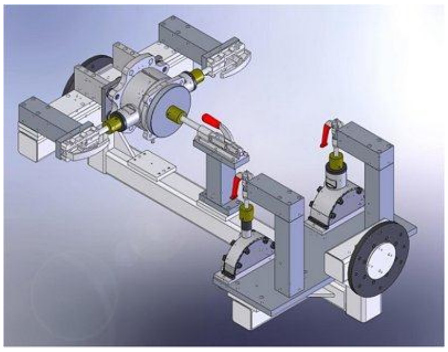
The mechanical properties of the sheet do not change along the process, they are already determined when the sheet is hot rolled. The two materials used for the TEC have identical forming capabilities at room temperature. Their ductility makes them suitable to be produced by sheet metal forming.

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.

8.1.5 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.



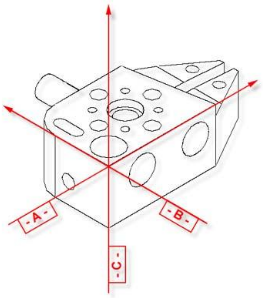


Figure 42 Tack weld fixture & example piece Target system (datum system)

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.

8.1.6 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.

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 contrast, deburring, operation to remove burrs after machining, is performed manually at VAC.

In the TEC manufacturing operations, a primary machining is made 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. Deburring operation is always performed after machining to achieve that smooth surface. The cost drivers of machining 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.

8.1.7 Welding

The joining method used to build the TEC is welding. Welding process 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 those sectors to obtain the final circular component. Before the weld itself, tack weld is done manually to fix the parts together. For the specific case, *project X*, all the welds are performed with plasma, except one small weld done at the curvature of the regular sectors, which is performed by TIG due to 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 as shown in the next figure.

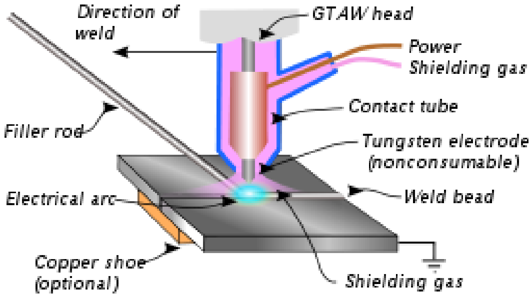


Figure 43 TIG weld area

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 concept alternatives have much different necessities in terms of welding. The cost drivers of this operation are the stress areas, since they are susceptible to weld cracks, so it is better not locate welds near those 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, as well as the influence during the design phase.

8.1.8 Inspection methods

There are several inspections methods performed during the manufacturing sequence to check the quality of the TEC. These inspections are X-ray, FPI, CMM, GOM and 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. The areas that have more density receive more radiation, which will get darker in the image captured by the film.

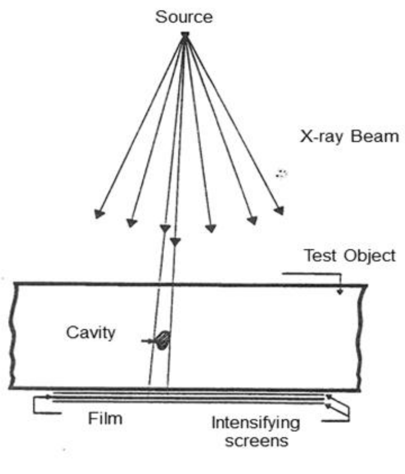


Figure 44 X-Ray process

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)

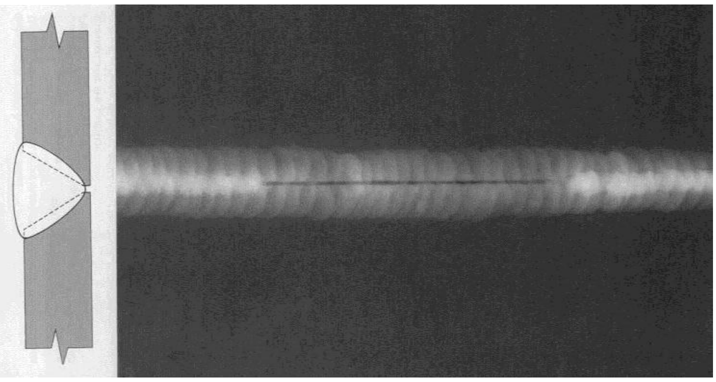


Figure 45 X-Ray defects detection

For the TEC, the X-ray is performed to inspect the welds. In the manufacturing sequence of *project X*, 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 TEC, from *project X*, 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 *project X*.

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 after compared with the original CAD model drawn by the designers. The final result is the deviations in all the parts compared to the nominal drawing. In the TEC of *project X*, 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 project X 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. To succeed with inspection, the machine has to access to every required location, due to that thickness and accessibility are critical parameters that will influence the operation performance. Also, if the method is manual or automatic will impact the final cost, due to automatic methods always decrease lead time.

8.1.9 Heat treatment

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

The heat treatment processes for both super alloys 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 (precipitation hardening, age hardening, and precipitation heat treatment are synonymous terms). 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 *[34]& [35]*.

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.

To conclude, 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 project 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.

8.2 COST MAP

Thirty-five cost drivers were identified by following the methodology explained in the previous section. These parameters where classified in six different groups such as “Project features”, “Customer Requirements”, “Purchasing Requirements”, “Design” “Operations” and “Features belonging to Operations”.

The reason of such a classification resides in the fact that all the identified cost drivers could not be compared at the same level. Therefore, this classification clusters the cost drivers in groups where there are similar characteristics. For instance, “Operations” are not requirements themselves but they will influence cost. “Features belonging to Operations” are the requirements coming from manufacturing processes, and they need to be taken into account during concept work since they will also influence cost. “Design” groups those requirements coming from design, but also those that are influenced by production period, such as accessibility and number of parts. The cost drivers belonging to “Customer Requirements” are transferred directly from the functional requirements such as load case (stress areas) or Temperature range (material). Purchased requirements are not developed in detail, only the supplier involvement aspect will be considered as well as the purchased operations, which are included in the group “Operations”. And finally two important cost drivers, lead time and industrial structure, classified as “Project features” that could represent the internal requirements.

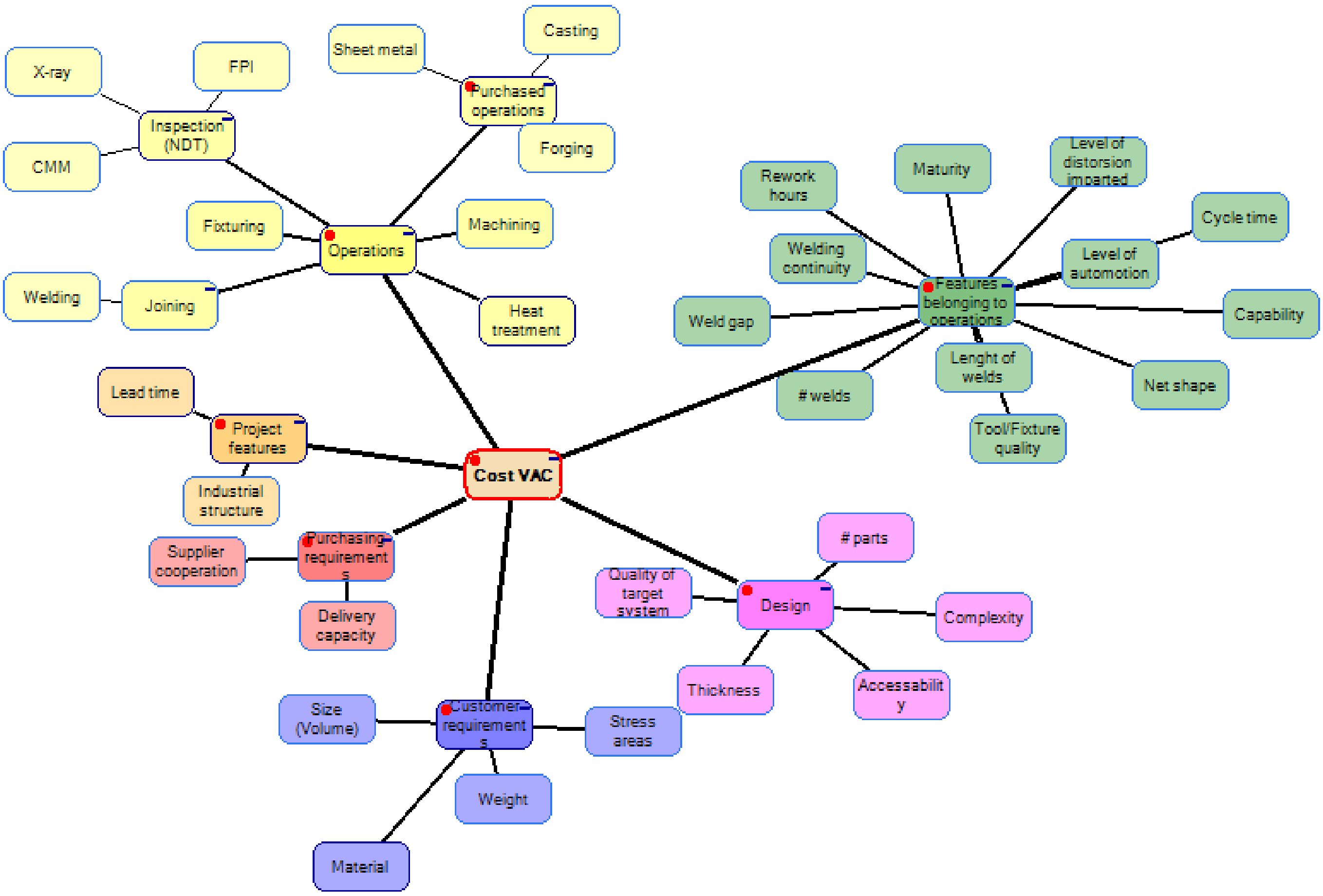


Figure 46 Cost Drivers clustered

8.3 DSM: Design Structure Matrix

Establishing dependencies between the different pair of cost drivers is a really difficult task. The reason is the big amount of parameters and the unfair comparison, since they do not have the same characteristics, cause that they are clustered in such a groups.

The chosen strategy to deal with this complex problem is Design Structure Matrix. However, before starting to establish dependencies and to enter marks in the matrix, a structure methodology is needed, in order to make feasible comparisons. Therefore, two tasks are carried out; the first one is to define every single parameter (Appendix G). The second one is to define the dependencies criteria between parameters from the same group and parameters from differences groups. That means, to clarify which are the specifications that a parameter should fulfill to influence other parameter (Appendix H). These two Appendixes should be used as a complement to understand the red marks within DSM.

The following matrixes show the DSM before manipulating and the DSM after automatically manipulation. The cost drivers mentioned before are located throught the rows and the columns.

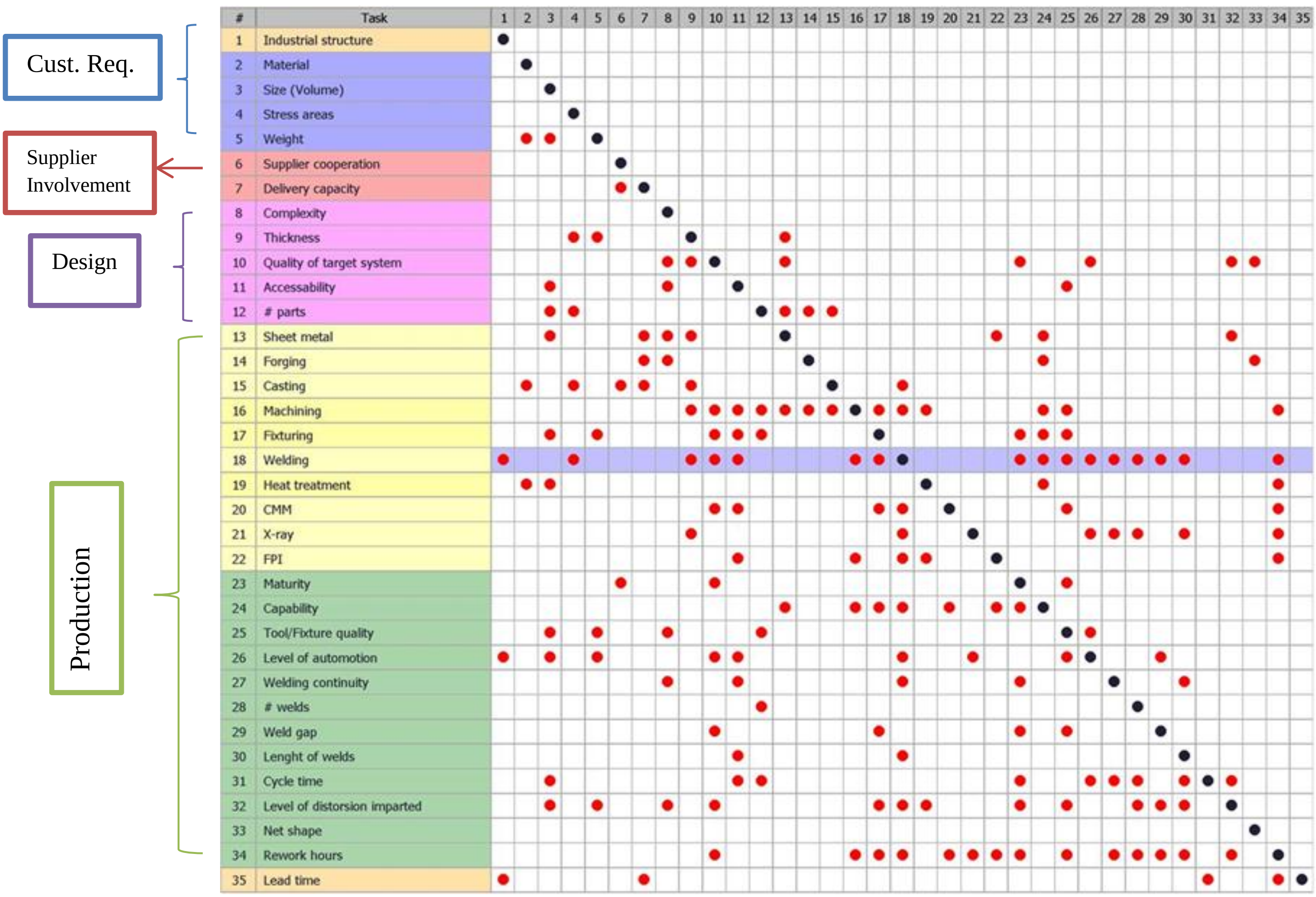
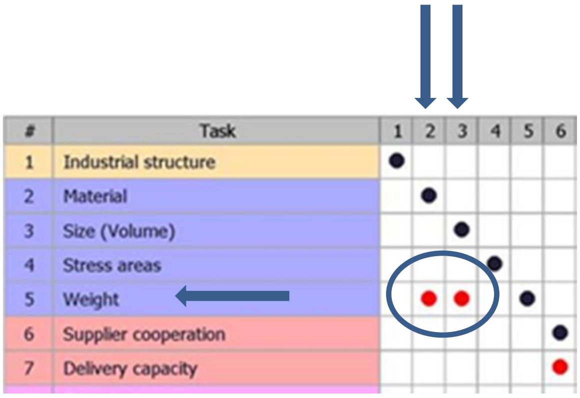


