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Correlation of Costs and Powertrain Functions in Early Development Phase

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Supervisor

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Institute of Innovation and Industrial Management
Univ.-Prof. Dipl.-Ing. Dr.techn. Christian Ramsauer

Graz, June 2019

Affidavit

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Acknowledgement

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Abstract

Functions have a significant importance in almost all kind of engineering activities. However, as their interpretation strongly depends on the context, in which they are used, there are some instances when their applicability is debatable. Therefore, this thesis addresses the question, whether they provide benefit in the field of automotive cost engineering and in this way make the cost assessment simpler, quicker, and more effective, especially in the early phase of the powertrain engineering.

Due to the fact that AVL’s Production and Cost Engineering department is often facing the challenge to perform product cost assessments in the early phase of the powertrain development, the purpose of this thesis is to figure out an approach and make a suggestion for a framework of a system, which is able to provide support in the cost estimation of powertrain elements based on functions.

The applicability of functions in the traditional context is rather argued in the field of cost engineering, because they do not contain any parameters or factors, which would serve as a basis for cost estimation. To get rid of this issue, the traditional interpretation of functions must be analyzed, and their nature must be reformulated, to use them for cost estimation purposes.

The theoretical part of this thesis consists of a theoretical- and empirical research, among which the latter was worked out with the company’s experts. The objective of interviewing the experts of the company was to get an overview about the currently applied approaches for the application of functions and cost assessment in the powertrain development.

Taking the research information, the principles of Systems Engineering, and the policies of the company into consideration, the result of this thesis is a framework of a comprehensive expert system, that classifies powertrain solutions, based on customer requirements and component functions in the beginning of the powertrain development process. Furthermore, the system displays the corresponding technical solutions and their impact on certain customer requirements without the intervention of any expert from the affected technological field.

Kurzfassung

Eine wesentliche Herausforderung der Production and Cost Engineering Abteilung der AVL ist, eine möglichst genaue Produktkostenbewertung in der frühen Phase der Antriebsstrangentwicklung zu treffen. Ziel dieser Arbeit ist, zu untersuchen inwieweit eine Kostenbewertung basierend auf Produktfunktionen einen Beitrag liefern kann, um schnellere und präzisere Ergebnisse zu generieren.

Die Analyse und Strukturierung eines technischen Produktes unter dem Gesichtspunkt der zu erfüllenden Funktion(en) findet Anwendung in beinahe allen technischen Disziplinen. Nichtsdestotrotz ist die Anwendung dieses Funktionsprinzips stark abhängig vom Kontext der Aufgabenstellung. Die vorliegende Arbeit beschäftigt sich mit der Frage, ob das Denken und Arbeiten in Funktionen, besonders in der frühen Phase der Antriebsstrangentwicklung, Vorteile im Bereich der Produktkostenbewertung bringt.

Um sich dieser Problemstellung zu nähern, muss zunächst die traditionelle Interpretation von Produktfunktionen analysiert werden. Darauf aufbauend müssen die Funktionen gegebenenfalls umformuliert werden, um sie für die Kostenbewertung in der frühen Entwicklungsphase einsetzen zu können.

Der erste Teil dieser Arbeit besteht aus einer theoretischen und empirischen Untersuchung wobei letztere zusammen mit firmeninternen Experten durchgeführt wurde. Das Ziel der Experteninterviews ist es, einen Überblick, einerseits über die derzeit im Einsatz befindlichen Methoden und Tools der Kostenbewertung, andererseits über die praktische Anwendung des Funktionsprinzips in der Antriebsstrangentwicklung zu bekommen.

Unter Berücksichtigung der recherchierten Informationen ist das praktische Ergebnis dieser Arbeit ein umfassendes Expertensystem, welches Antriebsstrangtopologien basierend auf Kundenanforderungen und Komponentenfunktionen im Anfangsstadium des Antriebsstrangentwicklungsprozesses klassifiziert. Des Weiteren ermöglicht der Ansatz die Vorauswahl technischer Lösungsmöglichkeiten, ohne den Einsatz eines Disziplinexperten, um die gewünschten Kundenanforderungen zu erfüllen.

Table of Content

1 Introduction

The present master´s thesis was developed in cooperation with AVL LIST Gmbh, in the frames of Systems Engineering Laboratory (SE-LAB). For this reason, as a first point, the following chapters give a brief introduction and overview about the core competences and main activities of the company, implied the so-called ´SE@AVL students initiative´ to provide an insight into the surroundings of the project.

1.1 AVL LIST Gmbh

“AVL is the world's largest independent company for development, simulation and testing technology of powertrains (hybrid, combustion engines, transmission, electric drive, batteries and software) for passenger cars, trucks and large engines.”[1] The company was founded in 1948 by Professor Doctor Hans List and has its headquarters in Graz, Austria. The firm employs currently more than 9500 people and has facilities in 45 countries all around the world.

“AVL achieves unique results in regards to the development and improvement of all types of powertrains as well as in the field of measurement and test technology.”[2] As the following picture represents, the company has solutions for most customer segments.

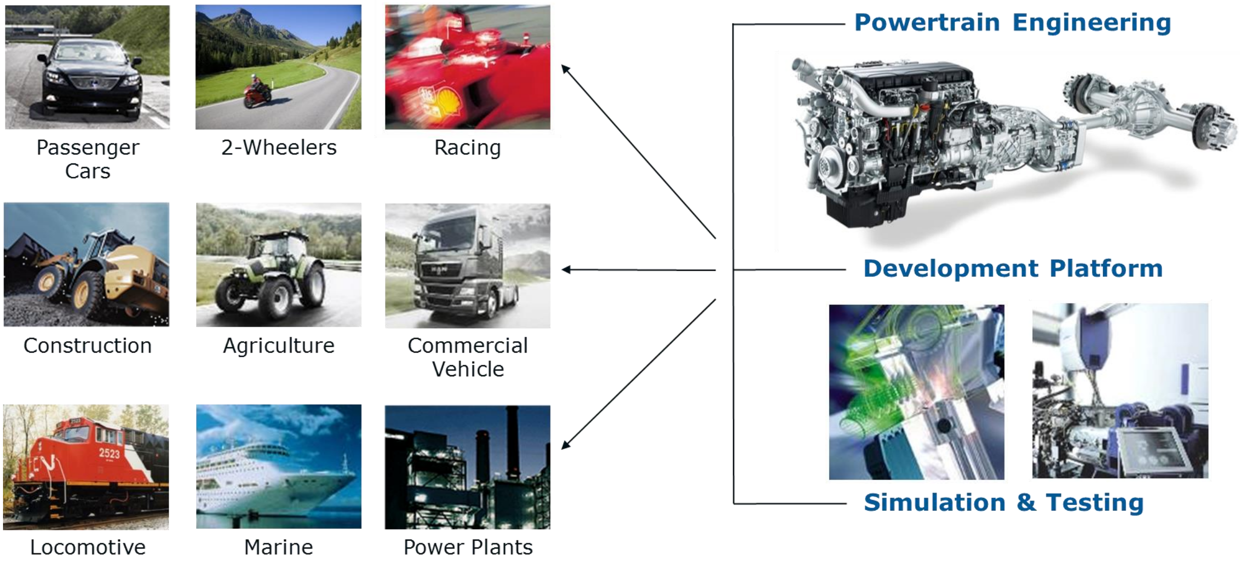


Figure 1: Fields of expertise at AVL[3]

[1] AVL Fact Sheet (2018), p. 1
[2] AVL Corporate presentation (2018), p. 3
[3] AVL Corporate presentation (2018), p. 8

1.2 The SE@AVL students initiative

Increasing digitization and growing complexity in the product development process pose new challenges for the automotive industry. Systems Engineering (SE) is concerned with sustainable methods, processes and tools that will help to continue to control this complexity.

“The students initiative supports the establishment of Systems Engineering@AVL through the education of SE-experts and the development of advanced SE methods, processes and tools. The team supports operative projects of business units inside AVL, by integrating SE students in the projects. This secures the knowledge exchange and the development of SE expertise and methodology across all AVL departments.”[4]

The students from different departments sit together in one central place, in the ´SE-Lab´, which consists of 42 students with different education backgrounds and field of expertise. These members are supporting their own departments in establishing SE with them, where the network between departments for regular communication and joint action plays an important role.

As it was mentioned, the thesis was developed in close cooperation between the SE-LAB and AVL´s Production and Cost Engineering Department (PTE/DOP), following the principles of Systems Engineering. The process of the project is represented by the following flowchart.

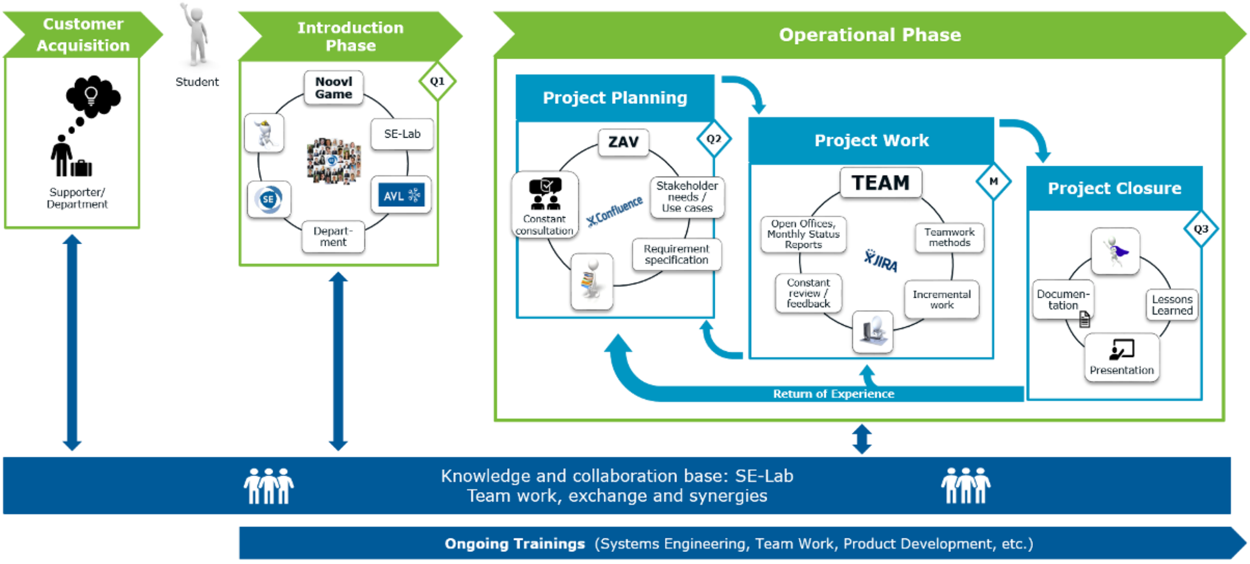


Figure 2: SE-LAB Process[5]

[4] AVL Internal Homepage, date of access: 15.11.2018
[5] SE-LAB Image Presentation (2018), p. 17

1.3 Initial situation

AVL’s Production and Cost Engineering Department (PTE/DOP) has often faced the challenge to perform product cost assessments in the early phase of the powertrain development process. In this phase usually, only the main development targets and high-level technical parameters are specified which do not allow a precise cost calculation with the available methods and tools.

Although there might be a mapping between the development targets and the required functions as well as possible product architectures, there is no method or tool in full operation, which ensures a systematic and reproducible documentation of the development process, including all its optimization loops. From the company´s department point of view, a method shall be established which is able to do systematic cost assessment in parallel to the development process, and satisfies the accuracy, required by the Cost Engineering Department.

