Master Thesis

Economical Assessment of Innovative Product Architecture for High Pressure Fuel Storage Systems

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Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources and resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

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Abstract

The purpose of this thesis is to examine the effects of innovative product architecture in regard to High Pressure Fuel Storage Systems (HPFSS) for automotive applications. It is conducted in collaboration with Magna Steyr Fahrzeugtechnik who discovered the possibility of this innovative approach for HPFSS components. However, the effects of this innovation on costs are not known and it needs to be identified whether it is economically feasible to further pursue this idea or not.

In this thesis the assessment of changes in costs due the innovation is conducted solely with quantitative methods. The main source of information is preliminary cost data from past projects which serve as a basis for an ABC-Cost Analysis in order to identify the cost drivers of HPFSS and their impact on total costs. In the next step, the past projects are redesigned using the modular component selection; then, the costs of the re-built systems are determined and compared with those of the original projects.

The research reveals that the main cost drivers of 200 bar Compressed Natural Gas (CNG) HPFSS are material and assembly cost. Therefore, these two cost types are assessed in-depth and result in up to 18% savings on material cost and up to 22% savings on assembly cost. Thus, it is discovered that significant savings in terms of recurring cost can be achieved if this innovative product architecture is used even though the comparison analysis is conducted very conservatively and without optimizing the components.

The author recommends that the innovative design of components for HPFSS should be pursued by Magna Steyr Fahrzeugtechnik. It is recommended to optimize the components in terms of design followed by a more detailed cost analysis to reveal the full potential of this innovative product architecture. Furthermore, research should be conducted if it is viable to use these components for other HPFSS configurations so that they may benefit from each other due to the synergy effect.

Acknowledgement

Studying, what an exciting thing to do. In the beginning everything was new and unknown and I had to stand on my own feet for the first time in my life. My time as a student was full of both sacrifice and joy at the same time. But it was worth it, because now I am about to finish my studies and I regret nothing. From my perspective, this thesis is a dignified way of saying goodbye to my life as a student and welcoming my life as a working professional.

At this point I would like to say thank you to everyone who supported and helped me in this process of becoming what I am today. First of all I would like to thank my parents (Theobald & Walburga Steiner) and my sister (Verena Steiner), who where always there when I needed them; who were happy and proud of me in good times; who were comforting and motivating me in bad times. Also, I am very grateful to have such a great girlfriend and good friends who supported me wherever they could. I would like to thank in my friend from Canada Mr.B.Eng & Mgmt. Rudy Langballe for proofreading my thesis in particular.

Furthermore, I would like to thank everybody at Magna Steyr who helped me throughout this thesis but especially I want to thank my supervisor Mr.Ing. Franz Mayr for his support and helping hand. Two more people I would like to thank are Ms.Dipl.-Ing. Verena Manninger and Mr.Dipl.-Ing. Hans Peter Schnöll who were the supervisors from the Technical University Graz and safely guided me towards successfully completing my thesis.

Thank you all!

Table of Contents

1 Introduction

This chapter introduces the company in which the thesis was composed and defines the outline and the context of the thesis.

1.1 Magna

Magna International Inc. was founded in 1957 by Frank Stronach and is currently one of the leading global automotive suppliers. Magna´s business activity comprises not only the development and production of parts, components, assemblies and modules for the automotive industry but also their integration into the vehicle. Moreover, Magna has the capability of developing and manufacturing complete customer specific automobiles. Furthermore, Magna employs 104,000 people globally in 338 locations in 26 countries on 5 continents including 84 development- and 269 manufacturing facilities.[1]

Magna features a decentralized corporate structure and consists of seven subsidiary companies:[2]

- Magna Seating
- Magna Exteriors & Interiors
- Magna Mirrors & Closures
- Magna Cosma (bodywork & chassis)
- Magna Steyr (complete automobile development & -manufacturing, fuel storage systems & roof systems)
- Magna Powertrain (propulsion system & transmission system)
- Magna E-Cars Systems – Joint Venture for hybrid- & electric vehicles and components

Magna with its corporate companies possesses the capability of developing and manufacturing all components that are needed to assemble a vehicle (exceptions: tires, glass and combustion engine).[3]

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[1] cf. MAGNA STEYR (2011a), pp. 2-3

[2] ibidem

[3] ibidem

Magna Steyr

Magna Steyr (MS) is a subsidiary company of Magna International Inc. For over 100 years, MS has manufactured components and systems for its customers. The founder of the company was Johann Puch and he started developing and manufacturing automobiles in Graz (Austria) in the early stages of the 20th century. In 1998 “Steyr-Daimler-Puch Fahrzeugtechnik” was taken over by Magna International. The name “Steyr-Daimler-Puch Fahrzeugtechnik” was changed after the foundation of “MS in 2001 to its current name; that is, “Magna Steyr Fahrzeugtechnik” (MSF).[4]

In the past 13 years MS has manufactured more than 2,5 million vehicles including 21 different models for ten Original Equipment Manufacturers (OEM). MS has established a global network consisting of 37 facilities on three continents and employs 10,200 people. With this worldwide presence MS maintains close contact to his customers and stays on the forefront of new technologies and innovations which are reflected in the Vision and Main Goals of MS.[5]

Magna Steyr Vision:[6]

The vision of MS is to be the leading global independent engineering and manufacturing partner as well as supplier for innovative solutions for the mobility in the future.

The Main Goal of Magna Steyr:[7]

The main goal of MS is to satisfy their customers with high quality products and services, in order to sustain profitability and therefore securing the jobs of our employees.

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[4] cf. MAGNA STEYR (2011a), pp. 5, 23

[5] ibidem

[6] cf. MAGNA STEYR (2011a), pp. 2-3

[7] ibidem

Business Activities Magna Steyr

The business activities of MS encompass not only the broad field of the automotive industry but also a small part of the aerospace industry (see Figure 1.1). The context of the thesis is domiciled in the Fuel Storage Systems group of MS. More precisely, it is located in the Alternative Fuel Storage Systems department.[8]

Engineering	Contract Vehicle Manufacturing	Fuel Storage Systems	Roof Systems
• Design and Vehicle Concepts • Complete Vehicle Development and Integration • Development of Modules and Assemblies • Body Interior / Exterior • Chassis and Drive Chain • Electric and Electronic System • Prototypes and small batch Manufacturing • Aerospace and Non-Automotive	• Flexible Manufacturing (2k-100k vehicles/year) • Up to five different Vehicles on one Assembly Line • High Volume Vehicle Manufacturing • Flex Plant • Customized Vehicles • Painted Body • Door Modules • Industrial Services • Composite Technologies	• Fuel Storage Tanks (plastic, steel, aluminum) • Filling Line Assemblies • Capless Systems • Gas Caps • Fuel Valves • Components for Oil and Water Cooling Systems • Alternative Fuel Storage Systems • Vessels for Compressed Gases • Plastic Vessels	• Softtops • Retractable Folding Roofs • Modular Roofs • Retractable Hardtops

Figure 1.1: Magna Steyr Business Activities[9]

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[8] cf. MAGNA STEYR (2011a), pp. 10, 26

[9] cf. MAGNA STEYR (2011a), pp. 8, 11, 15, 17

1.2 Alternative Fuel Storage Systems

In recent years, the trend towards environmentally friendly energy sources for powering vehicles and hybrid propulsion systems is getting more and more predominant. The reasons why Original Equipment Manufacturers (OEM) express interest in these technologies are quite obvious; environmental regulations for vehicles are getting stricter from year to year and every OEM is eager to be able to provide products that fulfill these regulations. The fact that the global oil resources are decreasing, due to the steep increase in oil demand every year results in an increase in oil prices and demand for alternative fuels. In addition, global warming is becoming a more significant environmental issue due to natural catastrophes', changes in climate and extinction of animal species.[10]

Every single new propulsion system includes storage for its energy resources that needs to be integrated into the vehicle. Therefore, the need for alternative fuel storage systems is increasing and represents a high potential for future business for Magna Steyr. However, storage systems for CNG in particular are part of a very competitive and maturing business environment (e.g. low price suppliers from Asia). Whereas, storage systems for Hydrogen (H_2) are much younger products in terms of development and as such are, experimental, expensive and associated with high risk. Therefore, storage systems for CNG can be called a mature product with the main issue being competitive cost, whereas hydrogen is still in the prototype phase and still remained to be more widely accepted by end-users of vehicles. If a company wants to be successful in this business area, it has to be able to provide lean and flexible products at a specified quantity and quality. MS sees the potential in these products and is working intensively on innovations and on their existing products to be on the forefront in this emerging business area in the future.[11]

The needs and expectations of OEMs are easy to describe but rather difficult to fulfill. Primarily, they are looking for a supplier for turn-key HPFSS for CNG and H_2 which is capable of providing flexible solutions for all compartment dimensions and vehicles. Furthermore, the products should comply with high quality and safety standards and feature a good cost/performance ratio. Secondly, excellent service/support and the capacity for high production volumes need to be ensured as well.[12]

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[10] cf. MAGNA STEYR (2010b), pp. 2-4

[11] Interview with Mr. Franz Mayr (05.10.2011), supervisor at Magna Steyr

[12] ibidem

1.3 Initial Situation at Magna Steyr

Currently projects regarding High Pressure Fuel Storage Systems (HPFSS) for CNG or H_2 (see example for 200bar CNG HPFSS in Figure 1.2) are handled at MSF as follows. The customer places an inquiry for a specific system including their needs, specifications and restrictions (e.g. size of system, filling capacity, pressure, price, weight, type of vehicle, range, safety, fuel type etc.). Then, MSF conducts an initial cost estimation and sends a proposal back to the customer. After receiving confirmation from the customer, MSF begins development on a custom system according to the exact predefined specifications.[13]

Figure 1.2: VW Passat Eco Fuel - Equipped with 200bar CNG HPFSS[14]

Such a system (see Figure 1.2) could be called a customized system or a tailor-made system which has its advantages in precisely fulfilling customer's needs but also its disadvantages; this Product Development (PD) approach is connected with high production costs due to low production volumes; high development cost due to the fact that every system has to be designed "from scratch" and high certification cost, because the pressure vessels mostly exhibit different dimensions and every single vessel type needs to be certified and tested.

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[13] Interview with Mr. Franz Mayr (05.10.2011), supervisor at Magna Steyr

[14] cf. MOTOR NEWS ÖSTERREICH (2009)

Moreover, the large variety of different components and the resulting low similarity decreases the safety and quality of the whole system and increases in particular material and logistics costs. Thus, there are few common parts in different HPFSSs which lead to the fact that components are produced and ordered in a very low volume which does not give any opportunity for volume discounts or big-scale production. This way of conducting business with HPFSSs represents a potential for costs savings and improvements in terms of quality, safety, interchangeability, maintainability, and much more.[15]

Modular High Pressure Fuel Storage System

The supervisor of this thesis at MS is Mr. Franz Mayr. He is an open minded thinker and he is not afraid of pursuing ideas which he sees potential in and others do not. In the Advanced Technology Development department he found the support he needed to work on his ideas and innovations. It was him, who had the idea to replace the "Tailor-Made" Product Development (PD) approach by a Modular Product Architecture in order to make it cheaper and better.[16] This hits exactly what Mr. Frank Stronachs' (founder of Magna International Inc.) guideline is "Make the product cheaper AND better"[17].

The modular system consists of a predefined, well thought-out selection of components which are used to assemble an HPFSS. It is planned that every system should be able to run on 200bar CNG and (with minor modifications) on 200bar/350bar H_2 as well. HPFSSs based on modular product architecture are to be adjustable in terms of size, filling capacity, pressure, fuel type, weight and price. The component selection is designed to have as little components as possible, to foster synergy, (different systems use as much "same parts" as possible) without sacrificing system functionality. Thus, the production and ordering volumes are likely to increase which enables one to utilize economies of scale which leads to lower production costs.[18]

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[15] Interview with Mr. Franz Mayr (05.10.2011), supervisor at Magna Steyr

[16] ibidem

[17] Interview with Mr. Frank Stronach (13.07.2011), Founder of Magna International Inc.

[18] Interview with Mr. Franz Mayr (05.10.2011), supervisor at Magna Steyr

Another advantage that comes along with such a PD approach is that parts and assemblies are standardized which increases the quality and safety of HPFSS as a whole. With the components of the modular system the customer is capable of ordering a HPFSS according to their specific needs and specifications (size of system, filling capacity, pressure, price, weight, type of vehicle, range, safety etc.). The business process starts with the customer designing a system using the components of the modular construction set. Then the customer sends the design to MS and the process of manufacturing the ordered HPFSSs starts. Only the vessel production, the assembly of the modules (sensors, valves, gauges, etc.) and the assembly of the system itself are done internally at MS, all other components are acquired from external suppliers. After assembling a system, MS sends the turn-key system back to the customer where it faces the final implementation in the vehicle. System installation into the vehicle is not the responsibility of MS when using this PD approach.[19]

1.4 Problem Definition

The idea of changing the product architecture and Product Development (PD) approach for HPFSSs from “Tailor-Made” to “Modular” is certainly innovative, but the primary question is how economically feasible is this approach. Is there a benefit associated with the modular PD approach compared to the prevailing one? If yes, what will the magnitude of the benefits be; what are the cost drivers and how will they change? It needs to be assessed whether modular product architecture for this particular type of product is feasible or not. From this assessment it will be determine whether further resources should be committed to exploring this potential new product architecture.

Summary of Problems

The cost landscape and the influence of each cost type on total cost of HPFSS are unknown. Further, changes in costs associated with the use of modular product architecture for HPFSSs are unknown. Moreover, a tool for quick cost estimation for HPFSSs is not available at Magna Steyr.

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[19] Interview with Mr. Franz Mayr (05.10.2011), supervisor at Magna Steyr

1.5 Objectives

The first objective is to assess and analyze prevailing HPFSSs which use the tailor-made approach and determine their associated costs. In particular, the cost landscape needs to be determined in order to identify the main cost drivers of HPFSS. Knowing the cost drivers ensures that the focus when carrying out the cost analysis is concentrated on the most relevant cost types. Furthermore, the cost structure serves as a basis when determining the comparison approach for comparing “tailor-made” and “modular” HPFSSs. Here, the changes in costs due to the new approach need to be quantified and implemented in a costing. Finally, the results and findings of the comparative analysis need to be presented, discussed and approved by MS experts. After that, the results are presented and ratios for rating HPFSS are established to quantify the performance of a system in terms of costs (e.g. €/performance unit). With the findings of the comparative analysis a Microsoft Excel Tool should be developed for quick estimations of costs for HPFSS. Based on the results of the analysis, the future potential of modularizing HPFSSs should be pointed out by making recommendations for future actions.

1.6 Deliverables

Primarily, the results and findings from the comparative analysis, including conclusions and recommendations, are subject to be delivered.

Secondarily, a Microsoft Excel Spreadsheet Tool for conducting estimations of costs for modular HPFSS should be delivered.

1.7 Out of Scope

Developing of the modular component selection is not part of the thesis and therefore not the authors responsibility. The component selection with all specifications is given to the author by MS for comparative purposes. Further, the technical functionality of the modular HPFSS is not the responsibility of the author.

1.8 Thesis Structure

The Master Thesis is subdivided into four phases (see Figure 1.3):

The **Actual State Analysis** introduces the company MS and the thesis in general. MS is described in terms of history, affiliation and business activities to give everybody an idea what this company is about and in what kind of business they are operating in. Furthermore, the context of the thesis is introduced and describes the motivation, initial situation and the expected outcome of the thesis.

The **Theoretical Analysis** is the Literature Review and deals with the essential theoretical background of the thesis which is subdivided in several parts. It includes a thorough overview regarding the context of the thesis (i.e. modular PD) and introduces quantitative tools and methods which will be used in the practical part of the thesis in phase three. In addition, it explains the functionality of HPFSS and gives the reader a fundamental technical understanding of the topic.

The **Practical Part** is the practical approach of the thesis and comprises the cost structure and comparison-analysis of modular product architecture in the HPFSS context. Assessment tools and methods which are explained in phase number two are used to generate results of informative value to the existing problem statement.

The **Presentation of Results** discusses and presents the results and findings of the assessment/analysis graphically and interprets it in written form. Moreover, the focus of this phase is on demonstrating the results in an effective and transparent way in order to provide a solution for the problems defined in “1.4 Problem Definition“. Finally, the conclusions and recommendations are presented in this part of the thesis.

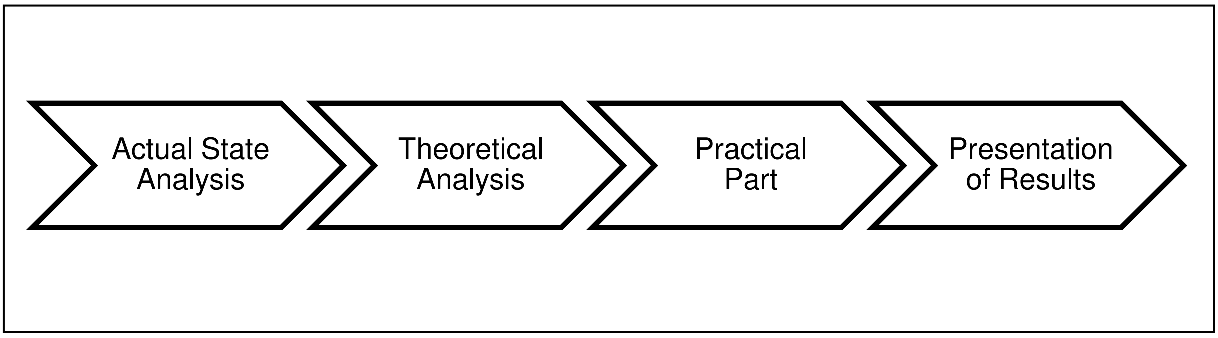

Figure 1.3: Phases of Thesis[20]

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[20] Own Illustration

2 Product Development

This chapter deals with essential background knowledge of the product as an element of the value chain and the role of costs in relation to modular product architecture. It starts with definitions, product structure, complexity costs, managing complexity and construction approaches; followed by variant management and modularization; and ending with costing and quantitative cost assessment/analysis methods and tools.

PD is to design a feasible solution for a certain problem and transform it into a physical embodiment. This embodiment may consist of numerous parts, assemblies and subassemblies which all should possess a certain degree of manufacturability.[21] Every product can be seen as a system (see Figure 2.1) of components and assemblies which may interact with each other on a functional and/or organizational level. The system boundary represents the transition between the product and the environment; further it includes existing connections and how the product affects the environment and vice versa.[22]

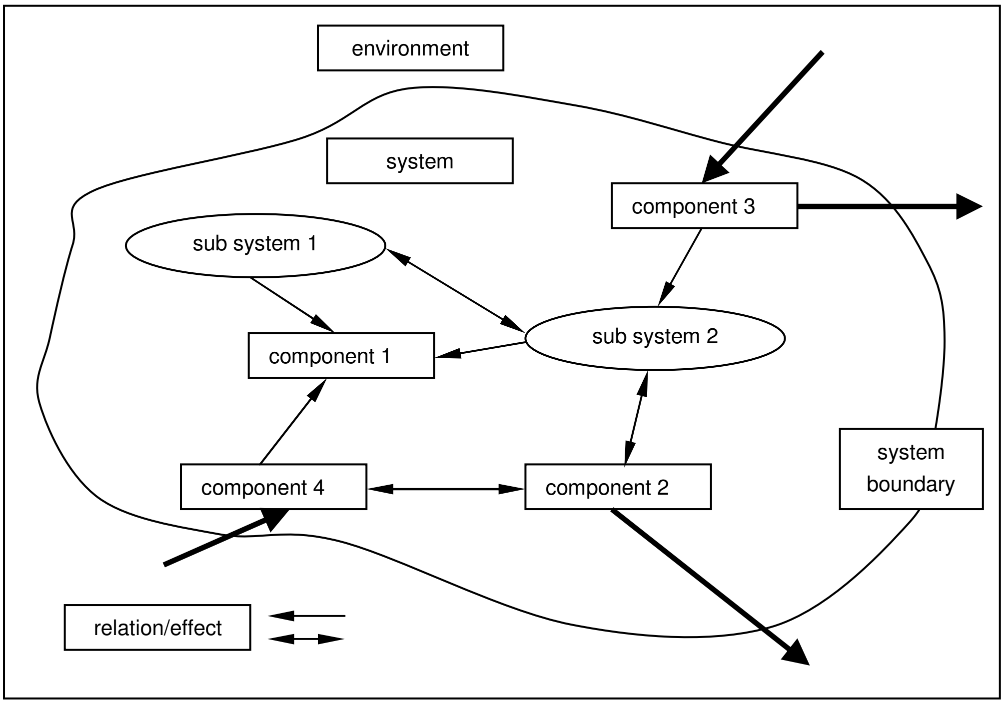

Figure 2.1: General Structure of a Product System [23]

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[21] cf. KOLLER (1998), p. 87

[22] cf. ENGELN (2006), p. 139

[23] ibidem

Nowadays, products no longer consist solely of components from a single technical discipline; components from numerous technical disciplines are used to varying degrees. This diversity represents potential for cost savings and simplified functions. However, the downside of this trend towards multi discipline engineering is that the complexity of products is increasing substantially. This complexity is mostly caused by differences between the disciplines in terms of PD approach, component functionality and organizational structure. Although there are differences amongst the engineering disciplines, the basic steps in PD are more or less the same for all of them.[24]

Fundamental PD steps: [25]

- identify goals of product on market
- set-up coordination structure
- market segmentation
- identify customers needs and drivers
- competitor analysis
- design concepts
- cost calculation according to test-results
- develop prototype
- start production, marketing and delivery
- continuous improvements

As a result of these steps, a new product is introduced to the market which may be called a product innovation under certain circumstances. All products which represent a new embodiment in the product range of a company and/or industry are called product innovation. During the development of a product the technological uncertainty is reduced with so called innovation projects.[26]

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[24] cf. ENGELN (2006), p. 140

[25] cf. LANGBEHN (2010), pp. 156-158

[26] cf. VERWORN (2004), p. 13

2.1 Product Structure

The product structure is the arrangement of functional elements, relations between them and the specifications of their interfaces. However, in a product structure it is not considered that components can have a relation to each other although there is not interface between them.[27]

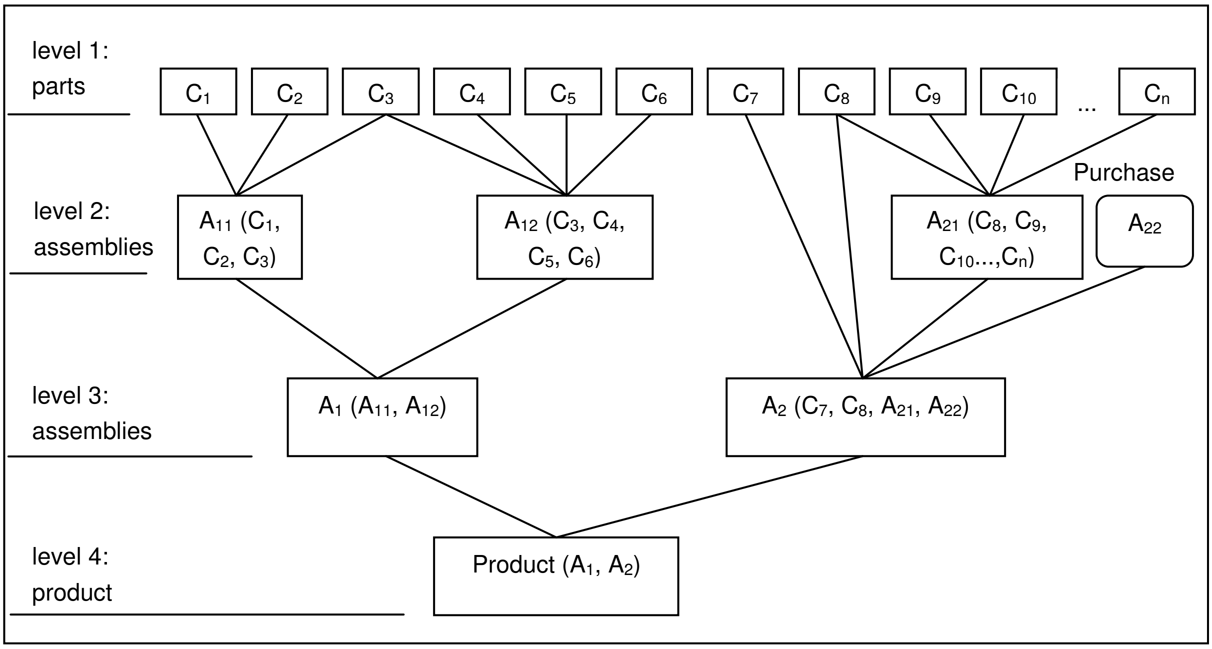

Figure 2.2: Product Structure Example[28]

The product in Figure 2.2 comprises several parts, three sub-assemblies, one purchased component and two main assemblies. All these elements are assembled in a four level process. Assemblies should always consist of other elements which are only one level higher as the assembly itself. For example on level two, all assemblies are solely built-up with elements from level one. Whereas, on level three not all elements are from level two (C_7 and C_8) which may cause higher planning and logistical costs. The structure of a product is mostly depending on the features of the product itself and its assemblies. Thus, all components and assemblies of the product need to be designed according to these features; having said that, the structure may differ from the demanded features due to specifications (see Table 2.1) of overriding importance.[29]

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[27] cf. RAPP (2010), p. 9

[28] cf. RAPP (2010), p. 68

[29] cf. ENGELN (2006), pp. 141-142

Such specifications are manufacturing specific characteristics which can be seen below in Table 2.1.

Specification	Approach
Low Development Costs	• reuse of assemblies and components • shortening of try-out time
Low Manufacturing Costs	• multiple use of assemblies and components • simple manufacturing processes
High Quality	• reuse of approved and optimized assemblies and components
Low Complexity	• use preferably simple elements • use as few elements as possible • simple connections and interfaces between elements • use as few connections and interfaces between elements as possible
Cost-Efficient Variability	• creating variety on a high level in the product structure through removing and adding of assemblies (configuration instead of construction) • construction set, modularization, design platforms
Cost-Efficient Recycling	• using similar materials in assemblies • easy disassembly through appropriate product structure
Flexible, Sustainable Solution	• modular product structure • product innovations through new modules • independent, parallel development of new
Clearly Defined Supply Chain	• development of assemblies which undergo a make-or-buy decision as a complete system

Table 2.1: Specifications and Approaches for Structuring a Product [30]

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[30] cf. ENGELN (2006), p.144

The specifications shown in Table 2.1 do not share the same impact on product structure layout. Depending on the features of the product, the product strategy and the economical efficiency, some specifications are of higher importance than others. In order to determine a product structure the specifications need to be ranked and sorted according to their importance to generate a design basis for the product structure.[31]

One way to categorize these specifications is by what they affect:[32]

- company strategy
- cost structure
- product planning and disposition
- coordination structure
- technology
- product functionality

This section makes it clear that a products complexity is strongly depending on its product structure. However, the product structure is not the only complexity driver in this context. An explanation of internal and external complexity, complexity categories, costs associated with complexity and ways to manage product complexity are described in the next sections.

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[31] cf. ENGELN (2006), p. 144

[32] cf. SCHUH, SCHWENK (2001), pp. 76-79

2.2 Complexity

Complexity is the interference of structural diversity, resulting from the number and diversity of elements in a system and the number and changeability of interfaces of elements in the same system. Complexity is driven by internal and external drivers which are described in Table 2.2.[33]

Causes for Complexity (Complexity Drivers)			
External Complexity Driver	**Internal Complexity Driver**		
	Structural Complexity Driver	Coordination Complexity Driver	Individual/Personal Complexity Driver
• request variety • dynamic in market • size of product range • number of customers • country specifics • number of suppliers • technological progress	• function oriented • number of hierarchies • length of decision processes • degree of division of labor • product design • manufacturing technology • number of interfaces • vertical range of manufacture • variant variety	• asymmetric information • media breaks • peculiarity of template management • character of task coordination	• striving for power • local egoism • push off responsibility • lack of social competence and expertise • lack of motivation / identification with the companies goals • negative emotions

Table 2.2: Complexity Driver Classification[34]

The thesis is more concerned about internal complexity drivers since assessing the magnitude of external complexity drivers due to new product architecture is rather difficult and does not relate to the context of the thesis. Anyhow, a way of categorizing internal and external complexity is shown in the next section.

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[33] cf. BLISS (1998), p. 5

[34] cf. WILDEMANN (1998), p. 48

2.2.1 Complexity Categories

Product complexity originates from the requirements of the market, product characteristics, complexity of production and complexity of administrating the product. Factors which drive these complexity categories are described in Table 2.3.

Complexity Category	Caused By
Market Complexity	• customer diversity • prevalence of small customers • high product range diversity • high request diversity
Product Complexity	• high number of elements • insufficient degree of standardization • non-optimized product design
Production Complexity	• multiple facility locations • numerous manufacturing steps • several manufacturing technologies • high vertical range of manufacturing
Coordination Complexity	• numerous activities causing confusion • permanent system development and modification

Table 2.3: Complexity Categories[35]

Since the thesis is assessing the changes resulting from a new approach of designing the architecture of a product, the product complexity and the costs associated with it is most important. Therefore, complexity drivers on the product level and the costs associated with them are explained in more detail in the subsequent sections.

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[35] cf. PEPELS (2006), pp. 585-586

Product complexity is strongly related to the complexity of its structure (see 2.1) which is shown in Figure 2.3. The type and number of elements determines the products variety and the type and number of connections/interfaces regulates the products connectivity. The combination of variety and connectivity determines product complexity. Approaches for managing product structure are shown in Table 2.1 and the complexity drivers in Table 2.2 are derived from the dependencies shown in Figure 2.3. From this it follows that as product complexity increases, the complexity of the development process increases as a result. However, the manner in which complexity is translated into costs is explained in the subsequent section.[36]

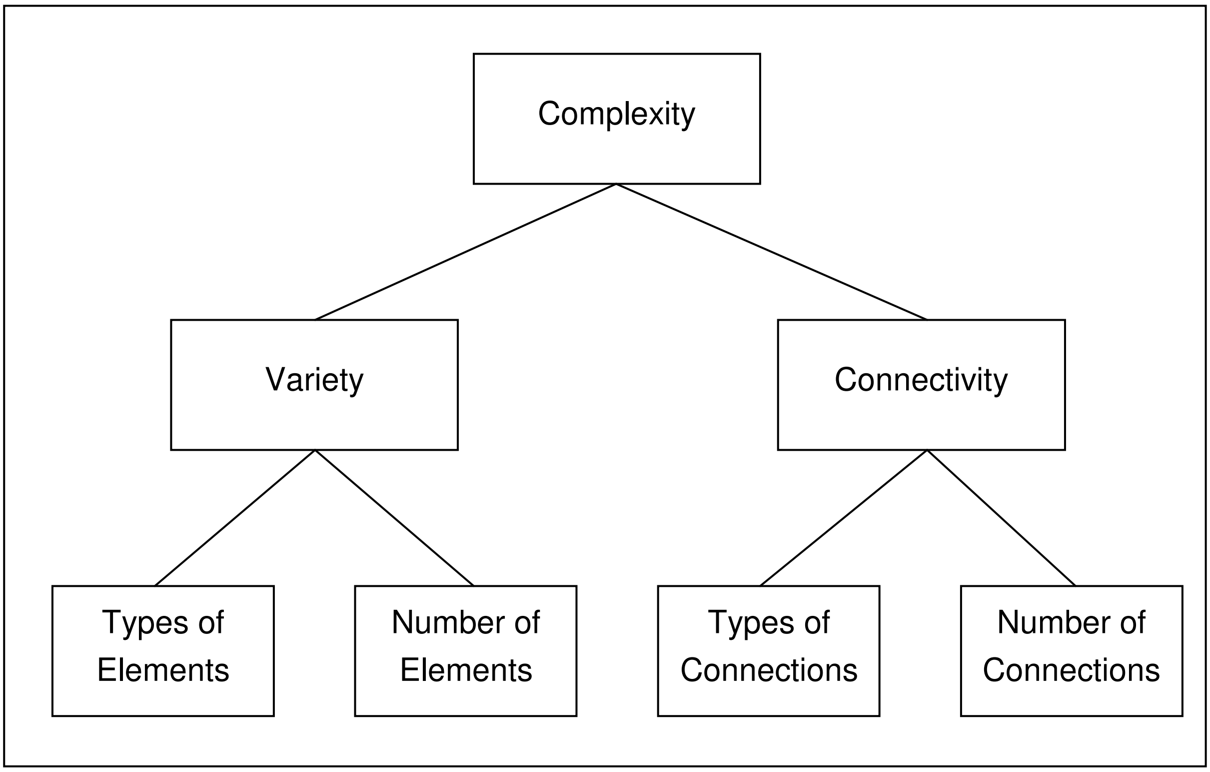

Figure 2.3: Complexity of Systems[37]

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[36] cf. GAUSEMEIER, EBBESMEYER, KALLMEYER (2001), p. 81

[37] cf. BRUNS (1991), p. 84

2.2.2 Complexity Costs

Costs due to complexity accrue on the product-, process- and resource level of a company. They are caused by the diversity of customers, products, versions, assemblies, components, materials and even suppliers.[38]

Depending on the department, complexity has a different impact in terms of cost. The departments most affected by complexity costs are research, development, design, production planning, logistics, purchasing and marketing. Complexity costs can be classified as diseconomies; this means as the number of products increases, costs associated with the non-value-adding areas of the company will increase as well. Non-value-adding areas are typically administration and coordination duties and responsibilities which do not add value in the value chain of a product. The coordination of numerous resources, departmental conflicts, avoidable and unavoidable additional tasks in the value-chain and other losses of efficiency inevitably leads to higher overhead costs. At the same time, it needs to be considered that the potential for cost savings in the value-chain may already be exploited; thus, the additional overhead costs might not be compensated sufficiently.[39]

There are three different types of complexity costs:

Non-Recurring Complexity Costs, caused by: [40]

- research and development costs for new products
- new features for versions
- development of new tools
- pilot production
- complex design challenges
- higher number of releases
- comprehensive documentation work
- increased complexity for assessing demand
- more complex production planning

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[38] cf. ENGELN (2006), p. 11

[39] cf. PEPELS (2006), pp. 585-586

[40] cf. PEPELS (2006), p. 585

Recurring Complexity Costs, caused by:[41]

- more complex quality and spare parts management
- version specific inventory and increasing number of special tools
- increasing cost price due to small lot sizes
- high set-up costs due to low lot-sizes
- less repetitive production processes and decreasing productivity
- higher consulting expenses and special training programs
- more comprehensive after-sales service

Indirect Complexity Costs, caused by:[42]

- cannibalization of products
- complex supply chain
- higher inventory of semi-finished- and finished products to compensate for fluctuations in demand

Within this section the connection between complexity and costs is explained. It is described what factors may drive different cost types. In order to prevent or reduce complexity induces costs, certain approaches and measures can be used which are described in the subsequent chapter 2.2.3.