Figure 47 DSM before manipulating & relation with project phases

The order of the cost drivers groups has a special significance; it follows the project development process. That means the first group is the customer requirements, followed by supplier involvement, the design phase and in the end, the production phase (Figure 47). This analogy with the project development phases led to identify two kinds of DSM within the same matrix. On the one hand, looking at the groups, the matrix can be considered as an Activity-Based DSM, used for modeling processes and activity networks based on activities and their information flow and other dependencies. On the other hand, looking at the single elements, the matrix can be classified as Parameter-Based DSM, used for modeling low-level relationships between design decisions and parameters, etc. *[32]*.

In addition, those parameters that have the time property, for instance the operations and the features belonging to operations since there will always appear in sequence along the time, are also ordered in time-base, hence loopbacks can be identified. For example, the purchased operation will come always first than welding operation or the cycle time will be the last feature of an operation, so that it will be positioned at the end of that group.

A red mark within the matrix means that the parameter in the column influences the parameter in the row. For instance, the material and the size influence the weight, due to the material represents the density and the size the volume of the component. Moreover, to see which are the parameters that influence and specific one, then the red marks within the specific parameter´s row should be checked.



$$mass = density * volume$$

Figure 48 DSM interpretation

Once all the dependencies are established, i.e. all the red marks are entered in the matrix. It is time to start manipulating the matrix, in order to get a triangular shape, which means loopback reductions if the time-based matrix is considered. Every point on the right side of the diagonal is a dependency back.

In order to get triangular shape, rows are exchanged by following some methods such as partioning or banding. The empty rows (no red marks), which represent those elements that can be determined without input from the rest of elements of the matrix, are placed up in the first rows. The empty columns, elements that do not deliver information, are placed on the right within the matrix. The rest of elements are located trying to achieve the perfect triangular shape.

The manipulated DSM can be visualized in the matrix below. After manipulating process there are still some red marks remaining in the right side. The interpretations of those ones are covered within the next section, as well as other conclusions coming from DSM matrix.

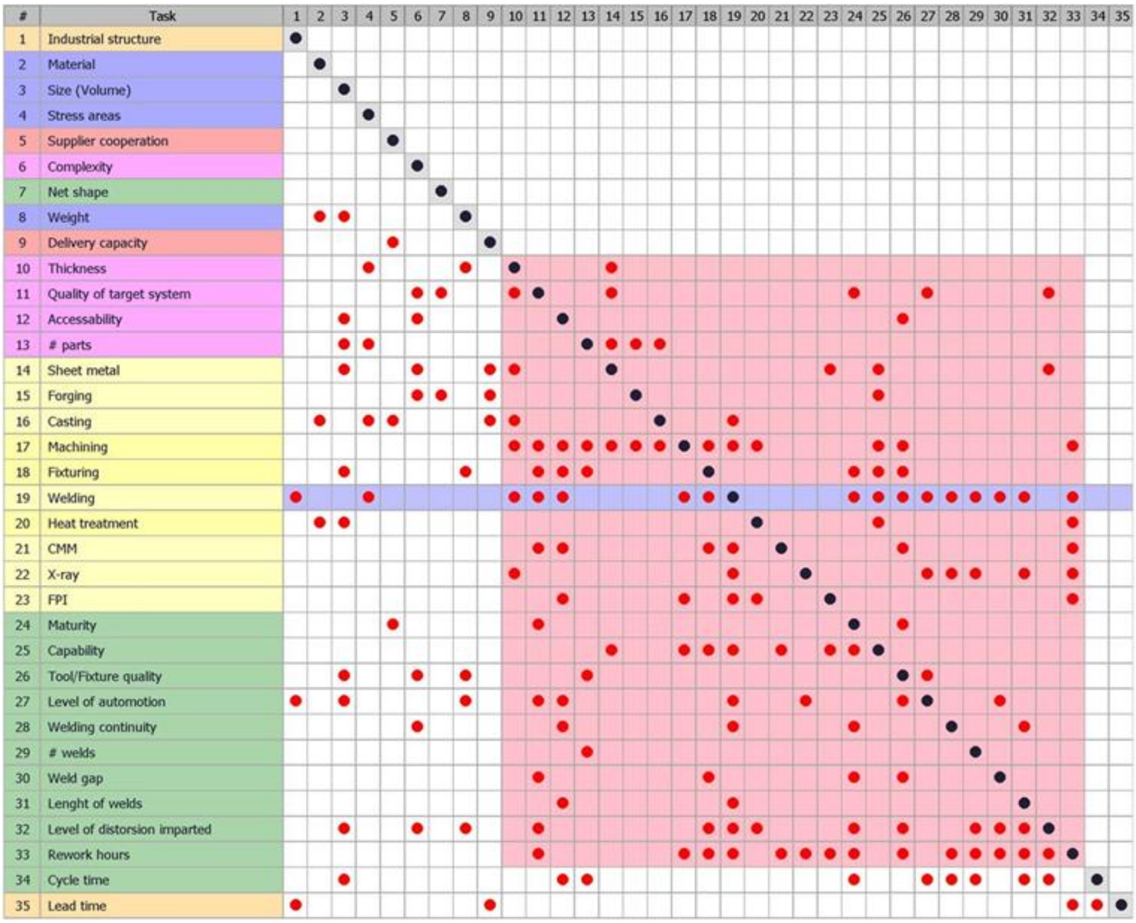


Figure 49 DSM manipulated

The following Spaghetti chart, Figure 50, obtained from the DSM software program shows the complexity of the problem and the critical points where loopbacks can arise. Those loopbacks are represented by pink lines within the Spaghetti chart, which represent the information backwards (see pink arrow concept in Figure 37).

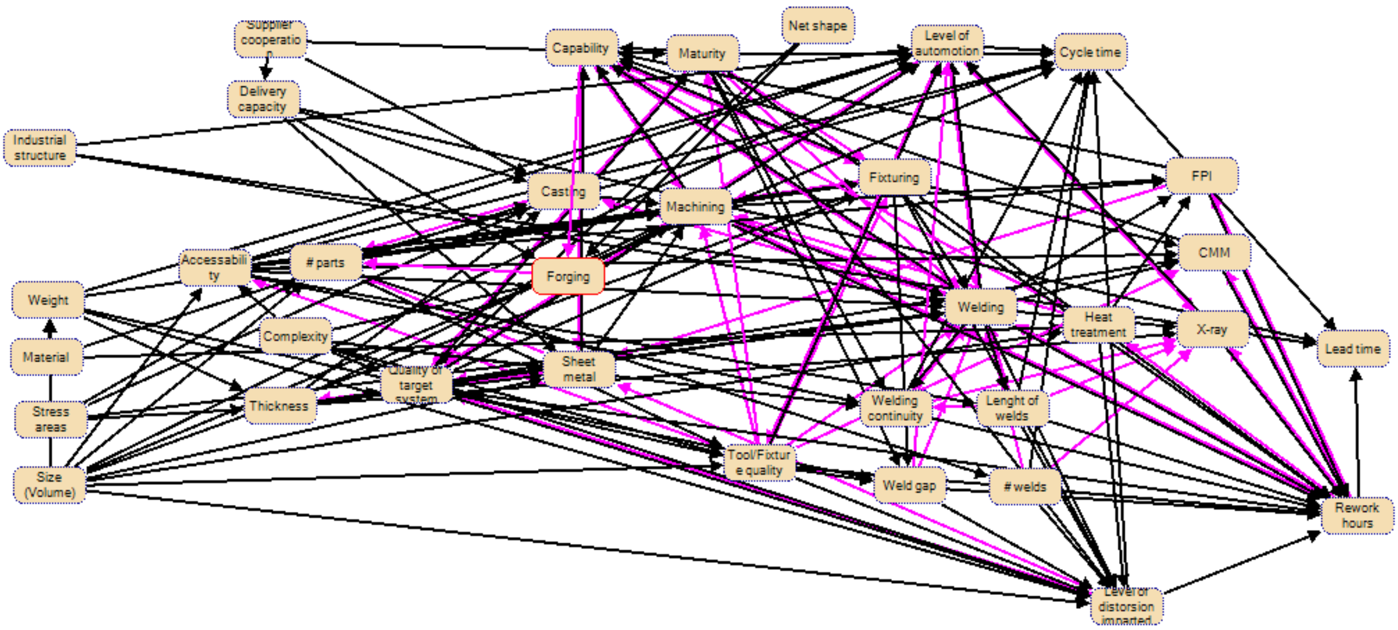


Figure 50 Cost Drivers relationships- a complex engineering problem

8.4 VAC Houses of Quality

VAC Houses of Quality are an adaptation of the theoretical House of Quality in order to show the importance of the production requirement integration during the concept creation and selection activities.

Customer requirements are considered as the top level of requirements, i.e. the functional requirements of the component. In this specific studied case it is important to point out that these global requirements are rather linked to technical aspects, therefore to the technical requirements. The first phase of QFD method, **Product Planning** is defined as the “conceive phase”. Within this phase the HoQ is built up. The customer needs are transferred to product properties.

A list of functional requirements for the TEC, which represents the customer voice, has been created by making use of the information gathered during the interviews period and the internal documents. Then a list of technical requirements has been made as well, which can be directly related to the functional requirements. All of this represents the first step of the Requirement Specification break down.

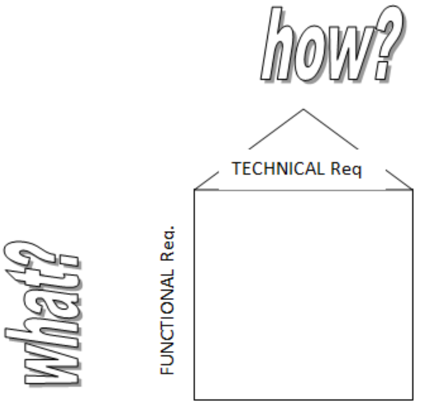


Figure 51 First VAC House of Quality

8.4.1 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).

8.4.2 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 (LCF) requirements.
- Fulfill temperature requirements (aircraft operated within a certain temperature range)

The following HoQ matrixes and the products used to evaluate them are examples not matching perfectly with the reality since exact results cannot be published due to Intellectual Property Rights for GKN. However are enough fair and valid to explain the method and transmit the main idea.

According to the theory, in the second HoQ, technical requirements are used to identify parts that will be critical for the product. In the third phase, the critical properties are transferred to production operations and the critical parameters are identified to create the last matrix, where production requirements are defined. However, the *VAC Houses of Quality* created do not exactly follow the theory, but they allow to reach the purpose of the tool, the production requirements integration.

The second VAC House of Quality (Figure 52) is based on the information obtained from DSM, where the most critical requirements, both from design and manufacturing aspect, were identified. This was done by looking at the parameters that mostly influence the operations, i.e., checking the red marks in the rows from 13 to 23 (range that covers the manufacturing operations) and taking the parameters that represent requirements for design, such as complexity, thickness, accessibility, number of parts, target system quality and tool quality. After, these requirements are evaluated against the different manufacturing methods. For the purchasing operations a code (++,+,-) is used. In contrast, for the operations in-house, a mark (X) implies that the requirement influence the operation, so there is a need to take into consideration this aspect when thinking about the specific manufacturing method.