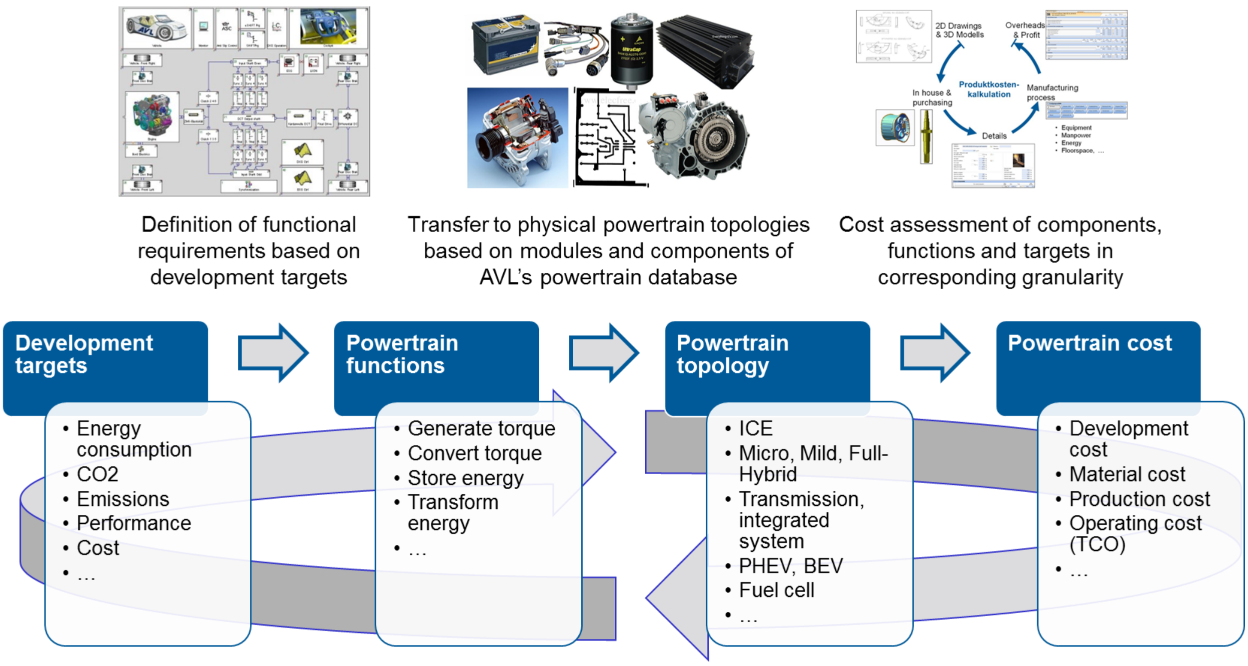


Figure 3: Combined Systems and Cost Engineering[6]

Figure 3 depicts the vision of the project stakeholder – Cost Engineering Department –, which served as a basis to formulate the tasks and the requirements to be satisfied. It can be remarked that in this concept, development targets, powertrain functions, powertrain topology and powertrain costs are represented as steps of an iterative process. By going along these steps from the beginning, cost estimation can be done in a more effective and systemized way. However, to make the process even quicker, the

[6] Sams (2018), p. 10

stakeholder suggested to skip the step powertrain topology and connect powertrain functions directly with powertrain costs.

Regarding AVL´s development procedure, the ´double diamond´ and the ´V-Model´ seem to be promising basis for deriving functions from customer requirements and transferring them into product architectures. However, it is still not solved how to determine functions precisely, neutrally from technical solutions, to be able to relate them to manufacturing costs. It is also not defined, on which basis should they be connected to a cost estimation process or tool to perform a reliable cost assessment in the very early phase of powertrain development.

Therefore, during the project, the task is to work out a methodology and make a suggestion for a framework, with which powertrain functions can be connected with costs in the early phase of AVL´s powertrain development process. Based on a systematic approach, the whole cost estimation process can be brought to an earlier development phase, which means competitive advantage and greater customer satisfaction for the department because of better trade-off between costs and product performances, furthermore shorter development time.

1.4 Challenges

While writing the thesis, numerous challenges came up, which cannot be ignored to avoid any issues throughout finalizing the project.

The biggest challenge of the department is that product cost must be estimated according to customer requirements, which always results in a different product variant. Furthermore, these requirements may change in different stages of the latter product development which results a claim for changing the design and product costs.

Precision is one of the most important factor and at the same time another big challenge during the project, because "the price of products must be defined during early stages of product design and during the bidding process, thus an overestimation of product development costs may lead to the loss of orders and an underestimation causes a profit loss."[7] Although AVL is proposed to calculate the costs of production, it takes place in each case by the product customer or its supplier. This means that for AVL accuracy is the most important and whether the costs are underestimated or overestimated, the company will lose the trust of customers and with this a meaningful proportion of the profit.

[7] Hooshmand/Köhler/Korff-Krumm (2016), p. 22

Finding the proper context of functions to make them applicable for cost estimation is another challenge, as the added value of embedding functions into cost engineering in their traditional interpretation is rather questioned.

The costs of a powertrain or vehicle function itself, cannot be estimated, without being familiar with a related parameter or a cost influencing factor. For this reason, it is necessary to find the proper interconnection between cost influencing factors and powertrain functions.

1.5 Expected outcome

The awaited solution should provide a basis for a system, which will facilitate the work of cost engineers in the early phase of powertrain development. The system should exploit opportunities regarding the company´s expertise and stored data, and connect them with each other in such a way, which among others systemizes the process of cost estimation, reduces the presence of failures, increases the accuracy of the estimate and cuts down the duration of the cost estimation procedure itself. These features must operate with the consideration of the company´s processes and policies.

At the end of the project, a suggestion will be made for a framework, which can serve as a basis of a follow up project in the SE-Lab and be operated by the Cost Engineering Department for a systemized and effective cost estimation in customer projects. The solution should also consider the opportunities for integration to artificial intelligence-based systems.

1.6 Thesis objectives and research questions

During the first steps of the thesis, the content was divided into sub-parts and was led by research questions, pointing on special topics of the project.

Objectives of the theoretical part

To begin with, a research on functions and their correlation to product costs must be made. The purpose of this part is to get a basic knowledge and an overview about the importance of functions and costs and identify, if there is any already existing theoretical approach, which is able to connect and apply them with the purpose of cost assessment. The research topic is particularly important, because function related areas in product development can have a significant overlap with SE.

Objectives of the practical part

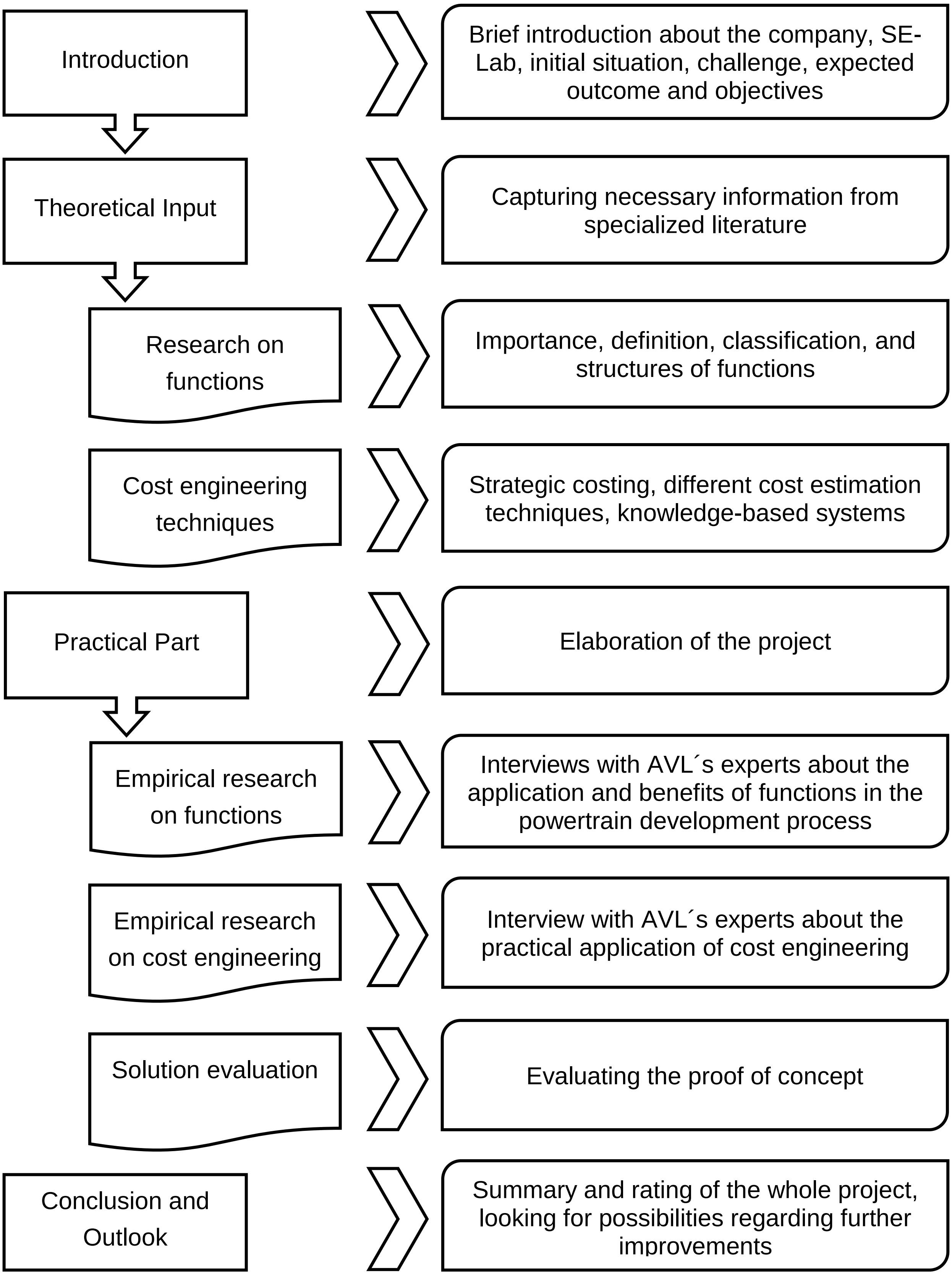
As next, the opinion of the company´s carefully chosen experts will be captured about functions and their relation to costs, with the help of thoroughly formulated questions. In this way, an insight can be gained about the usage of functions and cost engineering techniques in real-life circumstances.

In the last stage of the thesis the evaluation of the concept takes place. Here, the aim is to figure out the right formulation of functions, the appropriate linkage between functions and costs, and a solution proposal for a framework. The captured information from the theoretical- and empirical researches, will provide a solution for most of the issues during designing the final solution.

Based on these objectives, the thesis was driven by the following research questions:

- How should product functions be formulated in the early phase of the development?
- Which approaches can be used to link costs and functions?
- Which is the best approach for assessing the costs of the functions in the early phase of the powertrain development?

1.7 Sample reference definition technology



2 Theoretical Input

In this chapter all the relevant and important aspects from the literature regarding functions and their relation to cost estimation will be discussed. The content will also cover topics, which are not directly related to functions, but are beneficial during the evaluation of the final solution.

2.1 Functions

In everyday life, the term function is widely used for describing the purpose, behavior and feature of any products, but how is it defined according to the specialized literature, and how should they be used to apply them effectively in Cost Engineering? With chapter of the thesis, these questions will be answered. Clarifying this issue is highly important, as the target of the thesis is to figure out a possible solution for an approach which allows systemized cost estimation with the help of functions. Therefore, the first and obviously the most important thing which must be cleared in the beginning, is every important detail in connection with the term function. In the followings, system perspectives, and application sequence of functions will be discussed, to position them in time and place. Thereafter the meaning, definition and their importance in the powertrain development process will be discussed to get a broader overview about them.

2.1.1 System structures

To describe a system´s operating principle unambiguously, a functional structure is not enough. For this reason, it is essential to figure out, which models or structures are needed to characterize a system unequivocally for all disciplines.[8]

A product has three important perspectives:[9]

- Functional perspective
- Structural or physical perspective
- Hierarchical perspective

These perspectives are differing from each other, but they can be connected to each other to make the development process more effective. The system is the model of a wholesale, which contains relationships between attributes (inputs, outputs, states, etc.), linkage between parts and subsystems and their environments. This definition describes the linkage between these tree perspectives and if all of them are characterized, then the

[8] Cf. Ropohl (2009), p. 77
[9] Cf. Ropohl (2009), p. 76 et seq.

complete system model is determined. The representation of these perspectives can be seen on Figure 4.[10]

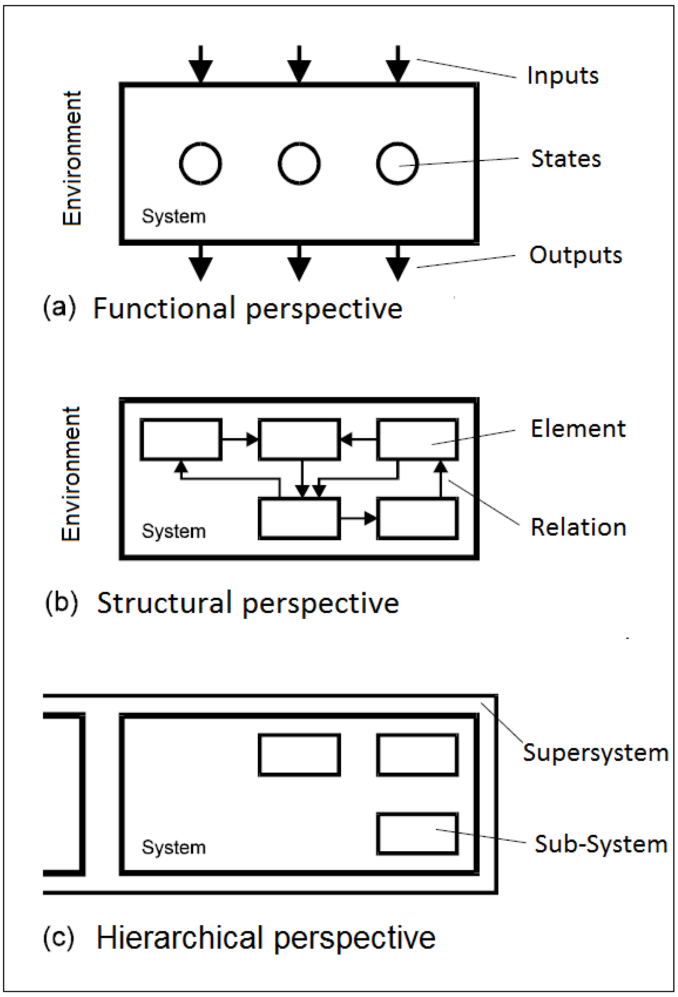


Figure 4: System structures[11]

2.1.2 Functions in the sequence of the development process

After examining the disposition of functions from a structural perspective, they must be positioned in the sequence of the development process too.