2.2.3 Approaches to Manage Complexity

The core problem of every organism is to control the complexity which is necessary for its survival.[43] This guideline regulates the design of the value-chain and processes for mass customization. Mass customization is an oxymoron consisting of two completely different terms; that is, mass production and customization. It combines best of both worlds, individualization strategy for producing products combined with economies of scale. Success of this strategy is not only depending on a high degree of product individualization but also on managing complexity which results from individualizing products.[44]

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[41] cf. PEPELS (2006), p. 585

[42] ibidem

[43] cf. SCHNÄBELE (1997), p. 174

[44] cf. HILDEBRAND (1997), p. 75

In the 1980´s the classic Computer Integrated Manufacturing (CIM) concept was used to control complexity. State-of-the-art information, communication and especially manufacturing technologies enabled companies to have a cost-efficient production despite the high degree of complexity in their products. However, McKinsey introduced radical approaches to simplify complex products not through controlling complexity but through avoiding it.[45] Presently, structural approaches which are actively reducing factors that increase directly or indirectly the complexity on the product-, customer- and process-level of a value-chain are used by most of the companies to manage complexity.[46] A list with different approaches to manage complexity regarding the effect on the degree of complexity of a component or product is shown in Table 2.4.[47]

		Approaches to Manage Complexity for Components / Products
Effect of Action on Degree of Complexity	Avoid Complexity	• parallel development of anticipated models • use of same parts and standardized components • product modularization, construction set system, design platforms • functional integration on component-level in assembly
	Reduce Complexity	• reduction of material- and semi-finished parts diversity • increasing multiple use of components & standardization • reduce product range to high-performance models (up-grading) • changing the point of creating variety in assembly
	Controlling Complexity	• implementing of storage levels in assembly • substitution of hardware-functionality with software • implementing standardized interfaces for products, assemblies & components

Table 2.4: Approaches to Manage Complexity [48]

Further information on managing complexity by changing product design related approaches is stated in 2.3.

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[45] cf. COENENBERG (1995), p. 1253

[46] cf. BLISS (1998), p. 17

[47] cf. PILLER (2006), p. 195

[48] cf. ADAM (1998), p. 59

2.3 Construction Approach

Adding components with specified functionality and complexity to an assembly with higher complexity and even greater functionality is still mostly done manually. Therefore, assembling costs are accordingly high but get even higher if storage, assembly planning and logistics is taken into account as well. Thus, one goal of PD should be to minimize assembly complexity. There are different ways of allocating features to components in product development to affect the ease of assembly of a product.[49]

Integral- and differential-construction are two different approaches to divide the functionality of a product into one or more components in order to reduce its complexity and to optimize its manufacturability and ease of assembly.[50]

The big difference between an integral or differential construction approach is the nature of relation between functions and components. If functions are depending on more than one component then it is called an integral approach. On the other hand, if the functions are only depending on one component it is called a differential approach.[51]

When deciding whether to use an integral- or differential product approach, it is essential to consider company specific constraints (e.g. availability of manufacturing technologies). Furthermore, market specific customer expectations (e.g. costs for spare parts) play a decisive role in this decision as well. Hence, an integral product construction may be powerful in terms of features but is also very expensive when it comes to prices for replacement parts. This may be disturbing for customers and should be taken into account when deciding about the construction method for a product.[52]

The integral- and differential-method are described in more detail on the next pages.

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[49] cf. ENGELN (2006), pp. 144-145

[50] cf. WIENDAHL, GERST, KEUNECKE (2004.), p. 47

[51] cf. PFAFFMANN (2001), p. 222

[52] cf. ENGELN (2006), p. 146

2.3.1 Integral Construction

Integral construction combines several features in one unit in order to lower the variety of parts and to foster the repeated use of the unit in other products as well (see Figure 2.4). This means that it tries to lower the number of variants in regard to the products product-group. This leads to an increased production/ordering volume of the particular unit and improved ease of assembly.[53]

However, if several features are combined into one unit, the unit itself becomes more complex and difficult to manufacture. However, with state-of-the-art manufacturing processes/technologies even very complex parts can be produced economically. Therefore, integral construction is mostly used for products with large-scale production.[54]

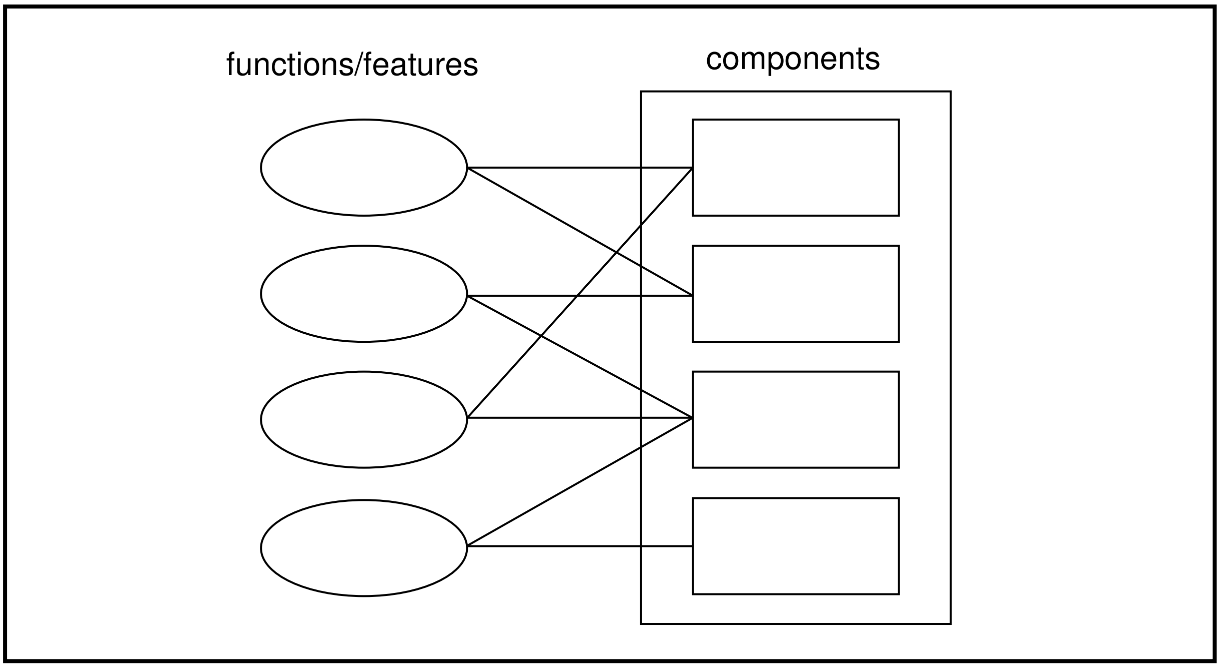

Figure 2.4: Functional Dependency - Integral Construction[55]

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[53] cf. WIENDAHL, GERST, KEUNECKE (2004.), p. 47

[54] cf. ENGELN (2006), p. 145

[55] cf. PFAFFMANN (2001), p. 222

2.3.2 Differential Construction

The differential construction is based on the separation of an assembly with several features into multiple components with a designated feature (see Figure 2.5). The goal of differential construction is to create as many same parts as possible within the variety of a functional unit. This means that it tries to increase the number of variants in regard to the products product group.[56]

Thus, assembling several simple components, each with their own specific feature, creates the desired function of an assembly. The higher the functional and physical independency amongst the components is the more it is a differential construction approach.[57]

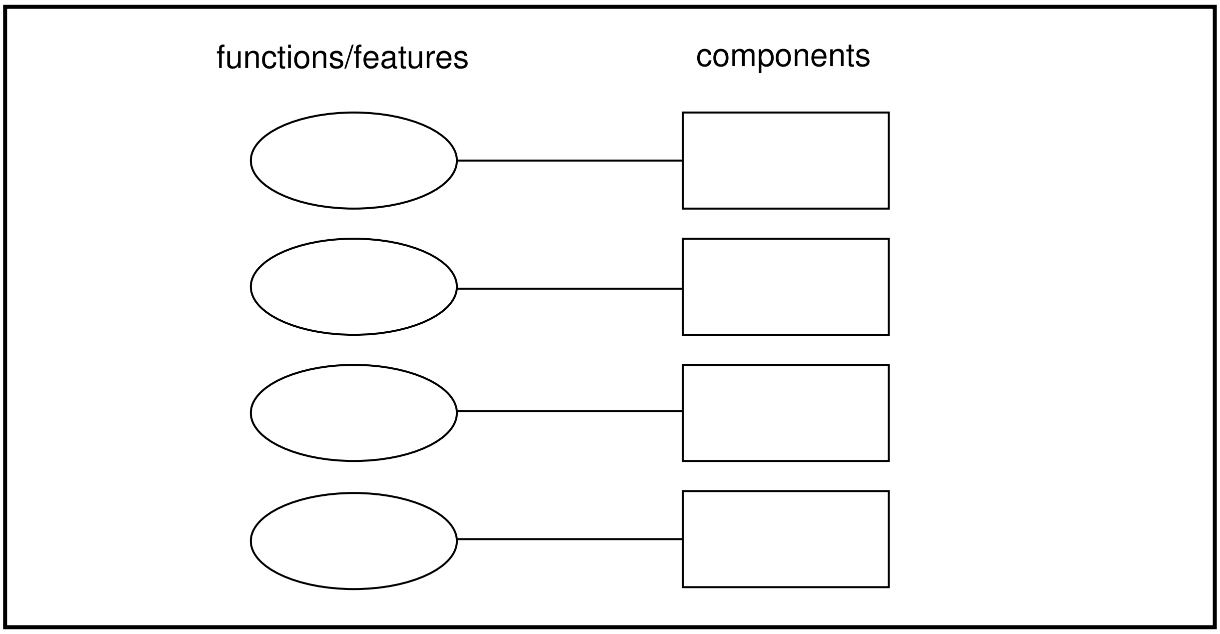

Figure 2.5: Functional Independency - Differential Construction[58]

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[56] cf. WIENDAHL, GERST, KEUNECKE (2004), p. 47

[57] cf. PFAFFMANN (2001), p. 223

[58] cf. PFAFFMANN (2001), p. 222

2.3.3 Consequences of Construction Approach

Using an integral- or differential-construction approach leads to certain consequences for the characteristics and behavior of a specific product. These consequences are listed in Table 2.5.

	Differential Construction	Integral Construction
technical performance	• optimization of local performance characteristics of components • requirement for advantages in the substitution of parts	• optimization of global performance characteristics (e.g. dimensions, design, weight) • advantages in efficiency through functional integration and optimization
product flexibility / variability	• possibility of combining components • upgradeability of products • exchangeability of components • customer specific product configuration • reusability of components	• low product flexibility/ variability
product diversity	• generating product diversity in manufacturing and assembly	• generating product diversity only in assembly
standardization of components	• standardized components on low process level for complex products possible	• not possible for complex products
structure of supply chain and competition	• vertically disintegrated companies • competition in components	• vertical integrated companies • competition in system

Table 2.5: Consequences of Construction Approach[59]

According to Table 2.5 the integral- and differential-construction approach can be used to manage the number of variants that a product embodies. However, more methods of managing the number of product variants are explained in chapter 2.4.

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[59] cf. PFAFFMANN (2001), p. 224

2.4 Product Variant Management

The increasing demand for higher number of product variants affects almost every company. A product variant is the modification of an existing product in terms of its customer-relevant characteristics.[60]

Variants of a basic product are all designs which have the same basic structure but differ to other products in terms of one or more characteristics. A variant can be pictured as a row or column vector which consists of characteristics that are relevant in terms of sales and production related aspects.[61] Equivalent or similar needs are satisfied through a variety of products.[62]

Trends towards more product variants are caused by: [63]

- Individualized customer needs; markets are getting split-up in smaller and market segments which do not have a high business volume.
- The increasing competition constraints demand that companies have to introduce new products faster.
- Companies are trying to compensate lower sales by introducing more and more products in order to serve as much market segments although they are small.
- Companies start business activities in foreign markets; this means different customer needs and country specific standards and restrictions which lead to country specific product variants.

Therefore, it is crucial for a company to thoughtfully plan their product range and increase its diversity through having more product variants.[64] If a company is implementing a varying production system it can serve more market segments through offering new products for new target groups. This enables the company to penetrate new markets or market segments.[65]

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[60] cf. ENGELN (2006), p. 147

[61] cf. WOLLSEIFFEN (1999), p. 69

[62] cf. LINGNAU (1994), pp. 26-28

[63] cf. ENGELN (2006), pp. 147-148

[64] cf. PFEIFFER. WEISS (1994), p. 48

[65] cf. WOLLSEIFFEN (1999), p. 69

By generating more variants, single customer or customer-groups can be targeted individually, taking into account their specific needs.[66] However, the downside of an increased number of variants is an increase in production complexity. At the same time, the marginal utility of the variant decreases as well. Besides the effect on direct costs, more variants will also influence quality and delivery time of products.[67] Effects of an increasing number of product variants can be identified throughout every department in a company (see Table 2.6).

Development / Design	• designing new components • maintaining additional parts and data • creating and administrate additional technical documents • higher efforts necessary for design changes • more complex market monitoring
Purchase / Logistics	• determining material requirements more difficult • more suppliers, higher inventory • search and choose additional suppliers • higher purchasing prices due to smaller quantities
Manufacturing	• smaller lot sizes, increased down- and set-up-times • more frequent commencement of production • probability of confusing parts during assembly is higher • more complex production control & higher inventory • higher number of special tools in stock • variety of different manufacturing technologies
Sales / Marketing	• many products but small lot sizes • many customers but low business volume • complex market monitoring & communication • additional efforts for sales information
Service / Customer Support	• more elaborate employee training • additional tools • higher spare-parts inventory • more complex planning for customer inquiries

Table 2.6: Affects of an Increasing Number of Product Variants in Different Departments[68]

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[66] cf. WOLLSEIFFEN (1999), p. 69

[67] cf. ROSENBERG (1996), p. 2127

[68] cf. ENGELN (2006), p. 150

All negative effects resulting from a higher number of product variants lead to the need of a thorough product variant management in a company. Variant management incorporates efforts to avoid, control or reduce complexity in production and coordination caused by an increasing number of variants. It can be subdivided into strategic- and operative variant management.[69] In this thesis the operative aspect of variant management plays a more important role than the strategic aspect. Thus, the focus of this thesis is geared more towards the operative variant management which is discussed in higher detail in chapter 2.4.2.

2.4.1 Strategic Variant Management

Based on the higher-ranked business objectives of the company, strategic variant management determines the number of variants in reoccurring decision cycles for the long-run[70]. Basically, a company should realize variant diversity through varying product properties which have not already been successfully altered by competitors[71]. The guiding principle is “the more the better” but only until it reaches a certain critical point. Especially the strategic variant management has to consider the diversity induced costs for customers when making decisions. Thus, the strategic variant management establishes the general framework for the operative variant management.[72]

2.4.2 Operative Variant Management

As already stated in section 2.4.1, the strategic variant management represents the general framework for the operative variant management which tries to distribute the predetermined diversity as efficient as possible over the whole value-chain.[73] Furthermore, the task of the operative variant management is to analyze the variant diversity and to coordinate the interfaces between different functional areas of the company.[74]

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[69] cf. WILDEMANN (1998), p. 367

[70] cf. ALBERS, HERRMANN (2007), p. 671

[71] cf. ULRICH et al. (1998), p. 190

[72] cf. ALBERS, HERRMANN (2007), p. 671

[73] cf. FRANKE et al. (2002), p. 22

[74] cf. SCHMID (2009), p. 42

Operative variant management has to control the number of variants determined by the strategic variant management and implement them as cost efficient as possible. In order to do so, product and/or process based approaches can be used.[75]

2.4.2.1 Product Based Approaches

Product based approaches change the characteristics and the configuration of the product itself in order to manage its number of variants. The following sections introduce methods and measures on the product level of the value chain which may be used to manage product variants. Amongst those methods one can find the concept of modularization which is used for High Pressure Fuel Storage Systems (HPFSS) in this thesis. Therefore, the method is discussed in greater detail in chapter 2.5.

Product Value Build-Up

The standardized integration of additional features in products decreases costs and concurrently increases customer satisfaction. Especially in the automotive industry the so called “Top-Versions” are very successful. Nowadays, OEM´s integrate the most inquired optional equipment like ABS or airbags as standard equipment. The goal is to overcompensate the costs of additional features with decreasing complexity costs.[76]

Product Bundling

Another possibility to reduce complexity in the development-, manufacturing- and marketing-process is through bundling products. Out of a limited number of components a large variety of products is generated while having the advantage of drastically reducing coordination costs. Moreover, the company is able to reduce its safety stock of additional equipment, because after bundling, these components are in serial production and are brought to it synchronically.[77]

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[75] cf. HERRMANN, HUBER (2009), p. 412

[76] cf. ALBERS, HERRMANN (2007), p. 672

[77] cf. HERRMANN, HUBER (2009), p. 412

Modularization

Another way of managing variant diversity is through product modularization. Under this approach, product complexity is reduced without decreasing variant diversity.[78] Modularization is applied to assemblies and components and product diversity is generated with variants of the assembled modules.[79]

Note: detailed information about the modularization design approach can be found in section 2.5. It is described more in detail, because the thesis is centered around this PD approach.

Standardization

Striving towards standardization often results in a “platform” or “same parts” based strategy [80]. Using standardized parts greatly reduces the diversity of components, supports economies of scale in manufacturing and lowers the complexity of adjacent departments in the value-chain. For instance, in the automobile industry not only the base plate but also engine, transmission and electronics and many other components are used for several models.[81] When standardizing parts, a company has to consider that the creation of variants should be done through varying customer-relevant-characteristics of a product in a way that customers still clearly see a distinctive difference between them[82].

Therefore, the main problem with standardization is the undesired creation of doppelganger-products. Thus, only components which are not easily visible for customers (e.g. brakes, transmission, suspension, etc.) should be standardized and not clearly visible ones (e.g. body parts, interior, etc.) should not.[83] However, standardizing parts can also increase unit cost, because the standardized components will be installed in the high-end variants and need to fulfill their quality standards; this means that the quality specifications for the standardized part will be higher than they were before.[84]

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[78] cf. BUCHHOLZ (1996), p. 226

[79] cf. EHRLENSPIEL (2007), p. 386

[80] cf. FISHER, RAMDAS, ULRICH (1999), pp. 297-298

[81] cf. ALBERS, HERRMANNN (2007), p. 673

[82] cf. ENGELN (2006), p. 148

[83] cf. KAHN (1998), p. 31

[84] cf. FISHER, RAMDAS, ULRICH (1999), pp. 86-87

2.4.2.2 Process Based Approaches

Process based approaches change the characteristics and the configuration of the products process in order to manage its number of variants. The following sections introduce methods and measures on the process level of the value chain which may be used to manage product variants.

Postponement-Strategy

One process based approach to manage variant diversity is through changing the point-in-time in the manufacturing process where a variant is generated. This point-in-time should be moved closest to the end of the manufacturing process.[85] This approach supports the standardization approach, because the longer a product is job-independent the lower is the complexity of its variants. A successfully implemented postponement-strategy will result in a product structure with a lean stem (see Figure 2.6). Ideally the creation of variants occurs at the customers place or at a store.[86]

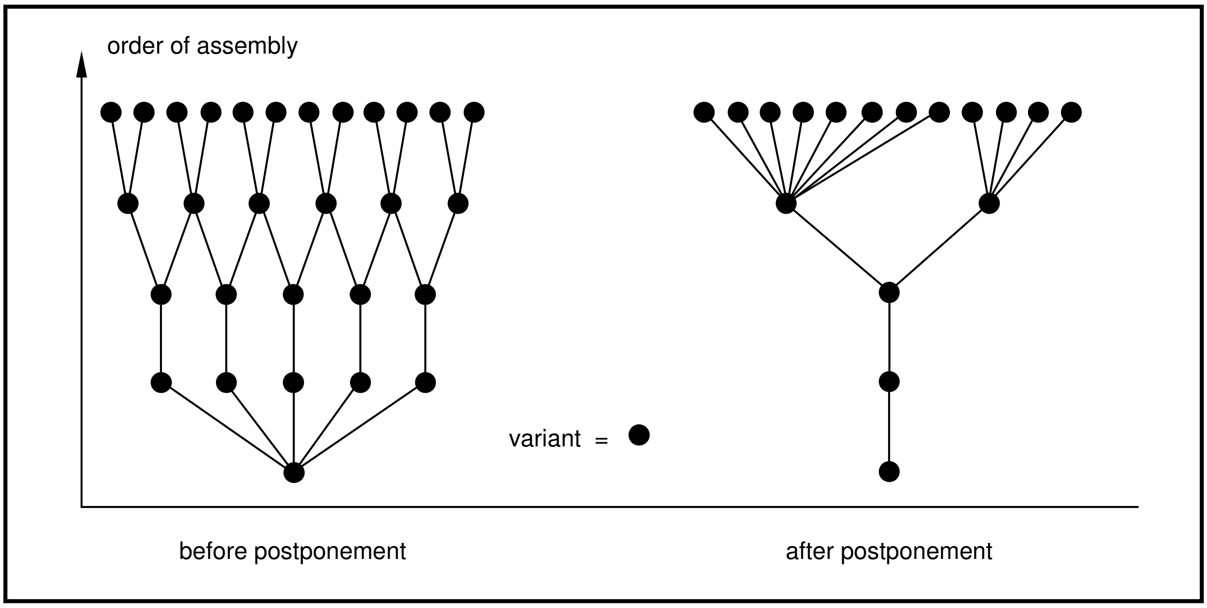

Figure 2.6: Effects of Postponement-Strategy on the Product Structure[87]

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[85] cf. EHRLENSPIEL (2007), p. 668

[86] cf. KAHN (1998), p. 32

[87] cf. HERRMANN, PEINE (2007), p. 674

Flexible Manufacturing Technologies

Investments in flexible manufacturing technologies are mostly for coping with variant-diversity induced changes in a production process. Flexible manufacturing process, CIM and Lean Production, allows for production of the demanded variants with minimal downtime while still maintaining the specified quality and process-stability.[88]

Moreover, if using numerically controlled machines, integrated computer control, fully-automatic just in time material flow, decentralized coordination of the production processes as well as a high degree of automation, many important objectives can be achieved. Changeover times and cycle times are decreasing due to fewer problems with interfaces; capacity utilization of the production equipment is consistently high and the delivery readiness is improved all while the locked-up capital is decreasing. [89] On the other hand, it needs to be considered that changeover times are only falling away for variants which can be manufactured with the currently used tool set. However, changing a tool may lead to enormous changeover times.[90]

Vertical Integration

When outsourcing activities which are complexity driving and value adding, the rate of variable costs in the company increases. Thus, the dependency on capacity utilization of the production equipment is reduced[91].

However, the competitive position may get worse due to the fact that complexity is influencing the up- and downstream of the value chain which may result in higher prices for purchased goods. Furthermore, the higher the magnitude of outsourced processes, the more the company depends on the relationship with suppliers. For instance, if the company only outsources some activities to suppliers but keeps their coordination internally, the complexity costs will be higher. On the contrary, outsourcing complete work-packages has a decreasing effect on costs. Altogether, a company needs to be careful with outsourcing tasks of strategic importance; it would reduce the endogen complexity but also provoke a strong dependency on suppliers.[92]

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[88] cf. ADAM (1998), p. 99

[89] cf. ALBERS, HERRMANNN (2007), p. 674

[90] cf. ADAM (1998), pp. 92-93

[91] cf. RATHNOW (1993), pp. 106-107

[92] cf. HERRMANN, HUBER (2009), p. 415

2.5 Modularization

The origin of modularization is in product design. The automotive industry in particular strives to control the increasing diversity and complexity of components by using modularization.[93]

Basic approaches to reduce complexity are to reduce the number of elements in a system and to change the intensity and number of relations between the elements[94]. The result of these two approaches may be realized by modularized product architecture. Modular systems are characterized by having a manageable number of elements which are designed to have as few and as minor connections as possible (see Figure 2.3). Components and assemblies which are made according to this approach are called modules. However, the dependencies between the internal elements of the modules are very strong. If systems are designed with a modular approach it leads to small "spots" of complexity which can operate relatively independent.[95]

The principle of controlling complexity by modularizing a system means from a technical perspective, design of components, assemblies and assembly-groups should have few but very well thought-out connections between them.[96] When dealing with physical components, it is important to distinguish between two kinds of independencies in order to classify two new product architectures besides integral- and differential architectures (see Figure 2.7). The bigger both independencies are the higher the magnitude of modularity in the system: [97]

Functional Independency: If a component is able to fulfill a certain function independently from other components, assemblies or other parts of the system. The module represents its own independent functional system.

Physical Independency: If components can be easily separated from each other through an appropriate design of their interfaces.

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[93] cf. WIENDAHL (2003), p. 6

[94] cf. SCHUH, SCHWENK (2001), p. 84

[95] cf. HUANG (2000), p. 155

[96] cf. GÖPFERT, STEINBRECHER (2000), p. 23

[97] ibidem

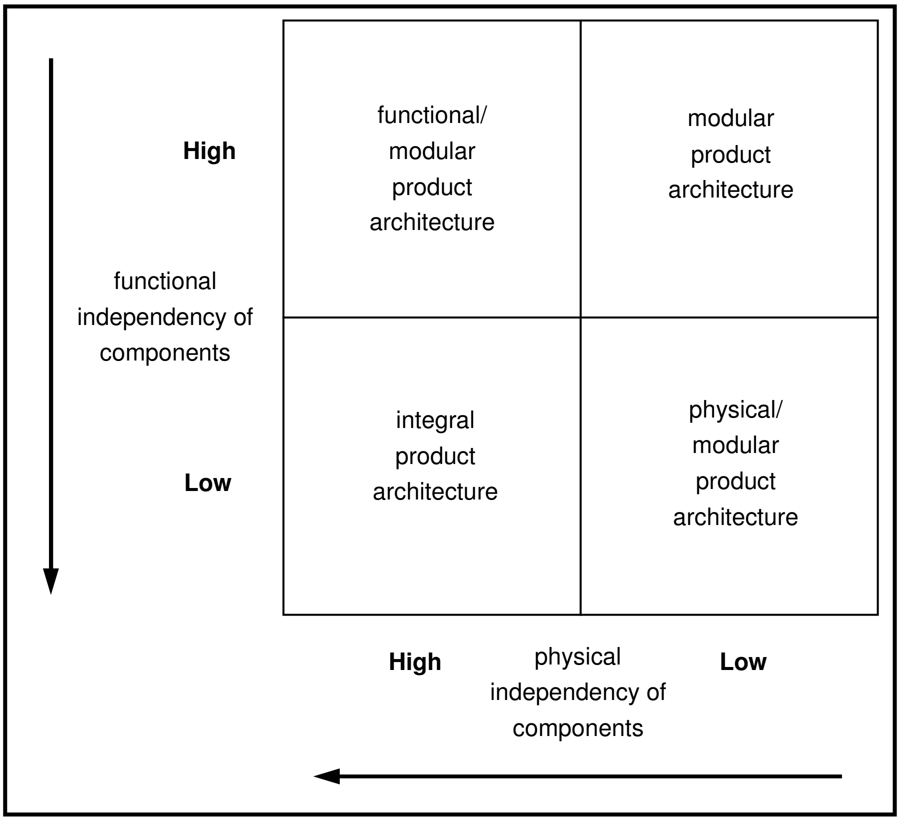

Figure 2.7: Types of Product-Architectures[98]

Different degrees of functional independencies can be achieved by using different types of modularizations. It starts with generic modularization which has a very low degree of functional independency and goes over to free modularization which offers the highest degree of functional independency of all modularization types.[99]

All modularization types and their characteristics are described in section 2.5.1.

2.5.1 Types of Modularization

There are four types of modularization which differ strongly in their characteristics and their configuration. They mainly differ whether they use a base body or not and by the number of standardized and customized components they consist of. Depending on these three aspects, one can determine which modularization is used for a specific product. Further, the type of modularization is determining the degree of flexibility of a particular product.

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[98] cf. GÖPFERT, STEINBRECHER (2000), p. 24

[99] cf. SCHUH, SCHWENK (2001), p. 84

Generic Modularization

Assembling a product when always attaching the same number of standardized components, which can have different characteristic features or functions, to one base body is called generic modularization (see Figure 2.8).[100] It includes a predetermined number of components which in conjunction fulfill the demanded functions.[101]

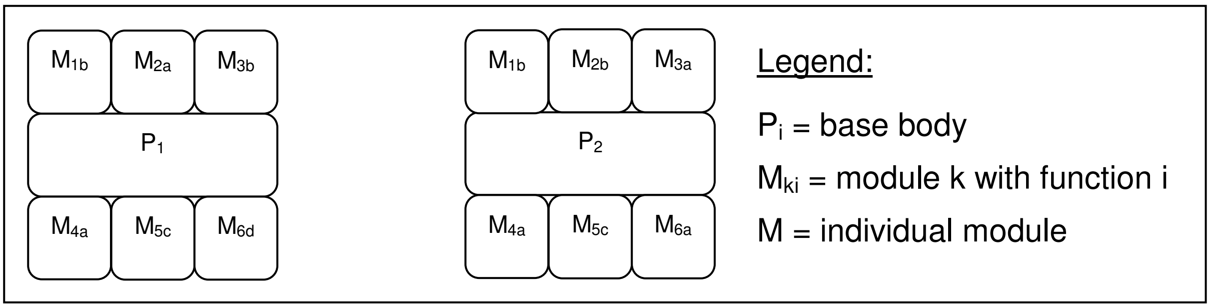

Figure 2.8: Generic Modularization Illustration[102]

Quantitative Modularization

Is the assembly of a product consisting of a variable number of standardized components mounted on one base body (see Figure 2.9).[103] The possibility of having a variable number of mounted components increases the number of variants. A good example is the PC; it is equipped with standard components but can be upgraded.[104]

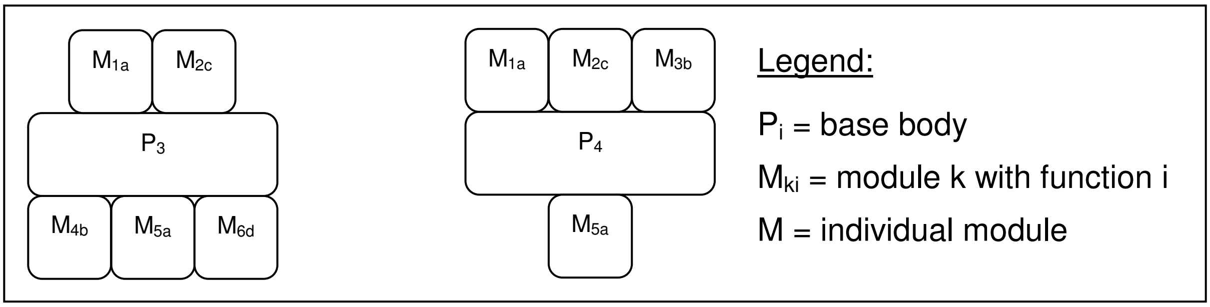

Figure 2.9: Quantitative Modularization Illustration[105]

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[100] cf. ENGELN (2006), p. 162

[101] cf. EHRLENSPIEL, KIEWERT, LINDEMANN (2000), p. 309

[102] cf. PILLER (2006), p. 229

[103] cf. PILLER (2006), p. 229

[104] cf. SCHÖTZKE (2002), pp. 59-60

[105] cf. ENGELN (2006), p. 162

Individual Modularization

Is an assembly of products which consist of a fixed or a variable number of components, which are partly customized and partly standardized (see Figure 2.10). All components are mounted on one standardized base body.[106] The individual modularization differs from the quantitative modularization by customized components which have the same interface in order to connect with the base body. A good example would be a soda machine which can produce different drinks. In this example the ingredients are standardized but the mixture of them is customized.[107]

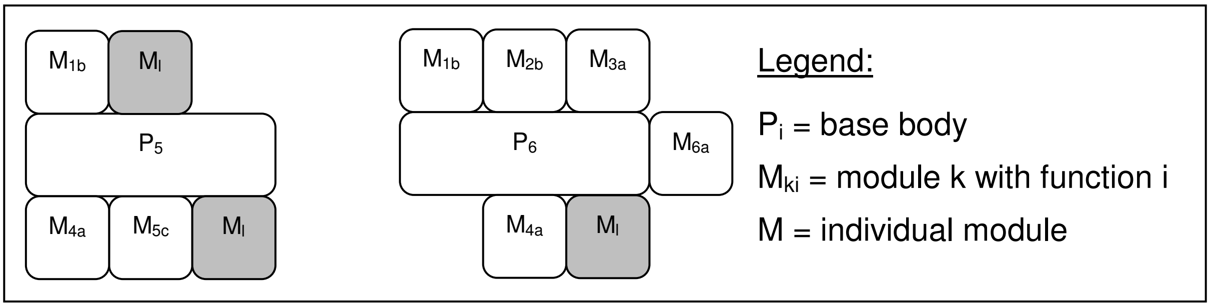

Figure 2.10: Individual Modularization Illustration[108]

Free Modularization

The free combination of standardized and customized modules or components without the need of a base body is called free modularization (see Figure 2.11).[109] For this type of modularization no base body is needed, because the modules and components can be combined in any order. An example for the most flexible form of modularization would be individualized textbooks for American universities.[110]

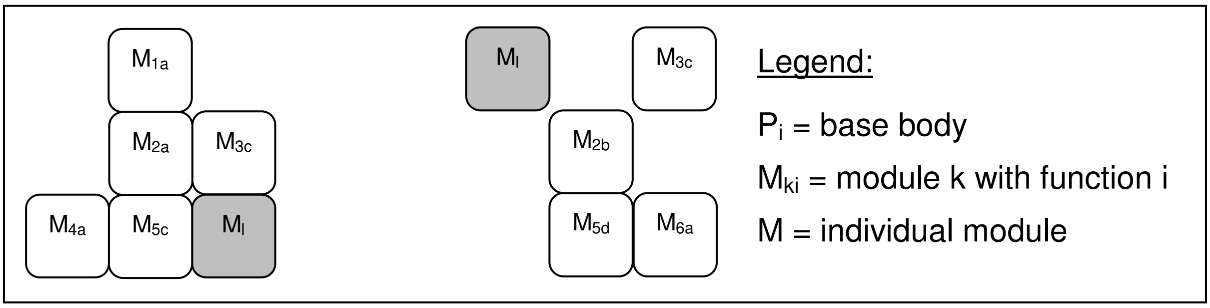

Figure 2.11: Free Modularization Illustration[111]

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[106] cf. ENGELN (2006), p. 162

[107] cf. SCHÖTZKE (2002), p. 60

[108] cf. PILLER (2006), p. 229

[109] cf. EHRLENSPIEL, KIEWERT, LINDEMANN (2000), p. 309; ENGELN (2006), p. 156

[110] cf. SCHÖTZKE (2002), p. 60

[111] cf. PILLER (2006), p. 229

The type of modularization used for HPFSS in this thesis can be classified under free modularization since it has no base body and features customized as well as standardized components. Modularization belongs to product based approaches of product variant management which suggests that it has an influence on the product level of the value chain. However, modularization also induces changes on the process level of the value chain which is discussed in chapter 2.5.2.

2.5.2 Changes in the Value Chain due to Modularization

Using modular product architecture gives a company the ability to assemble a customer specific product of a standardized, compatible, independent and finite selection of components. This induces several changes throughout the value chain of a business process which have advantageous effects in terms of costs. [112] These effects are explained in this section.