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

Figure 52 Second VAC House of Quality

The code meaning is explained as follows:

++ (very good) → Very well requirement fulfillment with this manufacturing method
\+ (good) → Well requirement fulfillment with this manufacturing method
\- (bad) → Bad requirement fulfillment with this manufacturing method

For instance, looking at the stress areas requirement, customer requirement which would represent the strength, when a part is manufactured by casting the final strength achieved is not so good as forged or sheet metal formed part, that is the reason why the relation has a - for casting and ++ for both forging and sheet metal forming. Other example would be looking at sheet metal forming operation. The formed material, as it was mentioned before, acquired really good properties regarding strength. In contrast, this process is no good to create complex shapes or to deal with variation in thickness.

It is very important to notice that these evaluations, reflected in this code, are made in relative comparison. That means that a manufacturing method is considered to be very good to fulfill certain requirement compared with the rest of methods considered here.

This "HoQ" presented above, is the previous step for the third VAC HoQ created, which compares the parts components with the production requirements from the different manufacturing methods. Regarding this project only the purchasing operations, casting, forging and sheet metal forming, will be object of evaluation within this matrix, the rest of methods are left for future work.

The third VAC House of Quality has a lot of uses. On the one hand this tool is a good way to compare different alternatives regarding purchasing operations. Two specific examples of the component TEC have been chosen for the purpose. The main different, between both concepts, is the way they have been split up in different parts and the purchased operation to form such as parts. Example 1 is composed by 13 H-sectors (H shape), that are assembled to form the whole piece; the purchased operations are casting and sheet metal forming. Example 2 is composed by 13 T-sector that are assembled to a hub in order to form the final piece; this time forging is also used as a purchased operation due to temperature requirements.

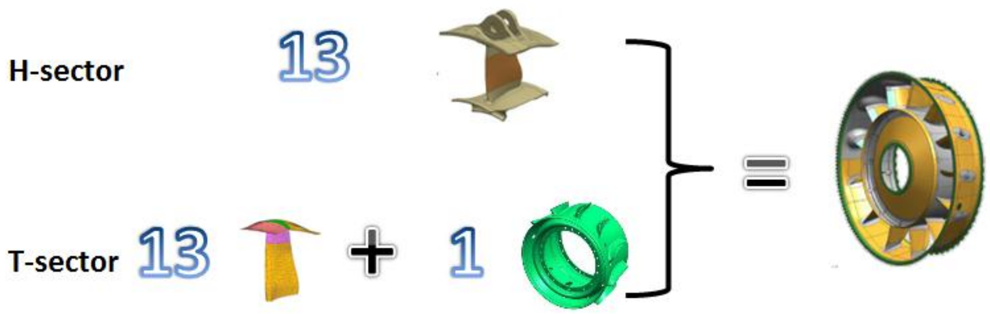


Figure 53 The two concept alternatives evaluated by the third VAC HoQ

On the other hand this tool also can be used to evaluate the different purchased operations to manufacture the same part. For instance it will response to the question, How would producible and which would be the cost of this part if forging is chosen as a purchased operation instead of casting? Both comparisons uses are made in terms of cost and producibility.

The tool has been made on an excel sheet, and it has matrix shape (see Figure 55). The rows represent the different subsystems of the component. That means the sublevel 4 are all the single parts; the sublevel 3 is the first assembly, the sectors; the sublevel 2 would represent the TEC assembly and sublevel 1 the final assembly, where the forged rings are joined to the whole TEC. This tool will evaluate only until sublevel 2 starting from sublevel 4, i.e., the single parts.

As it was mentioned, the single parts are located in rows and evaluated against the requirements of the different purchased operation, i.e. the production requirements. Additional information is added to the matrix regarding % weight, % load case and temperature from each single part.

First of all, in order to understand the evaluation of some requirements, specifically *strength*, load distribution for TEC needs to be explained. The detail description and explanation of the matrix evaluation will be presented after.

8.4.3 Load case

The study of the loads distribution in the single parts of the TEC was not based on any finite element software. It was based on rough information gathered. So that some assumptions were made in order to come out with those estimations.

Some single parts are not considered in this study such as flanges, cone of the hub and generic standard parts and bosses. In addition, it is only considered the loads transmitted to the mounts by the airplane, having the same value for the three of them (see Figure 54), without considering any angles of projection that would lead to have shear stresses in the vanes of the sides.

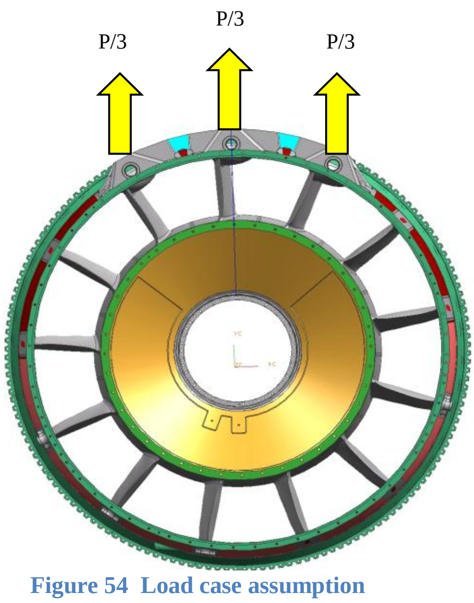


Figure 54 Load case assumption

The TEC component can be divided in 3 mount sectors and 10 regular sectors. 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 loads. Each sector is made up in turn by the shroud, the vane and the hub part. 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.

These load distribution percentages are presented within the matrix. On the other hand, the weight distribution was based on the volume distribution and the density. And the thermal case represents the range of temperature where the TEC has to act, coming from customer specification.

The following matrixes show the tools House of Quality for both TEC examples. The explanation regarding weighting parameters and how this code has been used to evaluate the subsystems against the production requirement is founded after them.

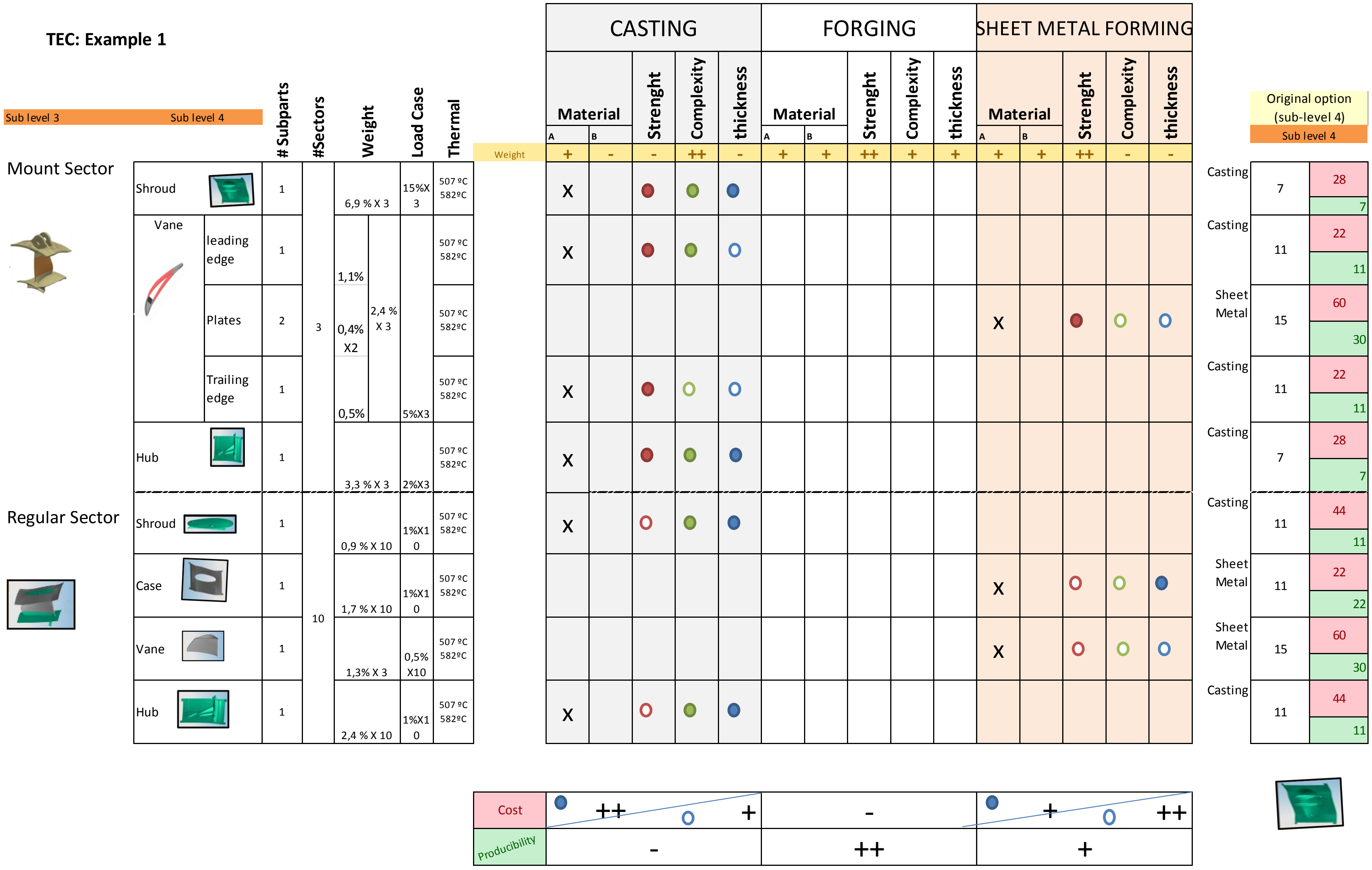


Figure 55 Third VAC House of Quality – Example 1

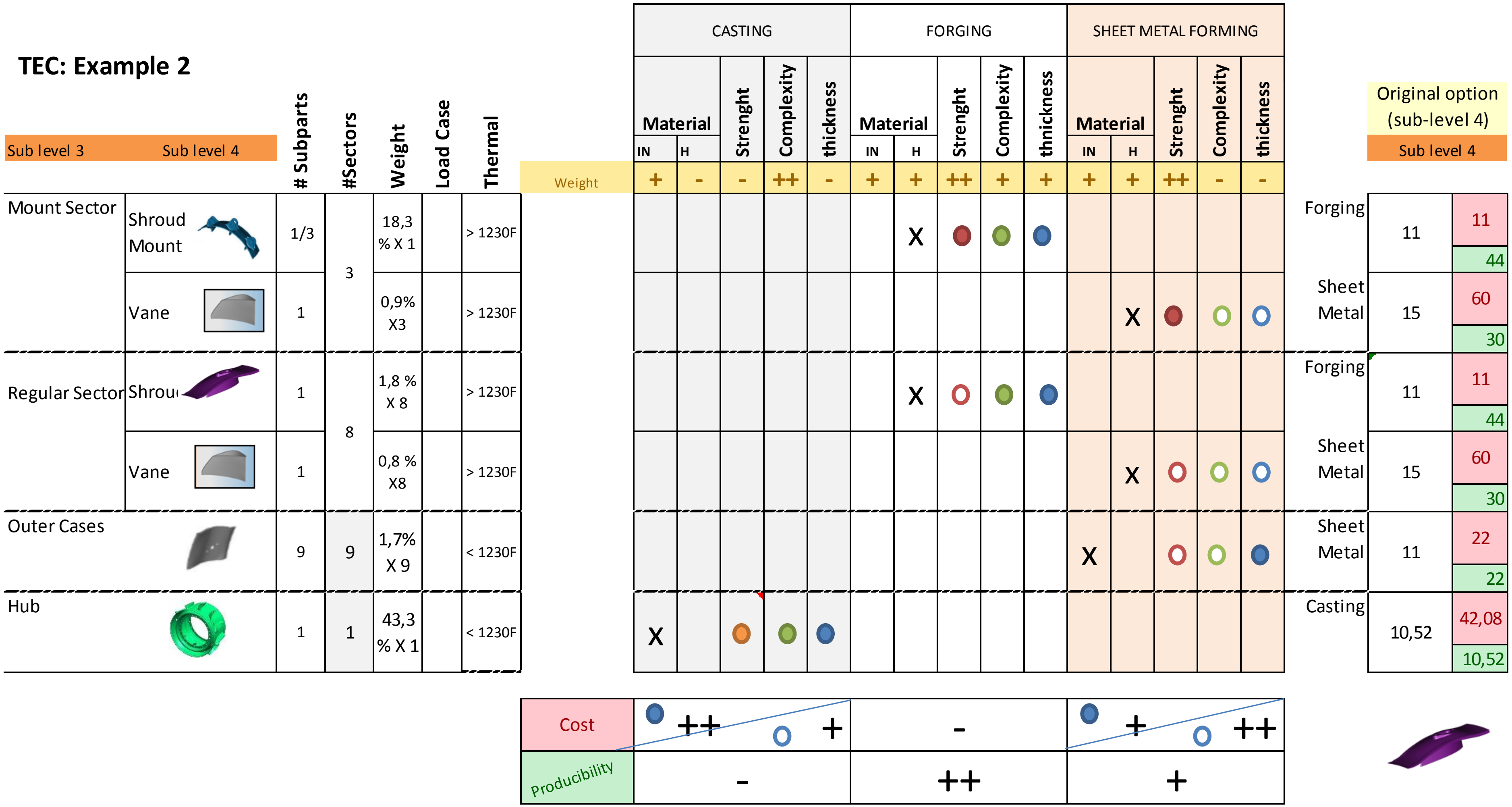


Figure 56 Third VAC House of Quality – Example 2

8.4.4 Weighting the House of Quality

When a House of Quality is performed, it is necessary to choose some weighting factors to give to the parameters, in order 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 specific third VAC HoQ, Figure 55, there are two main evaluations. Within the first one some requirements (strength, complexity and thickness) evaluated against the purchased operations which are weighted with the ++(very good)/+(good)/-(bad) scale, according to the characteristics of the manufacturing process. These relations are taken from the second VAC HoQ matrix (Figure 52) and their justifications were exposed before. Hence this evaluation is not new.