In a new product development process, functional structures are set up in the initial phase, because they serve always as a starting point, to determine the inner structure of the system. Finally, a bigger linkage is taken into consideration in form of a hierarchical perspective, in which the investigated functions and the associated components are settled.[12]

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[10] Cf. Ropohl (2009), p. 77
[11] Ropohl (2009), p. 76
[12] Cf. Ropohl (2009), p. 77 et seq.

To prove this way of thinking, the VDI 2221 is being considered, to determine the exact point, where functional structure must be set up in the development process.

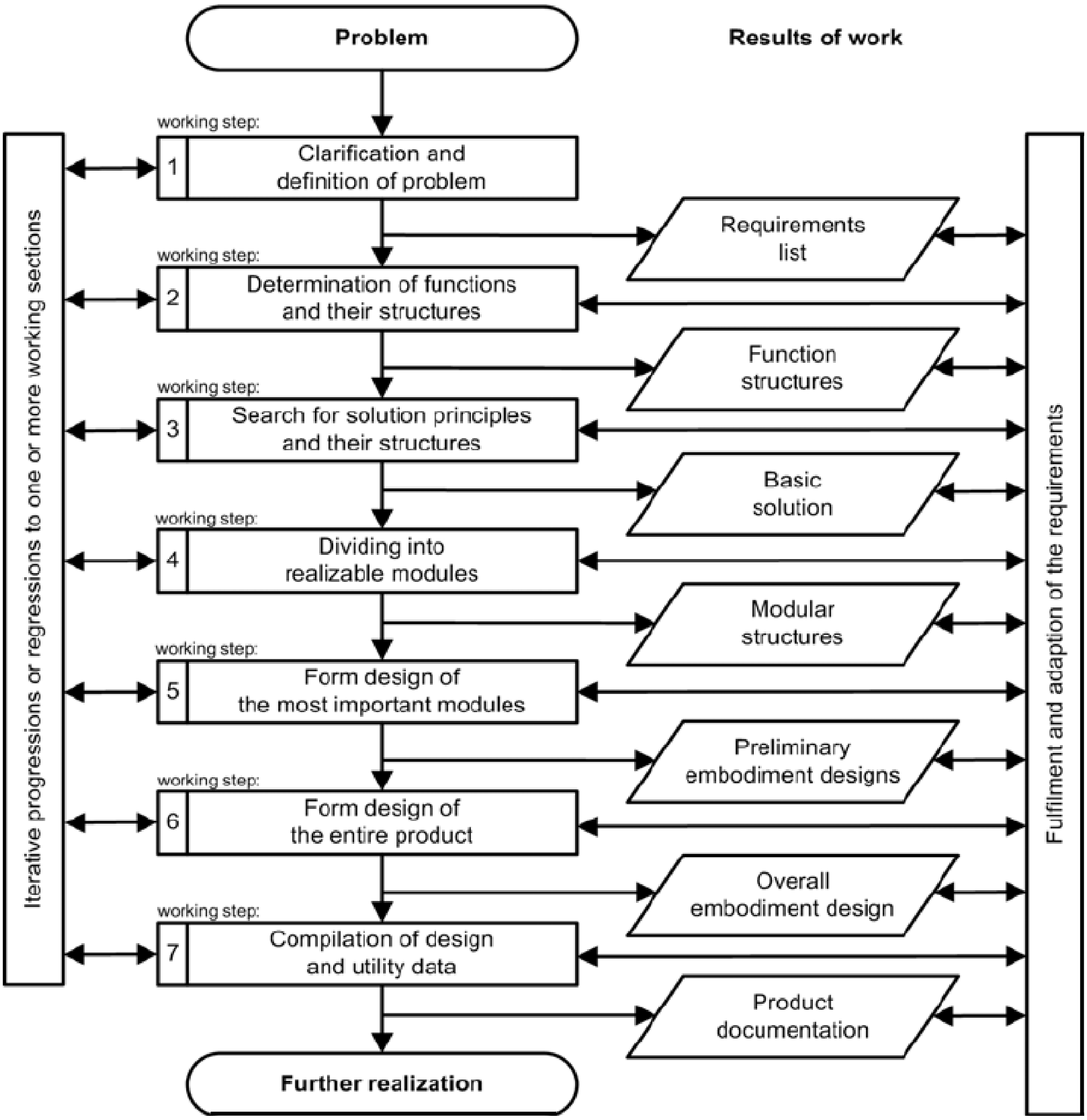

Figure 5: VDI 2221[13]

VDI 2221 is the most widely accepted guideline for development of and construction of technical systems and products. Based on its flowchart, it can be clearly realized, that the ´determination of functions and their structures´ phase is the second step in the development process and it is located before all the technical solution related steps. These fact leads to the assumption, that the application of functions might be beneficial

[13] Starcevic/Bux/Rohr/Lutz/Kostadinov/Ritterbusch/Müller (2007), p. 2

from strategic cost engineering point of view, because rough cost estimation takes also place in the early phase of the development process too.[14]

2.1.3 Importance of functions

Besides their application is matching the desired timepoint in the development process, their importance and benefits are not insensible from other aspects either.

Functions to be realized play an important role from the market point of view, as they reflect and describe which product functions are expected from the customer. That is the reason why it makes sense to begin the development process with specifying the overall function and the essential sub-functions. In this case, only those functions are taken into consideration, which are required by the customer. On one hand, this approach helps to filter those functions which are not creating value for the customer and in this way not necessary to be developed. On the other hand, it helps to decide and focus on those functions, which the customer is willing to pay for.[15]

From an engineering point of view, functions have more value than only realizing the requirements of the customer. Using them from the beginning of the development has a significant impact on the duration and the efficiency of the whole process. Firstly, functions help to define development tasks properly and to understand the behavior and purpose of the system easily at the stage of early product maturity. Secondly, inconsistencies between experts coming from different fields can be also cleared, as functions describe the system neutrally from disciplines. Finally, it enables engineers to create innovative solutions, as the solution space is not limited by them, which is probably one of the most important advantage of using them during a product development process. It can be assumed, that they are creating a bridge between customer requirements and technical solutions, because they can be stated as translations of requirements and descriptions of the technical solutions.[16]

2.1.4 Definition of functions

Reading through numerous chapters in the specialized literature in the field of product development and SE, there are countless different definition for a function, however its nature strongly depends on the considered field of technology. For instance, the term function is applied for totally different purposes in software development and in mechanical engineering. In the frames of this project the term is considered as vehicle,

[14] Cf. Bercsey/Horák (2007), p.128 et seq.
[15] Cf. Lindemann (2016), p. 691 et seq.
[16] Cf. Lindemann (2016), p. 694 et seq.; Cf. Pahl/Beitz/Feldhusen/Grote (2013), p. 237 et seq.,

especially powertrain function. According to the traditional aspect, the definition in the specialized literature is formulated in the following way:

“Under function is the general and intended connection between input and output of a system with the goal of fulfilling the task understood.”[17]

“Functions represents the system as a ´Black Box´ and label it according to its characteristics, which can be observed from outside. These characteristics are the inputs and outputs, with which the state of the system can be described.”[18]

“Functions are solution independent descriptions of product tasks… They are describing the interconnection between input and output unambiguously and reproducibly.”[19]

As it can be seen, the definition of functions can be found in the specialized literature in many ways, however their meaning is the same, except for some complements. Compiling these thoughts, the definition of function can be formulated in the following way:

Function is the description of the overall task of the system, which defines the connection between the input and the output of the system without the technical solution. In other words, it is describing, what the system should do without fixing how it should be done.

2.1.5 Types of functions

To understand the nature of functions in detail and to clear the importance of their interfaces, it is necessary to define the way they are realized.

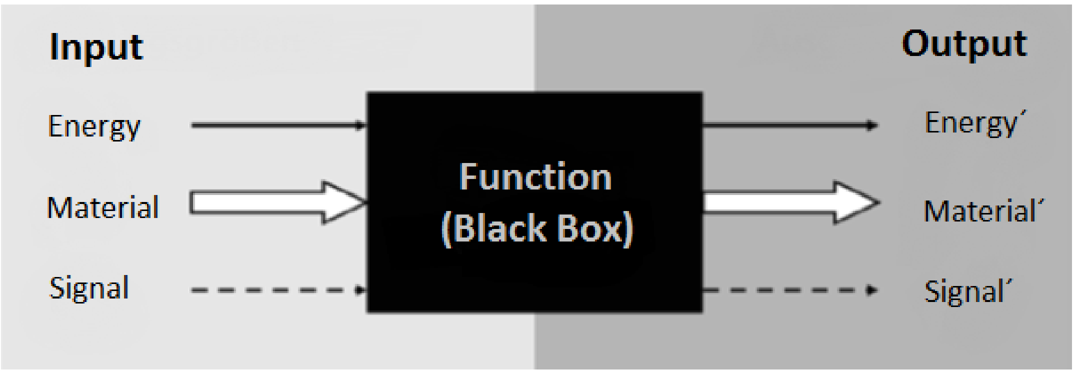

Figure 6: General functional description with unique functional connection, but unknown solution[20]

Figure 6 represents that any kind of system function transforms the input to output with different type of streams. The functions are taken as ´Black Box´ into consideration to

[17] Cf. Lindemann (2016), p. 691
[18] Cf. Ropohl (2009), p. 75
[19] Pahl/Beitz/Feldhusen/Grote (2013), p. 237
[20] Pahl/Beitz/Feldhusen/Grote (2013), p. 240

avoid the early determination of the technical solution. The type of the streams depends on the type of task and the way of solution and the type of main stream depends on the main function of the system. Streams which do not support the main function directly, are stated as a subsidiary stream.[21]

According to the type of streams, the technical creatures or systems can be named differently. If the system transfers energy then it is a machine, if material then it is an apparatus, and if signal then it is a device. These streams can be found together in a system as a main- or side-stream.[22]

2.1.5.1 Types of functions from functional structure/modelling point of view[23]

For the purpose of clarifying the characteristics of a product´s functional structure, functions must be divided according to their origin. To make the understanding easier, every function type is demonstrated with an example based on a coffee machine.

Overall function

Function that describes the overall task of the system – *make a coffee*

Sub-function

Function that describes a subtask of the system – *store water*

Main function

Sub-function that serves the overall function directly – *pumping water through the coffee powder to gain the flavor out*

Secondary function

Sub-function that supports the main function, and in this way serves the overall function directly – *heat up water, grind coffee beans*

Element function

Function that is not further dissolvable and can be used usually – *store coffee beans*

Functional structure

Connection of sub-functions to overall function

[21] Cf. Lindemann (2016), p. 691 et seq.
[22] Ibidem
[23] Cf. Lindemann (2016), p. 692

This classification can be highly valuable for the elaboration of the project, because with its help, the identification of diverse powertrain functions can be managed easier and based on this demonstrating example from everyday life, the analogy can be adjusted to the automotive world.

2.1.5.2 Types of functions according to AVL´s double diamond

At this point it is worth to mention that the application of functions is not only proposed because benefits are coming from their nature, but its advantages were realized earlier by AVL. This brought forth that the central element of AVL´s ´Double Diamond´ – the model of the main development methodology at AVL – is functions. To fit the solution of the thesis with this approach, the model is examined in detail.