Economies of Scale (Scale Economies)

Scale Economies are based on increasing the output quantity of a product while decreasing its average cost. This is based on the assumption that a higher output quantity would expand the size of the enterprise and the capacity of the manufacturing system in the long-run.[113]

Thus, the following advantages in terms of costs are facilitated; advantages through division of work, decreasing investment, lowering labor and operating costs with increasing capacity, reduced fixed costs per unit, better capacity utilization and advantages in purchasing. Furthermore, even the transaction costs decrease due to a better utilization of communication technology.[114]

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[112] cf. PILLER (2006), pp. 196-197, 200-201

[113] cf. ALBERS, HERRMANNN (2007), p. 958

[114] cf. PILLER (2006), pp. 204-205

Economies of Scope

Another cost savings potential can be found in the variation of capabilities. These economies of scope are based on the utilization of non-competing means of production in a multi-product manufacture if the production equipment would not be used to full capacity in a single production. If equipment is not operating at full capacity, idle time costs accrue which have their origins in the lack of coordination and/or information which basically can be understood as transaction costs.[115]

Economies of Integration

Economies of scale and economies of scope are very close to each other. The difference between them is that for economies of scale the output quantity of "same parts" is the decisive factor but for economies of scope only the number of different but synergic variants of a product is relevant. Economies of Integration are nothing else but to connect these two apparently conflicting effects of scope and scale.[116]

"Economies of Integration provide a high degree of production, process and infrastructure flexibility and the ability to produce a variety of customized products, as well as the ability to produce a large aggregate volume of low-cost products."[117]

Economies of Interaction

The direct interaction between company and customer, based on the fact that every product is still customized although having a big-scale production, represents an advantage in terms of information compared to an anonymous manufacturing approach. The resulting potential for cost savings is called economies of interaction, which are:[118]

- Lower costs of adjustment
- Lower fixed costs
- Advantages through customer loyalty and better allocation of Research and Development (R&D) resources

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[115] cf. ALBERS, HERRMANNN (2007), pp. 958-959

[116] cf. PILLER (2006), pp. 210-211

[117] NOORI (1990), p. 142

[118] cf. PILLER (2006), pp. 214-215

Summary

This chapter describes what factors drive and determine the costs of a product on a very fundamental and conceptual level. Nearly every product is an assembly of several other components which feature certain functions, dependencies and interfaces within each other. The resulting connections between these components are called product structure or product architecture and influences cost at a very early stage in the product development process. Costs in particular are driven by a products complexity which results from the variety and the connectivity of the elements it comprises. Complexity itself has many faces and can be categorized in many ways but ultimately they all drive the cost of a product. Thus, if the complexity is reduced the costs are reduced accordingly. Therefore, methods and measures are introduced in chapter 2, which aim to reduce complexity. They all fall under, product variant management and consist of product based and process based approaches. The product in this thesis (i.e. HPFSS) uses one of the product based approaches which is called modularization. Using such a method brings along changes in the whole value chain which can be translated into changes in costs. By understanding how complexity and therefore costs are driven on a very fundamental level of the product development process, one is capable of determining where changes in the value chain should happen if the product architecture of a particular product is changed. In order to quantify these changes, one needs to choose appropriate methods according to the given circumstances. Methods and sources are introduced in chapter 3 which represent the tools used in the practical part of the thesis to estimate costs and gather cost information.

3 Costing

Based on the theoretical background about how complexity drives product costs and ways to reduce complexity (see chapter 2) it is crucial to find appropriate methods to determine these costs. In this chapter different types of costings and estimation methods are explained. It starts with the influence of time on costs, goes over to costing types and methods and ends with methods to estimate costs at an early stage in the product development process.

Costing is one of the main functions of cost accounting in a company. It is the main basis for decision-making when determining the selling price and starting-point for controlling costs. Basically, costing represents product costing which is a part of cost object accounting. Furthermore, when talking about cost object accounting one distinguishes between product costing and period costing. Period costing calculates the costs for a predefined time period (e.g. month, year, etc.) whereas product costing determines the costs of a product or service which is about to be sold on the market. [119]

Thus, costing has the following main functions:[120]

- Delivering data for assessing the inventory of finished and semi-finished products as well as self-made equipment and tools in the balance sheet and the short-term profit and loss accounting.
- Allowing the planning and control of profit for a period by determining the primary costs of the items which were sold.
- Creating a decision-making base for the calculation of the offer price.
- Identifying the short- and long-term lower price limit considering the current market-based price; thus, establishing a decision-making base for accepting or declining inquiries as well as to decide whether the production of a certain product should be continued or stopped.
- Determining of the so called “net costs” for certain public contracts

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[119] cf. PREISSNER (2003), p. 25

[120] cf. JUNG (2006), p. 1142

A very important aspect which has a strong impact on the accuracy of a costing is the influence of time on the availability and changeability of costs. Figure 3.1 shows the influence on costs and the availability of cost information depending on the point-in-time when the costing is conducted. According to experience, the availability of costs increases with time and influence of costs decreases respectively. This needs to be taken into consideration when discussing the accuracy of costings or cost estimations.[121]

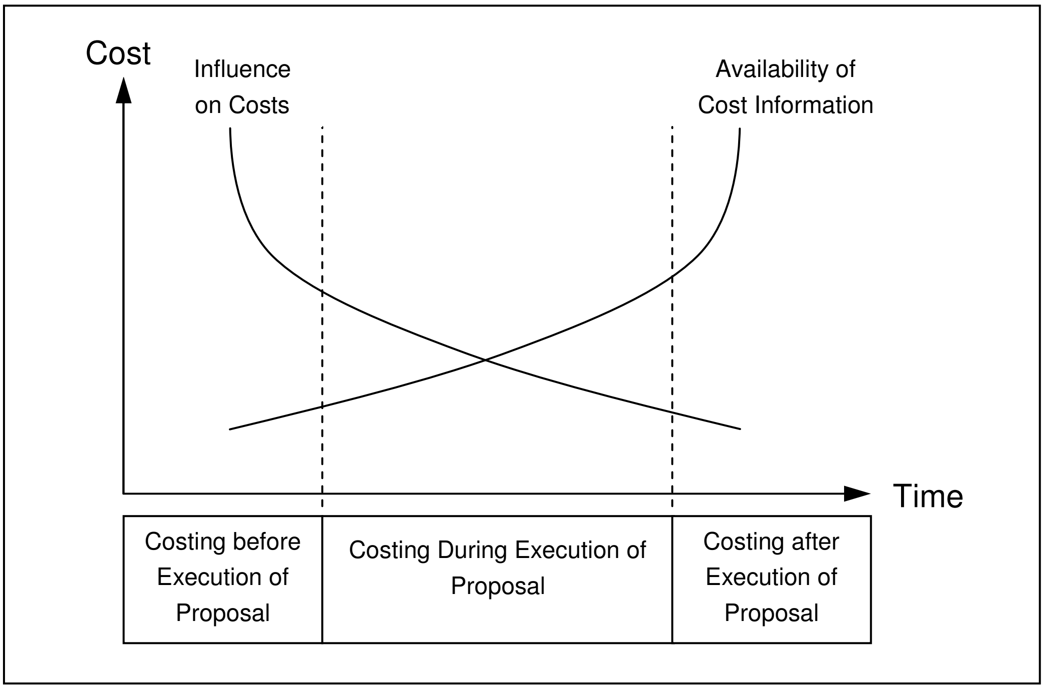

Figure 3.1: Influence of Time on Costs during the Execution of a Proposal[122]

However, there are many ways to categorize costings and its methods/sources; the most relevant categories are discussed in this chapter:

- According to the point-in-time when the costing is conducted (see chapter 3.1)
- According to whether it is a comparative or non-comparative costing (see chapter 3.2)
- According to which method is used to carry out the costing (see chapter 3.3)
- According to which method is used to estimate costs (see chapter 3.4)

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[121] cf. BOTTA (1997), p. 78

[122] cf. BERKAU, HIRSCHMANN, SCHEER (1997), pp. 194-195; BOTTA (1997), p. 78

3.1 Costing Types

Types of costings can be subdivided depending on whether they are carried out before, after or during the execution of a proposal (see Table 3.1).[123]

Costing for Goods and Services	
Before Execution of Proposal	Preliminary Costing
	Standard Costing
During Execution of Proposal	Interim Costing
After Execution of Proposal	Final Costing
	Target/Actual Comparison

Table 3.1: Costing Types[124]

In the subsequent sections all costing types their characteristics, functions and applications are explained. These types represent possible sources of information on costs which may be used in the practical part of the thesis. Therefore, a fundamental understanding needs to be developed in order to choose appropriate sources of information.

3.1.1 Preliminary Costing

Preliminary costing is always made before the execution of the production of goods and services. The main task is to predict the costs associated with the manufacturing of a single product which is called the “costing object”. Especially in companies with individual production and contract manufacturing, preliminary costing is used as a base for creating bids.[125]

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[123] cf. STEGER (2010), p. 308, see also GRÖNER (1991), p. 113

[124] cf. STEGER (2010), p 308; PROPOROWITZ, MALPRICHT, WOTSCHKE (2008), p. 80; GRÖNER (1991), p. 113

[125] cf. STEGER (2010), p. 308

Furthermore, it is always necessary to make such a costing when a new product is introduced to the market. Exact information about costs is not available at this stage; therefore, material usage, manufacturing times, purchasing prices, etc. need to be estimated in order to carry out a preliminary costing. This costing is used as a base for price determination and creating proposals.[126] Based on forecasted direct costs and allowance for overhead costs from the cost-centre accounting the preliminary costing predetermines the costs for goods and services needed for making proposals and to assist in strategic decisions as well.[127]

3.1.2 Standard Costing

Standard costing is an object based calculation as well as a method where all planned costs are allocated to specific objects (e.g. proposals). The major difference between preliminary and standard costing is that preliminary costing is made to determine the manufacturing costs of a specific product whereas in standard costing the costs for a product are calculated over a predetermined period of time (in most companies one year).[128] The characteristic feature of standard costing is consistency; in other words, the results of standard costing are not changed during the period in which they were calculated for. Manufacturing costs and primary costs of goods and services calculated using standard costing are based on data (see list below) coming from cost planning:[129]

- planned prices from outsourced production factors
- planned pay rates and salaries
- planned values per commodity unit for commodity direct cost but particularly for individual material
- cost unit rate of cost planning, in which the actual value rates are equal to the planned reference values
- planned reference values per commodity unit

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[126] cf. PREISSNER (2003), p. 28

[127] cf. JUNG (2006), p. 1134

[128] cf. PLINKE, RESE (2006), pp. 179-180

[129] cf. KILGER, PAMPEL, VIKAS (2007), pp. 509-510

As already mentioned in section 3.1.1, companies with individual production and contract manufacturing are using a job-oriented preliminary costing; after the execution of the proposal the preliminary costing is compared with the final costing; whereas in companies which produce standardized commodities, standard costing is used and compared after the end of the calculation-period with a target/actual comparison instead.[130]

3.1.3 Interim Costing

Interim costing can also be called “Costing during Product Development” and lies between preliminary/standard costing and finishing the manufacturing of the product. The data used in interim costing consists partly of actual- and partly of planned values. For all tasks which have already been carried out, the actual data is used for the calculation. However, for the remaining tasks of the project, the planned-, standard- or normal-costs are taken into consideration when creating an interim costing. Especially in industries were the manufacturing of goods and services goes over a long period of time, (e.g. equipment-, maritime-, construction- and aerospace-industry) interim costing is conducted in parallel with manufacturing. Reasons to conduct an interim costing is not only monitoring and controlling of cost trends but also providing quantitative and qualitative information for accounting and strategic decision making.[131] Therefore, interim costing is used to manage success-inhibiting deviations during the execution of a proposal and especially to guarantee the economical success of future standardized products as early as possible through circumventing unnecessary cost drivers. To do so, the product itself and all actions associated with the realization of the product needs to be monitored permanently in terms of costs. These activities are called interim costing.[132] Estimating costs is quicker than calculating them; however, estimating is deemed to be inaccurate and therefore one does not trust it in certain situations. Under appropriate circumstances and systematically conducted, estimating can deliver quick results with sufficient accuracy. Estimating should be based on similar situations, products and processes and not merely on a gut feeling. [133]

Methods for estimating costs during PD are outlined in chapter 3.4

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[130] cf. KILGER, PAMPEL, VIKAS (2007), p. 509

[131] cf. STEGER (2010), p. 309

[132] cf. BOTTA (1997), p. 78

[133] cf. EHRLENSPIEL, KIEWERT, LINDEMANN (2000), p. 409

3.1.4 Final Costing

In final costing the actual costs of manufacturing goods and services are determined. The results are compared with the results from preliminary costing in order to identify deviations. Possible deviations are then analyzed and may deliver helpful information for designing a more effective project handling approach for the next proposal.[134]

Final costing is conducted mainly for companies which provide individual production or contract manufacturing of goods. It is used to carry out a cost-per-unit-based control of success after executing an order/delivery.[135]

3.1.5 Target/Actual Comparison

Target and actual comparisons are made in companies which focus on the manufacture of standardized commodities. The target values which are defined in standard costing are compared with actual values which are known after the execution of the proposal.[136]

Since the economical assessment in this thesis is basically a comparison costing it is is explained in more detail in section 3.2.

3.2 Comparative Costing

A comparative costing uses past projects or proposals to deduce cost information by using scaling-mechanisms and similar products to assess a new product. This method is a very easy way to compare products but it is associated with errors, because it does not take the parameters shown below into consideration:[137]

- supplier issues and order/production quantities
- internal and/or external capacity issues
- quality of the product and of the team
- inflation or deflation related effects

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[134] cf. STEGER (2010), p. 309

[135] cf. KILGER, PAMPEL, VIKAS (2007), p. 509

[136] ibidem

[137] cf. SCHÖFFER (2010), pp. 133-134

In order to assist a cost-oriented product development approach, it is suggested to use methods which depend on process models and derive product costs on a knowledge based level. The so called “short costing” is one of the most well-known quantitative methods in comparative costing. In this method, a products cost driving properties are determined and analyzed in terms of change in costs based on the costing made after the execution of a similar product. However, the downside of short costing is that it can only be used as a tool for cost estimation due to the fact that it does not consider the parameters shown in the listing above.[138]

Knowing the different types of costings is important. However, the methods to conduct such a costing are explained in chapter 3.3.

3.3 Costing Methods

In product costing, several methods have been developed to determine the cost structure of a product. Whether a method is suitable or not depends heavily on the particular properties of the company (e.g. manufacturing methods) and the type of product they are making business with.[139]

The influencing parameters are:[140]

- productive capacity of the manufacturing process (mass-, batch-, unit- or charge- production)
- product type (single part goods, liquids, gases, pulverized goods or assembled goods like cars)
- manufacturing process (especially how many stages of production)

In order to determine whether a method is suitable or not, it is necessary to know if one or more products are produced. Assuming that more than one product is made, one has to ask the question if those commodities can be manufactured independently with the existing production process or if the manufacture of one product inevitably generates more goods (e.g. refinery).[141] Figure 3.2 gives an overview of the existing methods depending on the type of production and product.

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[138] cf. BERKAU, HIRSCHMANN, SCHEER (1997), pp. 194-195

[139] cf. GÖTZE (2010), p. 100

[140] cf. KILGER, PAMPEL, VIKAS (2007), pp. 509-511

[141] cf. GÖTZE (2010), p. 101

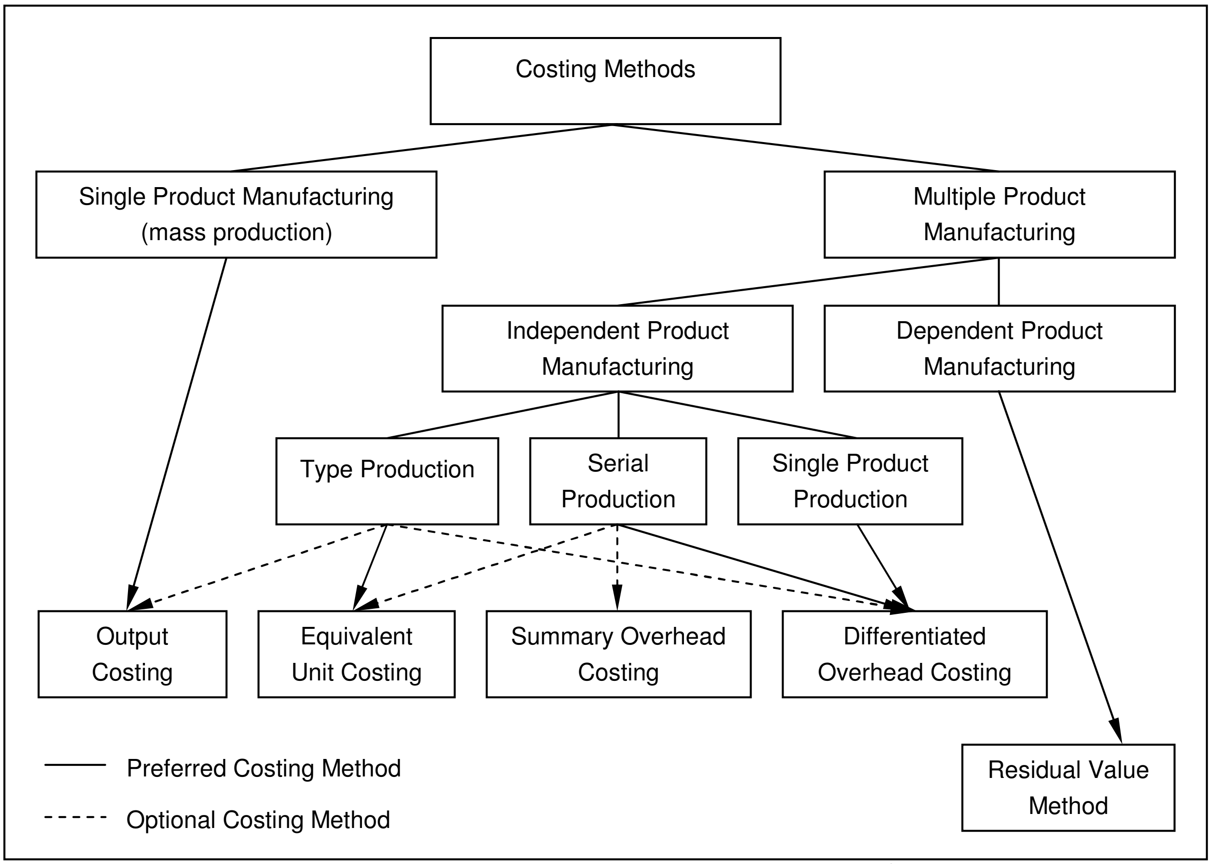

Figure 3.2: Costing Methods Depending on Type of Production/Products[142]

3.3.1 Output Costing

In the simplest form of output costing the total costs of a company, division, project or product are divided by the number of products without differentiating between direct and indirect costs[143]. A precondition of this method is that the produced goods are homogeneous and that only one type of product is manufactured. Homogeneous in this context means that every single product is consuming the same amount of resources during its creation.[144] This method is mostly used for mass production companies with a single product approach for cost estimation.[145] However, it is also used for companies with type production (see Figure 3.2).

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[142] cf. FREIDANK (2008), p. 157

[143] cf. HOITSCH, LINGNAU (2004), p. 221

[144] cf. KLÜMPER, ZIMMERMANN (2002), pp. 161-162

[145] cf. HOITSCH, LINGNAU (2004), p. 221

3.3.2 Equivalent Unit Costing

Equivalent unit costing can be used if the manufactured products are similar in their structure and processed resources; that is, the by-products (e.g. metallurgical industry, breweries, concrete factory, etc.). In this method the costs of products are proportional to each other due to similar manufacturing processes. Therefore, every product is identified with an equivalent number which indicates its costs compared to the product with the equivalent number one. For instance, the standard beer of a brewery has the equivalent number one, whereas a bock beer has an equivalent number greater than one because it is more expensive to produce.[146]

3.3.3 Overhead Costing

Overhead costing is used for batch production and contract manufacturing, because the manufacturing of the products consumes different amounts of resources due to no or few similarities in structure and design. Therefore, more sophisticated costing is needed to allocate costs according to their origin and reason. The method is based on allocating direct costs directly and allocating indirect costs through an overhead application rate to the product. Basically, there are two methods in overhead costing introduced in this section.[147]

Summary Overhead Costing

Summary overhead costing is a simplified version of overhead costing and is characterized by the fact that the total indirect costs of a company are allocated by an overhead application rate. As a base for the overhead cost rate the total direct costs, the material costs (especially in material intensive production) or the total manufacturing costs (especially in labor intensive production) can be used.[148] For this method cost-centre accounting is not necessary, because the indirect costs need not to be split-up between the different cost centres. However, this leads to relatively inaccurate results and it does not fulfill an origin and reason related allocation of costs.[149]

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[146] cf. BAUER (2008), Chapter 3, pp. 62-63

[147] cf. KALENBERG (2004), p. 120

[148] cf. FREIDANK (2008), p. 158

[149] cf. GÖTZE (2010), pp. 113-114

Differentiated Overhead Costing

The starting point of differentiated overhead costing is the cost-centre accounting which allocates all indirect costs to the cost-centre's to which they accrued.[150]

Indirect costs are included in the calculation through overhead application rates for each cost-centre which can be seen in the example below (see Formula 3.1):

Total Direct Production Costs Centre 1: € 200,000
Total Indirect Production Costs Centre 1: € 160,000
Direct Production Costs Centre 1: € 180/unit

Overhead Application Rate for Production Centre 1: $\frac{€\ 160{,}000}{€\ 200{,}000} = 80\%$

Indirect Production Costs Centre 1: $\boxed{€\ 180\ \cdot 80\% = €\ 144}$

Note: same scheme for all other cost centers available

***Formula 3.1: Differentiated Overhead Costing*[151]**

A general scheme for differentiated overhead costing can be seen in the table below (see Table 3.2):

<table>
<tr><td>Direct Material Costs</td><td rowspan="2">Material Costs</td><td rowspan="5">Manufacturing Costs</td><td rowspan="8">Primary Costs</td></tr>
<tr><td>Indirect Material Costs</td></tr>
<tr><td>Direct Production Costs</td><td rowspan="3">Production Costs</td></tr>
<tr><td>Indirect Production Costs</td></tr>
<tr><td>Special Direct Production Costs</td></tr>
<tr><td colspan="2">Indirect Administrative Costs</td><td rowspan="3">Administrative and Distribution Costs</td></tr>
<tr><td colspan="2">Indirect Distribution Costs</td></tr>
<tr><td colspan="2">Special Direct Distribution Costs</td></tr>
</table>

***Table 3.2: Differentiated Overhead Costing Scheme*[152]**

---

[150] cf. RÜTH (2006), p. 173

[151] cf. GÖTZE (2010), pp. 115-117

[152] cf. BAUER (2008), Chapter 3, p. 59; GÖTZE (2010), p. 115

3.3.4 Residual Value Costing

All discussed methods are used for single product manufacturing and independent product manufacturing. Residual value costing is used for products which cannot be produced independently from each other. This means that if a certain product is produced, one or more other by-products are generated inevitably (e.g. refinery: gas-oil-domestic gas; furnace process: raw iron-blast furnace gas-iron blast furnace slag). The task of residual value costing is to distribute the accrued total costs of the production process amongst all the generated products. One way to do so is to determine the revenue of each by-product and subtract it from the total costs. The remaining total costs are then divided by the quantity of the main product and leads to the unit price of one main product.[153]

All methods in this section assume that all cost information is available. The modular product architecture for High Pressure Fuel Storage Systems (HPFSS) is currently developed which implies that not all cost information is available yet. In order to determine missing cost information appropriate methods for cost estimation need to be identified and applied in order to achieve results of informative value and accuracy. Such estimation methods are stated in chapter 3.4.

3.4 Methods for Estimating Costs during Product Development

A successful cost management approach requires an early estimation of costs during product development. Since preliminary costing cannot be conducted due to the fact that detailed information about manufacturing technologies and design of the product is simply not available during development, the product characteristics need to be determined based on their estimated costs.[154] Estimating costs at an early stage is a critical function when proposals for customers and strategic decisions are at stake. The accuracy and the time needed to create a proposal are determining the success and the profitability of a project.[155]

Calculative and non-calculative methods for estimating costs during product development (see Figure 3.3) are shown and described in the subsequent sections.

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[153] cf. BAUER (2008), Chapter 3, pp. 63-64

[154] cf. EHRLENSPIEL, KIEWERT, LINDEMANN (2007), p. 457

[155] cf. FISCHER (2008), p. 131

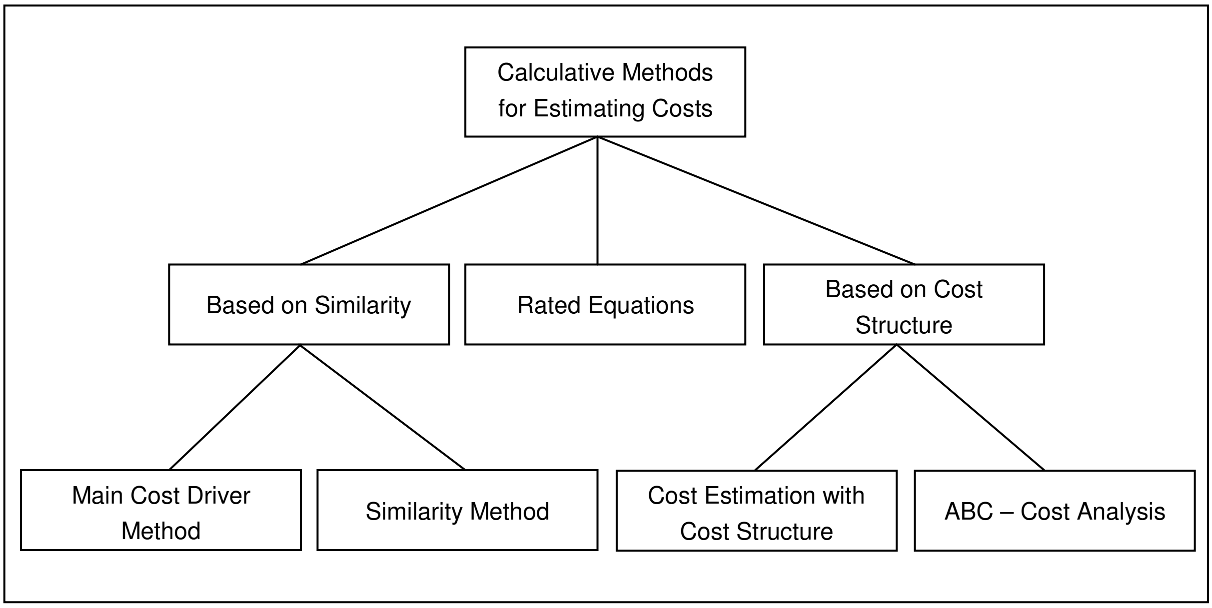

Figure 3.3: Calculative Methods for Estimating Costs during Product Development[156]

3.4.1 Similarity Method

The similarity method corresponds to past experiences with similar or equal products. Comparison of similarities plays a major role when assessing methods to estimate costs during product development. Similarity is defined as the degree of analogy of construction objects in regard to the characteristics of their changeable, cost-relevant features.[157] This method is a very common, relatively simple and quick way to estimate the costs of products during PD. Comparing is quick and reliable if the objects of comparison do not differ much and if sufficient, accurate and up-to-date information is available. However, a precondition of using the similarity method is to search and find suitable similar objects which can be difficult.[158] Objects may include functions, parts, assemblies and modules. Additional information may be bills of materials, used materials and operation charts. This information should not be used directly in the estimation without accounting for differing characteristics and features of the new product.[159]

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[156] cf. HORVATH, GLEICH, SCHOLL (1997), p. 118

[157] cf. BECKER (1997), p. 186

[158] cf. EHRLENSPIEL, KIEWERT, LINDEMANN (2007), p. 411

[159] cf. HORVATH, GLEICH, SCHOLL (1997), p. 119

3.4.2 Main Cost Driver Method

Very often a single parameter of a product determines its cost to such a large extent that it can be used to estimate the total costs of the product. Therefore, this method is very simple but it only delivers acceptable results if the new product is very similar, in terms of design and used manufacturing technologies, to the compared product/s. The three most common types of this method are:[160]

- weight as the main cost driver (e.g. gold mining, €/kg)
- material as the main cost driver (assumes that the ratio between material and assembly/production costs is the same for similar products)
- performance oriented cost drivers(e.g. electric motors, €/# terminal pairs)

Generally, this method is applied in geometrically similar products within a type series. Yet, a precondition is a completely elaborated and calculated base product with full transparency in terms of technical specifications and costs.[161]

3.4.3 Rated Equation Method

In a rated equation the connections between the costs of a product and its basic technical parameters are incorporated in a formula. In other words, technical products and single components always have to perform certain functions. A bolt has to hold parts together by applying a force; a conductor requires a certain conductivity; and a heat exchanger has to exchange thermal energy. These functions can be reproduced by physical-technical equations which are called operational demand equations.[162] The advantage of rated equations is that it includes essential dependencies of the product; hence, when having products with low complexity it leads to the cheapest, lightest, most effective products in qualitative and quantitative regards. Having said that, the disadvantage of this method is that for complex products it is very difficult to derive practically usable rated equations; this is mostly due to the very comprehensive and complex interrelations within the product.

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[160] cf. EHRLENSPIEL, KIEWERT, LINDEMANN (2007), pp. 412-413

[161] cf. HORVATH, GLEICH, SCHOLL (1997), p. 119

[162] cf. LOWKA (1997), pp. 138-140

Therefore, lots of simplifying assumptions are needed to be able to establish an equation. However, due to the assumptions, the accuracy and significance of the results is deteriorating to a degree which may not be acceptable.[163]

3.4.4 Cost Estimation with Cost Structure

Cost estimation by using cost structures is a method based on past experiences and costs of past projects and costings in order to determine their cost structure and their cost drivers. This method is often used when estimating costs in the early stages of product development.[164]

It is based on the following assumptions and calculations seen in Formula 3.2:

$PC = MC + CoL + OCT$

If this equation is divided by 100%, it yields:

$100\% = MC' + CoL' + OCT'$

Legend: PC = Production Costs, MC = Material Costs, CoL = Cost of Labor,

OCT = Other Cost Types;

Formula 3.2: Cost Estimation with Cost Structure - Fractions[165]

MC´, CoL´ and OCT´ are fractions based on the total costs (PC = 100%). The proportion between the cost types is called cost structure. It is assumed that the fractions for the costs types stay the same throughout development; unless, major changes in design or manufacturing technology occur. If it is required to re-estimate the production costs (PC_0) at a later point in time, the fractions are used to determine PC_0. For instance, if the new material cost MC_0 is known, PC_0 is calculated as shown in Formula 3.3.[166]

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[163] cf. EHRLENSPIEL, KIEWERT, LINDEMANN (2007), p. 415

[164] cf. HORNGREN, FOSTER, DATAR (2001), pp. 319-321

[165] cf. LOWKA (1997), pp. 137-138

[166] ibidem

$$PC_0 = \frac{MC_0}{MC'} \cdot 100\%$$

***Formula 3.3: Cost Estimation with Cost Structure - Estimation*[167]**

In the same manner, the costs of a product under development can be estimated under the precondition that the fractions of the cost types of similar products are available. Further, changes in costs due to certain characteristics of the new product have to be considered in the estimation in order to receive results of informative value and acceptable accuracy.[168]

3.4.5 ABC - Cost Analysis

Depending on the impact on total cost, certain cost types should be calculated and estimated more accurately and other cost types which do not have a big impact on total costs should be estimated with simpler methods or are even neglected. Thus, the total error of the estimation is smaller if the high-impact cost types are determined more precisely. The high-impact cost types are called cost drivers.[169] The ABC-Cost Analysis is a method to determine the cost drivers and to identify which cost type should be estimated with more or less accuracy.[170]

The main steps of an ABC-Cost Analysis are shown below:[171]

1. Calculation of the averaged percentage that each cost type holds from the total cost of its product.
2. Depending on the percentage, sort cost types in descending order.
3. Determining the value percentage in regard to the percentage of cost types and create a descending cumulative list of them.
4. Implementing data into a graph (see Figure 3.4) and split the percentage of cost types into three groups (A, B, C) according to the value percentage they hold (see Figure 3.4 with A (80%), B (15%), C (5%)).