Within the second evaluation, each part of the TEC component is evaluated against those same requirements, strength, complexity and thickness, with a full dot (strong relation) or empty dot (weak relation). Strong relation means that the parameter has to be taken into more consideration for that part than a weak relation or empty dot. That means that part is more critical regarding that requirement.

Therefore, a combination of two scales/coding will meet. And those combinations are ranked as follows.

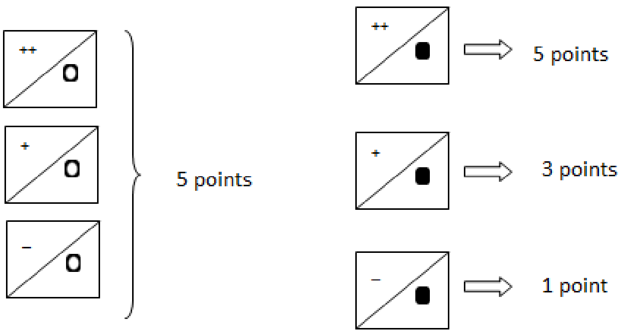


Figure 57 Evaluations´comnination coding

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 requirement for a specific process, rather than showing when a process is optimum for a requirement, because with more or less difficulty the parts can be manufactured with all the purchased operations, varying mostly in cost and producibility. The weight 5 is given for all the correlations when there is a weak relation (empty dot) because the parameter will not have a critical consideration for that part. So every manufacturing process will be adequate to produce such a part and to fulfill the requirement.

An example can be used to clarify this complex evaluation so far.

In Example 1 the Shroud part of the regular sector is made by Material A, so that the material cell representing Material A is marked by a cross. The material related with the casting process has a + since this material can be formed by casting without giving any problems in production afterwards. The Shroud has a strong relation (full dot) for the three requirements, strength, complexity and thickness since this part will support load, it is a complex shape part and it has important thickness variation to be considered. Therefore the three combinations for the Shroud of the mount sector are:

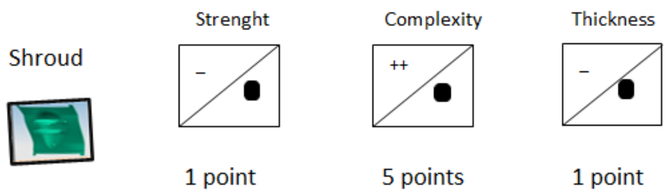


Figure 58 Evalutations´combination example

The purpose to give values to those combinations is to compare the different purchased operations in terms on cost and producibility. The cost only covers the purchasing and producibility refers to how producible the purchased parts are regarding operations in house. For instance, a casted material has worse producibility than a forged material since the casted material has worse weldability and welding is an in-house operation. In contrast casting is better regarding cost because is cheaper than forging.

Therefore, for each specific part, the three combinations of the two scales are summed. Then, the sum result obtained is multiplied for a weighting factor regarding cost and producibility.

The sum for the example would be 1+5+1=7

Cost and producibility are graded by using again the same scale than before ++(very good)/+(good)/-(bad) for each manufacturing process.

	CASTING	FORGING	SHEET METAL
Cost	● ++ / ○ +	-	● + / ○ ++
Producibility	-	++	+

Figure 59 Weighting factors regarding cost and producibility - coding

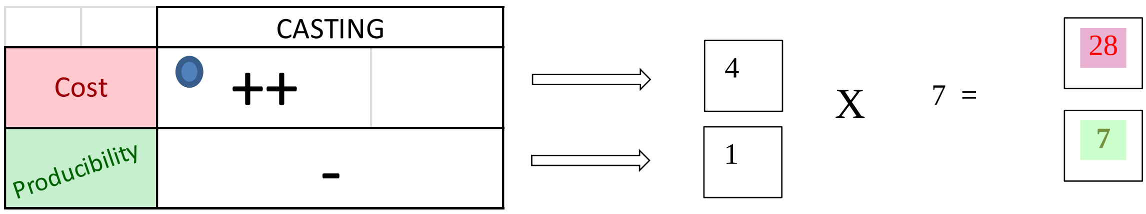
Regarding cost, the grade will vary depending on the thickness requirement (represented by the blue dot), because when a part does not have major variations in the thickness (empty dot), it is cheaper to produce it by sheet metal forming than by casting and vice versa. So, the following table applied for this case:

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

Figure 60 Special coding when thickness parameter

The weighting scale chosen for ++,+,- 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.

Coming back to the example, the previous result of 7 would be multiply times 4 for the cost and times 1 regarding producibility. The explanation is looking at the casting column, since this element is casted, and also considering that this part has a strong relation with the thickness requirement (blue full dot).



Now based on these final values, red for cost and green for producibility, it is possible to make use of this tools for the two applications mentioned above. The first application is about comparing two different TEC concepts. The second one is about comparing the different purchased operations for the same specific part.

8.4.5 First Application

Looking at the results of the third VAC HoQ, for both TEC examples presented above, a rough comparison between the two concept alternatives regarding only the purchased operations can be achieved. In order to get a fair and overall comparison it is necessary to transfer the cost and producibility numbers from each single part to the sector assembly level, and after that, to the whole TEC assembly level. It would not be fair to compare just the T-sector numbers (from Example 2) with the H-sector numbers (from Example 1) since the T-sector does not include the hub. Therefore the comparison has to be made looking at the final numbers related with the whole TEC. This procedure is shown in the next picture, Figure 61 & 62. A ranking value is 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.

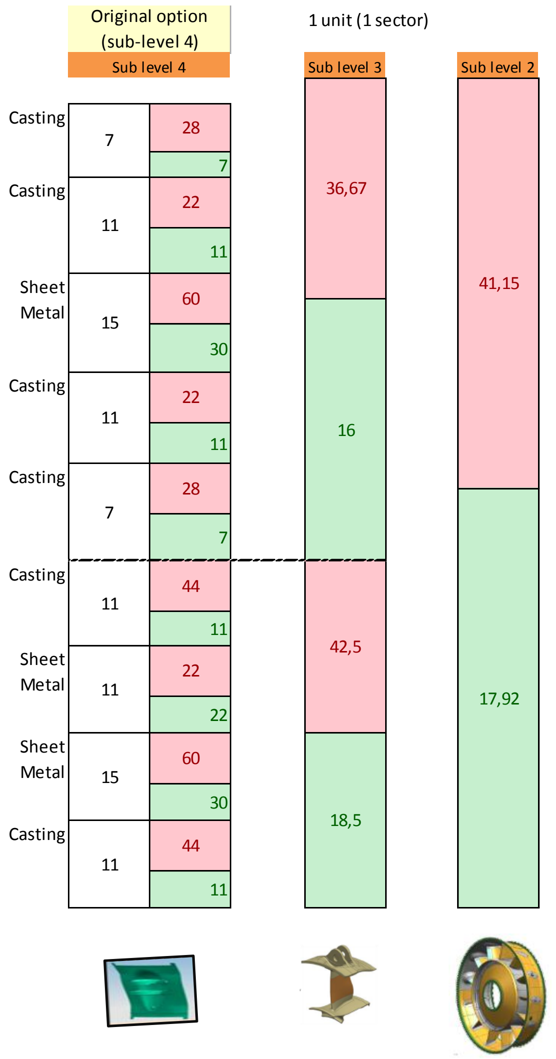


Figure 62 First Application: Example 1- cost & producibility number until whole TEC assembly level

Figure 61 First Application: Example 2- cost & producibility number until whole TEC assembly level

In this way, it is possible to make in a rough overall comparison in terms of cost and producibility between different concepts for the choice of the purchased manufacturing operations of a component.

8.4.6 Second Application

The second application is made for the different alternative concepts independently. In order to compare the different manufacturing processes to produce the same part and to know and to decide in a rough way which one is the best.

The comparison is made by looking at the sublevel 4, the single parts. The column named first option covers the original purchased operation. The column named second option covers the proposal operations. The matrix is used and the evaluations are made in the same way for both options just having in mind that there are changes in the purchased operations.

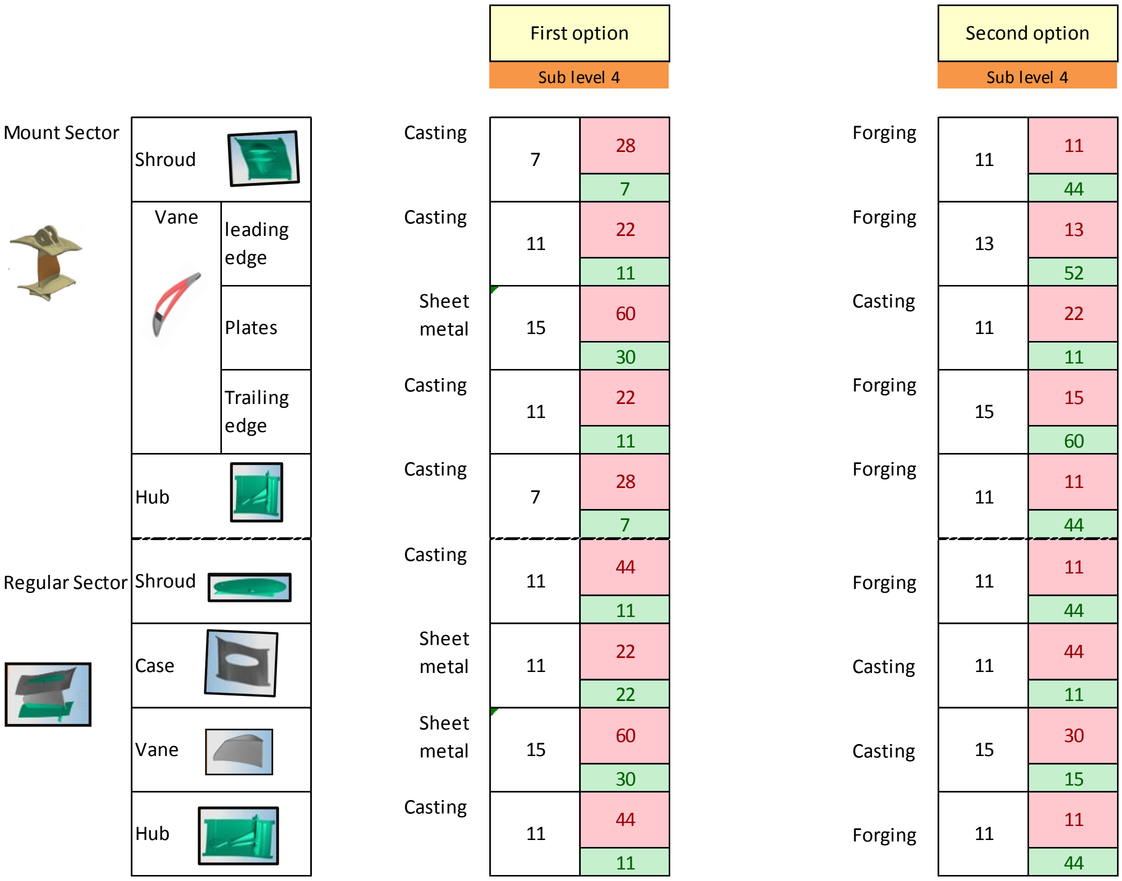


Figure 63 Second Application- Example 1 parts

In the next section both applications are carried out and conclusions are founded. The highest punctuation for cost and producibility will mean that that option is the cheaper and more producible.

8.5 Case implementation: DFM tool

The last HoQ created, so called DFM tool, evaluates the subsystems of the components against the flow of manufacturing operations and their critical production requirements. The current ULSAB model at VAC has been the base of this matrix, and it has served as a guide to complete it.

Once again the subsystems of the TEC component, classified as sub-levels of assemblies, occupy the rows within the matrix while the manufacturing operations are the columns. This tool is composed of two parts, the upper one contains the cycle time of each operation, since time can be directly transferred to cost. The ULSAB model was used to create this part, as well as the information gathered during the workshop tour following the flow of operations step by step.

In the bottom of the matrix the measurables or requirements that affect producibility, from each specific operation, are identified and quantified.