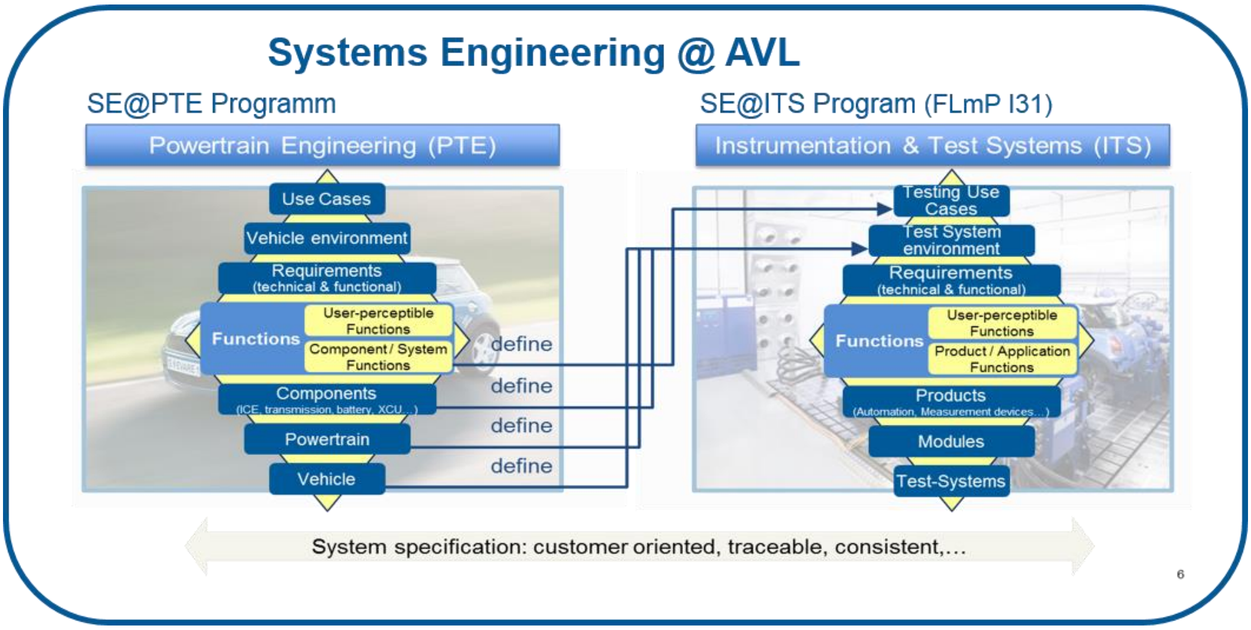

Figure 7: ´Double Diamond´ at AVL[24]

Before going into the classification of functions, a brief explanation of the model is necessary to understand the procedure. The diamond has two parts, but in the frames of this thesis, only the side of ´Powertrain Engineering (PTE)´ is being discussed, as cost estimation takes place here. In the first step, the ´Use Case´ of the system is determined, which defines the ´highest level function´, and answers to the question of what the system should do. At this level, the ´Black Box´ perspective is applied, with the purpose of not to limit the possibilities for the solution. In the next step, boundary conditions regarding the environment of the vehicle or the system to be developed are determined, which is tightening the agglomeration of potential solutions. In the followings, the system requirements are settled, which can refer to technical and functional aspects too. Starting

[24] AVL Internal Homepage, date of access: 15.11.2018

from the bottom tip of the model, the component structure of the vehicle or the system on different hierarchical levels is represented and the connection between powertrain components and requirements is created by functions.[25]

Based on Figure 7, functions can be divided into two groups: ´user-perceptible functions´ and ´component/system functions´. The reason for this division is, that the upper half of the diamond is related to the wishes of AVL´s customer, and the lower part depicts the product portfolio of the company. With this in mind, it can be stated that those functions which are important and also noticeable for AVL´s customer, are in the upper half, and the technical functions, which are important from engineering point of view are located in the lower half of the function box.[26]

By examining the single steps of this approach, it can be realized that it is rather redundant against dissatisfying AVL´s customer. In the first step, the customer sets out list about his requirements regarding the developed system or vehicle, which are later translated to user relevant functions. Based on these functions, development requirements are determined, which must be fulfilled by technical functions and through this by the exact technical solutions of the product. This means, that there is a double check in this process, as technical functions and targets are tested by development requirements as well as by customer requirements.[27]

It is remarkable, that there is a strong interconnection between this approach and the thesis, as functions are playing central role in both of them. It is obvious that an analogy can be set up between the ´diamond´ and the big picture of the stakeholder, as ´development targets´ in the big picture corresponds to the customer requirements, ´powertrain functions´ to functions and ´powertrain topology´ to powertrain.

The main idea behind the ´double diamond´ can be also found in the specialized literature as [28] describes the transition between functions and technical solutions in the same way.

As it was mentioned in 2.1.1 paragraph, a product has three perspectives, of which the functional and the structural one can be connected to each other to make the description of the product even more understandable. It can be remarked, that the representation of product architecture on Figure 8 unambiguously matches the lower half of the diamond regard to Powertrain Engineering.

[25] Cf. Denger/Fritz/Kissel/Parvan/Zingel (2012), p. 4 et seq.
[26] Ibidem
[27] Ibidem

Based on these facts, it is proved, that the way of thinking behind AVL´s development methodology is a promising approach for connecting functions with costs, as it matches not only with the big picture of the stakeholder, but with the content of the specialized literature too.

Going further with the thread, in the followings the details and methods for setting up a functional structure will be discussed to be able to apply functions in a systemized way.

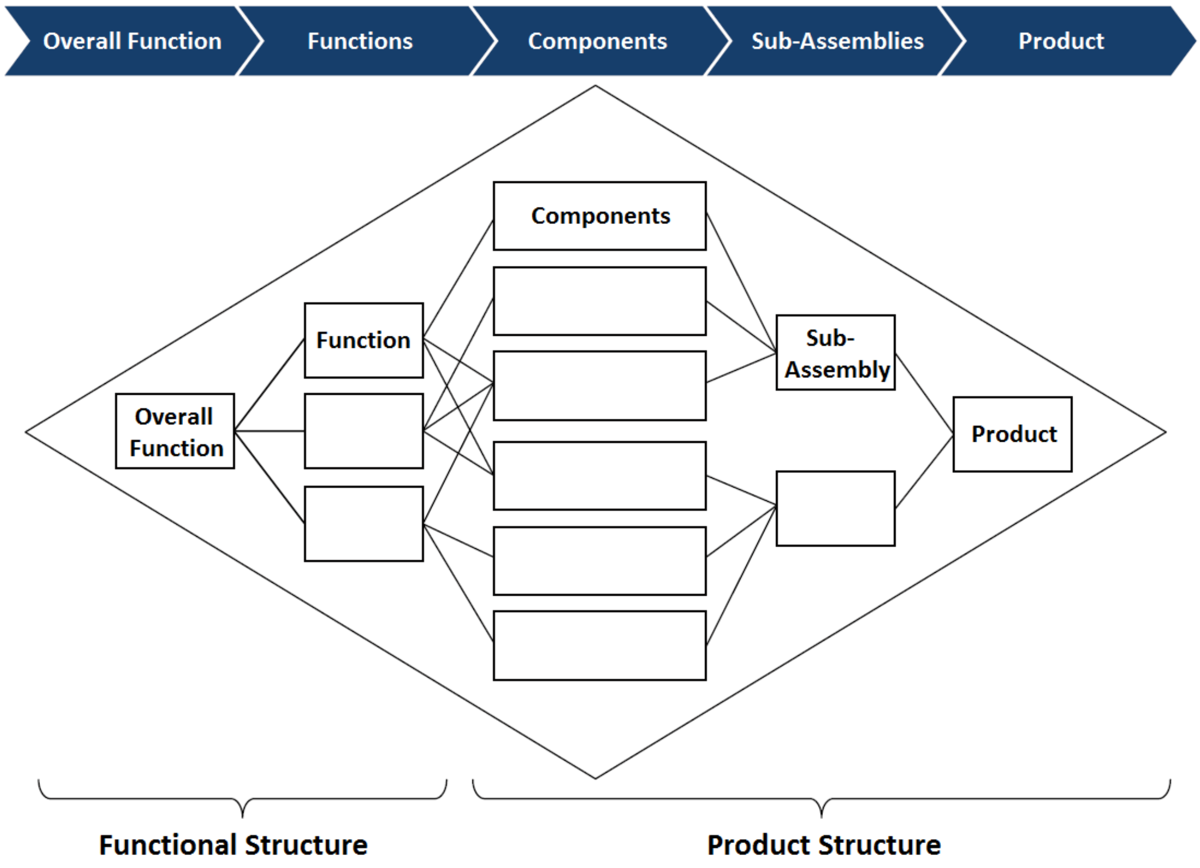

Figure 8: Representation of product architecture as the union of function and product structure[28]

[28] Pahl/Beitz/Feldhusen/Grote (2013), p. 257

2.1.6 Functional structure

A powertrain system contains numerous subsystems, which means that its operation can be described by a chain of functions. As the expected outcome of the thesis is to place cost estimation on a functional basis, the functional structure of the powertrain should be linked to a cost database in which costs of components are connected to those functions which they satisfy. To be able to create such a linkage, in the followings the nature of functional structures is discussed.

To organize single functions into a systemized structure, three formal elements are needed: in- and output state, its operation and its relation. These elements can be represented with a symbol to make the traceability of the structure better.[29]

State:

The state of a product is determined by the sum of its current properties.[30]

Operation:

The operation describes the property change between two states. Instead of the term ´operation´ one often finds in the literature also the terms ´process´ and ´procedure´. The specification differentiates according to technical, biological, chemical, and other processes or procedures.[31]

Relation:

The relation establishes the logical relationship between states and operations, in other words, which states should be linked by which operation.[32]

Coming from the definition of these formal elements, a function can be illustrated in the following way:

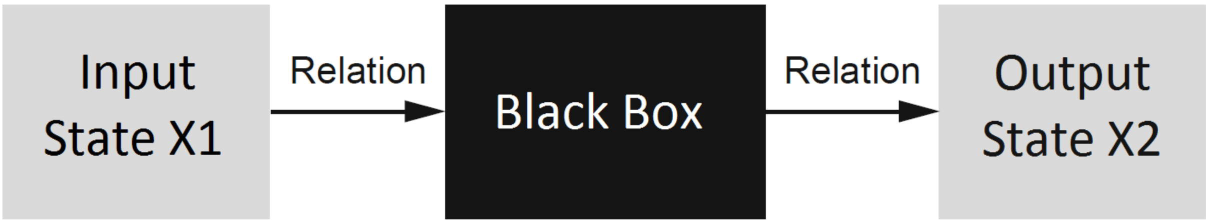

Figure 9: Formal elements to describe a function[33]

[29] Cf. Ehrlenspiel/Meerkamm (2017) p. 515 et seq.
[30] Ibidem
[31] Ibidem
[32] Ibidem
[33] Pahl/Beitz/Feldhusen/Grote (2013), p. 243

With this in mind, a functional structure can be represented according to the following figure:

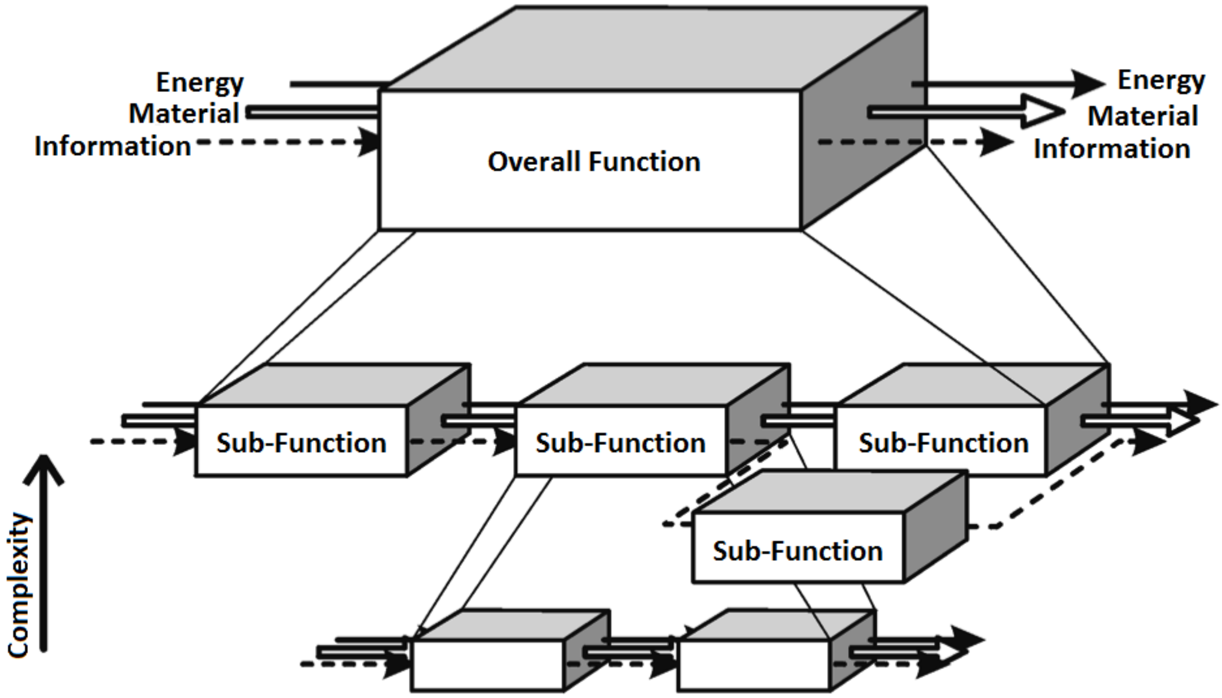

Figure 10: Representation of a functional structure[34]

Although, it must be remarked that this representation is rather dependent on the type of functional structure, which is influenced by the involved functions. According to [22], there are two viewpoints regarding a functional structure:

- Input-output view

  "In this case, main functions and side functions are considered as mathematical functions. They are understood as unambiguous connection between inputs and outputs."[35]

- Hierarchical view

  "The target of this viewpoint is to decrease the complexity of the function and to represent their hierarchical dependency."[36]