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[167] cf. LOWKA (1997), pp. 137-138

[168] ibidem

[169] cf. EHRLENSPIEL, KIEWERT, LINDEMANN (2000), p. 409

[170] cf. HEISS (2004), pp. 32-34

[171] cf. JUNG (2006), p. 325; SCHULTE (2001), pp. 62-63

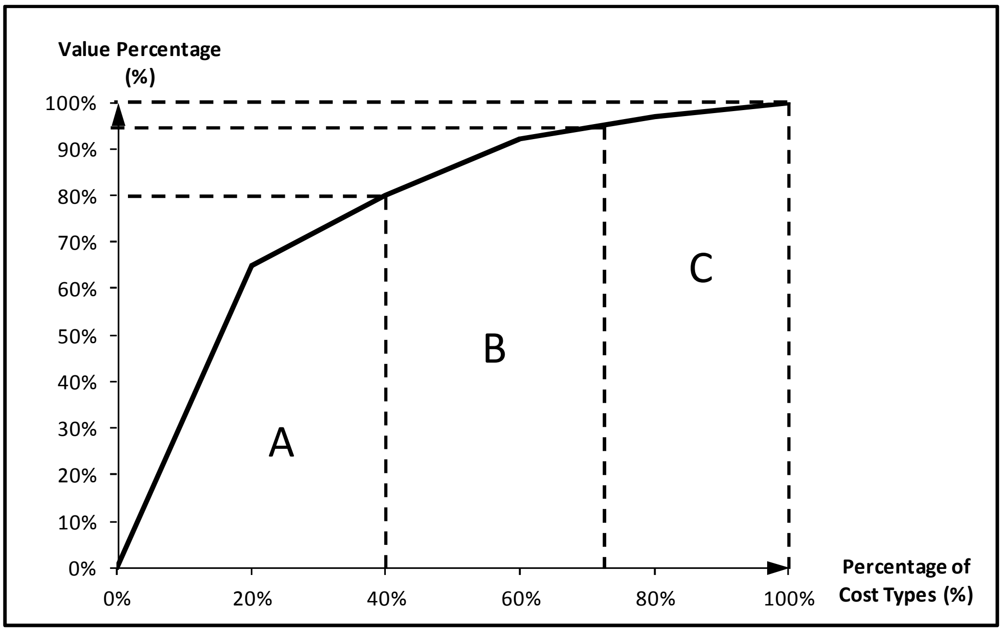

Figure 3.4: ABC - Cost Analysis[172]

3.4.6 Expert Consultation

Expert consultation is a non-calculative method for estimating costs and is quicker than calculating them. It is not as accurate as other methods, however under the right circumstances, pre-conditions and systematic usage it generates results with sufficient accuracy. An important pre-condition is that the experts must have appropriate technical and economical knowledge as well as professional experience with similar situations, parts and operations in order to participate in this approach.[173] Therefore, the expert consultation method is used when little or no information is known about a participating element in the process chain. First, costs are estimated and justified by several experts independently. After that, they are consolidated and averaged.[174]

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[172] cf. SCHULTE (2001), p. 62;JUNG (2006), p. 326

[173] ibidem

[174] cf. WOLF (2009), pp. 81-83

In praxis the following approach proved itself to be fruitful:[175]

1. establish assessment team including all necessary experts and specialists, determine a moderator
2. designer and developer explains the assignment for the product and the planned realization
3. the team discusses potentials for cost reduction and their practical feasibility
4. a controller gathers the information and incorporates it in the estimation
5. all missing costs are estimated by experts, here the work for the experts ends
6. the controller executes the costing independently which results in the estimated total costs for the product

The results of the estimation need to be documented thoroughly in order to compare them to the actual costs and to be used as a base for discussing deviations. In this way a continuous improvement of the results is achieved. However, in using expert consultation to estimate costs, one should be aware of its disadvantages:[176]

- Identified mistakes cannot be used sufficiently to improve future estimations; estimation is always a matter of feeling and intuition.
- Results are very subjective and hard to reproduce; if the expert is no longer available, the continuity regarding the result is no longer existent.
- Estimating cannot be “taught”

3.4.7 Scenario Planning

Scenario planning is a planning method which, based on present circumstances, describes future developments of elements under alternative conditions. An element can be for instance: customer behavior, competitive situation, technological changes, sales figures, etc. Contrary to other planning methods, scenario planning does not attempt to determine the most correct and exact picture of the future; it strives towards establishing and identifying several alternative future scenarios. The number of possible scenarios increases exponentially with time, which creates the characteristic trumpet-shaped graphical interpretation of scenarios over time (also called the scenario funnel see Figure 3.5).[177]

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[175] cf. LOWKA (1997), pp. 140-141

[176] cf. EHRLENSPIEL, KIEWERT, LINDEMANN (2007), p. 410

[177] cf. BEA, HAAS (2005), pp. 287-288

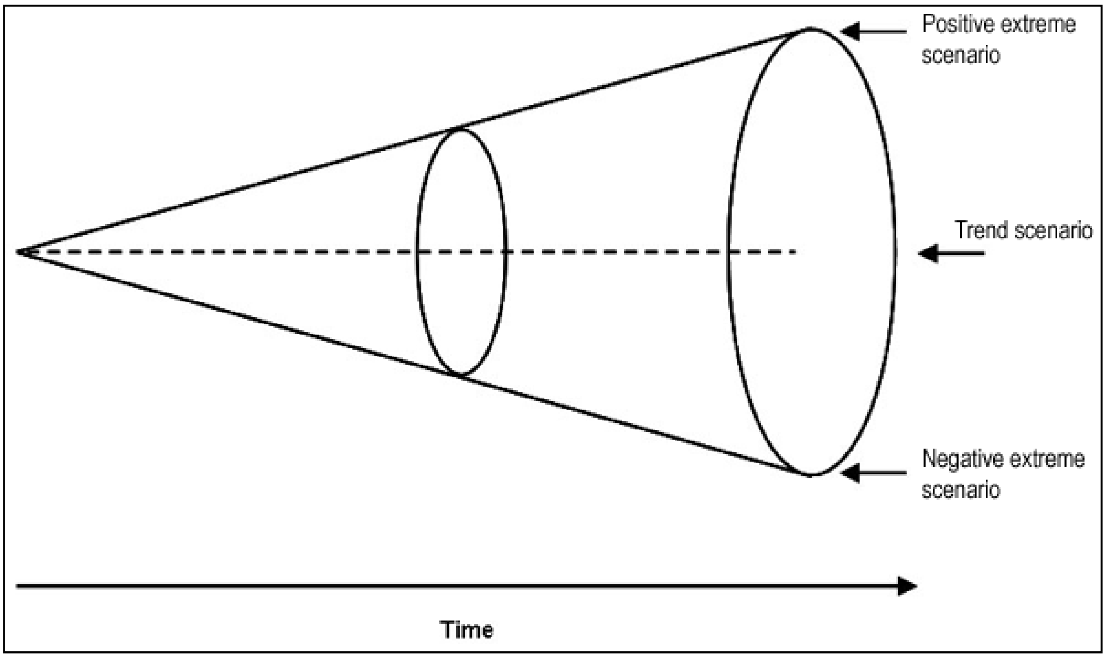

Figure 3.5: Scenario Funnel[178]

The scenario funnel (i.e. scenario planning) assumes optimal, average and bad developments of the analyzed elements. Hence, the scenario funnel includes a positive extreme scenario (best case scenario), a negative extreme scenario (worst case scenario) and a trend scenario (see Figure 21).[179] Further, the cross-section at the end of the funnel represents the total number of possible scenarios.[180] This method relies on statistical data and analysis and is especially useful to forecast chances, risks, sales figures and high-uncertainty-costs.[181]

Regarding scenario planning types, one distinguishes between:[182]

- **Tactical Scenario Planning**
  Uses quantitative methods and information and is rather short-term oriented.
- **Strategic Scenario Planning**
  Focuses on using qualitative methods and information and is rather long-term oriented.

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[178] cf. KUHNER, MALTRY (2006), p. 111; ZINGEL (2004), p. 108; BEA, HAAS (2005), p. 289

[179] cf. ZINGEL (2004), p. 108

[180] cf. KUHNER, MALTRY (2006), p. 112

[181] cf. ZINGEL (2004), p. 108

[182] ibidem

Based on this information, the following characteristics of the scenario planning method can be identified:[183]

- The method is either long- or short-term oriented
- Scenario planning does not extrapolate past data, or assume a deterministic future, it assumes a future which is predictable to a certain degree and considers speculative developments in its analysis as well;
- Several scenarios are established in order to cover as much future development scenarios as possible, which are based on alternative but consistent assumptions;
- Scenario planning does not only create future scenarios, it also illustrates their development from the present into the future;
- In addition to quantitative values and effects it also considers qualitative circumstances in regards to interdependencies between other elements;

Scenario Planning is a structured approach to answer three questions:[184]

1. Which future scenarios are thinkable?
2. Which future scenarios are credible?
3. Which future scenarios are representative?

Thus, the end-product of scenario planning is a small number of thinkable, credible and representative future scenarios. The purpose of scenario planning is to narrow the complexity of future developments down to a few manageable scenarios.[185]

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[183] cf. BEA, HAAS (2005), p. 288

[184] cf. KUHNER, MALTRY (2006), p. 112

[185] ibidem

Summary

Costing fulfills several functions and is particularly important to support decision making. In this chapter the different sources of cost information are stated in order to develop a rudimentary understanding what sources are available and how they are calculated. In this thesis preliminary costings are used as a basis for cost information since modular High Pressure Fuel Storage Systems (HPFSS) are situated in a very early stage in the product development process. Furthermore, a comparative costing is carried out where several parameters should be taken into consideration if one seeks to increase the accuracy of the results. The biggest problem with costing in the context of the thesis is that the earlier in the product development process it is conducted the higher the uncertainty and the lower the availability of cost information is. Preventive measures should be taken to ensure the correctness of costs in order to deliver results of informative value. This can be done by using proper methods to estimate costs which are introduced in this chapter.

The last two chapters (see chapter 2 and 3) are basically concerned with products in general and their behavior in terms of costs. This thesis is centered on a product called High Pressure Fuel Storage System (HPFSS); therefore, it needs to be explained in technical terms to understand its characteristics, functionality and components which can be found in the subsequent chapter (see chapter 4).

4 High Pressure Fuel Storage Systems

In this chapter the product which serves as the subject of this thesis is described in technical-terms. At first, the main assembly is broken down to its main components; then, the functionality and task of each component is described and also graphically displayed. The purpose of the chapter is to give the reader a fundamental understanding of the products functionality and the context in which it operates.

4.1 Purpose of Use

The purpose of a High Pressure Fuel Storage System (HPFSS), as its name states, is to store alternative sources of energy (e.g. gaseous fuels) in containers under high pressure. Demand for such systems (also called modules) originates from the idea to power vehicles with alternative sources of energy and the will to build more environmentally friendly means of transportation. To do so, sufficient fuel has to be stored somewhere in the vehicle. According to the type of fuel, the design, restrictions, industry standards, safety regulations and the characteristics of the HPFSS are developed.[186]

MS focuses on developing/manufacturing products which run on CNG and H_2 and since these fuels are gaseous under most circumstances they must be pressurized to achieve the energy density required to make the technology feasible for automotive applications. Therefore, fuels are compressed up to (CNG 200-280bar, H_2 200-700bar) 700bar and filled into the containers. Once pressurized, the fuel is stored until it is needed by a combustion engine or a fuel cell in order to produce energy to power the vehicle. Having high pressure vessels on board of a vehicle presents safety hazards which need to be minimized by appropriate measures. Depending on the country and the fuel type, a HPFSS has to comply with stringent safety standards and regulations. Pressure vessels, pressure regulator etc., and the system as a whole needs to be certified and validated by technical inspection agencies. The certification and validation may involve a considerable amount of effort in terms of time, investment and development.[187]

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[186] cf. SCHÜLE et al. (2008), pp. 132-133

[187] Interview with Uwe Thien (18.11.2011), Project Manager CNG Systems at Magna Steyr

4.2 Main Components and their Functionality

Below the main components of HPFSSs and their functionality are described. It should be mentioned that the description of the components does not go into technical detail; as a general explanation of the components functionality is sufficient in providing a fundamental understanding on the topic.

4.2.1 Assembly

Due to the fact that CNG HPFSSs are more widely used, the explanation refers to a 200bar CNG HPFSS. The description of the components starts with the filling-line and proceeds with those parts which are next in the fuel supply chain of a vehicle. The assembly of such a HPFSS can be seen in Figure 4.1.

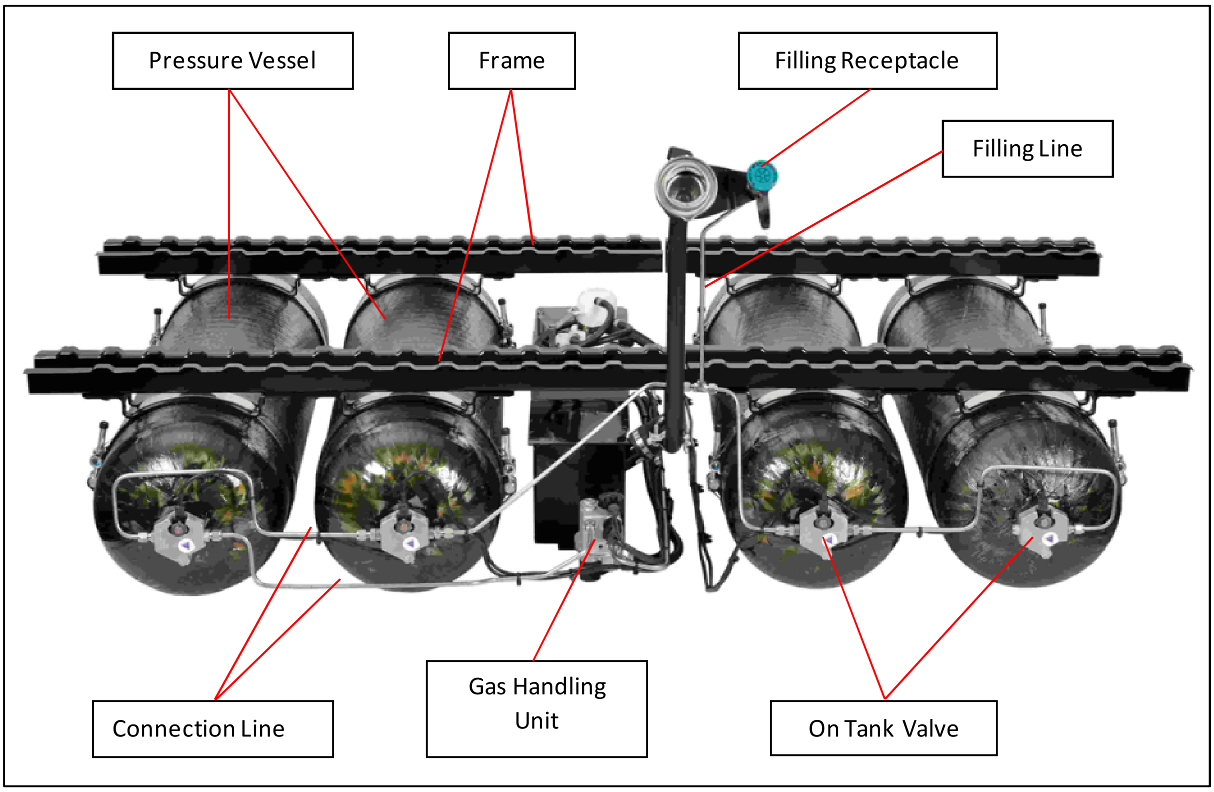

Figure 4.1: High Pressure Fuel Storage System Assembly[188]

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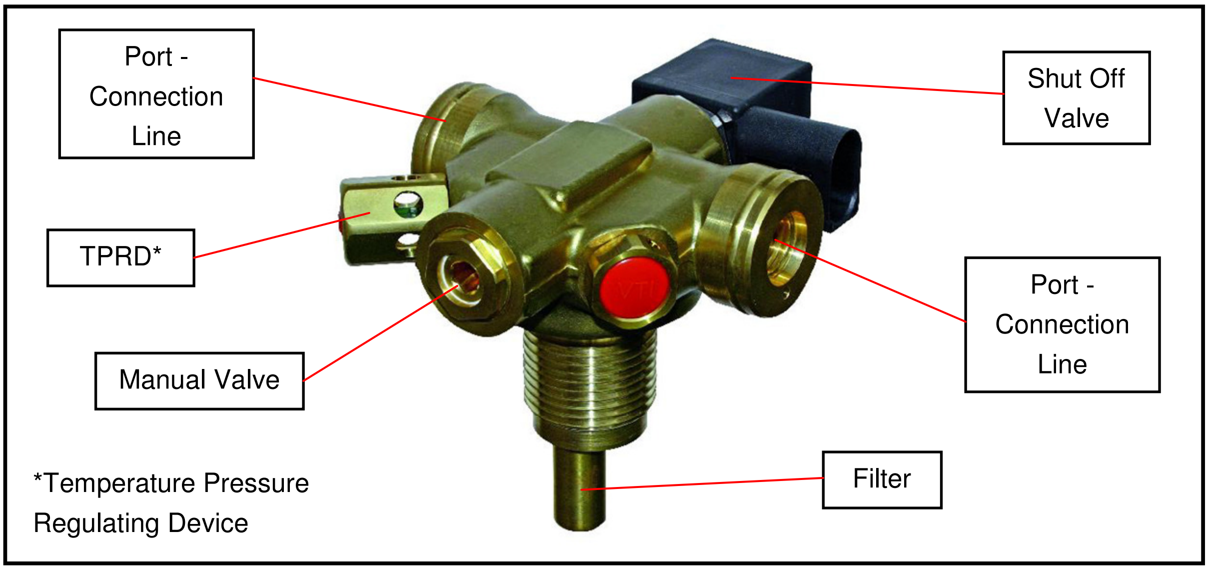
[188] cf. MAGNA STEYR (2012a), p. 2

4.2.2 Filling Line

As the name suggests, the filling line is the component between the refueling receptacle and the storage module responsible for establishing and maintaining a connection to the module during filling of the pressure vessels with compressed gaseous fuel. It consists of a refueling receptacle, a High Pressure (HP) line made of metal, a port, a filter and a check valve. The refueling receptacle is the part of the module connected with a spigot in order to transfer the fuel from an external storage container (e.g. gas station) to the module. Here, the fuel flows through a HP line until it reaches a port which is connected to the module. A check valve is built-in to ensure that fuel is not capable of streaming back and the filter is responsible for filtering down to 20µm particles. Note: The filling line has to cope with HP (up to 200bar CNG/700bar H_2) and therefore needs to be designed accordingly.[189]

4.2.3 On Tank Valve

The On Tank Valve (OTV) is mounted directly into the pressure vessel and comprises several components (see Figure 4.2). Basically, it is responsible to completely control the flow of fuel in and out of the pressure vessel and therefore ensures the safe operation of the pressure vessel it is attached to.[190]



*Temperature Pressure Regulating Device

Figure 4.2: CNG - On Tank Valve[191]

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[189] cf. HOLLEMBEAK (2005), pp. 341-342

[190] Interview with Uwe Thien (18.11.2011), Project Manager CNG Systems at Magna Steyr

[191] cf. VTI VENTIL TECHNIK GMBH (2012)

The OTV consists of the following components:[192]

Temperature Pressure Regulating Device (TPRD): If the surrounding temperature exceeds a certain value, the TPRD enables the gas to stream out via a venting line in a controlled manner. Otherwise, the temperature may increase the pressure inside the vessel to a critical value at which the pressure vessel may burst. Depending on the design of the system and on the customer’s specifications, a pressure vessel may feature one or more TPRD´s, which grants an even higher degree of safety for the system.

Shut Off Valve (SOV): The SOV controls the streaming of gas in and out of the element to which it is attached during regular operation (temperature is within boundaries, manual valve is closed) The SOV valve serves two functions. First, it closes the valve mechanically when the vehicle is turned off so that no gas can stream out of the pressure vessel. Secondly, it electrically regulates the amount of gas that streams out when the vehicle is turned on. However, this does not mean that it is able to regulate the pressure; it just regulates the amount of gas that streams through it.

Manual Valve (MV): The MV is used to manually open or close the line in which the gas streams in or out of the vessel. It is used for instance when repairing, maintaining or replacing a pressure vessel to ensure that no residual pressure is left in the pressure vessel.

Excess Flow Limiter: The excess flow limiter is, as its name states, a regulatory device that controls the amount of gas that flows through a defined position. In one direction it is completely open and the gas can flow without any restriction, however opposing flow is limited to specific rate. Note: Excess Flow Limiter not shown in Figure 4.2.

Filter: The filter is responsible for filtering particles down to a specified size. Usually the filter embedded into the OTV filters particles with a size of 10µm or bigger.

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[192] Interview with Uwe Thien (18.11.2011), Project Manager CNG Systems at Magna Steyr

4.2.4 Pressure Vessel

The pressure vessel is the storage container in the module which contains the highly compressed gaseous fuel. Therefore, it has to withstand enormous forces due to high pressure and it is the most critical component in terms of safety at the same time. Furthermore, there are several ways to mount the vessel to the vehicle in order to ensure its stability. Normally, they are either mounted rigidly to a frame by brackets, or tension belts (see Figure 4.3) which hold the container in place. A so called “boss” is inserted on both sides of the vessel which serves as a port to screw-in devices (e.g. OTV, TPRD) or simply a plug to close it. However, there are many types of pressure vessels which mostly differ in terms of their materials of construction (see Figure 4.4). [193]

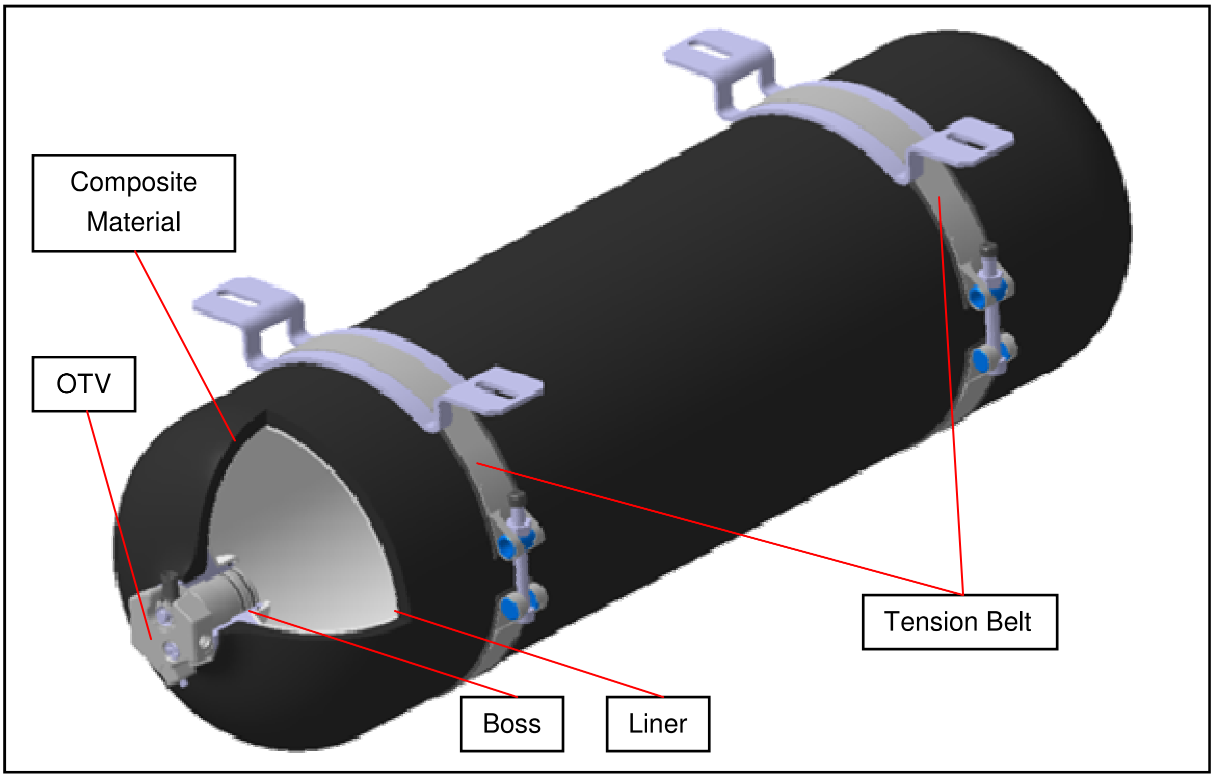

Figure 4.3: Type IV - Pressure Vessel[194]

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[193] cf. VASILIEV (2009), pp. 1-2

[194] cf. MAGNA STEYR (2012b), p. 3

Most common pressure vessel types are (see Figure 4.4):[195]

Type I: This type of vessel consists solely out of metal (i.e. aluminum or steel) and shows low cost in production but is also very heavy.

Type II: Here, a liner made of metal is combined with composite material (i.e. glas or carbon fiber). A liner is a thin walled vessel shaped part which, for Type I vessels, takes approximately 50% of the stress caused by the pressure. The other 50% is taken by the composite material which is only wrapped around the middle of the liner ("hoop wrapped"). This configuration is less heavy but has higher costs than Type I vessels.

Type III: Type III vessels are similar to Type II vessels with the exception that the composite is wrapped around the entire liner ("fully wrapped") and not only in the middle of the container ("hoop wrapped"). In this configuration the composite takes the biggest of amount of stress. This type of vessel is lightweight but it has higher production cost at the same time.

Type IV: This configuration is very similar to Type III vessels but it uses a plastic liner instead of a metal liner. Thus, the entire stress resulting from the internal pressure is basically taken by the composite material. Type IV vessels are very lightweight but also very expensive to produce.

Note: MS is focusing on the development and production of Type IV vessels.

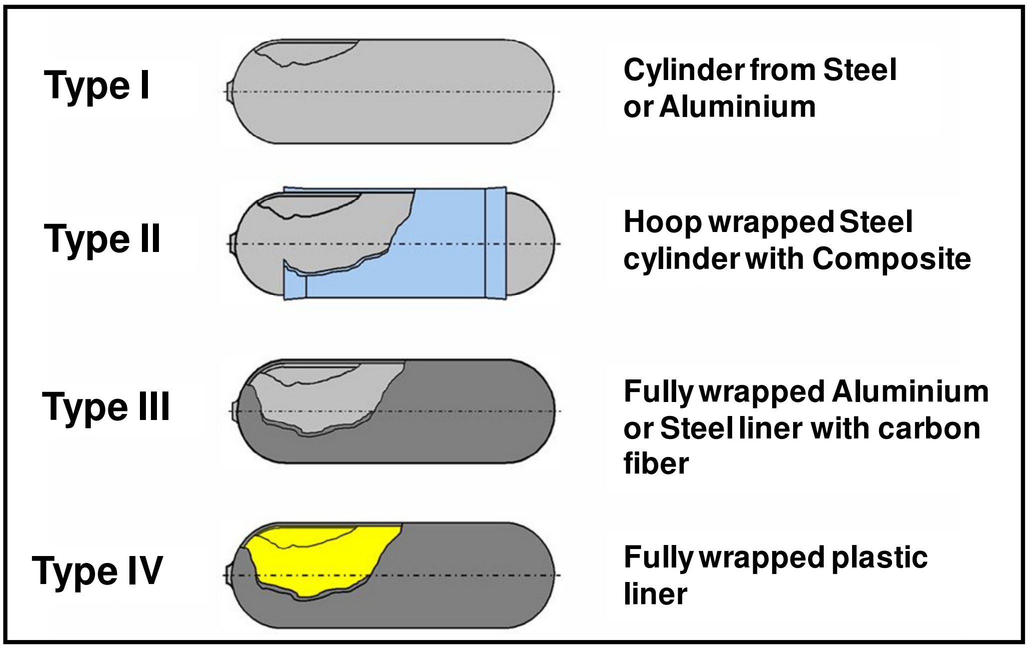

Figure 4.4: Pressure Vessel Types[196]

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[195] cf. SIROSH, NIEDZWIECKI (2008), pp. 294-296

[196] cf. MAGNA STEYR (2012a), p. 1

4.2.5 Connection Line

The purpose of the connection line, as its name states, is to establish and maintain a connection between two or more elements by usually using a high-strength pipe made of metal. Elements typically refers to OTV´s, because all other pipes serve other purposes such as venting, filling, defueling or providing fuel to the propulsion unit. All these lines are more or less the same; the differentiation is made to give a thorough description of the systems functionality. However, the main task of the connection pipes is to consolidate the gas streams coming from the OTV´s and leading them to the gas handling unit (see section 4.2.6). Connection lines have to cope with HP and therefore need to be designed accordingly.[197]

4.2.6 Gas Handling Unit

The Gas Handling Unit (GHU) is a collective term for the assembly in a HPFSS which is responsible for many assignments and consist depending on the fuel type out of more or less components. As already mentioned in section 4.2.5, the fuel is consolidated by connection lines and brought to the GHU where it undergoes a change in pressure. The components of a GHU are shown in Figure 4.5.

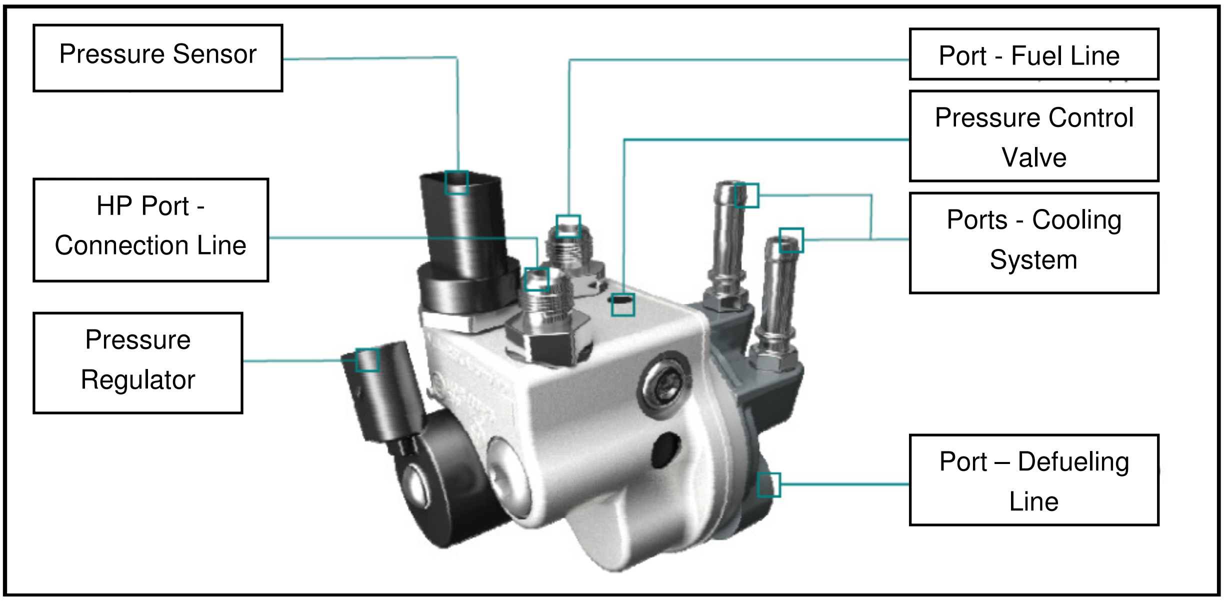

Figure 4.5: Gas Handling Unit (GHU)[198]

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[197] Interview with Uwe Thien (18.11.2011), Project Manager CNG Systems at Magna Steyr

[198] cf. VENTREX AUTOMOTIVE GMBH (2011)

The GHU consists of the following components (see Figure 4.5):[199]

Pressure Regulator: The main assignment of the GHU is to regulate the pressure to a lower level according to the needs of the propulsion unit (usually 8-10bar for CNG and H_2). This task is the responsibility of the pressure regulator which can be electrically or mechanically actuated.

Check Valve: The check valve is a regulatory device that controls in which direction the gas is able to flow and in which it cannot. For one direction it is completely open and the gas can stream without any restrictions. In the other direction, the gas is stopped from passing through the check valve.

Pressure Control Valve: The pressure control valve is a mechanically or electrically actuated device which serves as a safety mechanism against pressure overloads. Pressure overloads may lead to issues within the propulsion unit or even destroy it. Therefore, a pressure control valve is implemented after the pressure regulator; in case of a regulator malfunction, the pressure will signal the pressure control valve to release excess pressure.

Port - Fuel Line: This port is used to connect the GHU with the Low Pressure (LP) fuel line, which supplies the propulsion unit of the vehicle with fuel.

Port - Defueling Line (optional): This connects the defueling line with the GHU which is used to release pressure in a controlled way (see section 4.2.9).

HP Port - Connection Line: This port connects the GHU with the connection line (see section 4.2.5).

Ports - Cooling System: Due to gas expansion/compression, heat may be generated and raises the temperature within the GHU. Therefore, a cooling system is implemented into the GHU to keep the temperature at a specified level.

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[199] cf. SCHÜLE et al. (2008), pp. 138-139; HOLLEMBEAK (2005), pp. 339-341

4.2.7 Fuel Line

The fuel line is the actual connection between the HPFSS and the propulsion unit of the vehicle. Thus, it is responsible for establishing and maintaining a physical connection to provide fuel from the HPFSS to the propulsion unit. It usually comprises a metal pipe equipped with one port on each side; one is connected to the "Port - Fuel Line" (see section 4.2.6) of the GHU and one to the propulsion unit of the vehicle. The fuel line does not have to be as thick-walled as the HP lines, because the pressure has already been regulated down to a lower level (8-10bar) by the pressure regulator in the GHU.[200]

4.2.8 Venting Line

A venting line may be built into the module due to the need for a designated position where the pressure is released in case of a safety threat or when a parameter exceeds his boundaries (e.g. low pressure valve). This means, the venting line is connected with the safety and regulatory devices of all OTV´s and the GHU. This usually comprises all TPRD´s and the low pressure regulator. It consists of several ports and metal pipes which consolidate the gas from the safety devices and transports it to a defined location where it is released in a controlled fashion.[201]

4.2.9 Defueling Line

The purpose of the defueling line is to manually release pressure in a controlled way if necessary. This may be done during maintenance, repairs or exchanging one or more vessels to ensure that no residual pressure remains in the module/vessel. Using a separate defueling line is optional due to the fact that the venting line can be used or the gas can stream out directly at the OTV using the MV. If a defueling line is implemented, it comprises a port to connect it to the gas handling unit, a manual valve and of course a metal pipe.[202]

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[200] cf. HOLLEMBEAK (2005), pp. 339-341

[201] Interview with Uwe Thien (18.11.2011), Project Manager CNG Systems at Magna Steyr

[202] ibidem

4.2.10 Frame

The frame is the backbone of the module. It ensures the stability and integrity of the system and represents a rigid connection to the vehicle. It is responsible for securing all other elements of the module and holding them in place for proper performance. At the same time, it is exposed to mechanical, chemical and biological effects and needs to be able to withstand them. In general, it consists of a painted or coated metal frame using brackets and bolts to mount the vessels on the frame. Nowadays, flexible plastic tension belts are also used to hold the vessels in place giving them a higher degree of flexibility against deformation. However, these belts are still mounted on a rigid metal frame to ensure stability. [203]

Summary

A High Pressure Fuel Storage System (HPFSS) consists of many components which have to comply with stringent safety standards and country-specific regulations. The pressure vessels represent the containers in which the compressed gaseous fuel is stored. There are four different types of containers; Magna Steyr develops and manufactures only type VI pressure vessels which is the reason why solely type VI containers are assessed in this thesis. Some components are not subject to be modularized due to their characteristics. For instance, filling line, pressure vessel, connection line, fuel line, venting line and defueling line are components which are difficult to be modularized due to the fact that they need to be designed according to the customer's specifications and needs. On the other hand, the on-tank-valve and the gas handling unit can be easily modularized due to their application in the product.

Since the configuration of the modular architecture for HPFSS has to be kept confidential, a detailed description of the modular components is not subject to be published in this thesis. In the subsequent part of the thesis (see chapter 5) the theoretical background of the literature review is used to conduct a comparative analysis between the prevailing and the modular product architecture for HPFSS.

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[203] Interview with Franz Mayr (05.12.2011), supervisor at Magna Steyr

5 Comparative Analysis of HPFSS

Note: High Pressure Fuel Storage Systems (HPFSS)

In order to identify the effects when using a modular product approach to manufacture and develop HPFSS at MS a thorough and quantitative comparative costing is conducted. The goal is to compare the costs which accrue if using the prevailing approach with the costs of the same HPFSS build-up with a modular approach. The results of the costing will be used as a basis for making a strategic decision of whether to further pursue the modular product architecture for HPFSSs at MS or not.

Due to confidentiality reasons, costs, prices and names are replaced by placeholders. All costs and prices are expressed in a virtual currency which is called Storage System Unit (SSU). The real values are multiplied by a predefined but not published factor in order to keep the information confidential. Names of customers (e.g. name of OEM) are expressed in a way that it is impossible to trace them back (e.g. Project A, Project B, etc.) as well.

5.1 Comparison Approach

In this chapter, it is described how the comparison of the two product architectures is conducted. At first it states a summary of the initial situation followed by the prevailing limitations (e.g. technical-, information-wise, etc.) which have a strong impact on the approach used for the comparative analysis. Based on all this information the comparison approach is derived and explained (see section 5.1.3).

5.1.1 Initial Situation

There are several different configurations possible for HPFSSs. Currently the following versions are manufactured, developed or planned by MS:

- 200 bar CNG Modules (manufacture and development)
- 200 bar H_2 Modules (planned)
- 350 bar H_2 Modules (planned)
- 700 bar H_2 Modules (manufacture and development)

It needs to be decided which of these configurations is suitable for inclusion in a modular product architecture and to be part of the comparison analysis.

5.1.2 Limitations

When deciding which methods or tools are used in a practical approach it is crucial to identify the limitations at the current point in time in advance. Below the limitations regarding HPFSSs at MS are quoted.

Influence of Time on Costs in Costing

The influence on costs and the availability of costs is strongly dependant on the point in time when the proposal, costing or analysis is conducted (see Figure 3.1 in chapter 3). Since the focus of this thesis is on the comparison of two product development approaches which are heavily relying on costs, this limitation needs to be taken into consideration. HPFSSs are innovative, fast changing and "young" products which are still under development. The red mark in Figure 5.1 displays the point in time where the comparative costing is carried out. Thus, the availability of costs is likely to be very limited which most likely will have a considerable effect on the uncertainty of the results. This needs to be taken into consideration with appropriate measures. Such measures are discussed in section 3.4.