Any specific data cannot be puslished within this table due to Intellectual Property Rights for GKN

TEC

OPERATIONS IN HOUSE

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

Operation name		Casting		Sheet Metal		Machining **200**	Deburring **300**	Cleaning **400**	FPI **500**	Cleaning **600**	Final Inspection **700**
Set-up time	h										
Time per piece **Shroud** Mount	h										
Time per piece **Vane** Mount	h										
Time per piece **Hub** Mount	h										
Total time	h										
Time per piece **Shroud** Reg	h										
Time per piece **Case** Reg	h										
Time per piece **Vane** Reg	h										
Time per piece **Hub** Reg	h										
Total time	h										
Measurable (effect producibility)		Size (cm3)	Net shape (%)	Size (mm3)	Net shape	lenght of edges (mm)	lenght of edges (mm)	Pieces at the same time	Pieces at the same time	Pieces at the same time	Pieces at the same time
Shroud Mount											
Vane Mount											
Hub Mount											
Shroud Reg											
Case Reg											
Vane Reg											
Hub Reg											

* Maximun capacity

Figure 64 DFM tool – Example 1 -sublevel 4

OPERATIONS IN HOUSE

SUB-LEVEL 3

SUB-LEVEL 2 (Weld Assy)

		Operation name		Tack weld **200**	Welding **400**	GOM **450**	Cleaning **500**	FPI **600**	preparations (Machining) **700**	Deburring of mill welds prep **800**	Cleaning **900**	Final Inspection **1000**
Mount Sector 	3	Set-up time	h									
		Time per sector Mount sector	h									
		Time per sector Regular sector	h									
		Total time	h									
Regular Sector 	10	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	Sectors at the same time	Sectors at the same time
		Mount Sector (total)										
		Regular sector (total)										

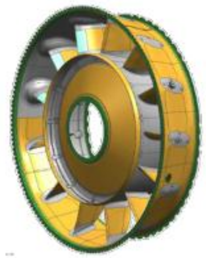


Figure 65 DFM tool - H sector – sublevel 3

9 CONCLUSIONS

Detailed conclusions from the different tools created to support the DFM methodology can be found within this section. At the end a brief summary, of the main conclusions, is presented.

9.1 CONCLUSIONS from DSM

The DSM potential is not totally developed within this project. This new tool for Volvo Aero can be used for many applications. There is still a lot of work to do in order to find out the *toolpower* of this matrix. However, some conclusions and uses of it will be presented here.

An interesting relationship between the architecture of the product development process and the structure of project organization exits, fact previously discussed. Using DSMs shows how the interactions between organizational entities such a project teams, can be anticipated based on the structure of predefined development activities.

Therefore, the first DSM application is based on the ordination of the six groups of parameters, “Project features”, “Customer Requirements”, “Purchasing Requirements”, “Design” “Operations” and “Features belonging to Operations”. These groups have been organized in order to follow the project development process. The same order has been attempted with the parameters within the groups. After manipulating the DSM rows, with the purpose of reducing the up-diagonal marks as much as possible, the order of the groups has not been changed almost. That means the original project steps sequencing is good enough, and customer requirements, internal requirements (represented by the “Project features”) and purchasing requirements are the first phases, followed by design, and finally production. The operations sequence did not change either, so that the conclusion is similar, the current routing made is good in order to have few loopbacks as possible. Consequently, DSM approach could be used with the purpose to compare different routing alternatives and to detect which generate more loopbacks, by counting the red marks off-diagonals.

If analysis is made in further detail, by considering the second type of matrix Parameter-Based DSM, some questions such as “Do these parameters interact? How?” or “Which teams should exchange information with?” or “What information do you need to begin your activity?” and “Where does it come from?” can be formulated to get more conclusions.

First of all, the empty rows, located up in the matrix, represent those parameters that not receive any information. That means these parameters interact but only in one direction, they are basically the top level requirements, the customer voice, which will push the project. They are an important source of information. In contrast, the empty columns, placed on the right side, such as cycle time and lead time, represents those parameters that only received information, which makes sense, since they are project results.

Secondly, looking to specific red marks or groups of marks up-diagonal, within the manipulated DSM, and thinking to answer the previous questions, some specific conclusions can be obtained. See Figure 66.

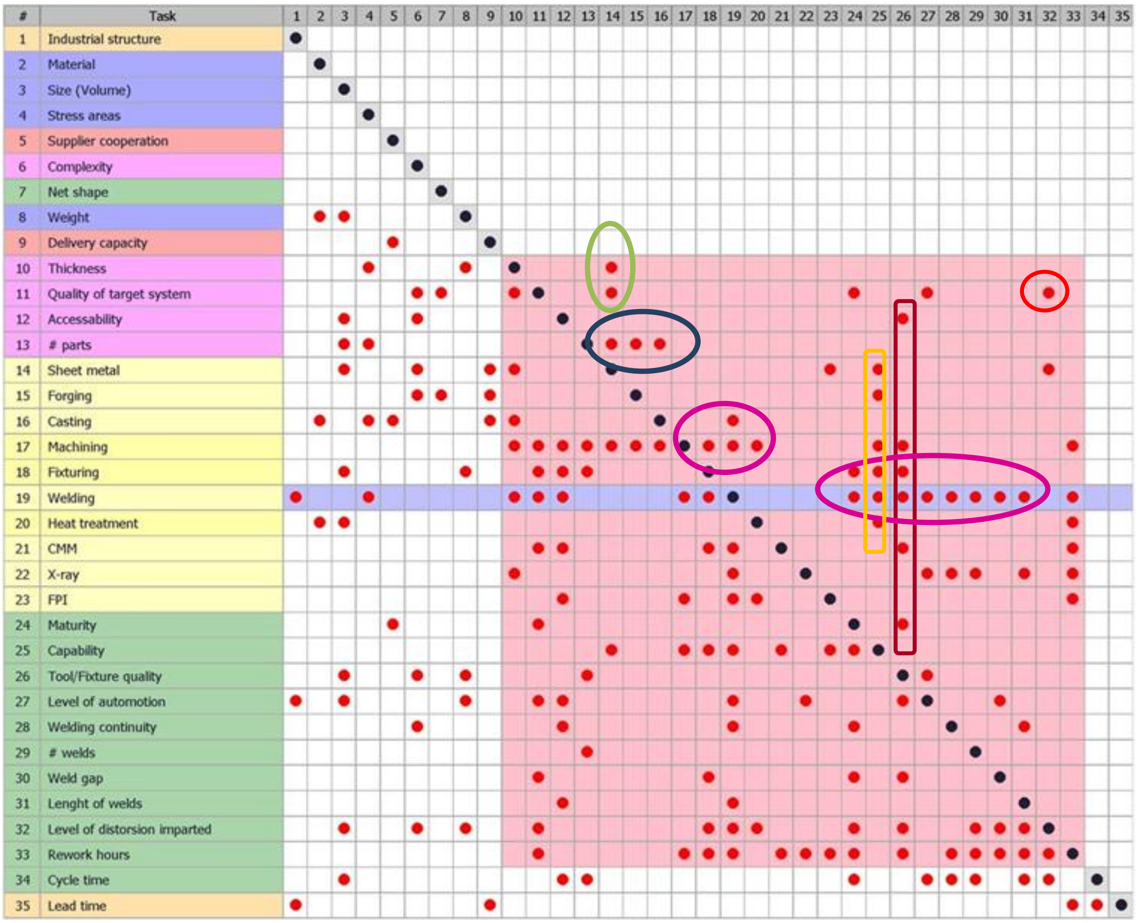


Figure 66 DSM red mark interpretation and conclusions

For a better understanding the red marks will be name as (i,j), by i representing the row and j the column.

The red marks (10,14), (11,14) represent the need to increase the sheet metal forming method specialist involvement during the design phase.

The group (13,14), (13,15), (13,16) are influences from purchased operations to the specific design parameter *number of parts*. This implies a need of purchasing area involvement while deciding the parts in which the component will be cut up. For the design activity to start, there is a need of purchasing information.

The group (i,26) represent the importance of the tooling. On the one hand the tool itself brings cost to the product. On the other hand it is also importance because will influence in the welding results and consequently rework. Tooling should be considered from early design work and through every manufacturing operation point of view.

In order to get a good quality of target system during the whole production process parameters such as level of distortion imparted (for instance by welding or heat treatment) should be considered from the beginning. That means the results of operations such as welding, heat treatment give information to the designer to create a good target system. Red mark (11,32).

The *pink group* (17,18); (17,19); (17,20); (16,18) and (19,j), (18,j) represent loopbacks within production, mainly caused by the 17 and 18 parameters, which are fixturing and welding. This result supports a conclusion previously made within this project, the welding process and the geometry variation are the most suitable parameters to create problems and loopbacks. Therefore, further researches need to be focus on welding manufacturing method and Geometry Assurance.

Finally, the red marks ([14-20]; 25) represents the lack of information flow from production capabilities to design.

It is interesting also to have a look in cycle time´s row and rework´s row in order to detect which are the parameters that increase the cycle time on an operation or those ones that produce rework.

Design Structure Matrix could be used as a procedure for product design knowledge management. Knowing system elements interaction in the product design process is critical for project management and decisions. DSM is a good tool mapping information flow in the product development processes; and it can visually represent the network of interactions among the development activities or design objects and facilities analysis of these interactions. Each of the DSM marks stands for a specific problem or question, and all the marks in the DSM together can support tracing the existing design routes and design history.

9.2 CONCLUSIONS from DFM TOOLS

The third VAC HoQ and its two applications bring some conclusions. These ones are not accurate results, since the matrix is not made based on technical deep detail. But it is enough to show the purpose. It is possible to create a tool to help within the creation and comparison of concepts. Moreover, it is possible to break down requirements and evaluate them against design from an early beginning.

From the First Application, the conclusions are obtained by looking at the whole component numbers of cost and producibility; so that a fair comparison of both alternative concepts is made.

Looking at the results for Example 1 concept the cost number is 41,15 and producibility number **17,92**. On the other hand, for Example 2 concept, cost is 31,78 and producibility **28,81**, see sublevel 2 of Figures 61 & 62.

Therefore, Example 1 alternative is better regarding cost than the Example 2 alternative, since the cost number is higher, but it is worse regarding producibility. Even though, the difference between producibility numbers is not so big, neither for cost. Consequently a further detail study should be performed here. However, this DFM tool is a quick method to reject an alternative with bad numbers for both, cost and producibility, while applying the Set-Based approach.

From the Second Application, a rough comparison between the purchased operations selected to produce the single parts of the TEC component can be achieved.

Based on the numbers, all the parts made by casting have higher cost number but lower producibility number. That means casted parts are better from cost point of view but worse regarding producibility. Depending on the part, the difference between both cost numbers of both producibility numbers varies, and this should be taken into study. For instance, the trailing edge could be reconsidered to be produced by forging instead of casting, since the number cost for both operations is more similar than for other part. As well as forging is more producible in this specific case.

The sheet metal formed parts of Example 1 alternative, which are the plates of the mount sector and the case and vanes of the regular sector are compared with the casting option. The result clearly points out that the best option is sheet metal forming since cost and producibility numbers are always higher, almost the double. Except for the regular sector case, that it is not so clear that sheet metal forming is better option than casting. The reason is resides in the thickness parameter, due to the variation of this requirement within the case, it could be possible that casted case is better than sheet metal formed case.

All the conclusions exposed before are logical and probably already achieved. However, the main purpose is to show that is possible to create a structure way to, on the one hand build up knowledge, on the other hand to implement production requirements and to break them down, so decisions can be based on facts and possible risks can be easily detected.

9.3 GENERAL CONCLUSIONS

The second part of this project has some implicit conclusions, summarized in the following list:

- Increases the **awareness regarding producibility** problems
- Shows the need of a **systematic approach** during concept phase
- Importance of **production requirement break down**
- It is possible a **DFM tool**
    - To integrate production requirements in the early beginning.
    - To support the concept alternatives creation and evaluation.

10 FUTURE WORK

Due to project limitations, mainly time, it has not been possible to develop every aspect, but at least it has been tried to address and to cover all of them. Here are presented some suggestions for future work.

Regarding the first part of the project, a strategy to implement a systematic approach for DFM should be carried out. Also, a knowledge management system should be created in order to improve the information flow inside the company.

Regarding the second part, future work basically refers to the continuation of developing the tools before presented. Firstly, trade-off curves. Trade-off curves development is a huge task. Some critical parameters from the already created DSM matrix have been detected in order to perform these curves. Since fixturing and welding methods are the most risky operations, requirements related with those are suitable to create these curves and study the relationships. The proposal trade-off curves are:

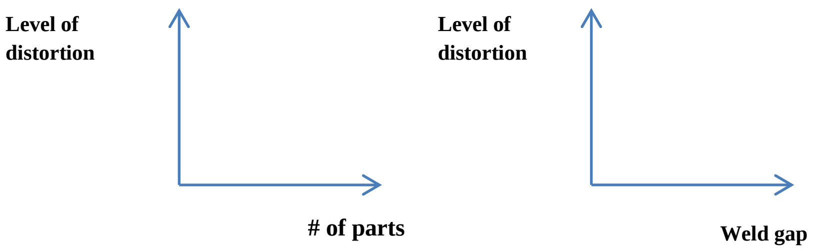


Figure 67 Proposal trade-off curves for future work

The DSM has a lot of applications, which were mentioned before. The toolpower of this matrix can be still developed. There are a lot of uses and conclusions left from this approach.

For the 3rd HoQ, this matrix could be further developed and extended, encompassing also the manufacturing operations done inside VAC to build the whole component. So the whole cost value of the product is covered, and not only the purchasing cost.

Finally, for the DFM tool, the same type of matrix could be done for the Example 2 concept; trying to compare both concepts with the flow of operations afterwards.

In general it will be necessary to refine and improve the matrixes, presented in this project, by using the expert help of experienced designers and also using tests, so the matrix is not filled in again with opinions. Instead it is filled with facts.

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12 Appendix Part I

12.1 Appendix A- Product Range

Volvo Aero is a company that designs and manufactures components for jet engines. The area of business is manly to civil aircraft engines from companies such as 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, jet engines usually 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.