The ´input-output model´ can be beneficial in cases, where the process flow of the system plays an important role. With this model, the behavior of a product can be easily represented, which is useful for detecting either the most important or the unnecessary features. On the other hand, ´hierarchical model´ is applied, if the sequence of events is

[34] Pahl/Beitz/Feldhusen/Grote (2013), p. 244
[35] Lindemann (2016), p. 694
[36] Ibidem

not important, but the dependence of functions on each other plays a central role. The following figure shows the representation of both models:[37]

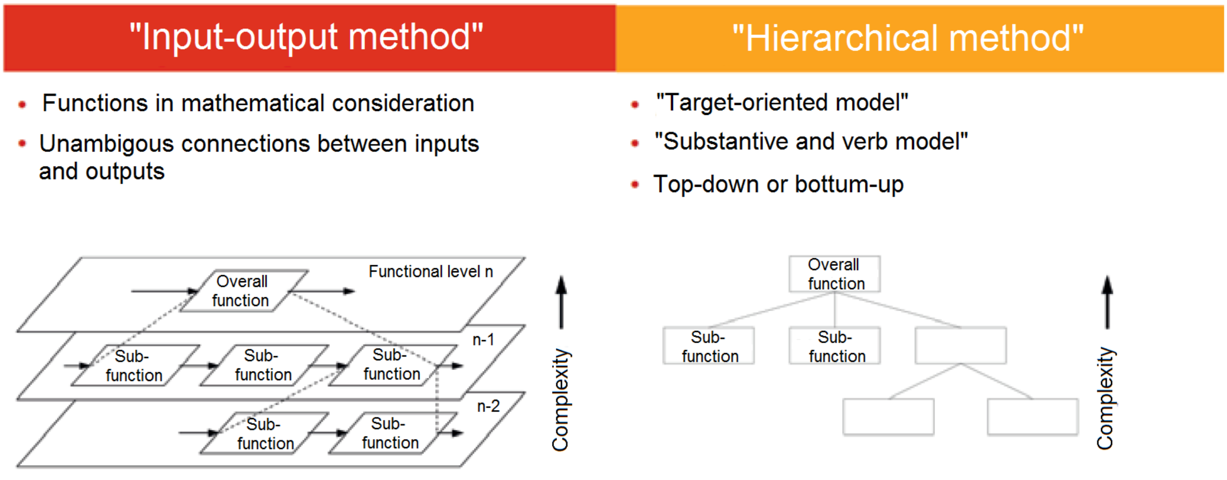

Figure 11: Representation of functional structures[38]

2.1.6.1 *Methods to set up a functional structure*

After the main types of functional modelling are discussed, the next step is to analyze the opportunities for setting up a functional structure. To do so, there are two methods to gather product functions and organize them into a structure.

The first approach is to do a bottom-up functional analysis on the existing product. This can be rather beneficial, as it helps to reveal the failures of the existing system, furthermore it can provide a basic functional structure for newly developed products too. In this way, the potential for further development can be detected and the functionality of the new, or even the existing product can be extended easily.[39]

This approach seems to be also suitable for addressing the functions with costs, as the costs of the existing components are already known. Existing functional structures can serve as a basis for a case-based reasoning cost estimation approach, which will be discussed in the subsequent chapters.

The other method is to set up the functional structure with top-down approach. This is usually applied in the very early phase of the development of an entirely new product, as it helps to identify and rate the possible solutions, furthermore it isolates product modules.[40]

[37] Cf. Lindemann (2016), p. 694 et seq.
[38] Lindemann (2016), p. 695
[39] Cf. Lindemann (2016), p. 697
[40] Cf. Lindemann (2016), p. 697 et seq.

By considering this method in cost engineering, it can be realized that its application is not beneficial, because the task of a cost engineer is to estimate costs based on past experience and knowledge and not to invent a whole new product. In this way, it can be stated that cost estimation process requires an existing functional structure.

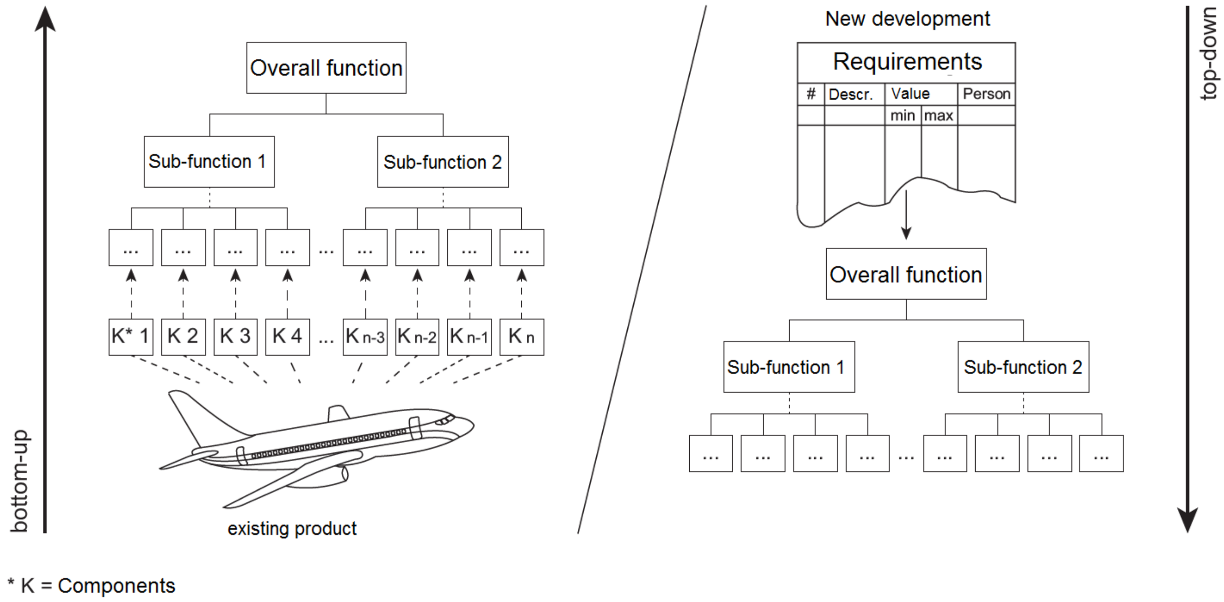

Figure 12: Two ways of setting up a functional structure: existing product (bottom-up) or new development (top-down)[41]

2.1.6.1 Depth of a functional structure

Each product serves to fulfill a function. The type of fulfilled function depends on the nature of the product and the context in which it is used. Within the framework of this project, function means the fulfillment of a technical task e.g. ´increase torque´, a function which is fulfilled by a gearbox. However, the question is that until which level of detailedness is it necessary to capture the functions of a system and in this way, how deep should a functional structure be established.[42]

[41] Lindemann (2016), p. 698
[42] Cf. Pahl/Beitz/Feldhusen/Grote (2013), p. 242

"Setting up a functional structure is not an end in itself and it is not about creating as many ´boxes´ as possible. The opposite of this. The functional structure should support the understanding of the task and make aspects of the task clear. At the same time, it shows the first possible solutions."[43] It means that a functional structure should reach so deep in the representation of a system that its task, purpose, and architecture can be easily and unambiguously understood by all disciplines. From another perspective, it can be declared that it should be set up until the that level which provides sufficient communication opportunities for the participating developers and teams. Furthermore, it should not be established so detailed that it would limit the space for solution and in this way would decrease the potential for any innovation.[44]

It is obvious that the more complex the developed system is, the more detailed functional structure can be created. As in automotive engineering powertrain systems are rather complex, the detailedness of the functional structure plays a highly important role. For this reason, there is a necessity to divide automotive systems into more, smaller sub-systems, to use their functional structure efficiently for development purposes.[45]

2.1.7 Conclusion of research on functions

With this information in mind, it can be assumed that in some points, the application of functions seems to be promising from cost assessment point of view and they are highly beneficial in new development processes. However, they must be tailored to and connected with cost engineering techniques, and approaches to be able to find out a methodology, which can enhance the overall cost estimation process at AVL.

[43] Pahl/Beitz/Feldhusen/Grote (2013), p. 242
[44] Cf. Lindemann (2016), p. 697 et seq.
[45] Ibidem

2.2 Cost engineering in theory

As the main purpose of this thesis is to simplify cost engineering processes at AVL, the outcome will be utilized at the Production and Cost Engineering (DOP) department. For this reason, besides functions, cost engineering is the second most important aspect of the work, which is a field with rather diversified project types. The final approach is going to give helping hand in cost engineering during the early phase of the powertrain development, which makes the clarification of cost engineering activities essential, especially those, which are already applied in the department. For this reason, in the followings, cost engineering techniques and methodologies will be discussed in detail.

2.2.1 Strategic costing

At AVL, strategic costing – as it is called in the DOP department – is the part of powertrain cost engineering process, means the estimation of product costs in the early phase of the development, based on customer requirements. In the specialized literature however, the term strategic cost management has a slightly different meaning. “It is a cost management technique that aims at reducing costs while strengthening the position of the business. It is a process of combining the decision-making structure with the cost information, in order to reinforce the business strategy as a whole. It measures and manages costs to align the same with the company’s business strategy.”[46]

The difference between this definition and the activity pursued at AVL, is the field of application. In specialized literature the term strategic costing is used for activities regarding the entire company, however in AVL´s practice, it is applied for offering a rough cost estimation for products, especially for vehicle propulsion systems.

Strategic costing as AVL sees it:

According to [4], strategic costing is a part of cost engineering with the purpose of making decision about the early concept, with the following activities:[47]

- “Evaluating cost differences on a system/subsystem level for alternative engineering,
- solutions as well as chosen benchmarks,
- provide alternative lower cost solutions including necessary trade-offs,
- perform cost scenarios for different manufacturing locations,

[46] https://businessjargons.com, date of access: 26.02.2019
[47] Barna/Oswald/von Falck (2018) p. 11

- provide insights into local supplier capability and market conditions for purchased components,
- perform cost scenarios for make-or-buy decisions,
- assist in definition of target cost for system/sub-system,
- assist in breaking down target cost to component level."

However, this approach can be found in the literature as ´Cost Estimation in Engineer-to-Order Manufacturing´. For this reason, in the following chapter the most important aspects of this approach will be discussed.

2.2.2 Engineer-to-order manufacturing

"Companies that produce their products only after receipt of a customer order are called order-oriented companies… An extreme case of these companies are ETO manufacturers, where the product development (PD) and production take place only based on specific customer orders and usually according to specific customer requirements and needs."[48] – As it was mentioned before, AVL is not producing goods, but it is offering solutions for production planning and product cost engineering for those automotive companies, which manufacture the products.

As costs must be estimated according to customer requirements, which tend to change during the development process, the result is numerous product variants. This requires the cost engineers to estimate product costs accurately already in the early phase of the development, where most of the information regarding manufacturing processes are not known. "To bridge this information gap, expert knowledge and experiences are needed"[49], which means that in the initial stage of development assumptions according to the best practice are applied.[50]

"To avoid the risk of high lead times and development costs, ETO manufacturers are trying to avoid radical product innovations as far as possible. Therefore, the new customized products are often designed based on already developed products and system solutions."[51]

[48] Hooshmand/Köhler/Korff-Krumm (2016), p. 22
[49] Hooshmand/Köhler/Korff-Krumm (2016), p. 23
[50] Cf. Gruß (2010), p. 87 et seq.
[51] Hooshmand/Köhler/Korff-Krumm (2016), p. 23

In this early phase, it is essential to respond to customer requests and deliver cost estimates as quickly as possible, which means that the following four areas have to be considered for each offer:[52]

- “Technical feasibility,
- delivery date,
- price,
- terms and conditions (e.g. penalties, etc.).”