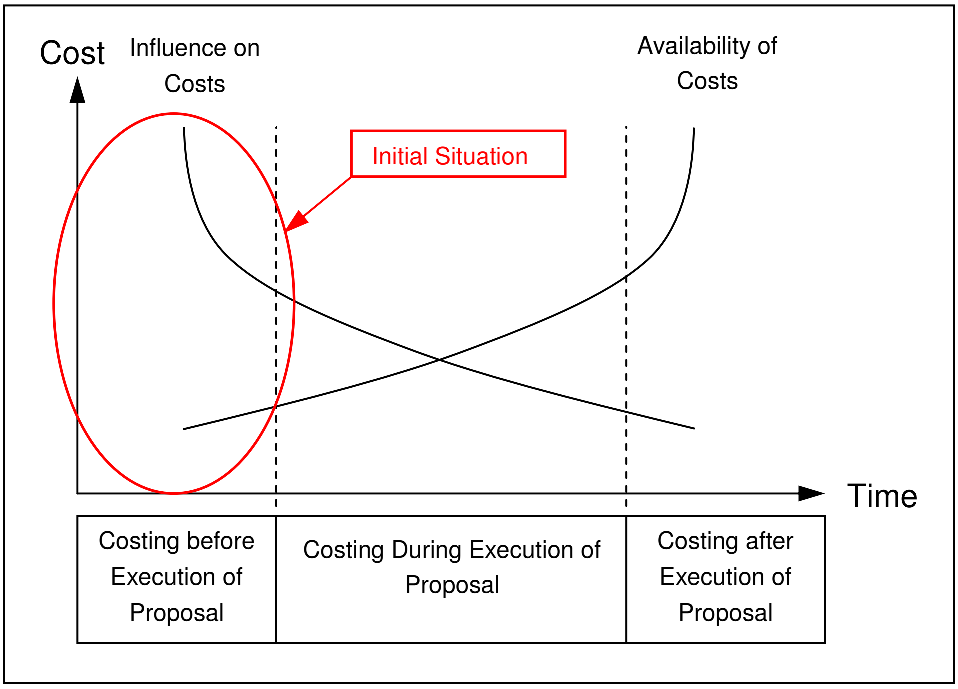

Figure 5.1: Influence of Time on Costs - Initial Situation[204]

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[204] cf. BOTTA (1997), p. 78; BERKAU, HIRSCHMANN, SCHEER (1997), p. 194

200-350bar H_2 Modules

This type of system is expected to be realized in the near future. Thus, neither information about costs and quantities, nor experience with such systems is available.

700bar H_2 Modules

For this configuration the production quantities are simply too low for utilizing Economies of Scale (EOS) using modularized components; 700bar H_2 modules are still in the developmental/prototype phase and cost information is connected with very high uncertainty or is even not available. Furthermore, this type of HPFSS is not suitable for a modular approach in technical terms as well; the components in a 700bar system differ too greatly from those in other systems due to the extremely high pressure; using the same parts in the other configurations with a significantly lower level of pressure would be overkill and cannot be economically justified.

5.1.3 Approach

After considering the initial situation and limitations the approach shown in Figure 5.2 is used to conduct the comparative analysis.

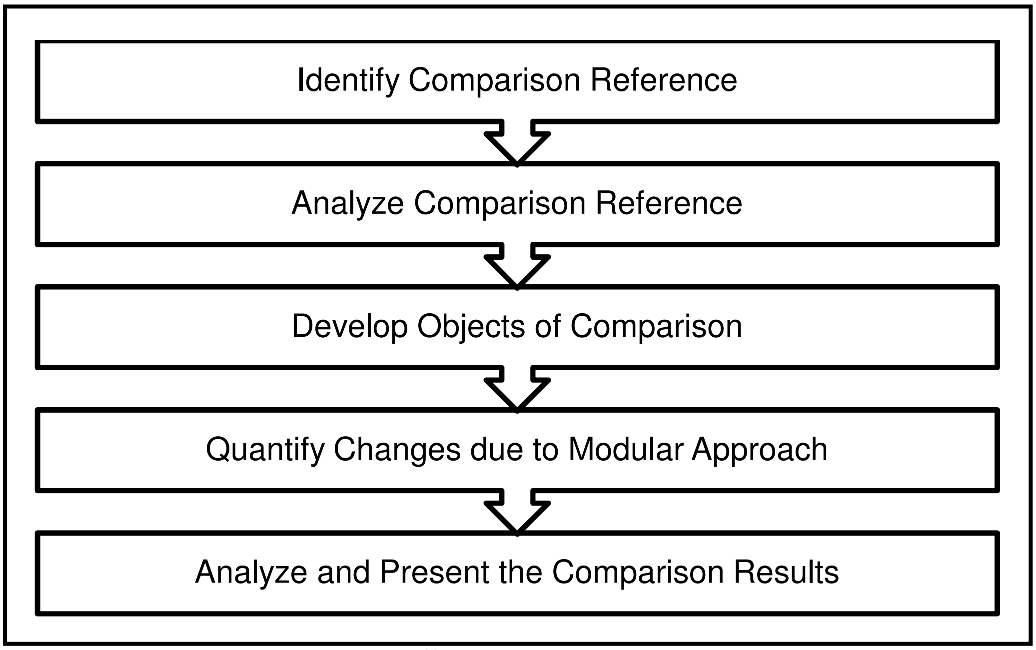

Figure 5.2: Comparison Approach[205]

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[205] Own Illustration

5.2 Identify Comparison Reference

First of all it needs to be pointed out that, according to the literature review, the comparison conducted in this thesis can be called an interim comparison costing based on preliminary costings of past projects and using the similarity method to compare them with each other.

Every basis of a comparison serves as a reference to compare everything with. There are four different types of HPFSS (200bar CNG, 200bar/350bar/700bar H_2). In section 5.1.2 it is described that 200bar/350bar H_2 are planned configurations which means there is insufficient information and experience available. Furthermore, 700bar H_2 was identified not to be included in the analysis due to technical and economical reason. The only configuration left is 200bar CNG modules which proved to be suitable for analysis because sufficient information about costs and sufficient experience with these systems is available at MS.

The five most recently conducted preliminary costings for 200bar CNG HPFSSs are subject to be assessed whether they are suitable to serve as a reference for the comparison or not. The basic information about the projects is shown in Table 5.1.

Basic Information	**Project Q**	**Project E**	**Project M**	**Project G**	**Project O**
Production Location	Graz	Graz	Graz	Graz	Graz
Modules Total	25.000	390	42.900	3.900	50.000
Modules per year	5.000	130	8.580	1.300	10.000
Price Basis	2012	2012	2012	2011	2012

Table 5.1: Basic Information - Available Costings[206]

Whether a project is suitable for serving as a reference is assessed in Table 5.2. The table comprises the most essential requirements for a project for being included in the comparison analysis. These requirements were established in collaborative work with MS experts.

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[206] cf. MAGNA STEYR (2010c); MAGNA STEYR (2010d); MAGNA STEYR (2010e); MAGNA STEYR (2010f); MAGNA STEYR (2011b)

Requirement	Project Q	Project E	Project M	Project G	Project O
Production Location in Graz	Yes	Yes	Yes	Yes	Yes
Sufficient Quantity for Modular System (>10.000 modules)	Yes	No	Yes	No	Yes
Price Basis not older than two Years	Yes	Yes	Yes	Yes	Yes
Sufficient Information Available	Yes	No	Yes	Yes	Yes
Technical Feasibility for Modular Approach	Yes	Yes	Yes	No	Yes

Table 5.2: Reference Costing Assessment [207]

As the assessment shows, all projects are suitable to be included in the comparative analysis except for Project E and Project G. All other projects (Project Q, Project M, Project O) are from now on called the "Reference" and are used as the basis for comparison.

On the following three pages, the reference systems are introduced including basic information about their characteristics, application and configuration followed by a summary of their preliminary costings.

---

[207] Own Illustration

5.2.1 Project Q - Reference

Project Q (see Figure 5.3) was designed to be implemented in a passenger vehicle application using an internal combustion engine powered by gas or CNG (also called bivalent hybrid). Therefore, three pressure vessels are installed for containing the CNG and separate regular gas storage provides regular fuel in case the CNG is exhausted.

Characteristics of the Project:

- designed for passenger vehicle application
- features an additional regular gas storage (not included in the module)
- two small vessels (Ø206mm x 1040mm), one big vessel (Ø390mm x 895mm)
- small vessels contains 26,3l CNG, big vessel contains 77,3l CNG
- CNG storage in total equals to 129,8l ≈ 20,9kg ≈ 320km cruising range
- Module is mounted on the rear bottom side of the vehicle
- Frame is used to hold module in place and is directly attached to the vehicle

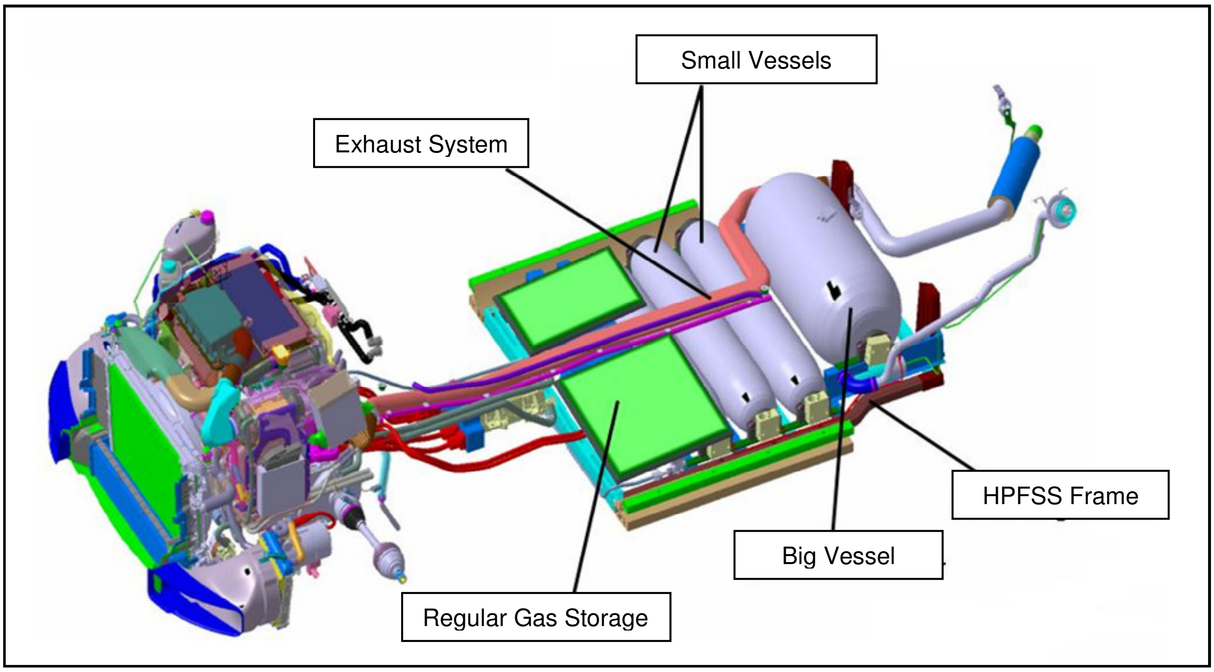

Figure 5.3: Project Q - Assembly [208]

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[208] cf. MAGNA STEYR (2010c)

5.2.2 Project M - Reference

Project M (see Figure 5.4) was developed for a bus application comprising an internal combustion engine which runs solely on CNG. Since a bus consumes a considerable amount of energy and requires a significant cruise range, the HPFSS was designed to store a large amount of CNG. Further, the module is directly attached to the roof of the bus near the front and is covered (cover is not part of the module) to protect against environmental influences.

Characteristics of the Project:

- Designed for bus application, mounted on the roof, 8 vessels per module
- All vessels have the same size (Ø324mm x 1400mm) with 82l of CNG each
- CNG storage in total equals to 656l ≈ 109,3kg ≈ 700km cruising range
- Module has one frame for the cover and one for mounting it on the roof
- Tensions belts are used to hold the vessels in place
- Connection lines use T-pieces for distribution

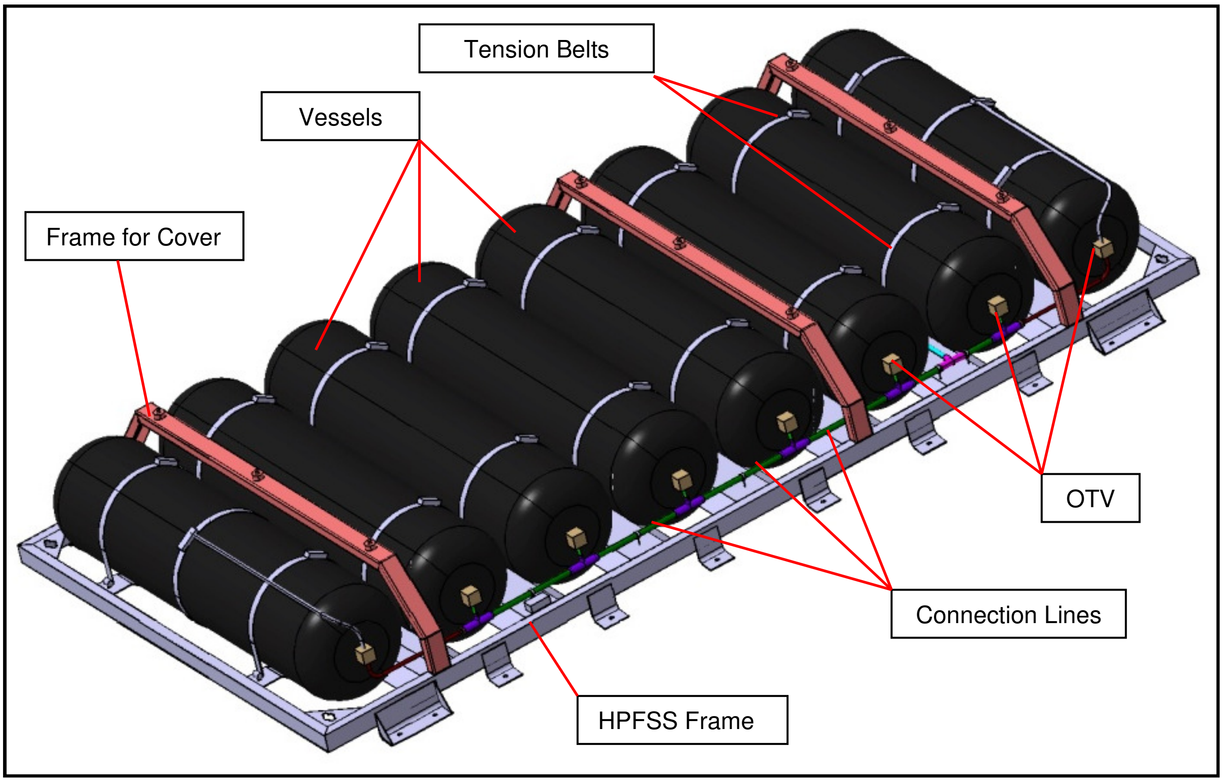

Figure 5.4: Project M - Assembly[209]

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[209] cf. MAGNA STEYR (2010f)

5.2.3 Project O - Reference

Project O (see Figure 5.5) was designed for a passenger car application equipped to perform as a bivalent hybrid. However, the specialty of this project is that two containers are located in front of the rear axle and the other two after the rear axle. This needs to be taken into consideration when designing the frame with the modular approach.

Note: Due to confidentiality reasons no illustration of Project O is allowed to be used; therefore, a similar system is used to visualize Project O.

Characteristics of Project:

- Designed for car application, with four differently sized vessels
- 1x(Ø260mm x 956mm, 38l CNG),1x(Ø240mm x 880mm, 30l), 1x(Ø279mm x 873mm, 39,5l), 1x(Ø279mm x 893mm, 40,5l)
- CNG storage in total equals to 148l ≈ 24kg ≈ 450km cruising range
- Module is mounted on the rear bottom side of the vehicle
- Tension belts are used to hold the vessels in place

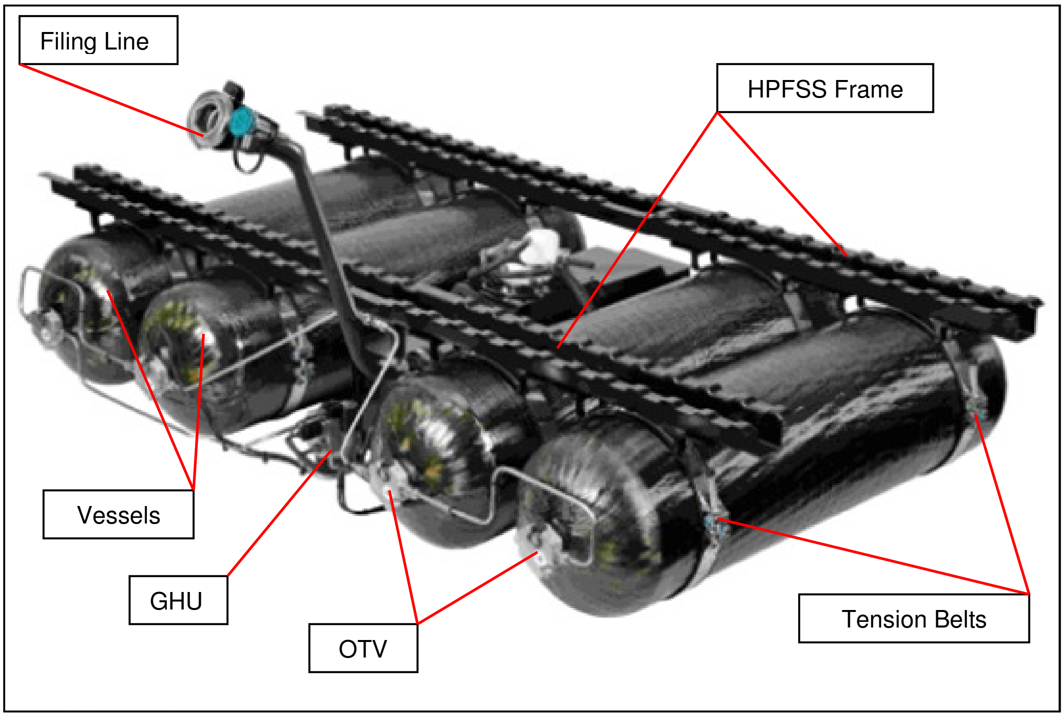

Figure 5.5: Project O - Assembly [210]

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[210] cf. MAGNA STEYR (2010d)

5.2.4 Costings of Reference Projects

Below the preliminary costings of the reference projects are displayed (see Table 5.3). They serve as a basis for further calculation and analysis. The Total Serial Price (TSP) does not include the Non-Recurring Costs (NRC) yet. However, for all further analysis it is assumed that all NRC will be charged against the serial price due to comparative reasons.

	Reference Projects	**Project Q**	**Project M**	**Project O**
Basic Project Information	Production Location	Graz	Graz	Graz
	Modules Total	25.000	42.900	50.000
	Modules per year	5.000	8.580	10.000
	Price Basis	2012	2012	2012
		Cost per Unit (SSU)	**Cost per Unit (SSU)**	**Cost per Unit (SSU)**
Production Costs	Material	806,6	2.478,4	925,6
	Inbound Transport & Customes	13,9	33,8	14,9
	Material & Freight	**820,4**	**2.512,2**	**940,5**
	Logistics Costs	62,3	77,0	64,2
	General Assembly Costs	276,9	413,3	307,5
	Warranty	25,5	119,1	40,3
	Production Cost II	**364,7**	**609,3**	**412,0**
	Sales & General Administration	39,4	74,7	37,3
	Total Assembly Costs	**404,1**	**684,0**	**449,3**
	EBIT	98,7	232,6	103,0
	Assembly Fee	**502,8**	**916,6**	**552,4**
	Total Serial Price	**1.323,2**	**3.428,8**	**1.492,8**
		NRC (SSU)	**NRC (SSU)**	**NRC (SSU)**
Non-Recurring Cost	**Engineering**	**1.732.643**	**1.015.170**	**1.373.906**
	Vendor Tooling	**725.781**	**177.304**	**451.543**
	Building and Infrastructure	304.152	520.980	412.566
	Machines and Equipment	2.136.018	3.657.120	2.896.569
	Special Tooling Production	1.087.161	136.800	611.981
	Special Logistics Racks	39.615	108.015	73.815
	Planning Production	976.838	1.239.465	1.108.151
	Start-up	151.202	75.810	113.506
	Production	**4.694.985**	**5.738.190**	**5.216.588**
	Total Non-Recurring Cost	**7.153.409**	**6.930.664**	**7.042.037**
	Direct Payment Customer	**4.713.239**	**1.015.170**	

Table 5.3: Costing Summary of Reference HPFSS[211]

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[211] cf. MAGNA STEYR (2010c); MAGNA STEYR (2010d); MAGNA STEYR (2010f)

5.3 Analyze Comparison Reference

In this chapter the reference costings are analyzed in order to understand the behavior and characteristics of costs in regard to cost types and cost structure. This is accomplished by a thorough explanation of each cost type and its cost divers according to MS experience; furthermore, a ABC-Cost Analysis is conducted to gather information about each costs type and its impact on the production cost of the product. This assessment is needed to prioritize which cost type needs to be analyzed in more detail when determining the changes of costs due to the modular approach.

5.3.1 Cost Breakdown

The cost breakdown used for MS costings is described in this subchapter. Further, it describes what each of these types conclude, their main cost drivers and what they are deduced from. Table 5.3 is an example of the design of a costing carried out by MS. It consists of three sections; the Basic Project Information, the Production Cost and the NRC. These three sections are explained in the following sections.

For cost information within a costing the following applies; if cells are filled with grey color it is a subtotal; cells filled with green color are subtotals of a subtotal and cells with no color are the actual cost types. If all costs of a section are added, they result in the total costs which are shown in cells with red color. The color blue is only used for a special position which is called “Direct Payment Customer”.

5.3.1.1 Basic Project Information

The first section in a costing displays general information about the particular project the costing was made for, such as; internal name of the project, production location, number of modules to be produced in total, number of modules to be produced per year and the price basis; that is, the year the costing was made for. Furthermore, a color coding is introduced in this thesis to easily distinguish between the three reference projects that are subject to be examined in the comparison (blue = Project Q, red = Project M, green = Project O).

5.3.1.2 Production Cost

The second section in the costing (see Table 5.3) shows all production costs and their main cost drivers which are explained in the following sections.

Material: The material costs comprise the sum of costs which accumulate for all purchased components and raw materials including additional costs. Direct material costs are shown in the Bill of Material (BOM) and include carry over parts (COP), unique parts, modified parts and indirect production material.[212]

Inbound Transport and Customs (ITransp&C): Represents freight inward costs charged by the supplier or carrier for delivering the material or resources to the production facility. Depending on the delivery conditions either the buyer or the seller has to pay the costs which accrue from the start until the end of transport. Further, it contains all costs associated with the purchasing process. The main cost drivers of ITransp&C are derived from the geometry, quantity, weight, variety and characteristics of the components that need to be transported. Furthermore, the transport distance, packing concept, means of transport and of course the choice of carrier is determining the magnitude of ITransp&C costs. [213]

Logistics: This cost type comprises the cost for logistic manning and for logistic overhead. Logistics cost are mainly driven by the needed inventory area, delivery interval, shift model and number of suppliers and parts. In addition, the influence of Information Technology (IT) on logistic costs is increasing due to the fact that more and more logistic processes are administrated very effectively by IT. [214]

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[212] cf. MAGNA STEYR (2010a), pp. 12-14

[213] cf. MAGNA STEYR (2010a), p. 14

[214] cf. MAGNA STEYR (2010a), p. 15

General Assembly Cost (GAC): Includes all direct and indirect costs associated with the manufacturing of the product. Therefore, it largely consists of manufacturing manning and the manufacturing overhead costs and is mostly dependant on the time needed to produce the product. The magnitude of GAC is strongly dependant on the manufacturing technology, degree of automation, processing time and the demanded productivity. Further, it is important to use a well thought-out IT-Concept according to the specific needs of the respective product. Other cost drivers are the product variety, quality requirements and of course wages, salaries and the shift model.[215]

Warranty: Warranty refers to the guarantee provided that the sold product will maintain certain properties and performance criteria over a specified time span. At MS the cost type “Warranty” is a value which is estimated based on experience with the particular type of product and is not necessarily dependant on the product architecture. When conducting a preliminary costing, it is estimated at MS by summing up Material, Inbound Transport & Customs, Logistics and GAC and multiplying it by a product specific factor.[216]

Sales and General Administration (SGA): Costs for SGA comprise all direct and indirect costs which accrue due to the activities in SGA. The deduction of this cost type is done through distribution keys which are based on cost drivers like manning, added value and more. The cost drivers of general administration are bank charges, cost for audits and the total of the administration units’ costs. On the other hand, marketing and acquisition costs are driving the costs for sales alongside with the sales units’ costs.[217]

However, when a preliminary costing is conducted at MS, SGA is estimated by summing up GAC and Warranty and multiplying it by a predefined product specific factor.[218]

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[215] cf. MAGNA STEYR (2010a), pp. 15-17

[216] cf. MAGNA STEYR (2010a), p. 28; Interview with Dieter Feigl (09.02.2012), Controller Special Projects Magna Steyr

[217] cf. MAGNA STEYR (2010a), p. 21-22

[218] Interview with Dieter Feigl (09.02.2012), Controller Special Projects Magna Steyr

Earnings before Interest and Taxes (EBIT): Earnings Before Interest and Taxes is the financial operating result of a company before interest and taxes. This “cost type” represents the operating result independent from the prevailing capital structure or pattern of finance; hence, it can be used to compare the operating results of projects internationally.[219]

At Magna Steyr EBIT depends on mainly on the guidelines of the executive committee, prices of competitors and usual margins in the particular business area. Furthermore, it needs to be determined whether the product is part of a new business or a routine business of the company, because obviously a new business is associated with a higher product risk. The Internal Rate of Return (IRR), which is a business ratio to assess the profitability of investments, plays also an important role when determining the EBIT of a product. [220]

However, if the EBIT for a preliminary costing needs to be calculated, it is assumed that it is a predefined fraction of the value added by MS. That is, the sum of Material & Freight and Total Assembly Cost. This fraction is dependent on the influence factors above.[221]

5.3.1.3 Non-Recurring Cost

The third section contains the breakdown of the NRCs not per unit but for the whole project. These costs are not included in the TSP yet. How these costs are considered in the price of the product is explained at the very end in this subchapter under “Direct Payment Customer”.

Engineering: Engineering includes costs for design & styling, construction, validation, building prototypes, testing & certification, homologation, documentation, project management, project controlling and cost of interacting with the customer. The main cost drivers are the customer requirements, specifications and the approach which is used to develop the particular product. In addition to that, the costs for engineering are dependent on the number of developed parts and on the number of iteration cycles that are needed for the completion of the development. [222]

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[219] cf. WAGNER (2011), p. 171

[220] Interview with Dieter Feigl (09.02.2012), Controller Special Projects Magna Steyr

[221] ibidem

[222] cf. MAGNA STEYR (2010a), pp. 17-18

Vendor Tooling: Vendor tooling includes cost for the development of new components and investments the supplier has to make in order to obtain the means and the capacity to manufacture the requested parts in a specified quality and quantity. The costs are mainly driven by the number of parts that needs to be developed and by the number of development iteration cycles. Besides that, the ordered components specification as well as its manufacturability, quantity and quality are determining the magnitude of vendor tooling costs.[223]

Production: The costs for production consists of all activities necessary to build-up a production process until it is stable and can be used for serial production. This includes building & infrastructure, machines & equipment, special tooling production, special logistic racks, planning production and start-up costs. The main cost drivers are customer specifications, requirements and product variety. Moreover, the complexity of the product is determining the layout of the production process and also the used production technologies which influences costs as well. Further, the non-recurring costs for production are depending strongly on the in-house production depth, which is the number of production stages that are carried out internally to create the product.[224]

Direct Payment Customer: The direct payment of the customer is the amount of money the customer must pay upfront to finance the expected NRC activities conducted by the contracted company.[225]

There are three different ways for a customer to handle this payment:

- One way is to pay all NRCs in advance; this represents the best possible way for the company that received the project.
- Another way is to pay nothing beforehand; this means that the full amount of NRC is charged by the developer against the total serial price.
- The most common way how to handle this payment is a mixture between paying in advance and charging the remaining costs against the price of the product. Simply, a part of the NRCs are financed by the customer in advance and the remaining costs are charged against the total serial price of the product.

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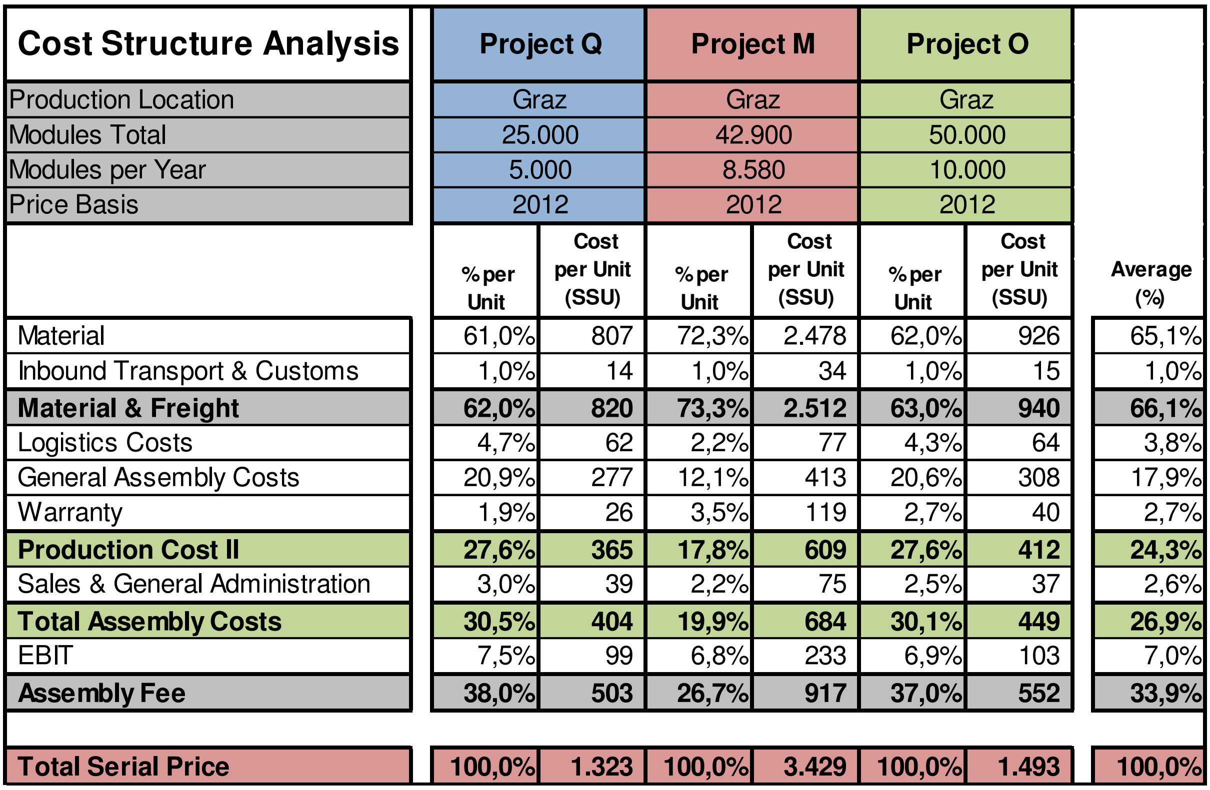
[223] cf. MAGNA STEYR (2010a), p. 19

[224] cf. MAGNA STEYR (2010a), p. 20-21

[225] cf. MAGNA STEYR (2010a), p. 17

5.3.2 Determine Cost Drivers

In order to determine the cost drivers a ABC-Cost Analysis is conducted. The costing of the three reference projects represents the basis for this analysis. Every single cost type (e.g. material, transport, logistics, etc.) holds a certain percentage on the TSP. The distribution of these percentages is called a cost structure or cost landscape. However, cost drivers are those cost types which hold the highest shares of the TSP; therefore, they are driving the costs and need to be analyzed in detail. The NRCs are not included in the analysis of the cost drivers due to the fact that in NRCs external factors have a predominant impact on costs and are connected with high uncertainty due to MS experience. How NRCs are included in the comparison analysis can be found in section 5.5.2. The assessment is conducted according to the steps in section 3.4.5. Firstly, a cost structure analysis based on the three reference projects is required. In the table below the calculation of the average percentage that each cost type from the TSP holds is shown. At first, the percentage that each cost type holds is calculated for every project. Then, these percentages are averaged over the three projects which provide the average percentage that a cost type holds on the TSP. All these calculations can be found in Table 5.4.



Cost Structure Analysis	**Project Q**		**Project M**		**Project O**		
Production Location	Graz		Graz		Graz		
Modules Total	25.000		42.900		50.000		
Modules per Year	5.000		8.580		10.000		
Price Basis	2012		2012		2012		
	% per Unit	**Cost per Unit (SSU)**	**% per Unit**	**Cost per Unit (SSU)**	**% per Unit**	**Cost per Unit (SSU)**	**Average (%)**
Material	61,0%	807	72,3%	2.478	62,0%	926	65,1%
Inbound Transport & Customs	1,0%	14	1,0%	34	1,0%	15	1,0%
Material & Freight	**62,0%**	**820**	**73,3%**	**2.512**	**63,0%**	**940**	**66,1%**
Logistics Costs	4,7%	62	2,2%	77	4,3%	64	3,8%
General Assembly Costs	20,9%	277	12,1%	413	20,6%	308	17,9%
Warranty	1,9%	26	3,5%	119	2,7%	40	2,7%
Production Cost II	**27,6%**	**365**	**17,8%**	**609**	**27,6%**	**412**	**24,3%**
Sales & General Administration	3,0%	39	2,2%	75	2,5%	37	2,6%
Total Assembly Costs	**30,5%**	**404**	**19,9%**	**684**	**30,1%**	**449**	**26,9%**
EBIT	7,5%	99	6,8%	233	6,9%	103	7,0%
Assembly Fee	**38,0%**	**503**	**26,7%**	**917**	**37,0%**	**552**	**33,9%**
Total Serial Price	**100,0%**	**1.323**	**100,0%**	**3.429**	**100,0%**	**1.493**	**100,0%**

Table 5.4: Cost Structure Analysis of 200bar CNG HPFSS[226]

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[226] cf. MAGNA STEYR (2010c); MAGNA STEYR (2010d); MAGNA STEYR (2010f)

Figure 5.6 displays the results of the percentages of each cost type on the TSP for each reference project.