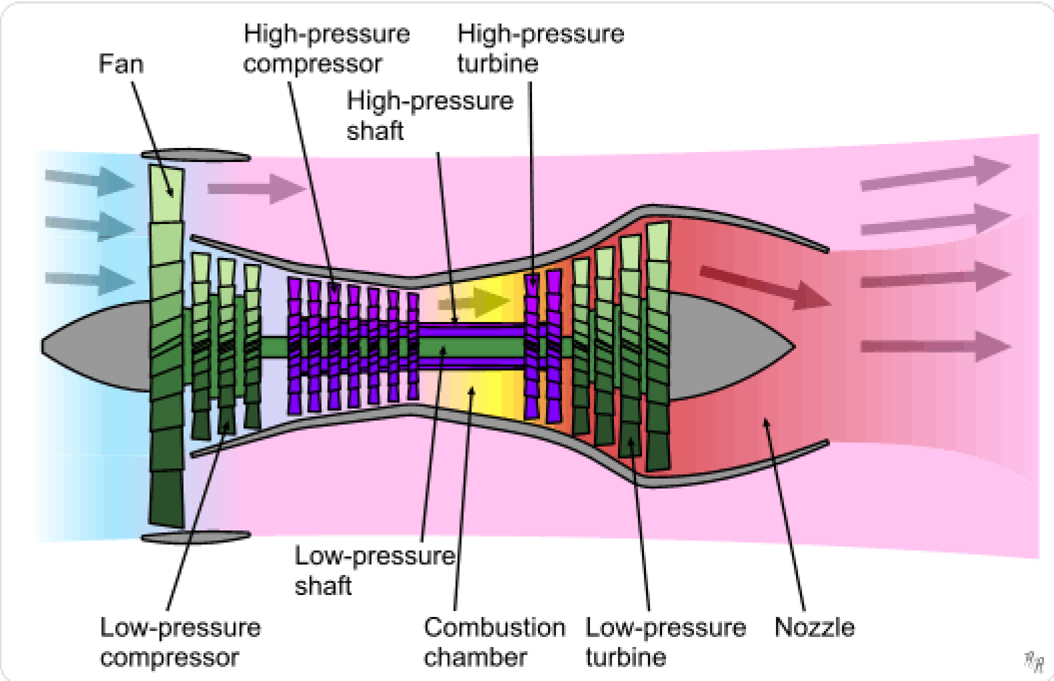


Figure 68 Jet engine performance

At VAC the engine's components is divided in the so called cold structures and hot structures. The cold structures are the ones located before the combustion chamber, and the hot structures the ones after it. In the following picture (Figure 69) is shown the Volvo Aero's component specialization.

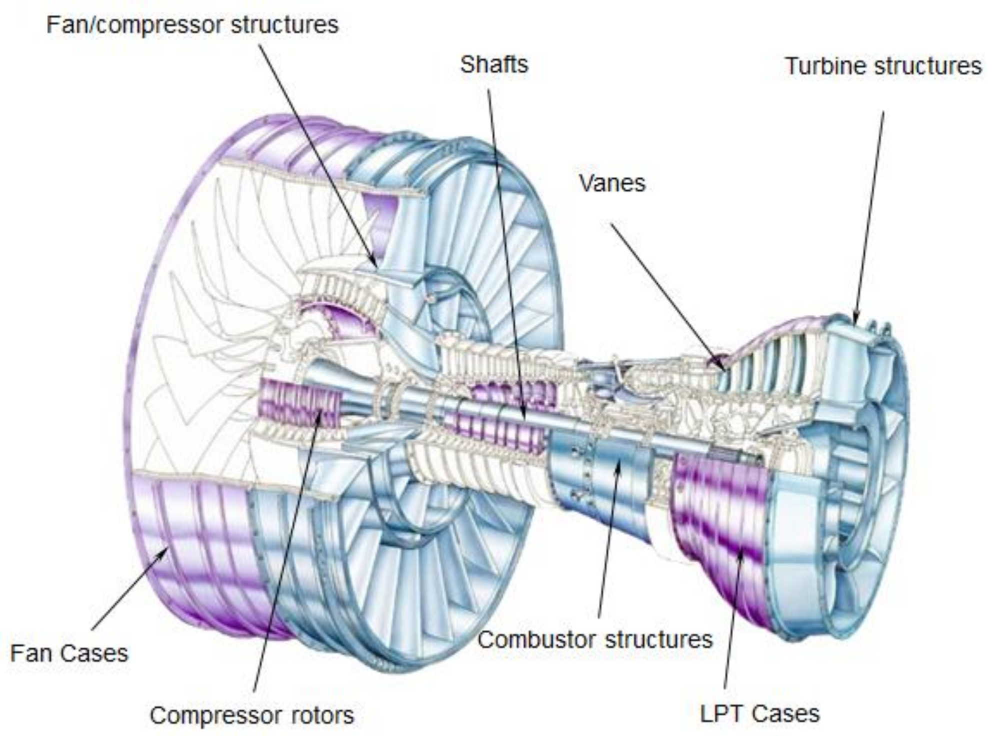


Figure 69 Volvo Aero's component specialization

Only the TEC component, which belongs to Turbine Structures, is described in detail since this is the component used for the whole thesis work.

Turbine Exhaust Case TEC

The Turbine Exhaust Case is considered as a hot structure component since it is located after the combustion chamber. In fact it is the cover of the turbine, hence the last component of the jet engine. As its name suggests this component basically has the functionality to cover the Turbine, protecting the rest of the plane from possible Flame Blade Out; and to provide a path for the exhaust fumes that the engine release in order to create the trust. Other functionality of this component is to provide a system so that the engine can be installed in the aircraft. The mounts of the TEC serve to this purpose, see Figure 70.

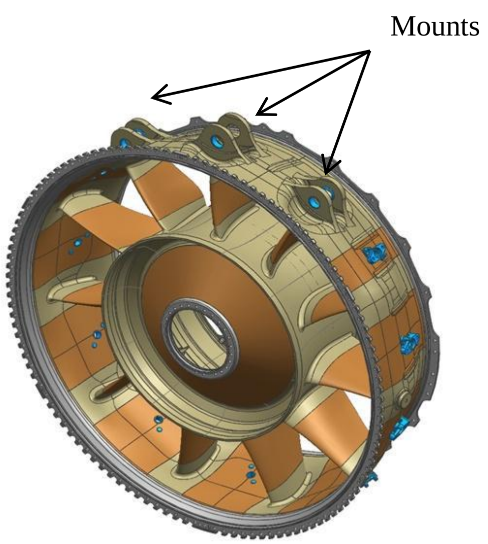
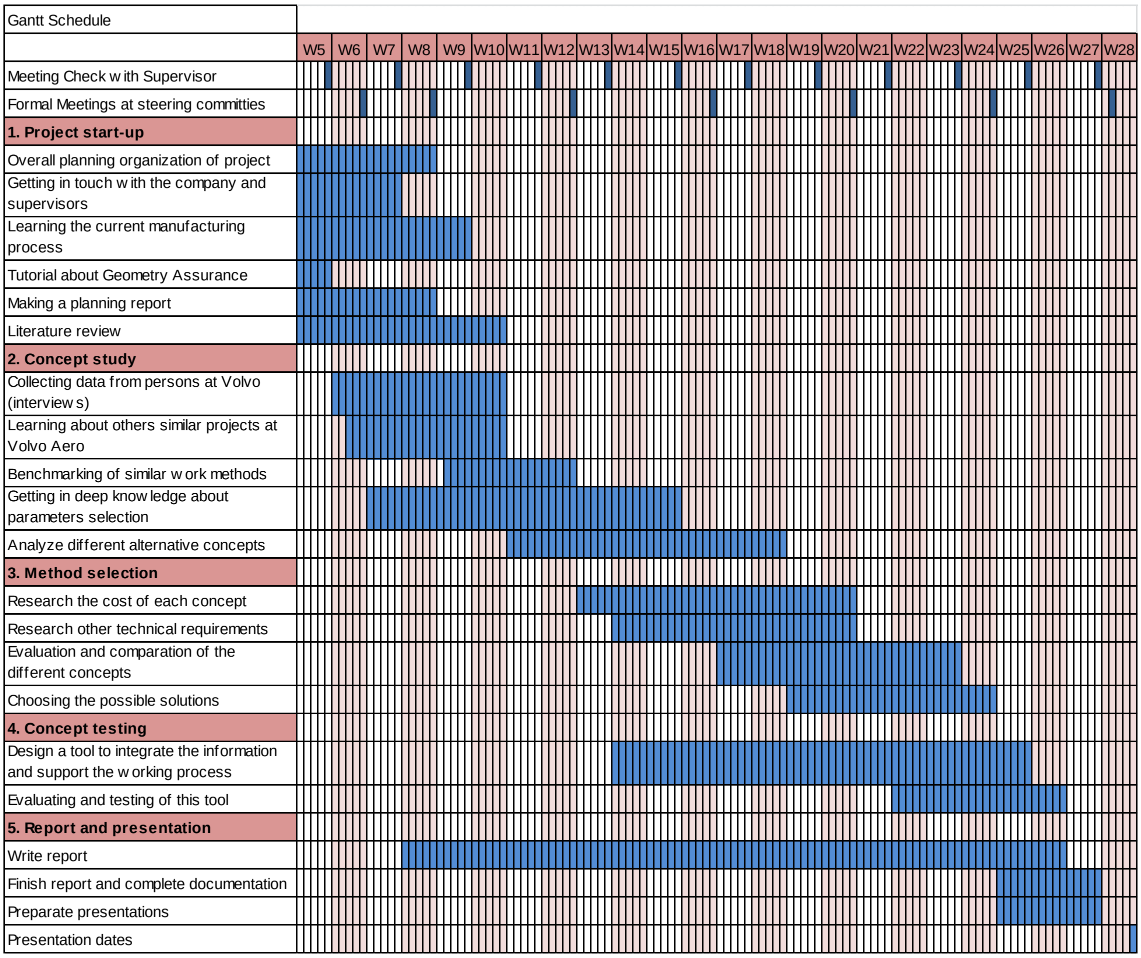


Figure 70 TEC Turbine Exhaust Case

12.2 Appendix B- Gantt Chart



12.3 Appendix C - 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.

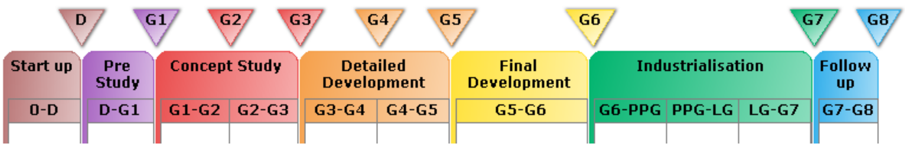
Introduction

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 Engineering" 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

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?

12.4 Appendix D - 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 product development time line and its phases? Within this time line, how long does the whole product development take? And the Concept Study or Concept work?

3. In which of those phases 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)

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" 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 (Company name)?

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?

12.5 Appendix E- Unstructured and Half structured Interviews

Information can be founded in following pages.

The names of the intervieews are company confidential and cannot be published in this report due to Intellectual Property Rights for GKN.

	INTERVIEWEE	JOB POSITION / AREA	MAIN IDEAS
8 Feb	*********** ***********	Manufacturing engineers	➢ Product families ➢ Production platform
	***********	Geometry Assurance	➢ Better geometry assurance→ better welding results ➢ Geometry assurance influence the design ➢ Possibility of manual adjustments within aerospace industry
	***********	Product and Process Definition	➢ Company structure ➢ DFM concept; needed to improve it
13 Feb	***********	Manufacturing engineer (technology development)	➢ Problems to reach the target cost ➢ Need of Systematic concept selection process
	***********	VAC tool	➢ DFM tool
27 Feb	***********	Risk Analysis	➢ FMEA ➢ TRL
5 March	*********** ***********	Processes verification engineers	➢ Communication between designers and method specialist ➢ Problems with the production platforms ➢ The supplier is not chosen at the early stage ➢ Problems with TRL condition
6 March	***********	Technology management (technology development)	➢ Time line → Where locate the project? ➢ Comparative assumption are more important than individual assumptions ➢ The right selection is critical → invest a lot of intelligence at the beginning
	***********	Design team leader (cold structures)	➢ Production platform-predict the customer demand for 25 years ➢ Difficult to make a robustness design since the problems come out with the concept details.
13 March	***********	Project manager for knowledge base engineering (Consultant)	➢ Taking information from the method specialist to create check list→ DFM tool
	***********	Product and Process Definition	➢ VAC tools ➢ Identify an area within the production.