It is obvious that the communication with the customer during the development is an iterative process, which is represented by the following figure:

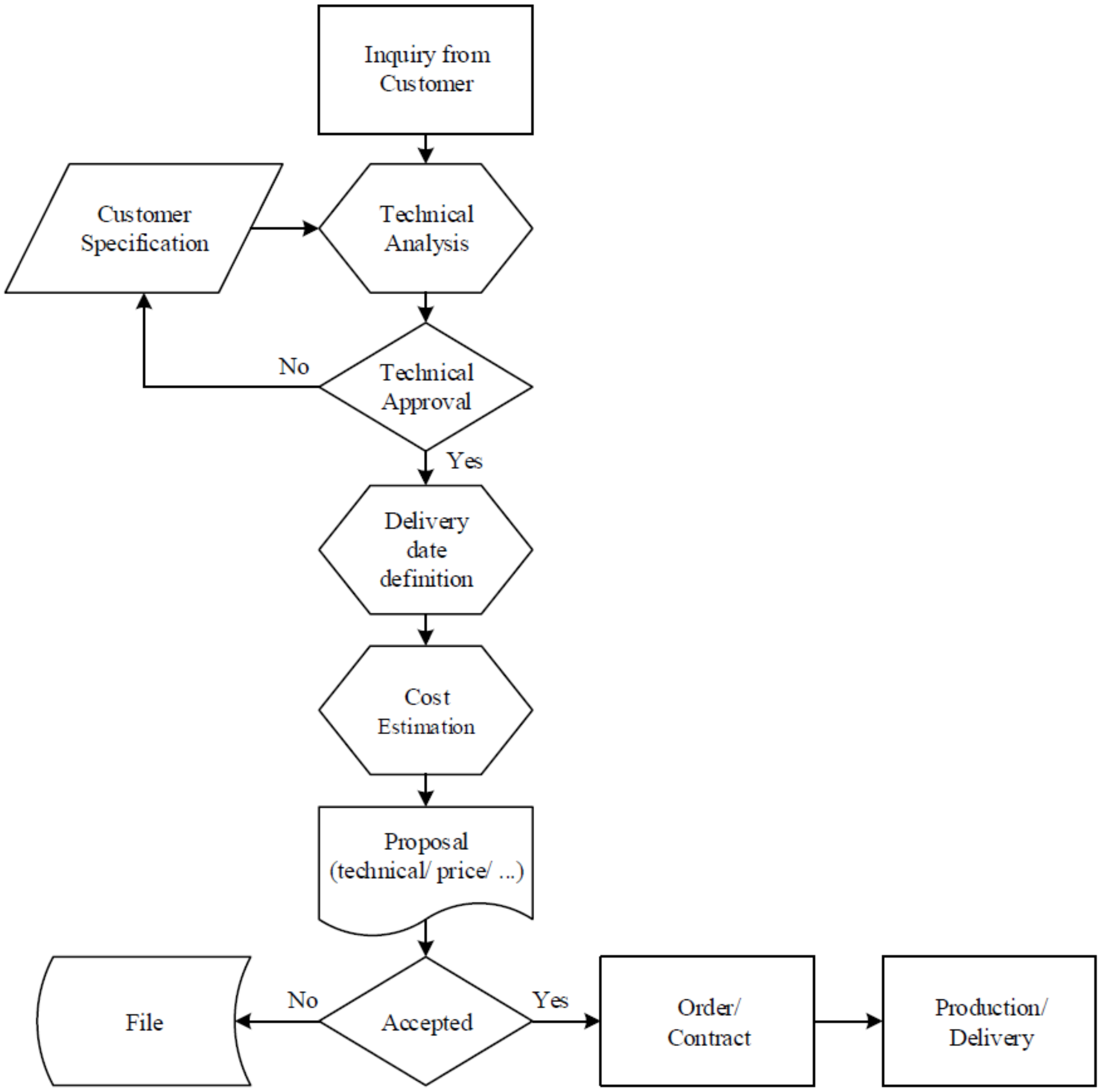

Figure 13: Bidding process in ETO manufacturing[53]

[52] Hooshmand/Köhler/Korff-Krumm (2016), p. 23
[53] Ibidem

To gather more information about costing in ETO manufacturing, the cost estimation step of the previous diagram will be discussed explicitly.

It can be stated that "as the PD progresses, the precision and reliability of PD cost estimation will be increased,"[54] which means that information, regarding cost calculation is available in stages of PD where its impact is low. This is represented by the following figure:

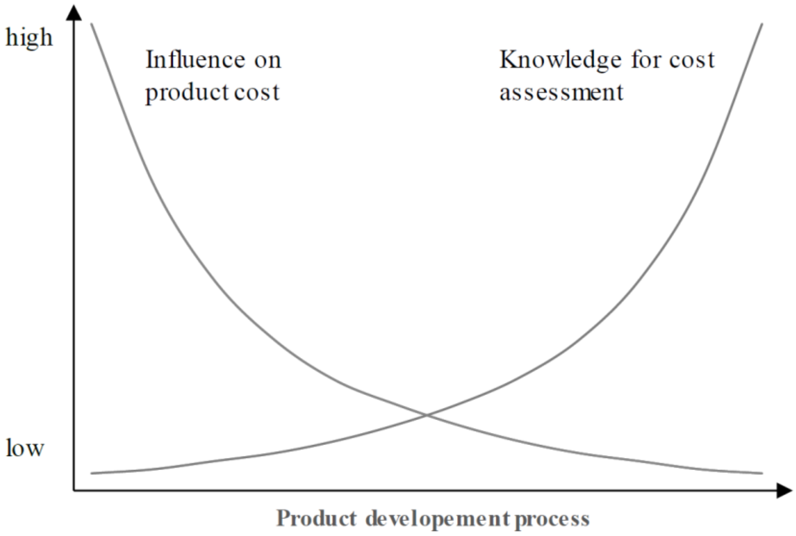

Figure 14: Cost estimation along the product development process[55]

In order to estimate the costs as precise as possible in the stage, where the impact of costs is high, each available technique and method must be considered. In such an early stage, experts estimate the costs based on projects from the past and the accuracy depends highly on their experience. For this reason, in the following chapter, those product cost estimation techniques will be analyzed, which can enhance the accuracy of cost estimates and support the work of cost engineers in the early phase of product development.

2.2.3 Product cost estimation techniques

In order to get an overview about the most widely applied cost engineering techniques, a comprehensive research was made on this topic. Over the years numerous methods were developed to estimate product costs, however their nature and purpose is differing from each other. For this reason, cost estimation techniques must be classified and discussed to reveal, which of them can be applied beneficially from this project point of view.

[54] Hooshmand/Köhler/Korff-Krumm (2016), p. 23
[55] Becker (1990), p. 355

On the highest level, product cost estimation techniques can be categorized into qualitative and quantitative groups.[56]

“Qualitative cost estimation techniques are primarily based on a comparison analysis of a new product with the products that have been manufactured previously in order to identify the similarities in the new one. The identified similarities help to incorporate the past data into the new product so that the need to obtain the cost estimate from scratch is greatly reduced. In that sense, the past design and manufacturing data or previous experience of an estimator can provide useful help to generate reliable cost estimates for a new product that is similar to a past design case… Historical design and manufacturing data for products with known costs may also be used systematically to obtain cost estimates for new products.”[57]

To sum it up, techniques which can be tied to the qualitative group, are able to obtain cost estimates for products in the early phase of the development. Qualitative techniques can be divided into two sub-groups, namely intuitive and analogical techniques.[58]

“Quantitative techniques, on the other hand, are based on a detailed analysis of a product design, its features, and corresponding manufacturing processes instead of simply relying on the past data or knowledge of an estimator. Costs are, therefore, either calculated using an analytical function of certain variables representing different product parameters or as the sum of elementary units representing different resources consumed during a whole production cycle of a given product. Although these techniques are known to provide more accurate results, their use is normally restricted to the final phases in the design cycle due to the requirement of a detailed product design… The two sub-groups of quantitative methods are parametric and analytical techniques.”[59]

It can be realized, that the biggest difference between these two main categories lays in the stage of application in the development process and in the accuracy of the estimated costs. It is obvious that in the frames of this thesis qualitative techniques can be rather applicable, as they are suitable for cost estimation in the early phase of product development.

[56] Cf. Niazi/Dai/Balabani/Seneviratne (2006), p. 563
[57] Niazi/Dai/Balabani/Seneviratne (2006), p. 563
[58] Cf. Niazi/Dai/Balabani/Seneviratne (2006), p. 563,
[59] Niazi/Dai/Balabani/Seneviratne (2006), p. 563

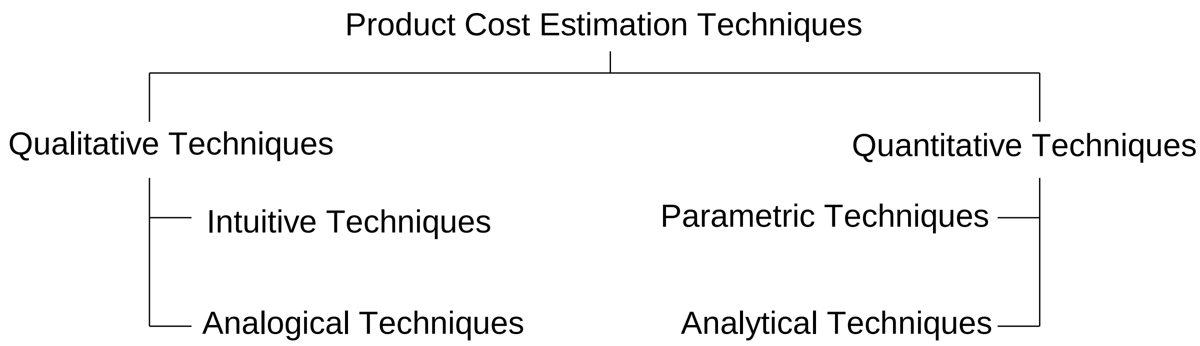

Figure 15: Initial classification of the PCE techniques[60]

2.2.4 Intuitive cost estimation techniques

Continuing the tread, in this chapter the qualities of intuitive techniques are being discussed. These techniques are using past experience of experts systematically to estimate product costs. As the name suggests, it is clearly intuitive, but "the knowledge may be stored in form of rules, decision trees, judgements, etc., at a specific location, e.g., a database to help the end user improve the decision-making process and prepare cost estimates for new products based on certain input information."[61] Techniques, which belong to this group are Case Based Reasoning and Decision Support Systems.[62]

2.2.4.1 Case-based reasoning

"This approach attempts to make use of the information contained in previous design cases by adapting a past design from a database that closely matches the attributes of a new design."[63]

The first step during the application of this method is to determine the specification of the required product. Secondly, the most similar project from the past is looked up from the design database with their adherent data from the cost database. Deviations between the required and the existing product are detected, and the old design is tailored according to the new requirements. Finally, the costs of adjusting the existing product and with this the cost of the new product is determined.[64]

This approach is only applicable if similar projects from the past are available, but not usable in case of new technologies and product as no historical data exists. The

[60] Niazi/Dai/Balabani/Seneviratne (2006), p. 564; Based on: Cf. Ben-Arieh/Qian (2003), p. 169 et seq.
[61] Ibidem
[62] Cf. Niazi/Dai/Balabani/Seneviratne (2006), p. 564; Cf. Relich/Pawlewski (2017), p. 40 et seq.
[63] Niazi/Dai/Balabani/Seneviratne (2006), p. 564; Cf. Zima (2015), p. 57 et seq.
[64] Cf. Balarman/Vattam (1998), p. 25 et seq.; Cf. Li-hua/Yun-feng (2004), p. 1605 et seq.

technique is robust and feasible, especially by companies which have similar product portfolio, as it can reduce the time of estimation and design rework.[65]

By considering the product range at AVL, this approach is very promising to estimate costs in the beginning of the development process.

2.2.4.2 Decision support systems (DSS)

“These systems are helpful in evaluating design alternatives. The main purpose of these systems is to assist estimators in making better judgments and decisions at different levels of the estimation process by making use of the stored knowledge of experts in the field.”[66]

Decision Support Systems include rule-based systems, fuzzy logic systems and expert systems and in most of the cases use artificial intelligence to utilize the stored knowledge and serve as a decision-aid tool. The disadvantage of these techniques is their high development time and costs.[67]

2.2.5 Analogical cost estimation techniques

“These techniques employ similarity criteria based on historical cost data for products with known cost, such as regression analysis models or back propagation methods.”[68]

2.2.5.1 Regression analysis models

These models are widely applied in the industry, among others, in AVL´s DOP department. Similarly to the intuitive cost estimation techniques, they use data from previous projects to systematically derive the existing relationships between the product cost and the selected product parameters (as variables). Costs are associated with different attributes of the product, such as manufacturing, design elements, and these interconnections are described by equations. These statistically developed formulas, based on the experience and knowledge of the experts, have limited complexity and their involved assumptions are comprehensible. However, the limitation of this system is the time-consuming acquisition and analysis of necessary data sets.[69]

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[65] Cf. Hooshmand/Köhler/Korff-Krumm (2016), p. 25; Cf. Ficko/Drstvensek/Brezocnik/Balic/Vaupotic (2005), p. 1329 et seq.
[66] Niazi/Dai/Balabani/Seneviratne (2006), p. 564
[67] Cf. Shehab/Abdalla (2002), p. 50 et seq.; Cf. Kingsman/De Souza (1997), p. 120 et seq.
[68] Niazi/Dai/Balabani/Seneviratne (2006), p. 567
[69] Cf. Lewis (2000), p. 107 et seq.; Cf. Poli/Escudero/Fermandez (1988), p. 101 et seq.