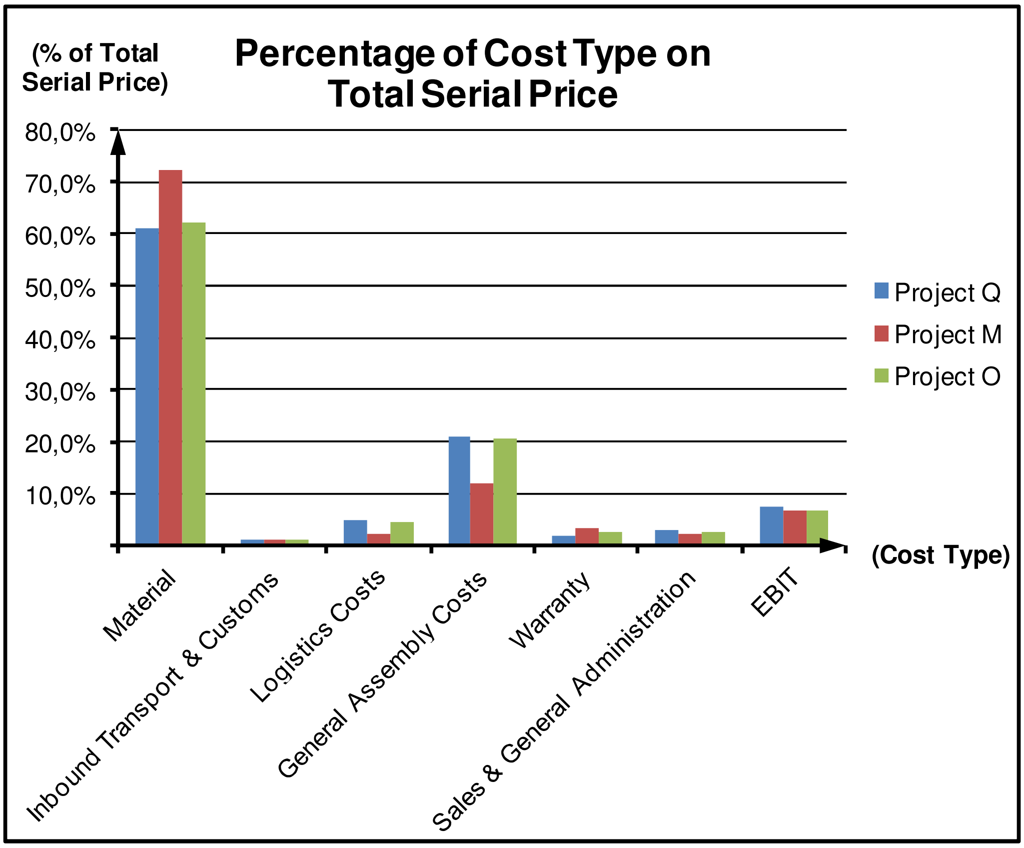

Figure 5.6: Averaged Percentage of Cost Type per Unit[227]

The averaged results of the cost structure analysis (see Table 5.4, very right column) are incorporated in Table 5.5 which serves as a basis for the ABC-Cost Analysis.

Cost Type	Average Percentage of TSP	Cumulative Average Percentage of TSP	Number of Cost Types	Percentage of Cost Types	Cumulative Percentage of Cost Types
Material	65,1%	65,1%	1	14,3%	14,3%
General Assembly Cost	17,9%	82,9%	2	14,3%	28,6%
EBIT	7,0%	90,0%	3	14,3%	42,9%
Logistics	3,8%	93,7%	4	14,3%	57,1%
Warranty	2,7%	96,4%	5	14,3%	71,4%
Sales & General Administration	2,6%	99,0%	6	14,3%	85,7%
Inbound Transport & Customs	1,0%	100,0%	7	14,3%	100,0%

Table 5.5: Data for ABC-Cost Analysis[228]

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[227] Own Illustration

[228] Own Illustration

Now, the parameters of Table 5.5 are visualized in a so called “ABC-Graph” (see Figure 5.7). The graph is divided into three groups. It is assumed that group A holds about 80%, group B holds about 15% and group C holds 5% of the TSP. However, these percentages need to be adjusted according to the results of the cost structure due to the fact that only seven cost types are part of the analysis and cannot be split. Splitting in this context means that a cost type cannot be shared between two different groups. Thus, it is assumed that group A holds 82,9%, group B holds 10,8% and group C holds 6,3% of the TSP.

As a next step, the data in the blue column (see Table 5.5) is applied to the y-axis (i.e. ordinate) and the data in the red column is applied to the x-axis (i.e. abscissa) of the ABC graph. After that, the groups are classified according to the amount of percentage that they are assumed to hold. This leads to the ABC-Cost Analysis graph shown in Figure 5.7.

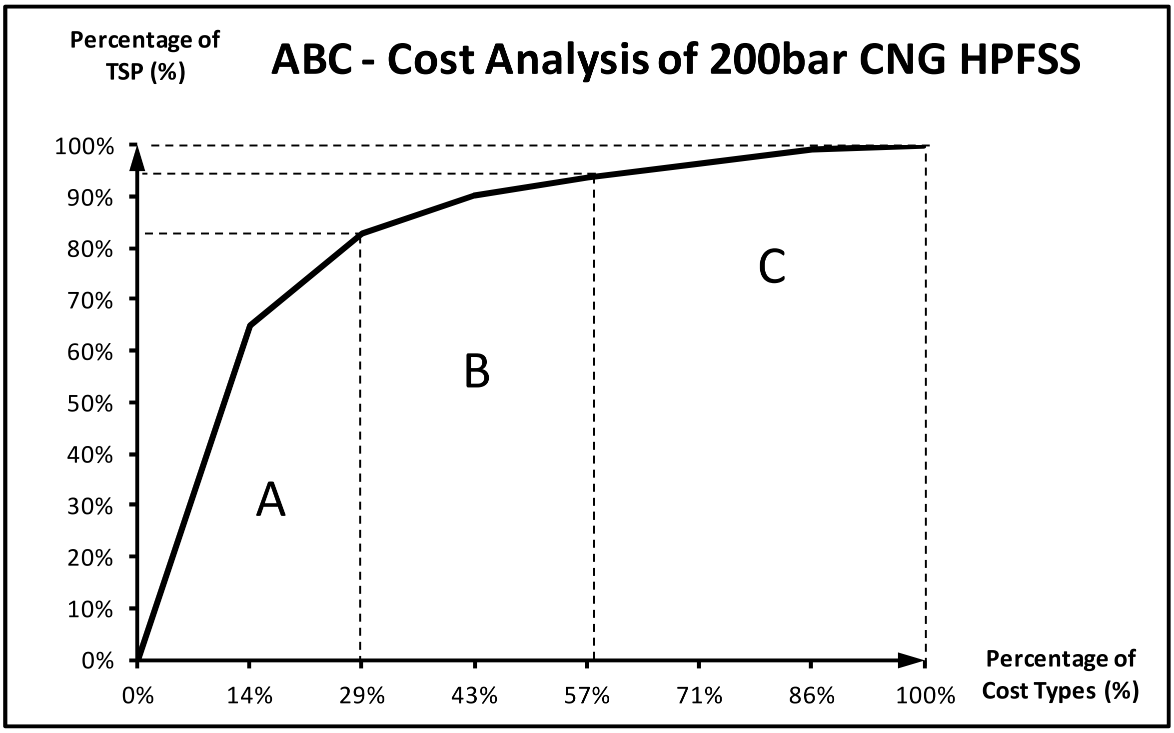

Figure 5.7: ABC - Cost Analysis 200bar CNG HPFSS[229]

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[229] Own Illustration

The ABC-Cost Analysis delivers a very clear result:

Group A

This group includes the cost types “Material” with 65,1% and “General Assembly Cost” with 17,9% of the TSP; there two cost types alone sum up to an astounding 83% of the TSP. Therefore, for all further analysis the primary focus is on these two cost types. However, since “Material” has such a predominant impact on the TSP it is treated as the main cost driver and needs the most attention when determining the changes in costs due to the modular approach. GAC on the other hand can be called the secondary cost driver since its impact on costs is comparably small to “Material”. For that reason the analysis of cost changes does not have to be as accurate as for “Material”.

Group B

This group consists of the cost types “EBIT” with 7,0% and “Logistics” with 3,8% of the TSP. These two cost types should be reasonably analyzed in terms of the needed effort to quantify changes. This means that the relation between cost impact and effort to quantify changes should be reasonable. Further information on this can be found in section 5.5.1.

Group C

This group comprises the remaining cost types; that is “Warranty” with 2,7%, SGA with 2,6% and Inbound Transport & Customs with 1% of the TSP. These cost types have such a small influence on the TSP (6,3% in total) that most likely they are kept constant in the comparison. However, if changes of these cost types are easy to determine, they are considered in the comparison as well.

5.4 Create Objects of Comparison

In this chapter the reference systems are re-built using the modular approach developed by Mr. Ing. Mayr. The costs of the rebuilt systems will provide valuable data to compare against the reference systems and help evaluate the feasibility of the modular approach. It should be noted that the construction set has a modular product architecture which belongs to “Free Modularization” (see section 2.5.1). Therefore, the HPFSS are assembled by a combination of standardized and customized modules/components without the existence of a base body. Modules and components are combined in any order which fosters the flexibility and changeability of the modular system. Due to technical reasons, several components are hard to change in their dimensions and cannot be standardized (e.g. pressure vessels, frame, filling line), because they are designed for the exact needs and restrictions of the particular vehicle. On the other hand, the pressure regulator and the pressure control valve are easy to standardize as long as they are suitable for the fuel type and the pressure level of the HPFSS.

It is important that the modular systems fulfill the same specifications and have the same characteristics as the original modules. This means they should be designed accordingly to be integrated in the same vehicle and to provide equivalent energy storage. The rebuild systems are used in the comparison analysis particularly when determining the material costs by developing a BOM for each modular system (see Table 5.8 in section 5.5.1) and the GAC by identifying changes in the assembly process.

Due to confidentiality reasons the modular system components cannot be shown and explained in detail. However, schematic illustrations of how the systems change are shown in the following three sections.

5.4.1 Project Q – Modular

Figure 5.8 shows Project Q in reference configuration where the "HPFSS System Boundary" indicates the scope of the comparison analysis. All other components are described in section 4.2.

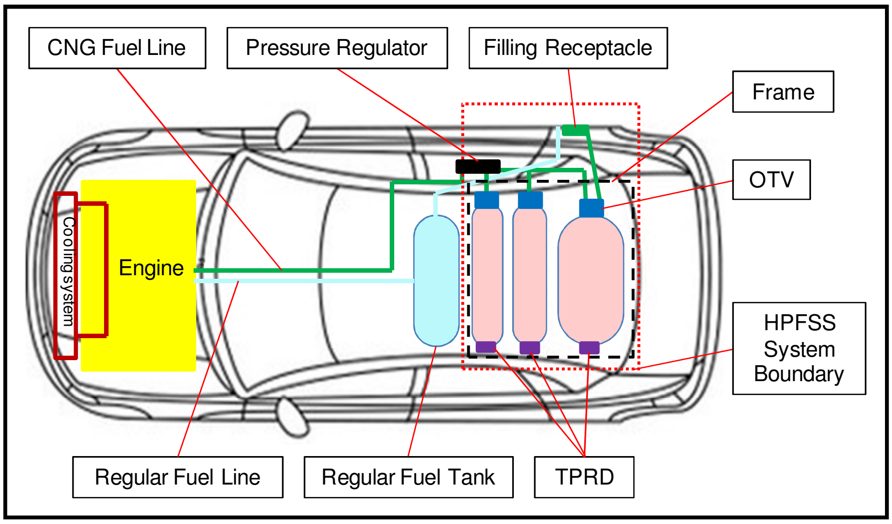

Figure 5.8: Project Q – Reference[230]

Figure 5.9 illustrates Project Q after it has been re-build with modularized components. As one can see in the figures, the so called connection block replaces several parts of the reference system. They take over the function of the connection lines and serve as a frame at the same time.

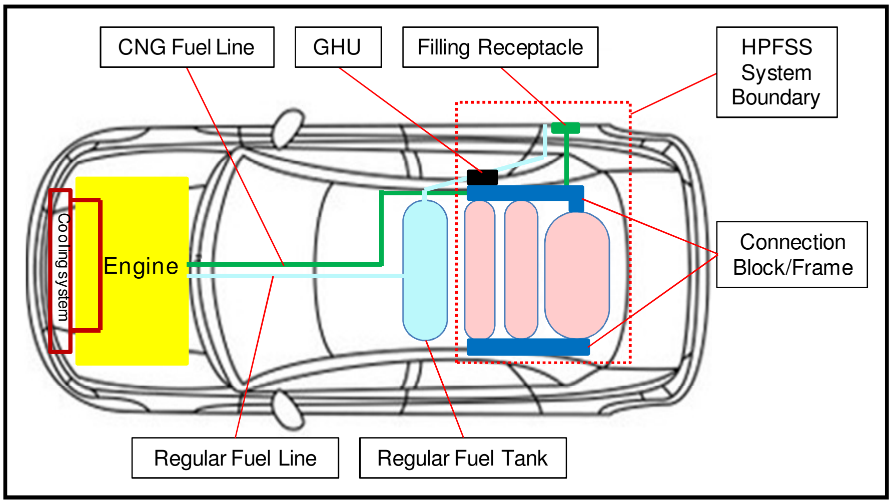

Figure 5.9: Project Q – Modular[231]

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[230] cf. MAGNA STEYR (2012c), p. 6

[231] cf. MAGNA STEYR (2012c), p. 8

5.4.2 Project M – Modular

Figure 5.10 displays how the HPFSS is mounted on the bus. It is located at the front of the bus for superior weight distribution, driving comfort and performance.

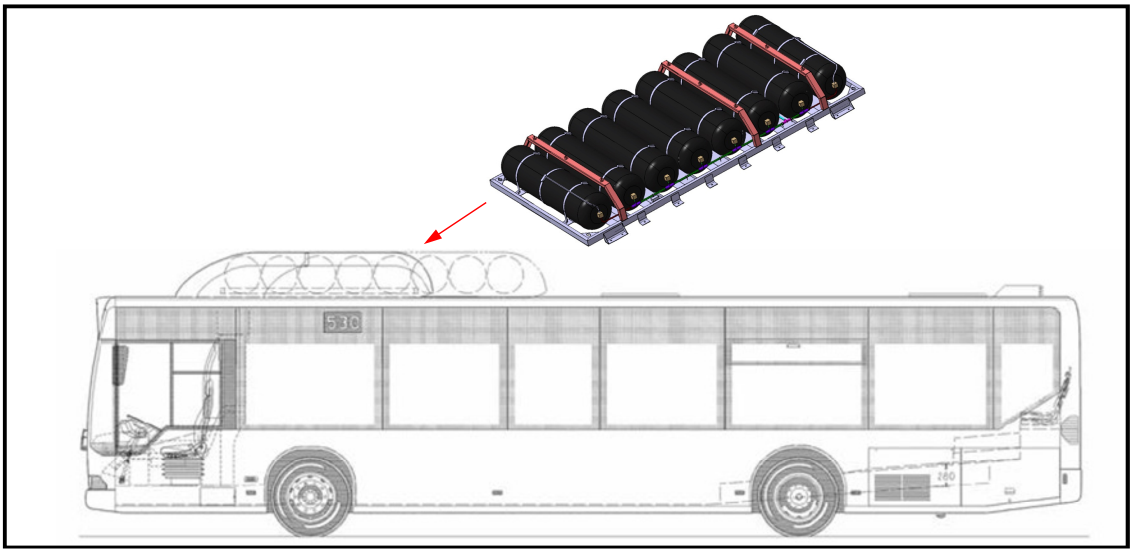

Figure 5.10: Project M – Reference[232]

Compared to the reference, the modular version (see Figure 5.11) replaces the frame and the connection lines with the so called connection block.

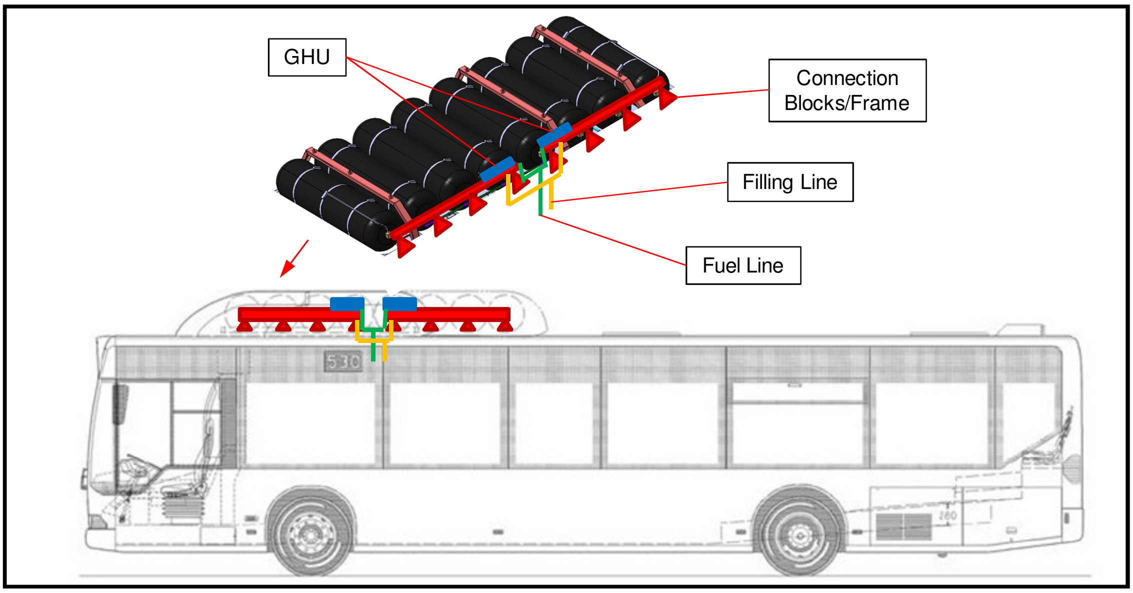

Figure 5.11: Project M – Modular[233]

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[232] cf. MAGNA STEYR (2012c), p. 10

[233] cf. MAGNA STEYR (2012c), p. 12

5.4.3 Project O – Modular

Figure 5.12 represents the reference configuration of Project O where the “HPFSS System Boundary” indicates the scope of the comparison analysis. All other components are described in section 4.2.

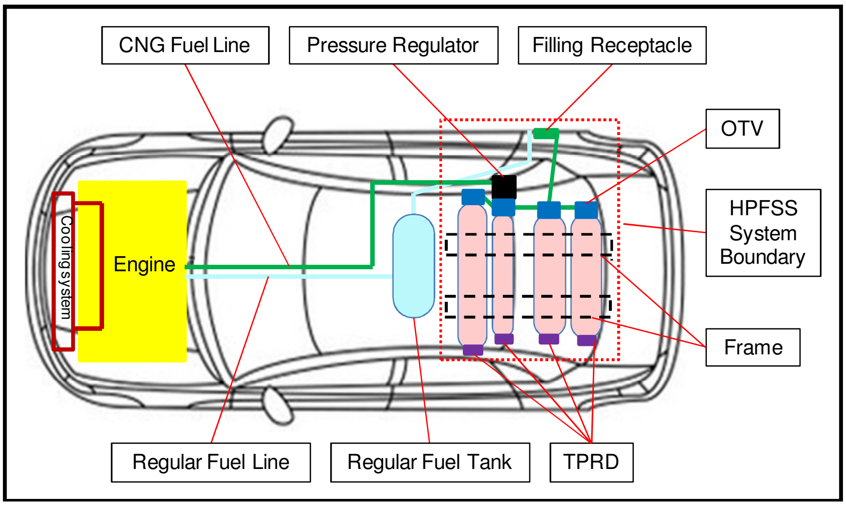

Figure 5.12: Project O – Reference[234]

Figure 5.13 illustrates Project O after it has been re-build with the modular approach. Again, the “Connection Blocks/Frames” replace several parts of the reference system as seen in Project Q and Project M. However, a short connection line is needed to connect the connection block with each other due to special circumstances of this project mentioned in section 5.2.3.

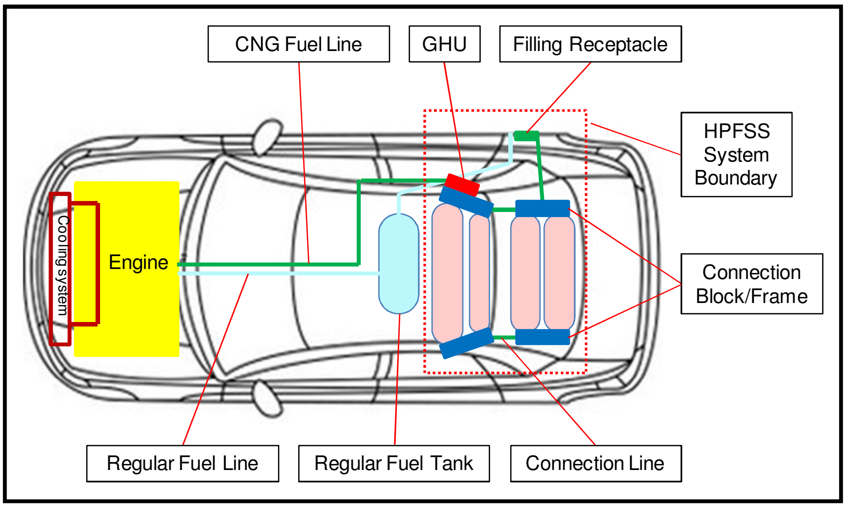

Figure 5.13: Project O - Modular[235]

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[234] cf. MAGNA STEYR (2012c), p. 17

[235] cf. MAGNA STEYR (2012c), p. 19

5.5 Changes in Costs induced by the Modular Approach

In this chapter the revised costings using the modular approach are stated. Firstly, all cost types associated with production costs are analyzed; Secondly, the NRCs are considered as well. The resulting quantified changes in costs for production and NRCs can be found in chapter 5.6.

5.5.1 Changes in Production Cost

The changes induced by the modular construction approach in terms of production costs are discussed in this subchapter. Every single production cost type is examined to a degree according to its relevance and impact on the TSP identified in section 5.3.2. Due to the fact that changes in NRCs are not examined in this subchapter yet, the results are called “Unadjusted Comparison Result”. They only include the production costs and need to be “adjusted” by considering the NRC in order to be complete. The results of this assessment are shown in section 5.6.1.

Material

Since material cost is the primary cost driver with an average 65,1% the analysis of changes induced by the new product architecture needs to be conducted in detail and as accurate as possible.

Table 5.8 contains the material costs for both, reference and modular systems. The listing of the reference systems is made in order to prove that the material costs are referring to the same component costs. The BOM for the modular systems is deduced from the rebuild systems and serves as a tool for determining the new material costs. Most component costs are deduced from similar projects and approved and/or estimated by MS experts. However, one component group is estimated to ensure its correctness by conducting a separate costing by the MS manufacturing department. That is, all versions of “Connection Block” which is a completely new part in HPFSS. Another component which needs to be estimated separately is the pressure vessel of Project M, because cost information is not available; this type of product allows for the use of the “Main Cost Driver Method” (see section 3.4.2) due to the given circumstances and characteristics for this type of product.

The main cost driver of pressure vessels is the quantity of gas, in liters, that the particular vessel is designed to store. As a basis for determining the component prices the quantities of the reference projects are used. That means, the total quantities of the three projects for all parts are calculated in the two very right columns of Table 5.8 which are needed to update the part costs per piece due to Economies Of Scale (EOS). Hence, the prices originally used are changing due to the increased quantities resulting from EOS. However, since this comparison analysis uses three reference projects, it is assumed that amongst the reference systems the synergy effect is considered as well due to conservative comparative reasons. Thus, the disadvantage of not considering changing order and production quantities in a comparative costing (see section 3.2) is removed for both modular and reference approach. Detailed information about all components, prices and quantities for each project (reference and modular) can be found in Table 5.8. The BOM leads to the new material costs for the modular system but also confirms that the reference material costs are according to the preliminary costings of the reference projects. However, the material costs of the modular systems are displayed and compared to the reference systems in Table 5.10 at section 5.6.1. Below and on the next page the estimation of the pressure vessel for Project M and for the Connection Block is explained.

Estimation of Pressure Vessel for Project M

Project M contains eight pressure vessels with 82 liters of volume each and a total quantity of 68.640 vessels p.a. (8 vessels x 8.580 vessels p.a. = 68.640 vessels p.a.). Since the costs for this vessel is not available a cost estimation needs to be conducted. After consulting the pressure vessel expert at MS it became clear that the costs can be estimated by a so called “Performance Oriented Cost Driver” (see section 3.4.2). That is, the liters of volume that a particular vessel should possess. However, the cost driver is depending on the total quantity of vessels as well which is expressed in the summary of the estimation in Table 5.6.

Vessel Quantity		25.000	50.000	Extremum
CNG/liter		4,389	3,705	3,534
Liters per Vessel =	82	359,9	303,8	289,8
% of Material Cost		58%	61%	61%
Material Cost		208,7	185,3	176,8

Table 5.6: Estimation of Pressure Vessel for Project M[236]

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[236] Interview with Uwe Thien (18.11.2011), Project Manager CNG Systems at Magna Steyr

Hereby it is assumed that the vessel material cost of Project M is equal to CNG 176,8, because the quantity per anno equals to 68.640 vessels which allows the use of the cost from column “Extremum”.

Estimation of Connection Block

A separate thorough costing is conducted by the manufacturing department of MS for the Connection Block. These components are used to connect the pressure vessels with each other and at the same time serve as a frame. No detailed description of the component is given due to confidentiality reasons.

The costing is conducted according to the following assumptions:

- used material is Al 6082
- preliminary internal costing, no supplier contact established yet
- only functional surfaces are machined
- production location is Central Europe
- no coating or Painting considered
- transport and packing is not included
- heat treatment for material included
- no NRCs are charged against the estimated cost
- x-ray inspection and helium examination included
- incoming components inspection not included

Under these assumptions the costs for the components are estimated by the manufacturing department of MS. The results of this estimation are shown below in Table 5.7.

Project Name	Component Name	Annual Volume (Pc.)	Lifetime (Years)	Estimated Cost (SSU/Pc.)
Project Q	Connection Block for 2 Vessels	40.000	5	27,4
Project M	Connection Block for 3 Vessels	10.000	5	45,6
Project O	Connection Block for 4 Vessels	34.320	5	62,7

Table 5.7: Estimation of Connection Block[237]

On the next page the summary of all material cost for reference and modular HPFSSs is shown in Table 5.8.

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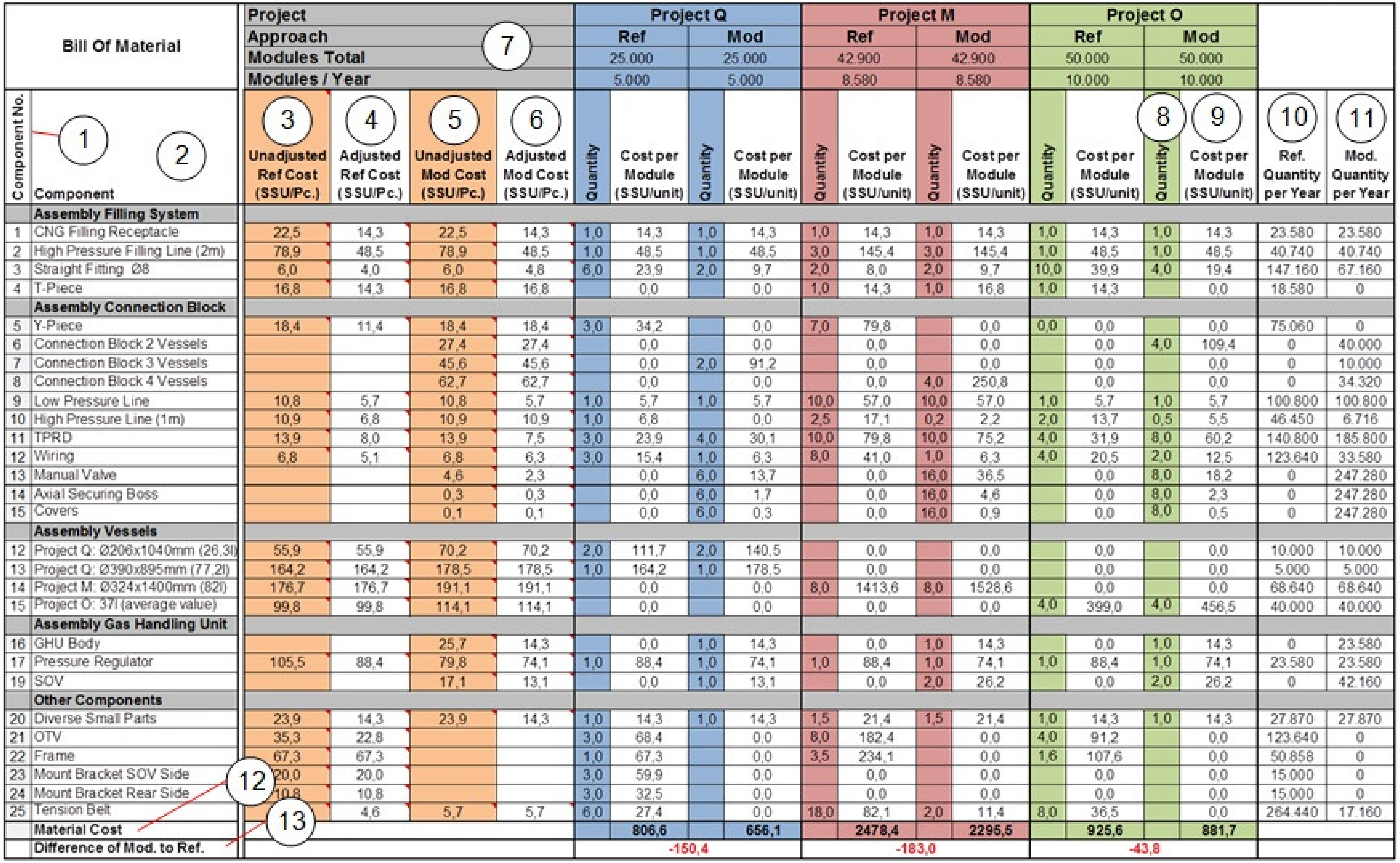
[237] cf. MAGNA STEYR (2012d)



Bill Of Material		Project				Project Q				Project M				Project O					
		Approach ⑦				Ref		Mod		Ref		Mod		Ref		Mod			
		Modules Total				25.000		25.000		42.900		42.900		50.000		50.000			
		Modules / Year				5.000		5.000		8.580		8.580		10.000		10.000			
Component No. ①	② Component	③ Unadjusted Ref Cost (SSU/Pc.)	④ Adjusted Ref Cost (SSU/Pc.)	⑤ Unadjusted Mod Cost (SSU/Pc.)	⑥ Adjusted Mod Cost (SSU/Pc.)	Quantity	Cost per Module (SSU/unit)	Quantity	Cost per Module (SSU/unit)	Quantity	Cost per Module (SSU/unit)	Quantity	Cost per Module (SSU/unit)	Quantity	Cost per Module (SSU/unit)	⑧ Quantity	⑨ Cost per Module (SSU/unit)	⑩ Ref. Quantity per Year	⑪ Mod. Quantity per Year
	Assembly Filling System																		
1	CNG Filling Receptacle	22,5	14,3	22,5	14,3	1,0	14,3	1,0	14,3	1,0	14,3	1,0	14,3	1,0	14,3	1,0	14,3	23.580	23.580
2	High Pressure Filling Line (2m)	78,9	48,5	78,9	48,5	1,0	48,5	1,0	48,5	3,0	145,4	3,0	145,4	1,0	48,5	1,0	48,5	40.740	40.740
3	Straight Fitting Ø8	6,0	4,0	6,0	4,8	6,0	23,9	2,0	9,7	2,0	8,0	2,0	9,7	10,0	39,9	4,0	19,4	147.160	67.160
4	T-Piece	16,8	14,3	16,8	16,8		0,0		0,0	1,0	14,3	1,0	16,8	1,0	14,3		0,0	18.580	0
	Assembly Connection Block																		
5	Y-Piece	18,4	11,4	18,4	18,4	3,0	34,2		0,0	7,0	79,8		0,0	0,0	0,0		0,0	75.060	0
6	Connection Block 2 Vessels			27,4	27,4		0,0		0,0		0,0		0,0		0,0	4,0	109,4	0	40.000
7	Connection Block 3 Vessels			45,6	45,6		0,0	2,0	91,2		0,0		0,0		0,0		0,0	0	10.000
8	Connection Block 4 Vessels			62,7	62,7		0,0		0,0		0,0	4,0	250,8		0,0		0,0	0	34.320
9	Low Pressure Line	10,8	5,7	10,8	5,7	1,0	5,7	1,0	5,7	10,0	57,0	10,0	57,0	1,0	5,7	1,0	5,7	100.800	100.800
10	High Pressure Line (1m)	10,9	6,8	10,9	10,9	1,0	6,8		0,0	2,5	17,1	0,2	2,2	2,0	13,7	0,5	5,5	46.450	6.716
11	TPRD	13,9	8,0	13,9	7,5	3,0	23,9	4,0	30,1	10,0	79,8	10,0	75,2	4,0	31,9	8,0	60,2	140.800	185.800
12	Wiring	6,8	5,1	6,8	6,3	3,0	15,4	1,0	6,3	8,0	41,0	1,0	6,3	4,0	20,5	2,0	12,5	123.640	33.580
13	Manual Valve			4,6	2,3		0,0	6,0	13,7		0,0	16,0	36,5		0,0	8,0	18,2	0	247.280
14	Axial Securing Boss			0,3	0,3		0,0	6,0	1,7		0,0	16,0	4,6		0,0	8,0	2,3	0	247.280
15	Covers			0,1	0,1		0,0	6,0	0,3		0,0	16,0	0,9		0,0	8,0	0,5	0	247.280
	Assembly Vessels																		
12	Project Q: Ø206x1040mm (26,3l)	55,9	55,9	70,2	70,2	2,0	111,7	2,0	140,5		0,0		0,0		0,0		0,0	10.000	10.000
13	Project Q: Ø390x895mm (77,2l)	164,2	164,2	178,5	178,5	1,0	164,2	1,0	178,5		0,0		0,0		0,0		0,0	5.000	5.000
14	Project M: Ø324x1400mm (82l)	176,7	176,7	191,1	191,1		0,0		0,0	8,0	1413,6	8,0	1528,6		0,0		0,0	68.640	68.640
15	Project O: 37l (average value)	99,8	99,8	114,1	114,1		0,0		0,0		0,0		0,0	4,0	399,0	4,0	456,5	40.000	40.000
	Assembly Gas Handling Unit																		
16	GHU Body			25,7	14,3		0,0	1,0	14,3		0,0	1,0	14,3		0,0	1,0	14,3	0	23.580
17	Pressure Regulator	105,5	88,4	79,8	74,1	1,0	88,4	1,0	74,1	1,0	88,4	1,0	74,1	1,0	88,4	1,0	74,1	23.580	23.580
19	SOV			17,1	13,1		0,0	1,0	13,1		0,0	2,0	26,2		0,0	2,0	26,2	0	42.160
	Other Components																		
20	Diverse Small Parts	23,9	14,3	23,9	14,3	1,0	14,3	1,0	14,3	1,5	21,4	1,5	21,4	1,0	14,3	1,0	14,3	27.870	27.870
21	OTV	35,3	22,8			3,0	68,4		0,0	8,0	182,4		0,0	4,0	91,2		0,0	123.640	0
22	Frame	67,3	67,3			1,0	67,3		0,0	3,5	234,1		0,0	1,6	107,6		0,0	50.858	0
23	Mount Bracket SOV Side	20,0	20,0			3,0	59,9		0,0		0,0		0,0		0,0		0,0	15.000	0
24	Mount Bracket Rear Side	10,8	10,8			3,0	32,5		0,0		0,0		0,0		0,0		0,0	15.000	0
25	Tension Belt		4,6	5,7	5,7	6,0	27,4		0,0	18,0	82,1	2,0	11,4	8,0	36,5		0,0	264.440	17.160
	Material Cost ⑫						806,6		656,1		2478,4		2295,5		925,6		881,7		
	Difference of Mod. to Ref. ⑬					-150,4				-183,0				-43,8					

Table 5.8: Bill of Material[238]

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[238] Own Illustration

Description of Bill Of Material (BOM)

1. The component number represents the sequential number which refers to the components used in the HPFSSs.
2. This column states the name of each component and also gives basic information about it (e.g. dimensions, volume)
3. This column incorporates the prices of components based on the quantity of the reference projects. Therefore, they are called “unadjusted”, because they are not adjusted due to the changing buying quantity when comparing three projects with each other.
4. Adjusted Ref Cost stands for the component cost after the EOS effect is taken into consideration. Hence, the original price is adjusted due to the changing quantities which can be found in the BOM at No. 10. These costs are used to calculate the material costs for each component in the reference HPFSS.
5. Here, the unadjusted cost of modular components is shown before they are adjusted by the changing buying quantity.
6. This column displays the adjusted modular component costs. As the name of the column says, the modular costs are adjusted due to the new buying quantities (see No. 11). These costs are used to calculate the material costs for each component in the modular HPFSS.
7. Delivers basic information about the projects and their configurations which are included in the comparative analysis. Here, “Ref” snatds for Reference and “Mod” stands for Modular.
8. Shows the Cost per Module of the respective component.
9. The quantity of components which are built in a particular HPFSS is put into this column. It is multiplied by the cost per unit (see No. 8) in order to receive the total cost for the particular component.
10. This column stands for the component quantities of the reference systems when comparing all three projects per year. For that reason, it is taken as a basis for determining the Adjusted Ref Cost.
11. The “Modular Quantity per Year” incorporates the component quantities of the modular systems per year. These quantities are used to identify the changes in material cost due to EOS and are called “Adjusted Mod Cost” (see No.6)
12. This row holds the total material cost of the particular project and configuration. All component cost are summed up in order to receive the total material cost. These values are taken and inserted into the unadjusted comparison results for further examination (see Table 5.10 in section 5.6.1).
13. Shows the difference in material cost of modular to reference system.