DATE	INTERVIEWEE	JOB POSITION / AREA	MAIN IDEAS
13 March	***********	Implementation checklist in CAD software	➢ Checklist→ casting & welding ➢ Checklist→ communication from method specialist to designer (knowledge management) ➢ Weak communication from designer to method specialist ➢ Check list→ focus on inexperience design engineer in the early design ➢ Suggestions
15 March	***********	Old employee at VAC Current employee at Volvo Trucks GTO	➢ Suggestions for benchmarking method/ideas ➢ Weakness → designer do not about geometry variation ➢ Designer driver position ➢ Set based
	***********	Risk assessment	➢ P-FMEA
20 March	***********	Product design leader	➢ Common design space→ needed to reduce the gap
	***********/ ***********	Manufacturing engineers	➢ Production platform for hot structures
22 March	***********	Cost engineer for TEC	➢ Cost assessment at the early concept stage but manually →Cost as a result not as a steering parameter. ➢ Important to do the same assumption in every concept in order to get the same maturity level→ fair comparison.
29 March	***********	ULSAB	➢ Cost assessment at the early concept stage but manually →Cost as a result not as a steering parameter. ➢ Important to do the same assumption in every concept in order to get the same maturity level→ fair comparison.
	***********	Business And Sales	➢ Cost estimations based on old projects.
11 April	***********	Geometry Assurance	➢ Robustness→insensitive to variation ➢ Reuse target systems and fixturing tools ➢ KPI

DATE	INTERVIEWEE	JOB POSITION / AREA	MAIN IDEAS
19 April	***********	Designer (Definition leader)	➢ Cross-functional team: Stress, Aero, Thermal, Definition, Production ➢ Limit of creativity due to design platform ➢ Need of purchasing platform ➢ Late changes in requirements ➢ Concept work frequent steps ➢ Communication with Technology Development ➢ More resources in concept creation ➢ Robustness→Non-conformances ➢ Requirements number→know the capability of machines
	***********	Designer (CVE)	➢ Systematic approach for design ➢ Knowledge systems not available ➢ Producibility related to cost
26 April	***********	Systems engineer	➢ Set-based concurrent engineering ➢ Fact based, quantify design limits, trade-off curves ➢ Integration events using key requirements to eliminate worst concept ➢ Documentation of everything to build knowledge
3 May	***********	Quality auditor	➢ Functional requirements ➢ System description (FEMCA)→special requirements ➢ Detailed solution (D-FMEA)→key characteristics ➢ Preliminary process flow (P-FMEA)→ control plan

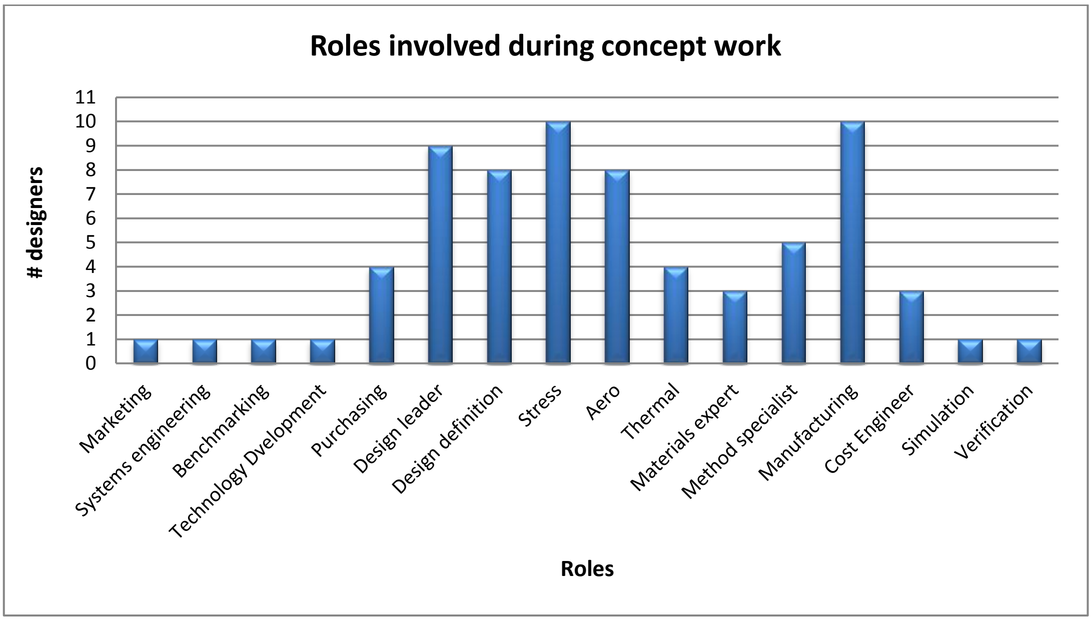
12.6 Appendix F - Designers Questionnaire Answers

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

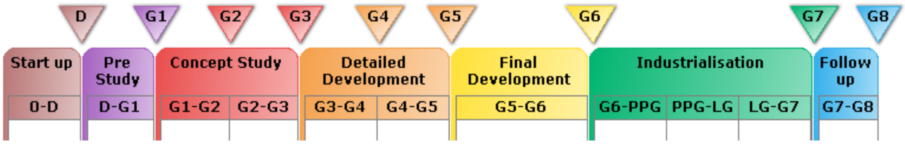
The Master Thesis project is regarding DFM philosophy. The purpose is to develop a DFM tool to support the designer work at the early stage of the concept development, creating a systematic approach to help in the evaluation of the different concept alternatives from a producible and cost point of view.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



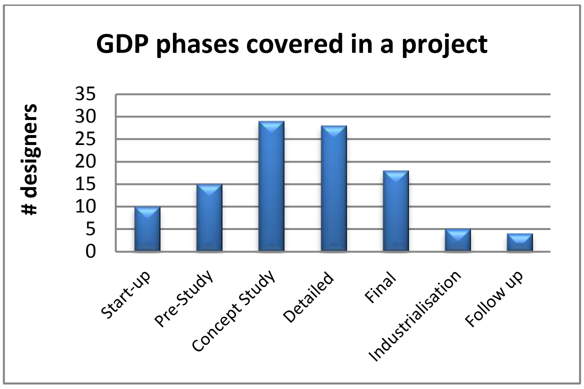
Comments: It is not a matter of which roles are involved; it more depends on the skills and experience.

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?**

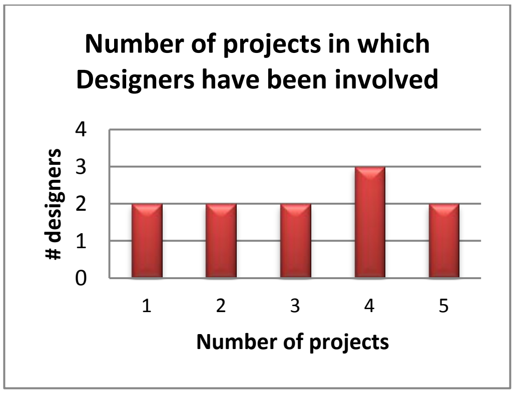


The following graphic shows how employee resources are located through the different project phases.

Note: there could be a limitation regarding this answer, since the GDP phases are not clearly limited, so it could be possible to mix phases. But still is possible to get the overall idea.

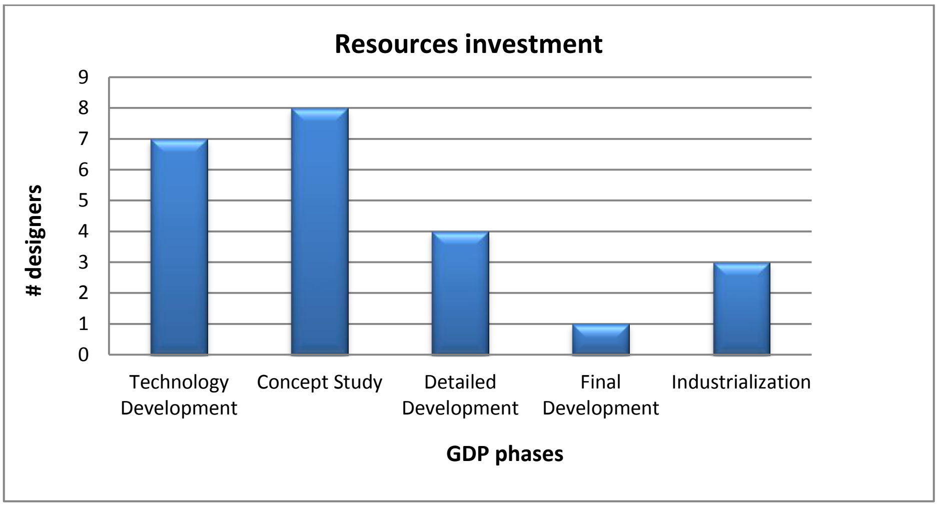


It is interesting to see in how many projects a person has been involved. The graphic below shows the number of employees that have been involved in a specific number or projects.



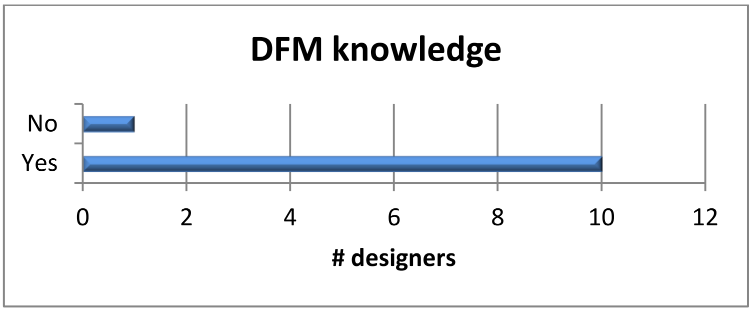
For instance, only 2 designers have been involved in 5 different projects

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).**



DFM

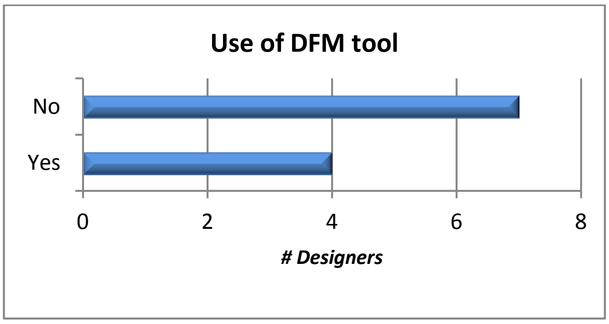
4. **Do you know what Design For Manufacturing (DFM) is?**



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

DFM Advantages and Definitions	Repeated Answers
Achieve producibility	10
Ensure the right requirement balance (producibility, cost & tech. req.)	2
Avoid poor cost predictions	1
Minimize re-work and firefights during late phases	2
Reduce Cost	4
Managing and verification of concept producibility at the early development work	2
Decisions and manufacturability aspects based on knowledge/data but not on feelings and opinions	2
Reduce lead time	1
DMF definition is rather wide to describe it	1

5. **Have you ever used any DFM tool or method to support your work?**

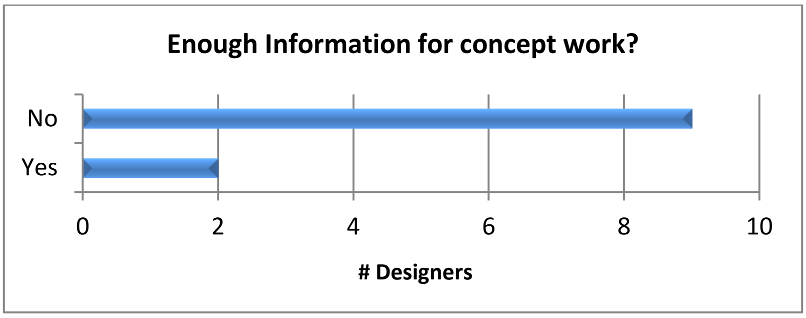


If Yes, please specify which Tools/methods:

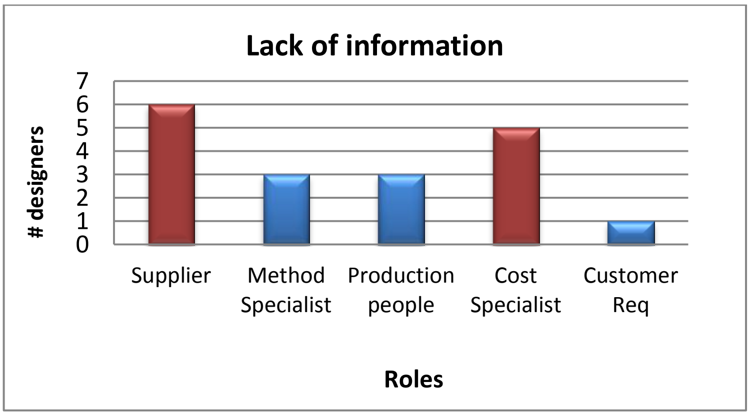
DFM tool / method	Number of Answers
Platform	1
Common sense and lessons learned	1
Cross functional teams (including manufacturing expert)	3
Pugh Matrix	1

Comment from Designer: There is missing data, unawareness of DFM methods

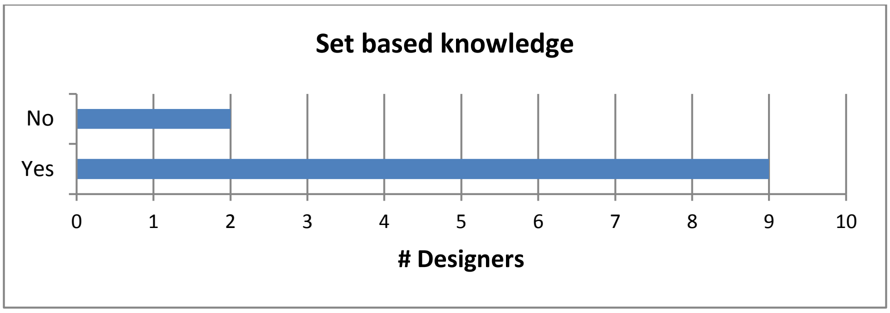
6. **Do you get sufficient amount of information (from supplier/method specialist/ production people) for the concept generating task?**



If No, which information is missing from?