2.2.5.2 Back-propagation neural-network (BPNN) models

As its name suggests, these models are using neural networks to estimate product costs. Coming from this, they are not as easy to follow as regression analysis models, as they are considered as a black box. They are able to store knowledge from previous projects and approximate the (hidden) relations between cost-related features and the whole product cost. The system is not applicable in case of development of a totally new product or radical innovations; however, it gives precise estimation based on the detailed cost estimation of previous products.[70]

2.2.6 Parametric cost estimation techniques

These models are based on statistical functions, determining the costs with the help of a set of mathematical relationships, rules, assumptions, variables and constants that describe the relationship between product features and costs. The complexity of the mathematical relationship depends on the complexity of the product itself. The advantage of such a system is that costs can be estimated quickly and systematically, however in case of products with high complexity, its application is expensive and extremely time intensive.[71]

2.2.7 Analytical cost estimation techniques

Techniques in the group of analytical cost estimation are used during detailed cost calculation of products, when the cost influencing details of single parts are known. It means that the product is disaggregated into single components and the cost of a product is expressed by the sum of its component costs. In this main group, among others, the operation-based approach, breakdown approach, tolerance-based cost models, feature-based cost estimation and activity-based cost estimation are involved. As these approaches can be applied in a lateral stage of product development, in the frames of this thesis they are not discussed in the followings. They are already in use in the DOP department, and their results can serve as a basis for the other estimation techniques.[72]

[70] Cf. McKim (1993), p. 31 et seq.; Cf. Shtub/Zimerman (1993), p. 190 et seq.
[71] Cf. Hajare (1998) p. 172 et seq.; Cf. Roberts/Hermosillo (2000), p. 30 et seq.
[72] Cf. Niazi/Dai/Balabani/Seneviratne (2006), p. 568; Cf. Jung (2002), p. 227 et seq.

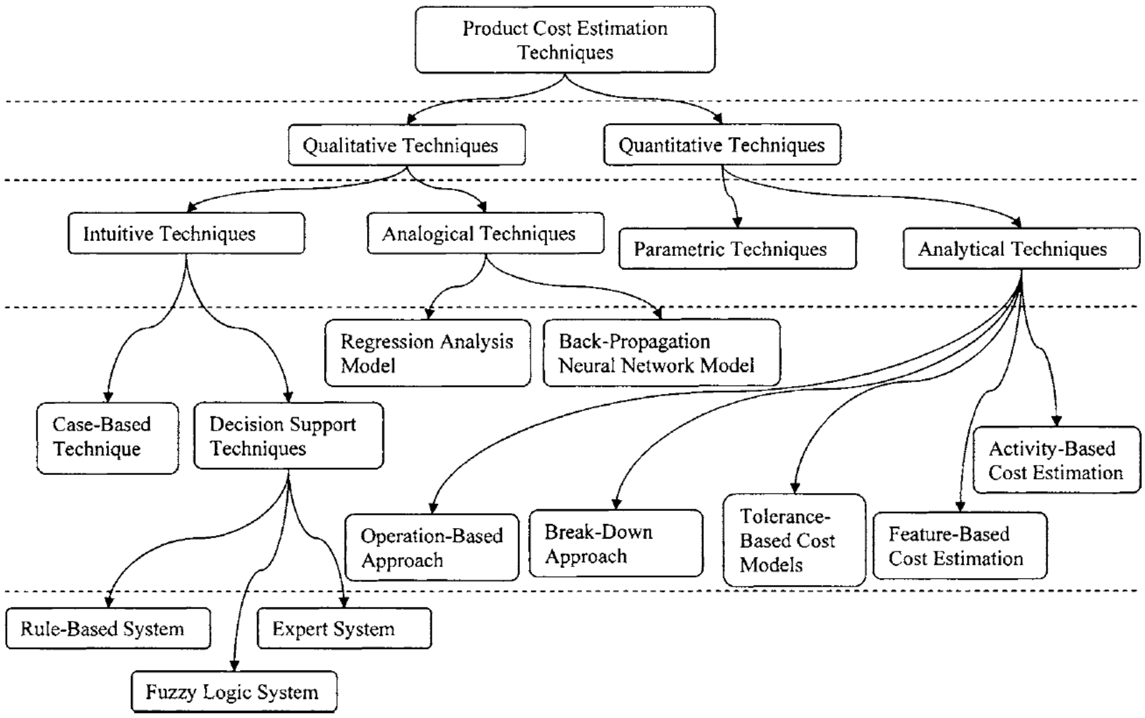


Figure 16: Classification of PCE techniques[73]

To make the understanding of the most common used product cost estimation techniques easier, Figure 16 depicts their classification. It can be clearly realized that approaches which have a potential for application in this project are positioned under the branch of qualitative techniques. Furthermore, it can be also seen that these techniques are rather domain-oriented, and their single application may not satisfy the expectations. In the frames of this project, a comprehensive approach is needed, which incorporates a mixture of the mentioned techniques, hence creating a hybrid solution.

[73] Niazi/Dai/Balabani/Seneviratne (2006), p. 569

In order to get a better overview about the advantages and disadvantages of the mentioned product cost estimation techniques, the following table summarizes their most important properties:

Product Cost Estimation Techniques				**Key Advantages**	**Limitations**
Qualitative Cost Estimation Techniques	Intuitive Cost Estimation Techniques	Case-Based Systems		Innovative design approach	Dependence on the past
		Decision Support Systems	Rule-based Systems	Can provide optimized results	Time-consuming
			Fuzzy logic Systems	Handles uncertainty, reliable estimates	Estimating complex features costs is tedious
			Expert Systems	Quicker, more consistent and more accurate results	Complex programming required
	Analogical Cost Estimation Techniques	Regression Analysis Model		Simpler Method	Limited to resolve linearity issues
		Back Propagation Neural network model		Deal with uncertain and non-linear problems	Completely data-dependent, higher establishment costs
Quantitative Cost Estimation Techniques	Parametric Cost Estimation Techniques			Utilize cost drivers effectively	Ineffective when cost drivers cannot be identified

Table 1: The PCE techniques: key advantages, limitations, and list of discussed references[74]

In case of this project, it cannot be declared, that one specific approach or technique could be used, because the task is rather complex. For this reason, the best approach is to analyze those benefits of the listed techniques which are relevant from the project point of view and formulate a method which applies all these advantages to calculate product costs in a more effective way.

[74] Own illustration, based on Niazi/Dai/Balabani/Seneviratne (2006), p. 570

2.2.8 Knowledge-based systems in cost engineering

According to [1],” building design and material type used are the two main parameters that have a significant impact on the cost of a building. Therefore, it is important for a cost estimating tool to have a mechanism that allows the designer to perform a rapid ‘what if’ analysis on design alternatives and materials selection at the early planning stage without the accompaniment of detailed design and drawings.”[75]

Based on this assumption, knowledge-based system seems to be a promising approach, as it contains the necessary information, which can guide the cost estimation process with supporting the decision making of the cost engineers in the early phase of the product development.[76]

What is a knowledge-based system exactly? “A Knowledge-based System (KBS) is a system implemented with the goal to imitate human problem-solving behavior using Artificial Intelligence (AI) techniques. Development and maintenance of KBS is the objective of Knowledge Engineering (KE). It has many commonalities with Software Engineering (SwE).”[77]

But why does decision supporting is such an essential element of cost engineering? The answer is the lack of experience or necessary qualification to estimate or analyze alternatives in estimation the costs of a new development. For this reason, AVL should provide an approach, with which the requirements of the customers can be analyzed and based on their preferences an adequate solution can be offered. On the other hand, the system can help cost engineers, to provide the proper technical solution for clients, without the help of experts in the affected field. This can spare time for the department to provide estimates, furthermore the impact of the different technical realizations and customer requirements on each other can be made visible.[78]

Knowledge-based systems are widely used in the industry, but they are all applied in different fields. One of the most similar case was worked out by [1], where they created ´an integrated knowledge-based system for alternative design and materials selection and cost estimating´ in the field of civil engineering, especially in building construction. In their project, they started to implement the system with knowledge acquisition, which was done by a literature review and expert´s interaction. During capturing data for their system, they classified buildings as residential, offices, and schools and further classifications of low-rise, mid-rise, and high-rise were made too. Afterwards, they

[75] Abdulrezak/Tahir (1998), p. 329
[76] Cf. Musgrove (1992), p. 480 et seq.
[77] Steinbauer (2015), p. 5
[78] Cf. Abdulrezak/Tahir (1998), p. 329; Cf. Venkatachalam/Mellichamp/Miller (1993), p. 355 et seq.

gathered engineering judgements and dimensions of building elements for different categories from experts, and finally, they have studied numerous as-built historical drawings to supplement the existing knowledge.[79]

After the proper acquisition of data, they set up a system, in which the sequence of choosing technical solutions was determined in a systemized way. With the help of this system, the time-consuming traditional quantity- and cost estimation could be avoided, and the offer could be delivered under a shorter period of time.[80]

To set up such a system in the frames of this thesis, firstly the acquisition of the proper data is needed. After the right data is captured, the next step is the right formulation of the gathered input, namely the definition of functions so, that they must be connectable on one side with AVL´s customer requirements, on the other side with the technical solutions. This step is the adequate representation of the knowledge. As powertrain functions can be defined in many ways, in the practical part, the application of different functional structures will be represented and discussed from their usability point of view. Finally, the right structuring is necessary, which means the determination of connections between the captured inputs. The system must be easily maintainable, as in today´s changing world, new technical solutions and functionalities are emerging day by day, which makes the continues update of the knowledge base essential.[81]

But what is knowledge exactly? At this point, the definition of different expression must be cleared to understand the term knowledge:[82]

- “Data: Symbols
  - 1, 2…
  - Jaguar
  - -2°
  - Rainy
- Information: Data with given meaning (semantics)
  - temp= -2°
  - weather= rainy
- Knowledge: Application of data and information
  - temp<0° → street-temp=cold
  - street-temp=cold → driving-cond=slippery”

[79] Cf. Abdulrezak/Tahir (1998), p. 330 et seq.
[80] Ibidem
[81] Ibidem
[82] Steinbauer (2015), p. 8

This means that a knowledge-based system must contain data, information and their unambiguous connection to use them as an effective tool for cost engineering.

As it was mentioned in the definition, knowledge-based systems use artificial intelligence techniques to support the accomplishment of a specific problem. However, the details of artificial intelligence techniques are not being discussed, as the final target of this project is to determine a methodology and not the entire system. Probably, one of the most state of art solution would be the application of strong AI on the determined approach, which can be proposed as a follow-up project in the SE-Lab.

2.2.9 Conclusion of cost engineering in theory

With all this information in mind, it can be assumed that a cost engineering technique is needed, which is not only able to estimate the costs, but also help cost engineers in the decision process. It cannot be declared unambiguously yet, which of the described techniques can be applied effectively to set up such a system, but after figuring out the final solution, the approach will be traced back.

In the following chapter, the outcome of the empirical research, conducted with experts in the field of cost engineering and systems engineering, and the evaluation of the possible solutions are discussed.

3 Practical Part

In the previous chapter all those key facts were discussed about functions and cost-engineering, which are relevant from this thesis point of view. In this chapter the real-life application of functions and cost engineering techniques is reviewed with the help of an empirical research session, made with experts inside AVL. Afterwards, in the evaluation phase, a recommendation will be made on a framework of a cost estimation-supporting system, which considers all of the rules, techniques and methods, which turned up during the stage of research.

3.1 Empirical research

The target of the empirical research is to understand the current application of functions and cost engineering techniques, methods. For this purpose, experts chosen from different business units were interviewed. They were divided into two groups based on the field they are coming from, and their questionnaire was worked out in a systematic, target-oriented way, which resulted in two different lists of questions. The results of the interviews are handled in a confidential way, which secures the anonymity of the participants, even inside the company. The structure of the guideline was worked out based on [52].

3.1.1 Function-related expert interviews[83]

In case of the function-related experts the questions were directed towards the following topics:

- Demographic data,
- practical examples for application of functions and requirements,
- system communication and documentation in the early phase of the development,
- correlation between requirements and functions,
- cost estimation based on functions,
- definition,
- functional structures,
- purpose, advantages and disadvantages of the practical application of functions.

[83] Cf. Interview with person A from ITS business unit, date: 18.09.2018;
Cf. Interview with person B from ITS business unit, date: 27.09.2018;
Cf. Interview with person C from PTE business unit, date: 28.09.2018

3.1.1.1 Demographic data

In this interview session, two of the interview partners are coming from the Instrumentation and Test Systems (ITS) business unit, which offers testing and inspecting applications and solutions for the entire powertrain. The third interviewed expert is active in the Powertrain Engineering (PTE) business unit, which provides solutions for each sub-part of the powertrain.

After elaborating the interviews, it turned out that all the interview partners are active on different management levels and in different processes, which is quite advantageous in this case, because each of them answered the questions based on their unique perspective. The following figure represents those areas where the interviewed experts are mainly active.