Inbound Transport / Customs

Inbound Transport & Customs holds a share of 1% on average of the TSP and is identified in Group C in the ABC-Cost Analysis. Therefore, its impact on the TSP is negligible such that sometimes it is not explicitly mentioned in a costing but is subsequently added to the material cost. Thus, it is assumed that the absolute value of Inbound Transport & Customs remains constant compared to the reference due to its marginal impact on the TSP. Keeping the costs constant is a conservative assumption and fosters the spirit of a comparative analysis. The modular costs for Inbound Transport & Customs are shown in Table 5.10 at section 5.6.1.

Logistics

The logistical costs possess 3,8% of the production costs and are classified in Group B in the ABC-Cost Analysis. According to the results of the ABC Cost-Analysis the changes of logistical costs should be assessed in the comparison. However, the opinion of MS experts is that the efforts associated with identifying changes of costs in “Logistics” are by far larger than the impact they may have. Further, the modular approach most probably has advantageous effects on logistical costs due to higher synergy, lower number of components and decreased storage area in the modular system.

Moreover, since in this thesis an interim comparative costing is conducted the conservative assumption that the logistical costs are not changing due to the modular approach can be justified. Thus, it is assumed that the absolute value of Logistics compared to the reference cost remains the same. Nevertheless, if a detailed cost analysis is carried out in the future, Logistics needs to be analyzed accurately in order to quantify the changes and reveal the full potential of the modular approach. The modular costs for Logistics are shown in Table 5.10 at section 5.6.1.

General Assembly Cost

General Assembly is the cost type with the second highest percentage of the production cost with a total of 17,9%; the calculation can be found in. Therefore, it is identified to be the secondary cost driver after the material cost. Since, the modular system includes several changes in terms of components, connections and interfaces it is important to assess the changes resulting from the modular approach. Furthermore, the modularized components support the “Integral Construction” approach which has advantageous effects on the ease of assembly (see section 2.3.1). In Figure 5.14, the main steps in the assembly process of a module are illustrated.

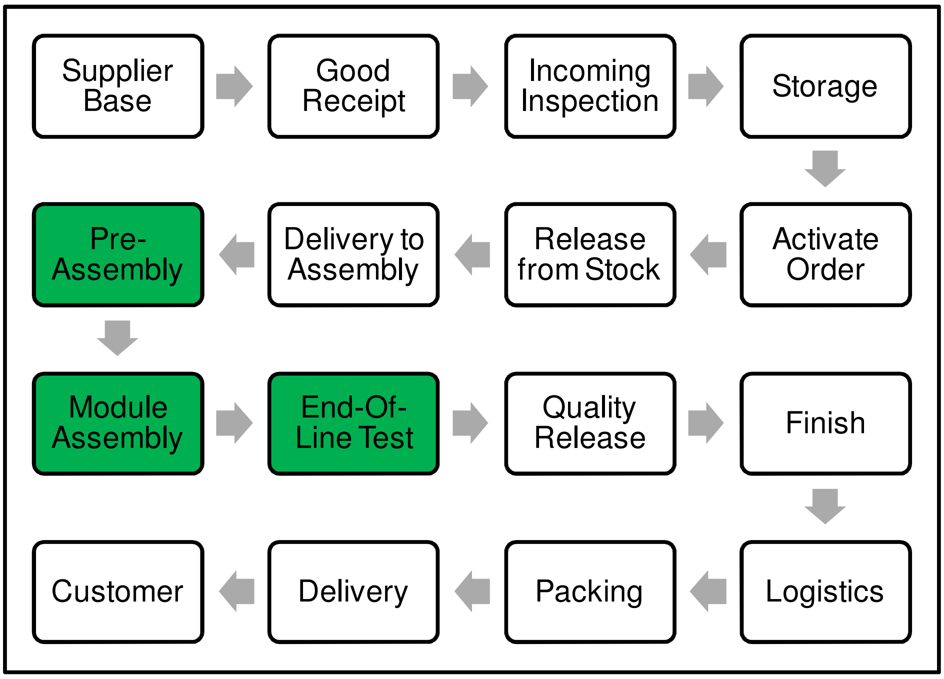

Figure 5.14: Assembly Process CNG Modules[239]

The green markings in Figure 5.14 indicate the process steps which are concerned with the assembly of HPFSSs. These three process steps are explained and assessed on the next pages.

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[239] cf. MAGNA STEYR (2012e), p. 13

Pre-Assembly is concerned with building together sub-assemblies which is necessary before the Module Assembly starts. For some components /assemblies the pre-assembly is mandatory, because they need to be tested before the final implementation in the module (e.g. pressure vessel, pressure regulator, etc.). Mounting the bosses into the liner before it is getting wrapped by fiber material is a good example for pre-assembly.

Module Assembly deals with the complete assembly of the HPFSS. It mainly consists of the sub-assemblies which are mounted and tested during the pre-assembly. All sub-assemblies face their final implementation and become a part of the HPFSS.

End-Of-Line Testing is made after the Module Assembly has finished. It represents the final test in terms of technical functionality. For this test, high pressure is applied to the whole system and it is checked whether it leaks or not.

Pressure Vessel Production is not mentioned in Figure 5.14, because it is not part of the assembly process in particular. Since MS is manufacturing pressure vessels internally it does become a part of the GAC and includes the production of the pressure vessels and their EOL testing. However, the pressure vessels do not change in their quantity, dimensions, material and characteristics due to modularization whatsoever. Therefore, it is easy to justify that no changes in terms of cost are occurring in regard to the pressure vessel production.

Based on the re-build systems and in collaboration with module assembly experts of MS, changes in the assembly procedure due to the modular approach are discussed. The modular system features different interfaces, less connections and a decreased number of components. All this fosters more economic work procedures and makes it easier and quicker to assemble HPFSSs. In order to estimate the changes in GAC induced by the modular approach, a team assessment with MS experts is conducted. The assessment comprises six steps which are explained in section 3.4.6. The results of the assessment are shown on the next page in Table 5.9. The percentages refer to 100% of the general assembly cost; for that reason the values of both steps are added up and lead to the change in terms of GAC due to the modular approach. A negative value represents cost savings compared to the reference systems and vice versa. The effect of these changes on the production costs can be seen in Table 5.10 at section 5.6.1.

Subject of Analysis	Changes Pre-Assembly	Changes Module Assembly	End - Of - Line Testing	Total Changes in Cost
Project Q	-1,0%	-3,0%	-1,0%	-5,0%
Project M	-8,0%	-12,2%	-2,0%	-22,2%
Project O	-2,0%	-1,5%	-1,0%	-4,5%

Table 5.9: Changes in General Assembly Cost[240]

Warranty

As already mentioned in warranty costs are depending more on experience with the type of product and not on the products architecture. This means that Warranty holds a certain percentage on the sum of Material, Inbound Transport & Customs, Logistics and GAC. In addition, warranty cost hold only 2,7% of the TSP and are classified into Group C in the ABC-Cost Analysis. MS experts have the opinion that the warranty cost will change according to this certain percentage when using modularized components. For that reasons, the assumption is made that the percentage for Material, Inbound Transport & Customs, Logistics and GAC remains the same for the modular system.

Sales and General Administration

SGA is classified into Group C in the ABC-Cost Analysis and it holds the second lowest percentage on the Unadjusted TSP with 2,6%. After discussions with MS experts it became clear that modularization of components is more inclined to decrease SGA cost than to increase them. This is mostly due to a decreased variety of components in a modular system compared to a customized system. Thus, less coordination between departments and resources is needed and this leads to lower complexity induced costs (see section 2.2.2). However, SGA costs are usually calculated at MS by applying a set percentage on the sum of Warranty and GAC. In order to keep the comparison conservative, it is assumed that this percentage remains the same for modular systems. All results can be seen in Table 5.10 at section 5.6.1.

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[240] Interview with Christoph Sifferlinger, Herbert Plesch, Franz Mayr and Uwe Thien (23.02.2012), Module Assembly Experts at Magna Steyr

Earnings before Interest and Taxes

EBIT is classified to Group B in the ABC-Cost Analysis and holds a percentage of 7,0% on the total serial price. Actually, EBIT represents the third-highest cost type in regards to production cost. Therefore, it needs to be identified whether it may change due to the modular product architecture or not. The factors that influence EBIT are listed and assessed below:

- **Executive Committee**
  It cannot be determined with a reasonable amount of effort whether the EBIT changes due to the modular approach or not.
- **Business ratios (especially the internal interest rate)**
  According to MS experts it does not change
- **New business / Routine business (e.g. product risk)**
  A different approach is used to conduct the same business as before. Therefore, no or minor changes should occur.
- **Prices of Competitors**
  This may influence the EBIT but in order to keep the comparison conservative it can be assumed that it does not change.
- **Usual margins in the particular business**
  For this factor the same as in “Prices of Competitors” can be applied.

The effect of the modular approach on the parameters that determine the EBIT, delivers a clear result. That is, when changing the product architecture no or marginal changes in regard to the EBIT should result. Thus, it is assumed that the fraction of the value added throughout the value chain remains the same for the modular approach.

5.5.2 Changes in Non-Recurring Cost

HPFSS are operating in a very young and innovative environment which means that high uncertainty, fast & surprising changes and unexpected problems in terms of costs can be particularly expected for NRCs. Determining the exact NRCs of a HPFSS using modular product architecture is a difficult task since not much experience is available in this field of application. Therefore, when dealing with these circumstances, the best solution is to use scenario planning (see section 3.4.7) in order to maneuver around these issues. In particular, a short-term oriented tactical scenario planning is used. In this way the uncertainty of NRC is avoided by establishing several thinkable, credible and representative future scenarios (see Figure 5.15).

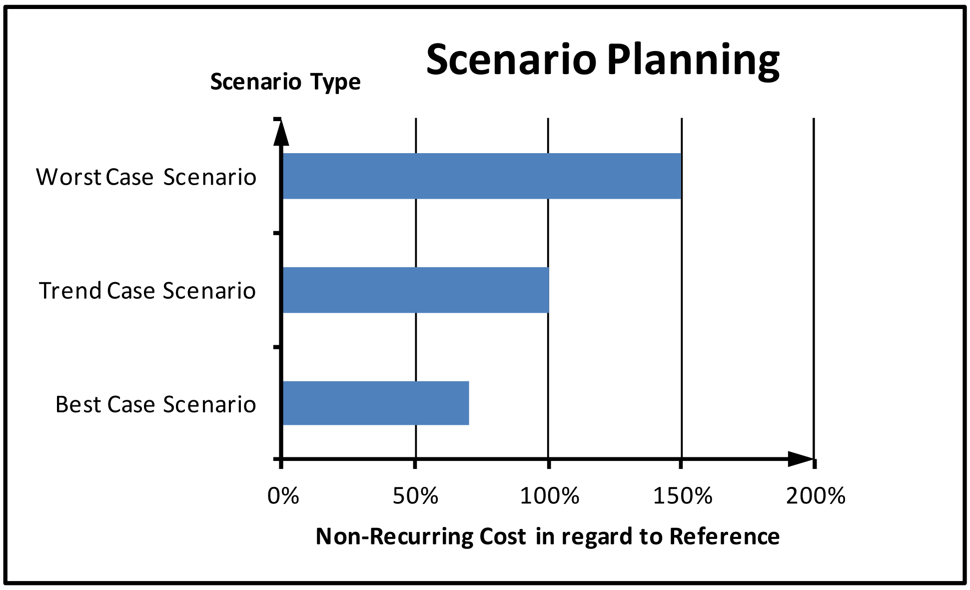

Figure 5.15: Scenario Planning for Non-Recurring Cost[241]

The **Best Case Scenario** in this thesis equals to the 70% of the reference NRC of the particular project.

The **Trend Case Scenario** in this thesis equals to the reference NRC of the particular project. This is used to get a direct comparison between the tailor-made and the modular approach assuming that NRCs are constant.

The **Worst Case Scenario** in this thesis equals to be 50% higher as the reference NRCs of respective project.

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[241] Own Illustration

Assumption

The non-recurring costs of every project are charged against the unadjusted comparison result in both the reference and the modular systems. In doing so, output costing is used to allocate the NRCs. Normally output costing is used for mass production with a single product approach. However, it can also be used for Type Production and the circumstances allow using it for NRCs due to the fact that they are available for each project/product separately and each unit consumes the same amount of resources during its creation. Furthermore, output costing is chosen, because this method ensures that the NRCs are distributed over the unadjusted TSP for all projects in the same way.

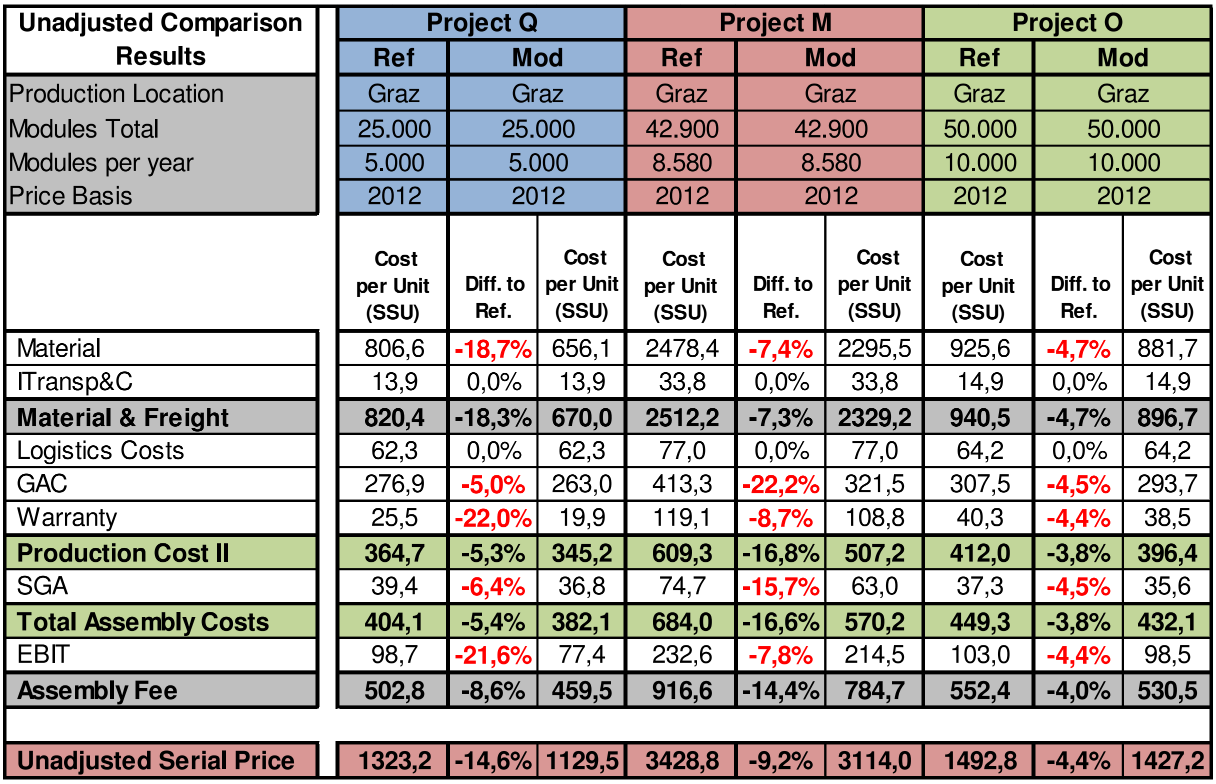
Thus, “Direct Payment Customer” equals zero for all projects. For detailed information about how the NRCs are considered in the comparison analysis see section 5.6.2.

5.6 Comparison Results

In this chapter the results of the comparison analysis are illustrated and explained. The first part discusses the unadjusted comparison results which originate from the changes to the production costs induced by the modular approach. Secondly, the final results of the comparative analysis are shown in terms of the adjusted comparison results in which the NRCs are integrated in the analysis as well.

5.6.1 Unadjusted Comparison Result

In Table 5.10 the unadjusted results of the comparison are displayed which result from the changes in production costs due to the modular approach. It shows the reference project next to the modular project in order to compare the values. In columns “Diff. to Ref.” the difference- to the reference-costs expressed in percent are mentioned. A negative value means that the modular approach is cheaper than the tailor-made approach and vice versa. Percentages highlighted in red color indicate that the value of the particular cost type changed due to modularization.



Unadjusted Comparison Results	Project Q			Project M			Project O		
	Ref	Mod		Ref	Mod		Ref	Mod	
Production Location	Graz	Graz		Graz	Graz		Graz	Graz	
Modules Total	25.000	25.000		42.900	42.900		50.000	50.000	
Modules per year	5.000	5.000		8.580	8.580		10.000	10.000	
Price Basis	2012	2012		2012	2012		2012	2012	
	Cost per Unit (SSU)	Diff. to Ref.	Cost per Unit (SSU)	Cost per Unit (SSU)	Diff. to Ref.	Cost per Unit (SSU)	Cost per Unit (SSU)	Diff. to Ref.	Cost per Unit (SSU)
Material	806,6	-18,7%	656,1	2478,4	-7,4%	2295,5	925,6	-4,7%	881,7
ITransp&C	13,9	0,0%	13,9	33,8	0,0%	33,8	14,9	0,0%	14,9
Material & Freight	**820,4**	**-18,3%**	**670,0**	**2512,2**	**-7,3%**	**2329,2**	**940,5**	**-4,7%**	**896,7**
Logistics Costs	62,3	0,0%	62,3	77,0	0,0%	77,0	64,2	0,0%	64,2
GAC	276,9	-5,0%	263,0	413,3	-22,2%	321,5	307,5	-4,5%	293,7
Warranty	25,5	-22,0%	19,9	119,1	-8,7%	108,8	40,3	-4,4%	38,5
Production Cost II	**364,7**	**-5,3%**	**345,2**	**609,3**	**-16,8%**	**507,2**	**412,0**	**-3,8%**	**396,4**
SGA	39,4	-6,4%	36,8	74,7	-15,7%	63,0	37,3	-4,5%	35,6
Total Assembly Costs	**404,1**	**-5,4%**	**382,1**	**684,0**	**-16,6%**	**570,2**	**449,3**	**-3,8%**	**432,1**
EBIT	98,7	-21,6%	77,4	232,6	-7,8%	214,5	103,0	-4,4%	98,5
Assembly Fee	**502,8**	**-8,6%**	**459,5**	**916,6**	**-14,4%**	**784,7**	**552,4**	**-4,0%**	**530,5**
Unadjusted Serial Price	**1323,2**	**-14,6%**	**1129,5**	**3428,8**	**-9,2%**	**3114,0**	**1492,8**	**-4,4%**	**1427,2**

Table 5.10: Unadjusted Comparison Results[242]

Interpretation of Unadjusted Comparison Results

All information and data shown in Table 5.10 originates from different sources throughout the previous chapters. The basic project information is taken from the three reference projects and all values in the columns "Ref" (i.e. Reference) refer to Table 5.3 in section 5.2.4. These values are based on preliminary costings carried out at MS for the three reference projects. It represents the data to which the cost of the modular approach is compared with. The columns "Mod" (i.e. Modular) contain the costs of the three projects build-up with modularized components.

Positive effects of the modularization can be easily seen in the unadjusted comparison results. Astounding savings in terms of material cost up to 18,7% and savings in GAC up to 22,2% are identified in the comparison analysis. This is mostly due to new innovative components which replace several "older" parts and exhibit interfaces which foster a faster assembly of the HPFSS. Furthermore, the synergy between the three projects decreases the cost per piece by utilizing EOS.

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[242] Own Illustration

Project Q turned out to have the highest relative cost savings in material with 18,7% or SSU 193,7 which can be justified by the optimized frame/interface to the vehicle. Having said that, Project M holds 7,4% of savings in material. However, it needs to be taken into consideration that Project M has a considerably higher amount of absolute material costs and still represents the highest absolute material cost savings with SSU 314,8. On the other hand, Project O performs not as well as the other projects but nevertheless the modular approach is more economic than the reference approach. Savings in material cost amount to 4,7% or SSU 65,6.

Compared to the material cost, the changes of GAC are rather simple to interpret. Project M represents the highest savings in GAC by far; this results from the fact that Project M is a bus application and incorporates a considerably higher amount of components than the other two projects. Therefore, Project M benefits the most from the changed connection interfaces of the pressure vessels and the reduction of parts in the HPFSS.

Since it is assumed that three other costs types (i.e. Warranty, SGA and EBIT) are directly depending on the two main cost drivers (i.e. material and GAC) it is easy to understand that Warranty, SGA and EBIT are changing accordingly. Ultimately they are all dependant on the two main cost drivers, however, from the results it can be derived that Warranty and EBIT are more dependent on changes in material cost and SGA is more reliant on changes in GAC.

5.6.2 Adjusted Comparison Result

The main difference between the adjusted and the unadjusted comparison result is that in the latter the NRCs are not incorporated. In Table 5.12 the results of the adjusted comparison are presented. They contain the relative difference between the reference and the modular system for all projects in terms of adjusted TSP; also, the average difference between modular- and reference-modules is calculated; further, the absolute savings per year which result from using modularized components determined; another figure is introduced which contains an assessment of the HPFSS in terms of monetary units per performance measure (see Table 5.11). That is, SSU (virtual currency) per kWh for each project and scenario. This ratio is used to assess whether the main cost driver method can be applied for 200bar CNG HPFSSs or not. All results are shown in Table 5.12.

Calculation of Energy Content

The ratio at the very right column in Table 5.12, that is SSU/kWh, is simply calculated by dividing the adjusted TSP of a product configuration by the energy content of its HPFSS in kWh. How this calculation is carried out is explained below. The whole calculation was carried out according to MS experience and assumptions (Formula 5.1).

Assumptions:

$\mathrm{Fuel\ is\ Real\ Gas;\ Pressure,\ p = 200bar;\ Ambient\ Temperature,\ T = 293K;}$

$\mathrm{Energy\ Density\ of\ CNG\ (87 - 99Vol.\%\ of\ Methane)} \sim 13{,}16 \frac{\mathrm{kWh}}{\mathrm{kg_{fuel}}};$

$\mathrm{Real\ Gas\ Constant,\ R_s = 518{,}27 \frac{J}{kg\,K};\ Volume,\ V = 1m^3 = 1000dm^3 = 1000l;}$

$\mathrm{Compressibility\ Factor,\ z = 0{,}81114;}$

Goal: $m_{fuel} = ?$

$$\mathrm{p \cdot V = z \cdot m_{fuel} \cdot R_s \cdot T => m_{fuel} = \frac{p \cdot V}{T \cdot R_s \cdot z}}$$

$$\mathrm{=> m_{fuel} = \frac{p \cdot V}{T \cdot R_s \cdot z} => \frac{200 \cdot 10^5 N \cdot 1000dm^3 \cdot kg\,K}{293K \cdot m^2 \cdot 518{,}27\,J \cdot 0{,}81114}} \quad => \boxed{\mathrm{m_{(l_{fuel})} = 0{,}16237\ kg}}$$

Formula 5.1: Calculation of Energy Content[243]

After the conversion of m_{fuel} to l_{fuel}, the ratio is simply multiplied by Total l_{fuel} to receive Total m_{fuel}. Then it is multiplied further with the energy density of the fuel (i.e. 13,16 kWh/kg_{fuel}) in order to receive the energy content of the particular HPFSS. This calculation is conducted for all projects; the results of the energy contents for each project can be seen in Table 5.11. It needs to be pointed out that Project M possesses very high energy content due to the fact that it is designed for a bus application.

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[243] cf. WISCHNEWSKI (2012)

Project	Vessels (Ø x length in mm)	l_{fuel}	Quantity	Total l_{fuel}	Total m_{fuel}	Energy Content (kWh)
Project Q	Ø206x1040mm	26,3	2	52,6	8,54	112,40
	Ø390x895mm	77,2	1	77,2	12,54	164,96
Sum				129,8	21,08	277,36
Project M	Ø324x1400mm	82,0	8	656	106,52	1401,75
Project O	Ø260x956mm	38,0	1	38	6,17	81,20
	Ø240x880mm	30,0	1	30	4,87	64,10
	Ø279x873mm	39,5	1	39,5	6,41	84,40
	Ø279x893mm	40,5	1	40,5	6,58	86,54
Sum				148	24,03	316,25

Table 5.11: Calculation of HPFSS Energy Content[244]

As mentioned on page 111, the adjusted TSP of a particular project is now divided by its energy content (see Table 5.11) to receive the performance ratio SSU/kWh. This and all other results of the calculations can be found in Table 5.12.

The NRCs are incorporated in the comparison analysis by creating several scenarios. It considers all projects including the tailor-made reference scenario and three scenarios for the modular system (Best Case, Trend Case, and Worst Case). At first, the unadjusted TSPs which originate from Table 5.10 in section 5.6.1 are embedded in the analysis. Then, the NRCs of the reference projects are used to create the future scenarios. After that, the NRCs are divided by the total number of modules of the particular project and allocated to the unadjusted TSP. This leads to the adjusted TSP of the modular systems which is now compared to the adjusted TSP of the references in order to receive the ultimate difference between them.

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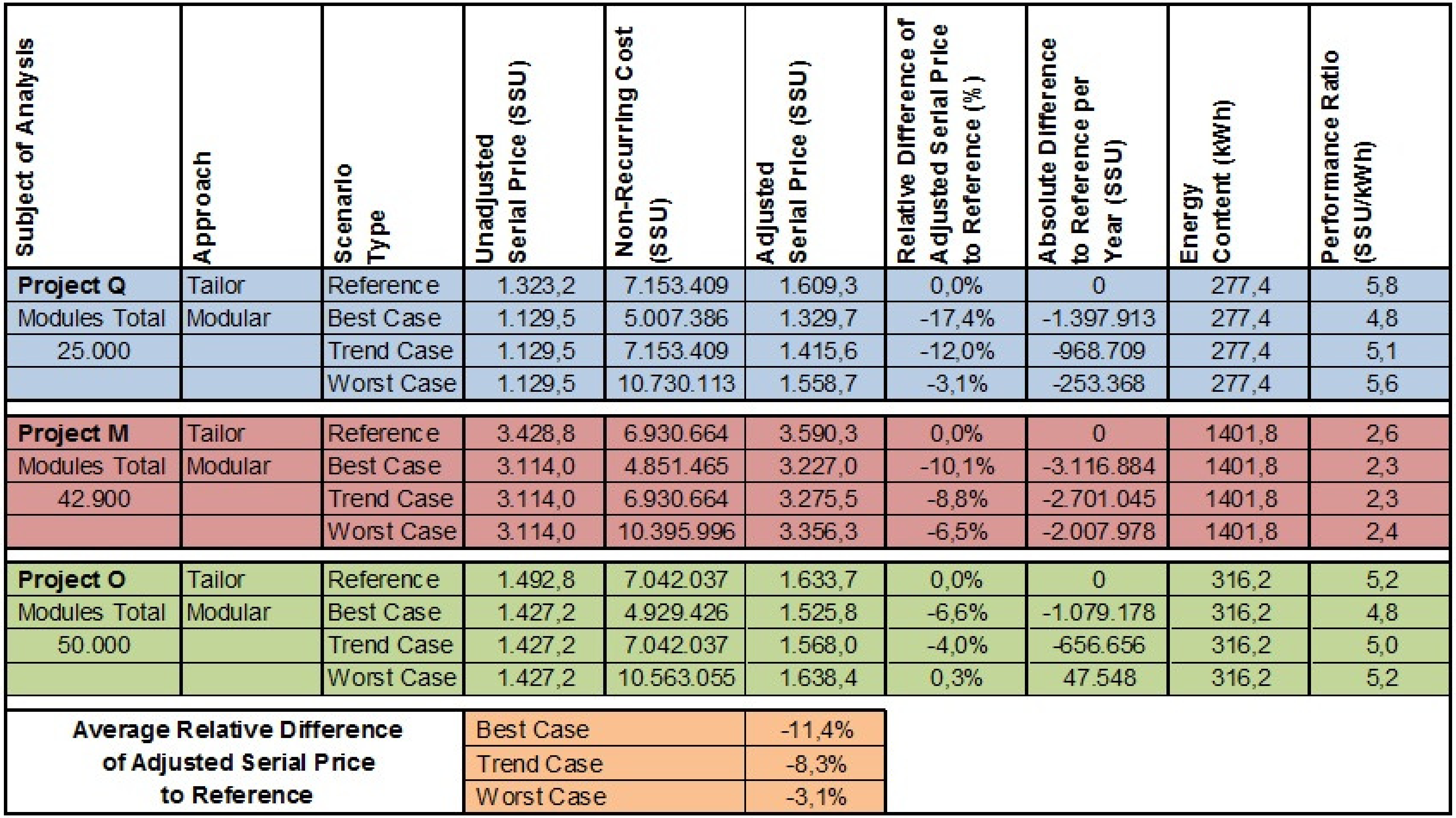
[244] cf. MAGNA STEYR (2011c), pp. 23-25



Subject of Analysis	Approach	Scenario Type	Unadjusted Serial Price (SSU)	Non-Recurring Cost (SSU)	Adjusted Serial Price (SSU)	Relative Difference of Adjusted Serial Price to Reference (%)	Absolute Difference to Reference per Year (SSU)	Energy Content (kWh)	Performance Ratio (SSU/kWh)
Project Q	Tailor	Reference	1.323,2	7.153.409	1.609,3	0,0%	0	277,4	5,8
Modules Total	Modular	Best Case	1.129,5	5.007.386	1.329,7	-17,4%	-1.397.913	277,4	4,8
25.000		Trend Case	1.129,5	7.153.409	1.415,6	-12,0%	-968.709	277,4	5,1
		Worst Case	1.129,5	10.730.113	1.558,7	-3,1%	-253.368	277,4	5,6
Project M	Tailor	Reference	3.428,8	6.930.664	3.590,3	0,0%	0	1401,8	2,6
Modules Total	Modular	Best Case	3.114,0	4.851.465	3.227,0	-10,1%	-3.116.884	1401,8	2,3
42.900		Trend Case	3.114,0	6.930.664	3.275,5	-8,8%	-2.701.045	1401,8	2,3
		Worst Case	3.114,0	10.395.996	3.356,3	-6,5%	-2.007.978	1401,8	2,4
Project O	Tailor	Reference	1.492,8	7.042.037	1.633,7	0,0%	0	316,2	5,2
Modules Total	Modular	Best Case	1.427,2	4.929.426	1.525,8	-6,6%	-1.079.178	316,2	4,8
50.000		Trend Case	1.427,2	7.042.037	1.568,0	-4,0%	-656.656	316,2	5,0
		Worst Case	1.427,2	10.563.055	1.638,4	0,3%	47.548	316,2	5,2

Average Relative Difference of Adjusted Serial Price to Reference		
	Best Case	-11,4%
	Trend Case	-8,3%
	Worst Case	-3,1%

Table 5.12: Adjusted Comparison Results

Table 5.12 contains the end results of the comparative analysis between the three reference systems and the three re-built modular systems. All further graphs and figures in this chapter are based on these values.

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[245] Own Illustration

Relative Difference of Reference- to Modular Serial Price

Figure 5.16 represents the relative difference in costs of the reference systems to the adjusted TSP of the modular systems. The difference in costs is applied on the y-axis (i.e. ordinate) and the scenario type is applied to the x-axis (i.e. abscissa). A negative value states that the respective configuration is cheaper by that percentage than the reference system and vice versa. Hence, the abscissa represents the reference system, because the difference to the reference is clearly zero percent. The "Trend Case" is a direct comparison of the reference production cost and the modular production costs, because the same NRCs are assumed in both. This graph gives a quick overview in terms of costs in regard to 200bar CNG HPFSS under different circumstances (i.e. scenarios). Moreover, it gives the analyst an idea of how the costs behave (i.e. gradient) and their progression depending on the NRCs.

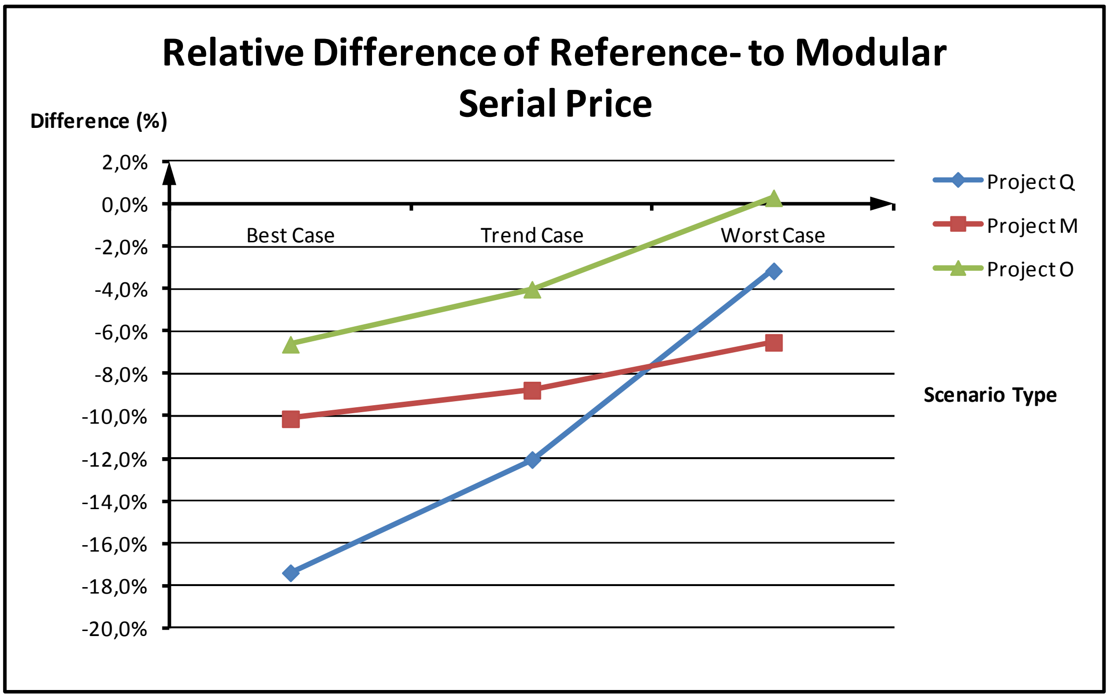

Figure 5.16: Relative Difference of Reference- to Modular Serial Price[246]

The results in Figure 5.16 clearly show that in the best case-, trend case- and even in the worst case-scenario the modular approach maintains its cost advantages compared with the reference systems. The only exception is Project O in the worst case scenario which is slightly more expensive than the reference. On the next page Figure 5.17 displays these differences in cost averaged over all three projects.