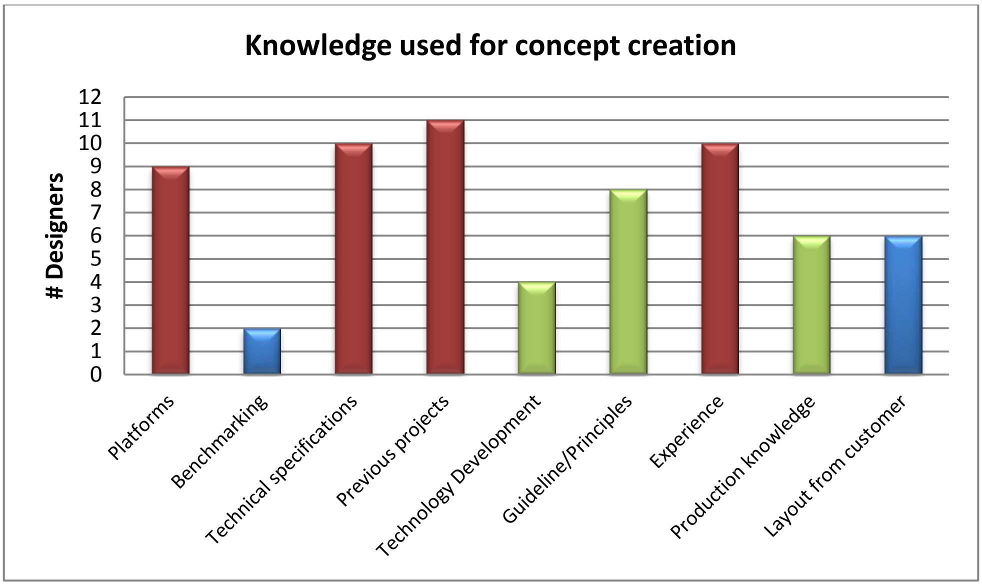


7. **Do you know what "Set Based Engineering" is?**

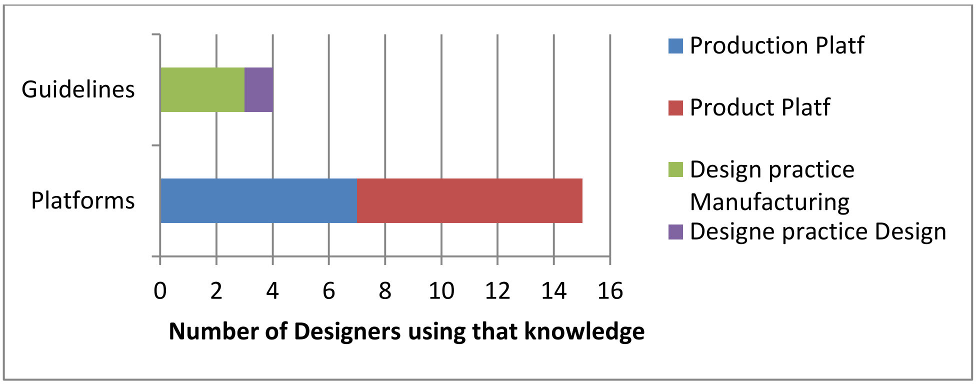


CREATION OF CONCEPTS

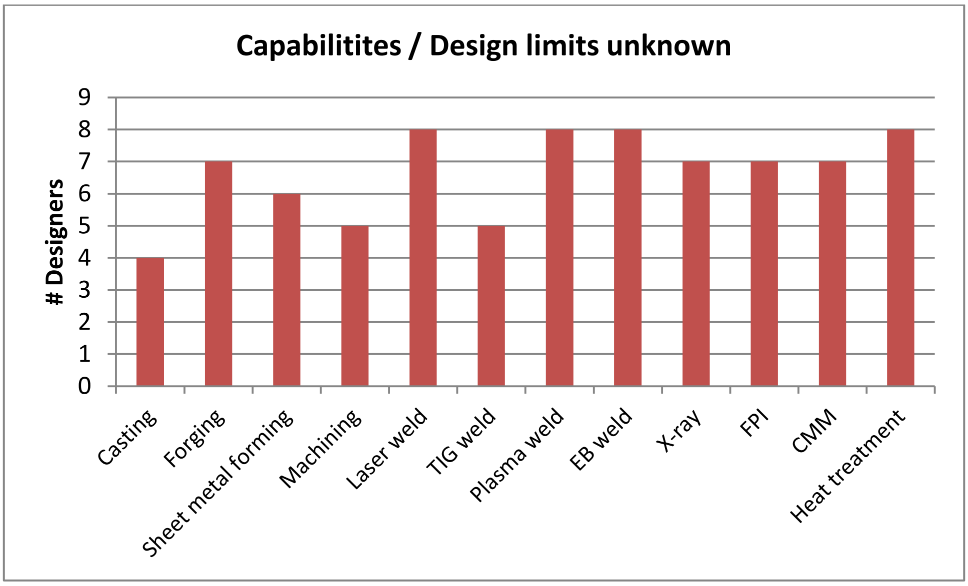
8. **Which knowledge do you use when creating concepts along the concept study phase?**



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



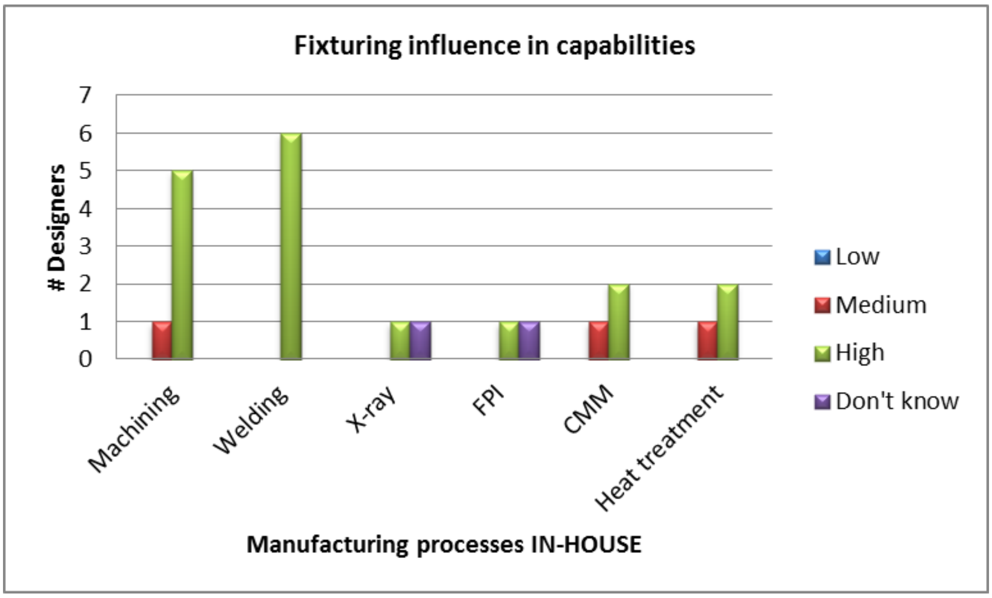
9. Select the processes from which you know the capabilities or design limits.



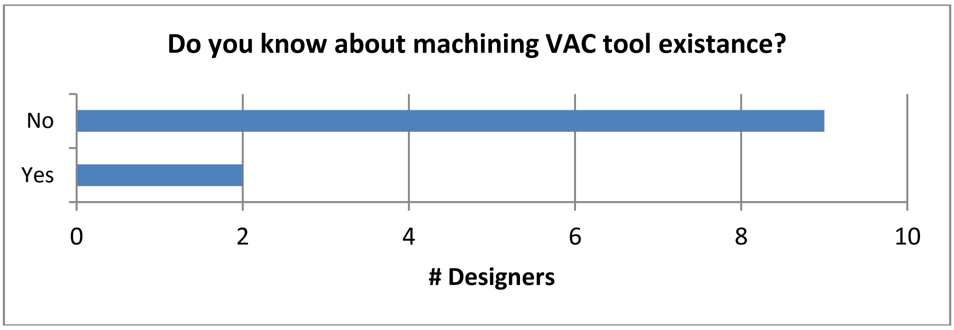
Could you suggest where there is a lack of knowledge or need to improve the knowledge from the processes above (or additional ones)?

- 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 isn´t being developed.
- It´s missing the transfer of knowledge from research and technology development into the production environment.
- 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
- LBW, PAW, EBW, 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.

10. **<u>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)*</u>**



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



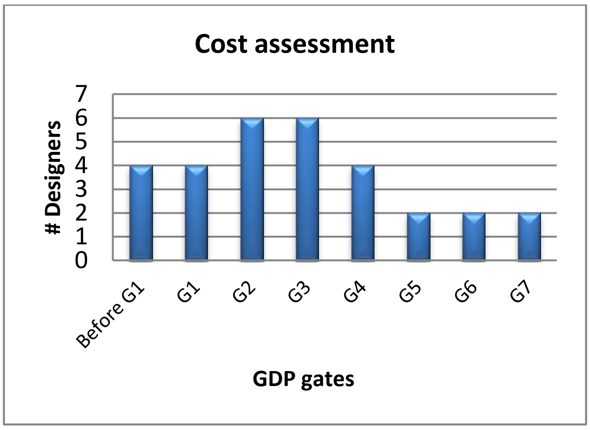
In addition, the only two person who know about this tool don't make use of it

12. **<u>Other existing DFM tools are the checklist for welding and casting implemented in the NX software. Do you make use of them?</u>**

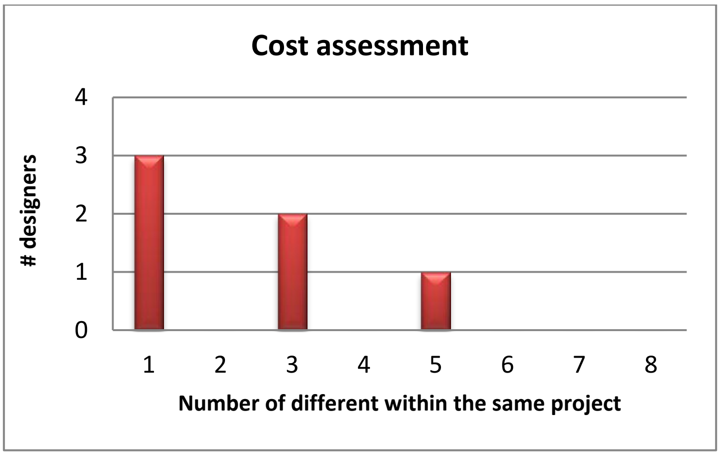
Nobody make use of these checklist implemented within the NX CAD program

CONCEPT/COST EVALUATION AND SELECTION

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



The following Graphic represents : Number of different gates in which a Designer has been involdeved within the same project regarding cost assesment



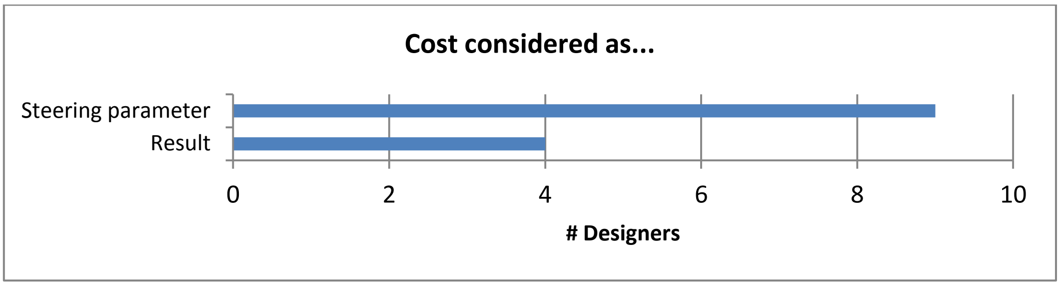
This shows that usually Designers are involved only within 1 or 3 phases.

Which disciplines are involved?

- Manufacturing leaders
- Process specialists, purchased engineers
- Cost engineers
- Project team
- Project manager, Design, Production, Purchasing
- Design leader, Production leader, Purchasing leader

Comments:
-There is a need of considering the sensitivity within the assessment to not end up in worng estimations

14. <u>Do you consider the cost as a result or as a steering parameter</u>?



15. <u>In your opinion, which are the main cost drivers?</u>

- 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
- Small number of suppliers
- Lange changes from customer (late change in technical requirements)
- Late process capabilities assessments
- NDT
- Volume of production
- Producibility

13 Appendix – Part II

13.1 Appendix G - Cost Drivers Definition

Apart from the parameters definitions, some comments will be added in order to assist a better understanding of the DSM dependencies (red marks). Further explanation regarding every parameter can be found in the next Appendix. By using both Appendixes, the DSM creation is defined.

This Appendix cannot be published in this report due to Intellectual Property Rights for GKN.

13.2 Appendix H - Dependencies criteria

The purpose of this Appendix is to clarify some of the dependencies. Here some of the criteria that a parameter has to fulfill in order to influence other are explained. The goal again is to help understanding the DSM creation. Not all the dependencies are covered, just the most complicate.

This Appendix cannot be published in this report due to Intellectual Property Rights for GKN.