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[246] Own Illustration

Average Relative Difference of Reference- to Modular Serial Price

Figure 5.17 displays the average relative difference of reference- to adjusted-TSP over three possible future scenarios. The significance of this figure is that the changes in terms of costs are averaged over all projects that are included in the analysis. This is used to develop a fundamental understanding of changes in terms of cost induced by a modular system in general when manufacturing several projects with the modular approach. The average difference is applied to the y-axis (i.e. ordinate) and the scenario type is applied to the x-axis (i.e. abscissa). A negative difference implies that the particular scenario holds a reduced price compared to the reference system and vice versa. For a direct comparison of average cost changes between reference- and modular-HPFSS, the “Trend Case” scenario is used. Again, the abscissa embodies the reference system since the difference is clearly zero percent.

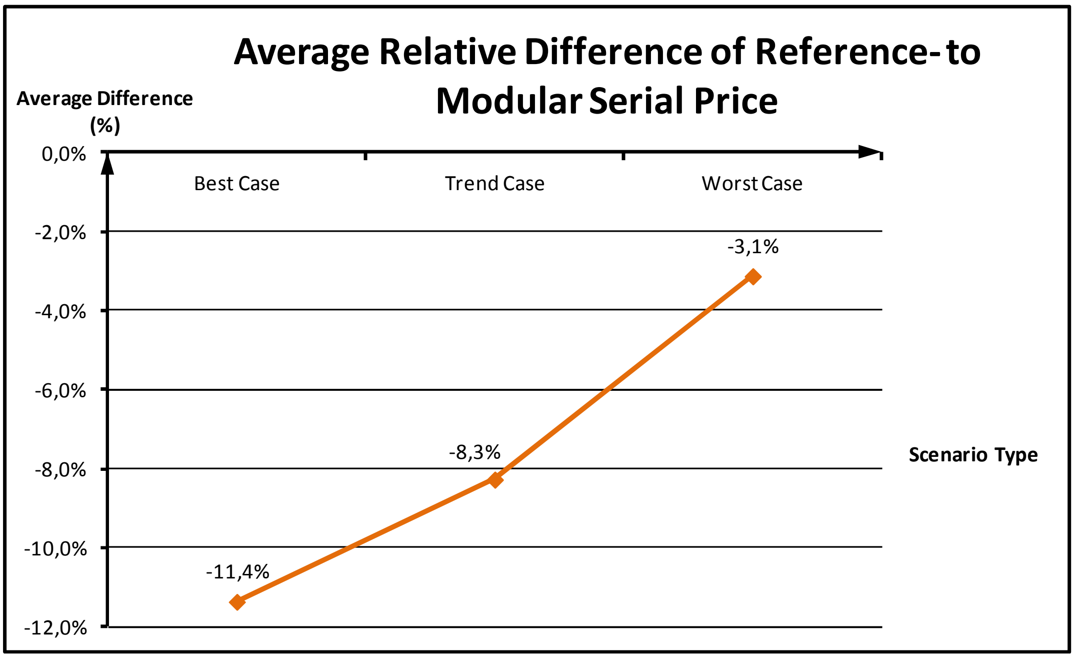

Figure 5.17: Average Relative Difference of Reference to Modular Serial Price[247]

Since all values in Figure 5.16 and Figure 5.17 are expressed in percent, it develops an understanding of the relative differences in terms of costs. However, in order to conceive the changes in absolute values as well, the absolute differences in cost are presented in the subsequent section.

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[247] Own Illustration

Cost Savings per Year

As mentioned on the last page, Figure 5.18 presents the absolute differences in cost received from the comparative analysis. Here, the absolute difference in cost per year is applied to the ordinate and the scenario type is applied to the abscissa. Again, the abscissa represents the reference systems, because the difference equals zero. This means, that a negative difference indicates cost savings for the modular approach compared to the reference systems and vice versa. Further, it needs to be pointed out that no valorization is taken into account in this assessment. However, if valorization is considered, the savings would most likely increase which fosters the conservative spirit of the comparison even more.

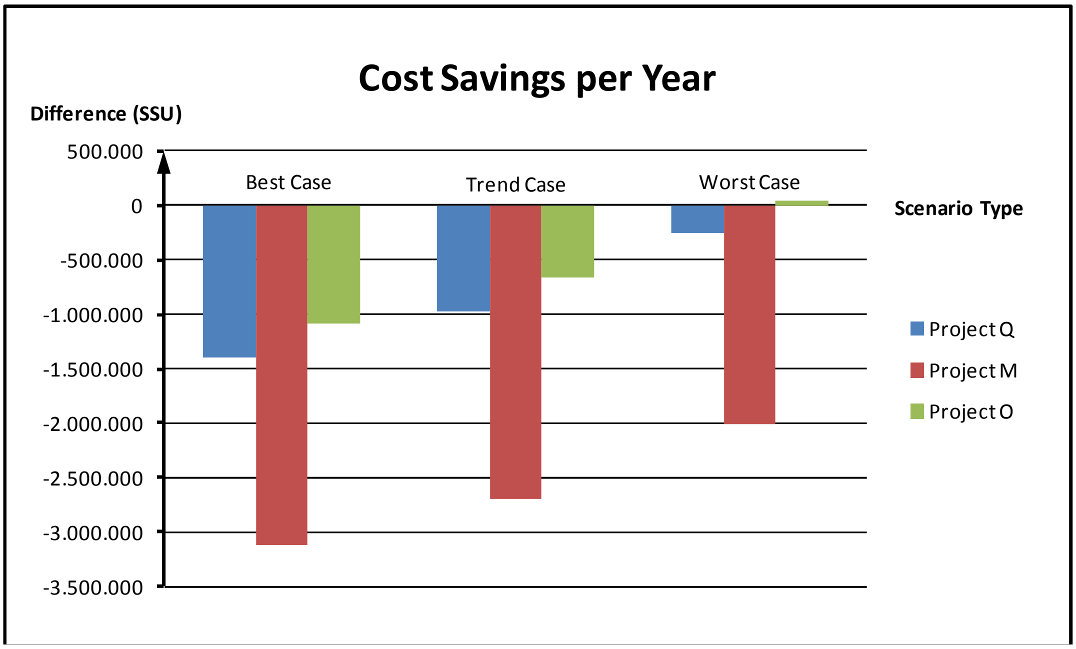

Figure 5.18: Cost Savings per Year[248]

The results in Figure 5.18 speak for themselves; a considerable amount of savings throughout all three projects and even in the worst case scenario are achieved by modularization. The only exception is Project O which shows slightly increased cost in the worst case scenario. However, in particular, Project M accomplishes a very good result which is mostly due to the fact that it embodies a bus application in which the number of parts is considerably reduced by the modular approach. Therefore, the assembly cost for Project M is significantly decreased which heavily effects the production cost. Furthermore, it has the highest absolute savings in material cost with SSU 314,8.

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[248] Own Illustration

SSU (virtual currency) per Energy Content of Module

A different way to assess the cost and performance of a product is to introduce performance ratios which may be used as a rough cost estimation of costs as well. Whether a product is suitable for using the main cost driver method or not depends on its behavior in terms of costs when changing certain performance parameters. The ratio "Price per Energy Content" belongs to Performance Oriented Cost Drivers and it serves as a ratio which helps to identify whether it is feasible to use the main cost driver method for estimating costs for modular 200bar HPFSS or not. Further, it provides information about the price one has to pay for certain energy content with a particular product configuration. Figure 5.19 shows the results of the analysis, in which Price/Energy Content is applied to the y-axis (i.e. ordinate) and the scenario type is applied to the x-axis (i.e. abscissa). Again, the color code represents the three different reference systems of the comparison.

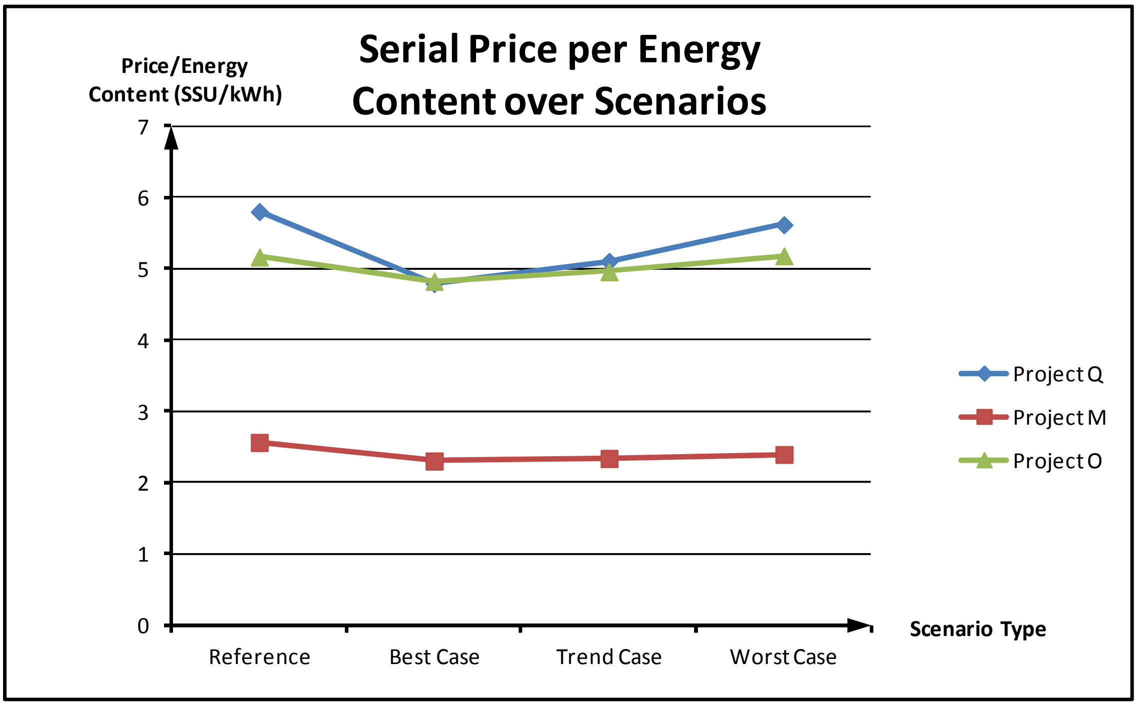

Figure 5.19: Serial Price per Energy Content over Scenarios[249]

According to the results shown in Figure 5.19, 200bar CNG HPFSSs are not suitable for the main cost driver method, because the differences in terms of progression and absolute values are too high between the three projects. This means, that the behavior of the price per energy content differs too much amongst the three projects.

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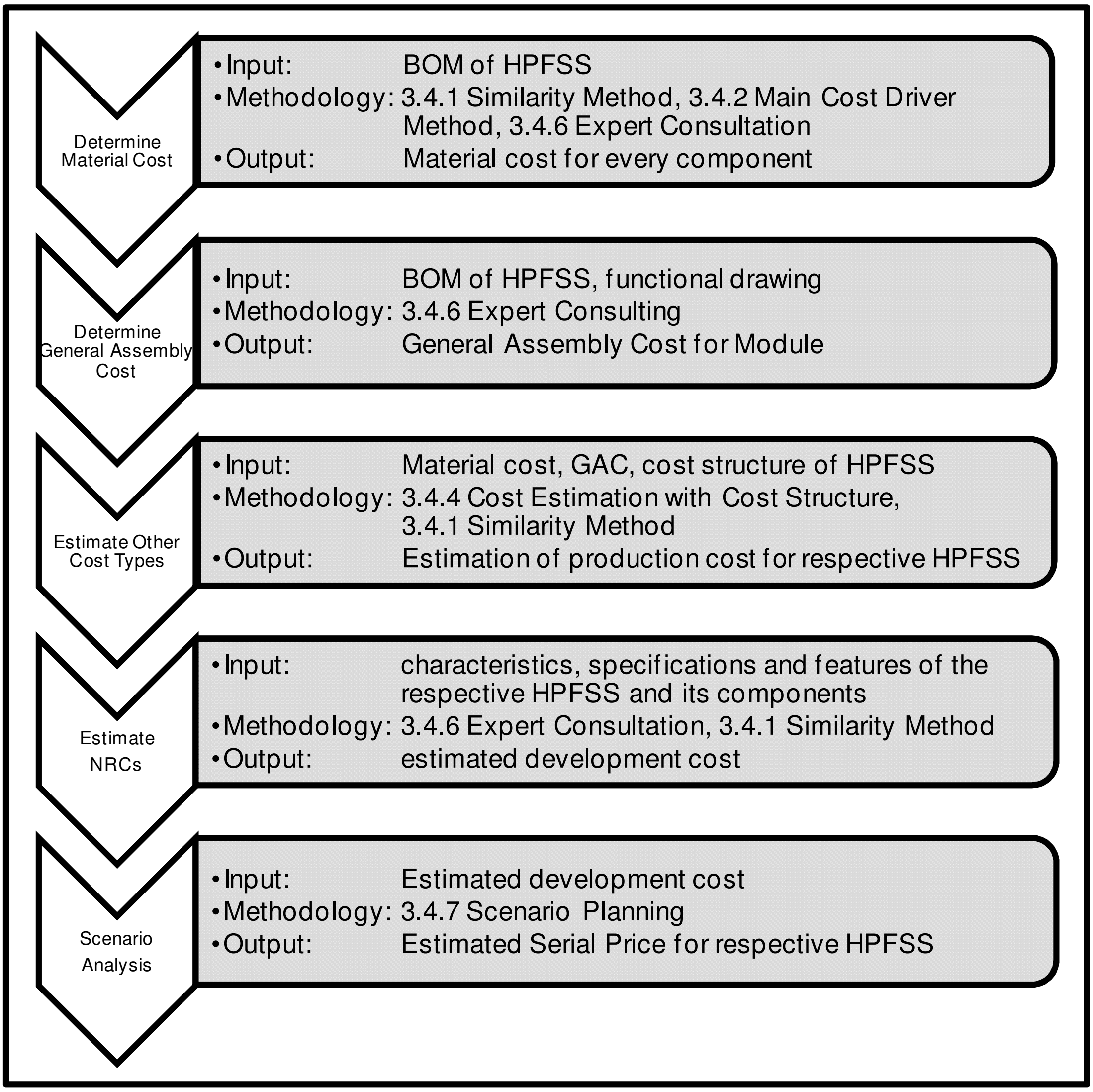
[249] Own Illustration

6 Cost Estimation Tool

Based on the methodology used to conduct the comparative analysis, a cost estimation tool for modular HPFSS (200bar CNG) is developed. This serves the purpose of providing several departments at MS with a tool to estimate the costs of a HPFSS that has a reasonable trade-off between time and accuracy. The preceding chapter describes the behavior and characteristics of this type of product in terms of cost. Furthermore, it provides a fundamental understanding of the cost drivers and influences on cost of HPFSSs which is now used to develop a cost estimation tool. The below chart explains the estimation process for a new HPFSS and its steps with the respective input, output and methodology (see Figure 6.1).



Determine Material Cost
- Input: BOM of HPFSS
- Methodology: 3.4.1 Similarity Method, 3.4.2 Main Cost Driver Method, 3.4.6 Expert Consultation
- Output: Material cost for every component

Determine General Assembly Cost
- Input: BOM of HPFSS, functional drawing
- Methodology: 3.4.6 Expert Consulting
- Output: General Assembly Cost for Module

Estimate Other Cost Types
- Input: Material cost, GAC, cost structure of HPFSS
- Methodology: 3.4.4 Cost Estimation with Cost Structure, 3.4.1 Similarity Method
- Output: Estimation of production cost for respective HPFSS

Estimate NRCs
- Input: characteristics, specifications and features of the respective HPFSS and its components
- Methodology: 3.4.6 Expert Consultation, 3.4.1 Similarity Method
- Output: estimated development cost

Scenario Analysis
- Input: Estimated development cost
- Methodology: 3.4.7 Scenario Planning
- Output: Estimated Serial Price for respective HPFSS

Figure 6.1: Estimating Tool - Process Steps[250]

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[250] Own Illustration

The estimation process shown in Figure 6.1 is implemented in a Microsoft Excel Spreadsheet which is described on the next pages.

Determine Material Cost

Since the material costs have such a predominant role (more than 65% of total production cost) in terms of costs for HPFSS, it is crucial to determine them carefully and with a high degree of accuracy in order to receive meaningful results. Therefore, the BOM should be deduced from preliminary designs, sketches or customer specifications in collaboration with experts. Then, the cost for each component needs to be identified and adjusted according to the buying quantities of the project(s). Depending on the particular component the costs can be estimated by similar projects, with a Main Cost Driver (e.g. pressure vessels, see Table 5.6) or a separate costing which is conducted by a suitable department at MS. The illustration of the BOM can be seen in Table 6.1 in which the material costs are determined. Numbers which are highlighted in red stand for values which need to be inserted by the user of the tool. The results or interim results are highlighted in green.

All data shown in Table 6.1 may be adjusted according to the specific needs of the estimation or of the HPFSS. That means, if new components are used which are not included in the standard component selection, their name and cost need to be inserted into the BOM to be included in the estimation.

Bill Of Material		**Project**		**Project XY**			
		Lifetime		**5**			
		Modules Total		**25.000**			
		Modules / Year		**5.000**			
Component No.	**Component**	**Reference Quantity (Pc./Year)**	**Reference Cost per Unit (€/Pc.)**	**Actual Quantity (Pc./Year)**	**Quantity**	**Actual Cost per Unit (€/Pc.)**	**Cost per Module (€/unit)**
	Assembly Filling System						
1	CNG Filling Receptacle	23.580	14,3	5.000	1	22,5	22,5
2	High Pressure Filling Line (2m)	40.740	48,5	5.000	1	78,9	78,9
3	Straight Fitting Ø8mm	67.160	4,8	30.000	6	6,0	35,9
4	T-Piece	18.580	14,3	0			0,0
	Assembly Connection Blocks						
5	Y-Piece	75.060	11,4	15.000	3	18,4	55,2
6	Connection Block/Frame 2 Vessels	40.000	27,4	0			0,0
7	Connection Block/Frame 3 Vessels	10.000	45,6	0			0,0
8	Connection Block/Frame 4 Vessels	34.320	62,7	0			0,0
9	Low Pressure Connection Line	100.800	5,7	5.000	1	10,8	10,8
10	High Pressure Connection Line (1m)	6.716	10,9	5.000	1	10,9	10,9
11	TPRD	185.800	7,5	15.000	3	13,9	41,7
12	Wiring	33.580	6,3	15.000	3	6,8	20,5
13	Manual Valve	247.280	2,3	0			0,0
14	Axial Securing Boss	247.280	0,3	0			0,0
15	Covers	247.280	0,1	0			0,0
	Assembly Vessels						
12	Project Q: Ø206x1040mm (26,3l)	10.000	55,9	10.000	2	55,9	111,7
13	Project Q: Ø390x895mm (77,2l)	5.000	164,2	5.000	1	164,2	164,2
14	Project M: Ø324x1400mm (82l)	68.640	176,7	0			0,0
15	Project O: 37l (average value)	40.000	99,8	0			0,0
	Assembly Gas Handling Unit						
16	GHU Body	23.580	14,3	5.000	1	25,7	25,7
17	Pressure Regulator+Control Valve	23.580	74,1	5.000	1	79,8	79,8
19	SOV	42.160	13,1	0	1		0,0
	Other Components						
20	Diverse Small Parts	27.870	14,3	5.000	1	23,9	23,9
21	OTV	123.640	22,8	15.000	3	35,3	106,0
22	Frame	5.000	67,3	5.000	1	67,3	67,3
23	Mount Bracket SOV Side	15.000	20,0	15.000	3	20,0	59,9
24	Mount Bracket Rear Side	15.000	10,8	15.000	3	10,8	32,5
25	Tension Belt	264.440	4,6	30.000	6	5,7	34,2
	Material Cost						**981,5**

Table 6.1: Estimating Tool - Determine Material Cost[251]

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[251] Own Illustration

Determine General Assembly Cost

The second step in the estimation process deals with the GAC. Since this cost type is identified to be the second highest with roughly 20% of the unadjusted TSP, it needs to be estimated more accurately than all other cost types (except material cost). GAC includes the pre-assembly, the module assembly, end of line test and the pressure vessel manufacturing. The costs associated with these activities need to be estimated by MS experts based on the particular characteristics, features and customer specifications of the respective HPFSS.

After determining the GAC, the main cost drivers (i.e. material cost and GAC) are quantified for the specific HPFSS and based on that information all other cost types are estimated in step three of the estimation process.

Estimate Other Cost Types

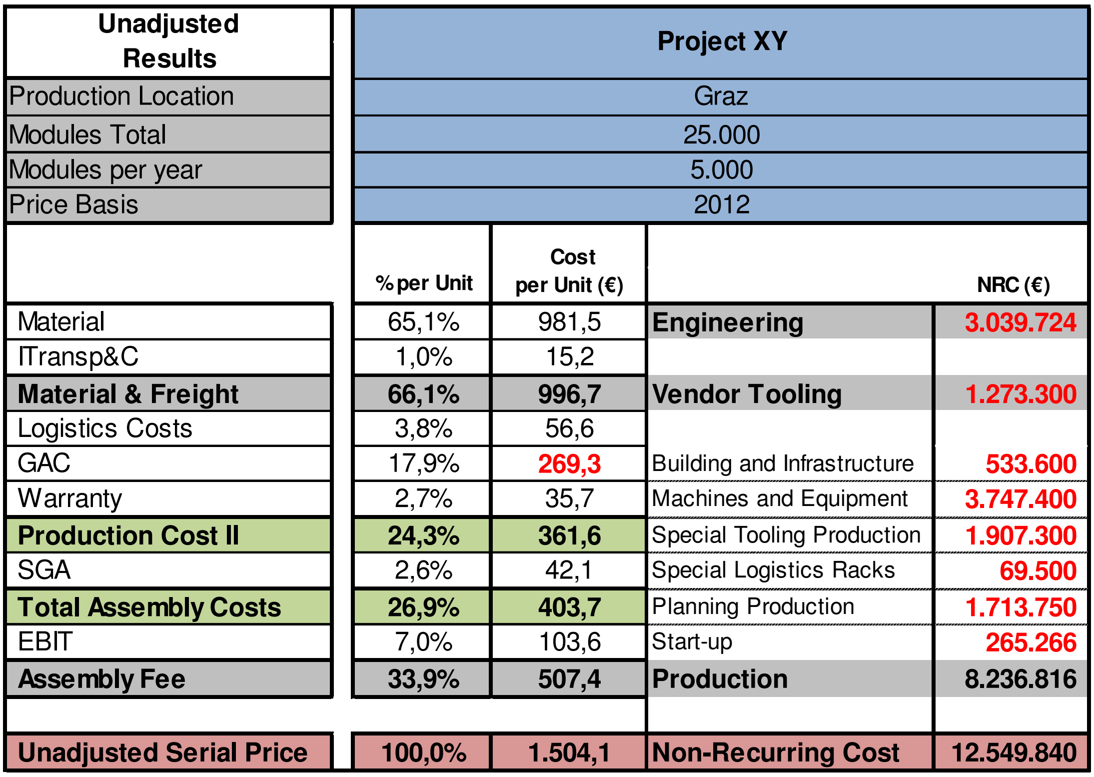
Since the main cost drivers (i.e. material cost and GAC) are already identified, all other cost types can be estimated. Due to the results of the cost structure analysis it is clear that the remaining cost types sum up to slightly less than 20% of the TSP. According to the findings in section 5.5.1 some cost types are not changing due to the modular approach and it is assumed that their fractions on specific values stays constant (i.e. Warranty, SGA and EBIT); Inbound Transport & Customs has a marginal impact on the production costs; on the other hand, Logistics does not have a considerable impact on the production costs and the effort connected with identifying changes does not stand for the possible outcomes. Hence, these two cost types (Inbound Transport & Customs and Logistics) are estimated by the cost structure of the product. The method uses the average percentages of the cost structure analysis in order to estimate the costs for the remaining cost types by simply inserting the material and GAC into the costing and calculating all other cost types according to their percentages. This leads to the total production costs of the particular HPFSS. See Table 6.2 for a graphical illustration of the estimation.

However, the NRCs for the product need to be considered as well which is carried out in the next two steps of the estimation process.

Estimate Non-Recurring Cost

Until now, the estimating process is only concerned with production cost. However, in such an innovative environment the NRCs play an important role in terms of cost. For that reason, they should be estimated by all departments involved in the project and also be compared to past projects. Still, the NRCs are connected with high uncertainty and may change rapidly due to unexpected events. NRCs consist of engineering, vendor tooling and the production investments and are used in the last step of the estimation process to carry out a scenario analysis which incorporates the NRCs into the unadjusted TSP and converts them to the adjusted TSP. The design of this estimation can be seen below in Table 6.2.

Altogether, material costs identified in Table 6.1 are inserted into the unadjusted results. Furthermore, the second step of the estimation process is carried out by inserting the estimated GAC into the costing as well. After that, in step three all other cost types are calculated according to their percentages which are calculated in the cost structure analysis (i.e. Inbound Transport & Customs, Logistics) and which are predefined by MS (i.e. Warranty, SGA, EBIT). This results in the production costs or unadjusted TSP of the particular HPFSS (see Table 6.2).



Unadjusted Results	**Project XY**			
Production Location	Graz			
Modules Total	25.000			
Modules per year	5.000			
Price Basis	2012			
	% per Unit	**Cost per Unit (€)**		**NRC (€)**
Material	65,1%	981,5	**Engineering**	**3.039.724**
ITransp&C	1,0%	15,2		
Material & Freight	**66,1%**	**996,7**	**Vendor Tooling**	**1.273.300**
Logistics Costs	3,8%	56,6		
GAC	17,9%	**269,3**	Building and Infrastructure	**533.600**
Warranty	2,7%	35,7	Machines and Equipment	**3.747.400**
Production Cost II	**24,3%**	**361,6**	Special Tooling Production	**1.907.300**
SGA	2,6%	42,1	Special Logistics Racks	**69.500**
Total Assembly Costs	**26,9%**	**403,7**	Planning Production	**1.713.750**
EBIT	7,0%	103,6	Start-up	**265.266**
Assembly Fee	**33,9%**	**507,4**	**Production**	**8.236.816**
Unadjusted Serial Price	**100,0%**	**1.504,1**	**Non-Recurring Cost**	**12.549.840**

Table 6.2: Estimation Tool - Unadjusted Results[252]

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[252] Own Illustration

Scenario Analysis

Since estimating the NRCs for a HPFSS is connected with high uncertainty measures must be taken to address this problem. The best way of dealing with such issues is to create several thinkable, credible and representative future scenarios based on the available information. This means, that scenario planning is used to circumvent the high uncertainty associated with estimating NRC for HPFSS. It is conducted in the exact same way as seen in the comparison analysis with the exception that the scenarios should be adjusted according to the particular situation and product by multiplying factors (see Table 6.3, column “Factor”).

In Table 6.3 the calculation of the adjusted TSP is shown. The only thing that needs to be inserted by the operator is the factors. The factor is a value which is multiplied with the estimated NRC in order to create possible future scenarios. However, the adjusted TSP is simply determined by dividing the NRCs by “Modules Total” and this is then added to the respective unadjusted TSP. Furthermore, these results are presented in a graph which can be seen in Figure 6.2.

Adjusted Results	**Scenario Type**	**Unadjusted Total Serial Price (€)**	**Factor**	**Non-Recurring Cost (€)**	**Adjusted Total Serial Price (€)**
Project XY	Best Case	1.504,1	**0,5**	6.274.920	1.755,1
Modules Total	Trend Case	1.504,1	**1,0**	12.549.840	2.006,1
25.000	Worst Case	1.504,1	**1,5**	18.824.760	2.257,1

Table 6.3: Estimation Tool - Scenario Planning[253]

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[253] Own Illustration

After determining the production costs, considering the NRCs and creating several possible future scenarios, a reasonable but nevertheless quick cost estimation for a HPFSS is received. The results are shown in Figure 6.2 where the adjusted TSP in € (virtual currency) is applied to the ordinate (y-axis) and the scenario type is applied to the abscissa (x-axis).

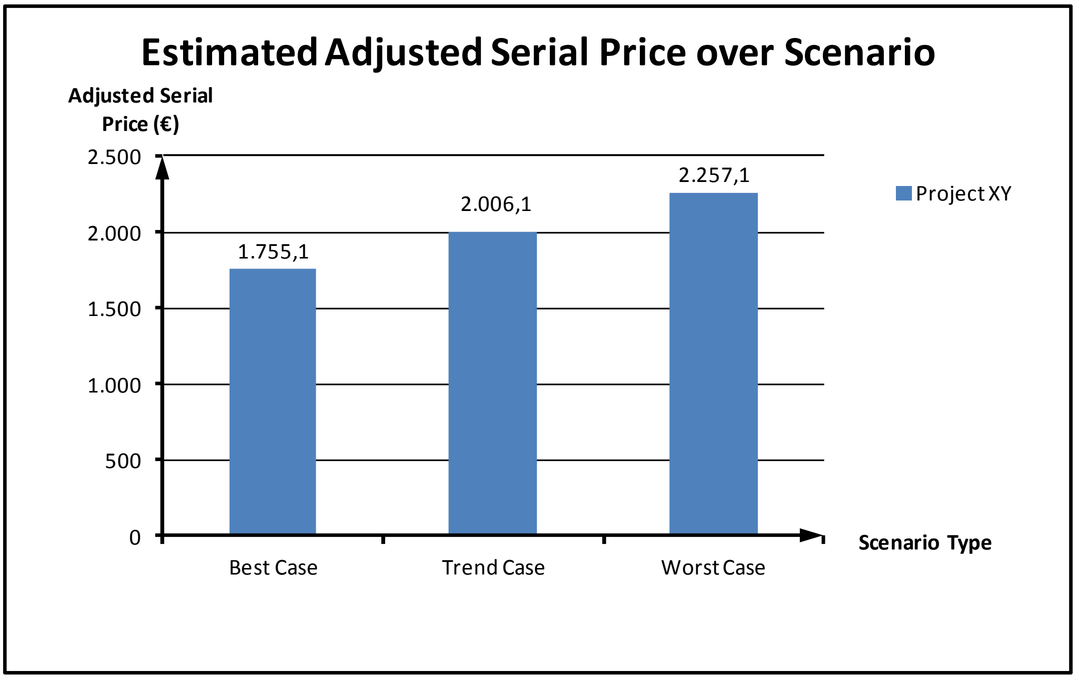

Figure 6.2: Estimation Tool - Adjusted Serial Prices[254]

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[254] Own Illustration

7 Conclusions

The whole thesis is centered on how product architectures affect high pressure fuel storage systems for automotive applications. In particular, it is explored how modular product architecture influences the costs of a fuel storage system compared to a customized product architecture. Further, the behavior and characteristics of HPFSS production costs are researched. The basic research data comprises several preliminary costings conducted for past projects at MS. To address all these topics the information of the preliminary costings is used to conduct a thorough cost structure analysis of 200bar CNG HPFSS production cost in order to develop a fundamental understanding of what factors drive costs. With this knowledge, three past projects are re-built with modularized components and the subsequent changes in terms of costs due to the modular approach are conservatively assessed and compared with the reference systems. Here, the high impact cost types, which are identified in the ABC-Cost Structure analysis, which have a considerable impact on total production costs are assessed in more detail. After that, the NRCs are considered in the comparison by carrying out a scenario analysis in order to address the high uncertainty associated with the estimation of NRCs for modular systems.

As a result from the comparison analysis, the main conclusion is that HPFSSs based on modular product architecture can be produced at considerably lower production cost than with customized product architecture. The reason for this can be found in the significantly lower material and assembly cost for modular HPFSS which are identified to be the main cost drivers of 200bar CNG HPFSSs. Here, savings in material cost up to 18% and savings in GAC up to 22% can be achieved. Furthermore, Warranty, SGA and EBIT are dependent on Material and GAC; therefore, these cost types are reduced accordingly. If considering the NRCs with a scenario analysis the cost associated with the modular approach is considerably lower even in the worst case scenario in which it is assumed that the NRCs are 50% higher than those of the original projects. All in all, it is concluded that HPFSSs based on modularized components represent great potential for cost savings in production cost. However, cost savings in NRCs cannot be identified yet due to the lack of experience with this type of product.

Actions in the future should include a more detailed cost analysis of modular systems especially for the cost types Logistics and EBIT since those are held constant in the analysis but may represent even higher cost advantages when analyzed in more detail. A more detailed analysis would reveal the true potential of modular HPFSS which cannot be determined with the conservative analysis used in this thesis. In addition, NRCs should be estimated accurately in order to identify whether they would tend to increase or decrease when using a modular approach. When doing so, changes in risks needs to be considered as well (e.g. lower number of parts ~ lower probability that system fails). Furthermore, qualitative assessments of the modular system should be conducted to identify more components with potential for modularization in order to increase the degree of modularity (e.g. Quality Function Deployment - QFD) and potentials for improvements of prevailing modular parts as well (e.g. Module Indication Matrix - MIM).

The author recommends pursuing the modular system at MS, because even in a conservative comparison analysis it reveals great potential for cost savings at a very early stage in the product development phase. Moreover, it is recommended to assess whether it is feasible to use modularized components for other HPFSS configurations as well. Since the differences in design, components and restrictions should become rather small, the future HPFSSs may benefit from synergies between each other and MS may be on the forefront of this technology and gain a competitive edge.

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List of Abbreviations

BOM	..... Bill Of Material
CF	..... Carbon Fiber
CIM	..... Computer Integrated Manufacturing
CNG	..... Compressed Natural Gas
Diff. to Ref.	..... Difference to Reference
EBIT	..... Earnings Before Interest and Taxes
EOL	..... End Of Line
EOS	..... Economies of Scale
GAC	..... General Assembly Cost
GF	..... Glass Fiber
GHU	..... Gas Handling Unit
H_2	..... Hydrogen
HP	..... High Pressure
HPFSS	..... High Pressure Fuel Storage System
IRR	..... Internal Rate of Return
IT	..... Information Technology
ITransp&C	..... Inbound Transport & Customs
LP	..... Low Pressure
Mod	..... Modular
MS	..... Magna Steyr
MSF	..... Magna Steyr Fahrzeugtechnik
MV	..... Manual Valve
NRC	..... Non-Recurring Cost
OEM	..... Original Equipment Manufacturer
OTV	..... On Tank Valve
PD	..... Product Development
R&D	..... Research and Development

Ref	.....	Reference
SGA	.....	Sales and General Administration
SOV	.....	Shut Off Valve
TPRD	.....	Temperature Pressure Regulating Device
TSP	.....	Total Serial Price

List of Figures

List of Tables

List of Formulas