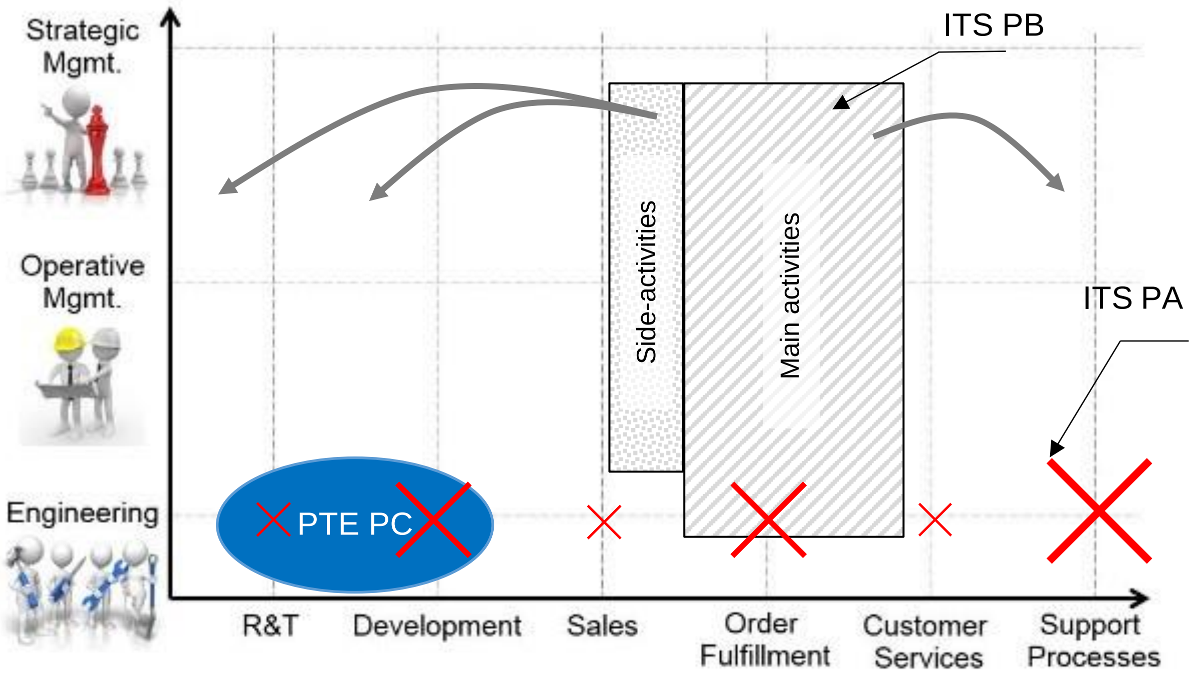


Figure 17: Management levels and processes of the interviewed experts[84]

[84] Own illustration, based on: Interview with person A from ITS business unit, date: 18.09.2018;
Interview with person B from ITS business unit, date: 27.09.2018;
Interview with person C from PTE business unit, date: 28.09.2018;
Zingel (2015), p. 2

3.1.1.2 Practical examples for application of functions and requirements

As first, they described the practical application of requirements and functions with an example, which is actual in their current work. It can be assumed, that independent from business unit, they have similar processes regarding requirement management process.

All of them have mentioned, that the documentation of customer requirements is not a simple and easy procedure.

At the Instrumentation and Test Systems (ITS) business unit one of the interview partners described a case, in which he is involved. In this project, he is supporting a software centric customer project for a well-known car manufacturer, in which various kinds of complex testing facilities are set up in different configurations. As the OEM is very demanding, it is requesting lots of new functionality and a lot of non-functional requirements as the testbeds are designed for propulsion systems based on different principles (ICE, HEV, BEV, etc.)

In this specific project, the customer created a request for quotation and multiple user requirement specifications. These documents were given to AVL, where they were analyzed and disaggregated to single customer requirements as single objects. In other words, the modularization of the user requirements specifications.

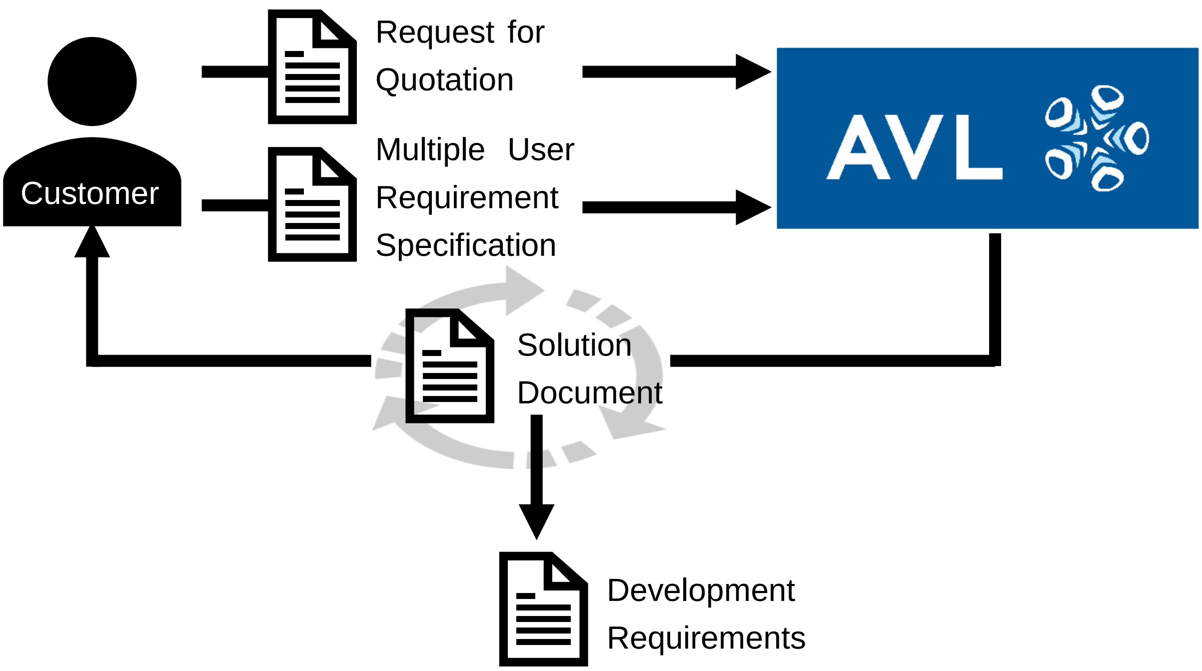


Figure 18: Requirements management at ITS business unit[85]

[85] Own illustration, based on: Interview with person A from ITS business unit, date: 18.09.2018; Interview with person B from ITS business unit, date: 27.09.2018

After deriving what the customer wants to have, the list of the single requirements – structured into different functional topics – is created. Based on this list, the so-called solution document is generated, which can be stated as a proposal to the customer, how AVL aims to design the solution. If this proposal is approved by the customer, then the development requirements – the requirements, which will serve as a basis for the development process – are derived from the desired solution proposal.

He noted, that in the requirements management tool, a functional classification was introduced for an internal project for testing purposes. Although, this classification is not connected with the customer requirements yet, there is an initiation for the application of this approach also in customer projects. The long-term target is to classify various kinds of requirements, such as customer or development requirements into a standard functional structure order to e.g. determine affected functions, by customer requirements across multiple projects.

The expert coming from the Powertrain Engineering (PTE) business unit assumed, that in general, customer requirements are not documented in a straight-forward way. The first step is always to identify and collect what the customer really wants and put them into a ´Vehicle Requirement Document´, which is an individual script with predefined structure. In this document everything is compiled that was gathered from customer meetings, e.g. documents, simulation results.

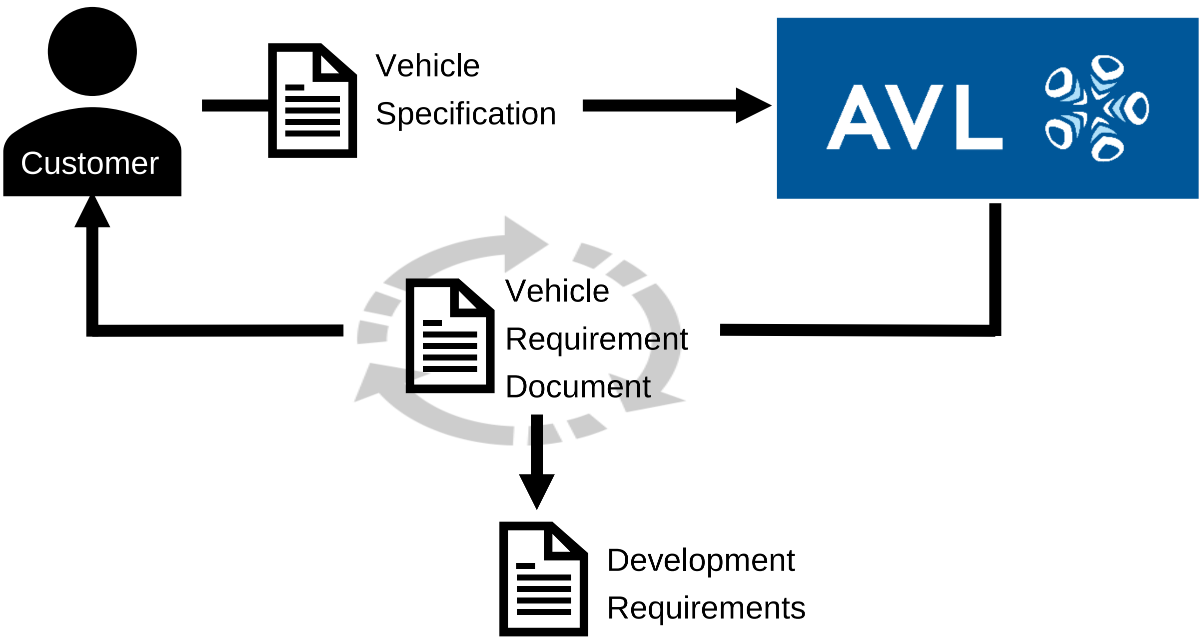


Figure 19: Requirement management at PTE business unit[86]

[86] Own illustration, based on: Interview with person C from PTE business unit, date: 28.09.2018

A document, provided by the customer, called ´Vehicle Specification´, contains the basic technical specifications – e.g. weight, friction, driving resistance – that AVL needs to know about the vehicle, in order to derive development requirements. However, it is an iterative process, as the customer is not able to reveal all its requirement in the beginning of the development process.

He assumed, that his team is modeling also the functionality of the systems, which is managed by ´SysML´ models. Vehicle functions are only modelled in a higher level, as they are taken as an input, but powertrain functions are recorded in detailed way. The functionality of all smaller elements is captured too, to observe their contribution to the main powertrain function.

Taking into consideration, that recording requirements from the customer is an iterative process in both business units, and development requirements are always derived from a document, which counts as an agreement between AVL and the customer, it can be concluded that the process of the requirement management process is the same in both business units. However, the application of functions has a totally different sense in the two business units. While at ITS only in-house tests are made, at PTE, in powertrain development, the usage of functions is a widespread practice.

3.1.1.3 System communication and documentation in the early phase of the development

At ITS, the communication of the technical concept is based on customer requirements in ´JIRA´ and the solution document in ´Confluence´ internally. These tools are software for requirement management in the business unit. The interlink between these tools is that requirements are classified according to the certain solution chapter. Each solution chapter means a certain functionality of the system. In Confluence each of these chapters have their own page, where the related customer requirements are listed, as well as the solution concept can be found. Externally the communication is conducted with the help of the solution proposal document.

At PTE, after the derivation, development requirements are inserted into a so-called ´Powertrain System Specification´ document, which describes the realization of the powertrain from a technical perspective. It characterizes the architecture, as well as the boundary conditions, components, functionality of the powertrain and functions of numerous sub-components. It is a shared document, which is edited by different domains inside the company (e.g.: functional, thermal, electrical). Behind the ´Powertrain System Specification´ there are tools – e.g.: PTC Integrity Modeler – which together with the document – serve as a basic communication platform within the department. The modeler contains models about the system from different perspectives, which makes the understanding of the system simpler and easier for each discipline.

3.1.1.4 Correlation between requirements and functions

It is obvious, that all the interviewed experts are on the opinion that requirements and functions are not standing far away from each other. One of them assumed, that functions are specific forms of requirements, and they connect requirements with the technical solution, while others noted that requirements describe what is desired to be developed and functions are standing for describing how to realize the given requirements. Furthermore, requirements are always testable and serve as a basis for validation and verification of functions.

As it was already discussed in chapter 2.1.5.2, according to the ´double diamond´, functions are the translations of requirements. This figuratively suggests the same thoughts, which were mentioned by the interviewed experts. Coming from this, it can be declared, that the main development methodology of the company can serve as a starting point in the evaluation of the final solution.

3.1.1.5 Cost assessment based on functions

The experts were asked, if they have or would integrate functions in any kind of cost estimation. None of the partners were involved in a cost estimation project yet, but all of them had an opinion about this topic. One assumed, that the procedure of cost estimation is very rough and not systemized on a company level. For this purpose, calculating the costs based on function would make the whole process quicker and more effective, as the reuse potential of a product´s functional structure is very high. Another expert noted, that function-based cost estimation is not the approach which can generate value in this case, because the functions are only suitable for establishing a connection between customer requirements and technical solution. He noted that unfortunately, functions do not involve cost influencing parameters of a component or the exact technical solution. Without these parameters cost calculation simply does not make sense, as the highest-level functionality of most of the vehicles is the same. It was mentioned as an example, that the function of a conventional fuel tank and a hydrogen tank is to store energy. In this case the function does not involve the technical parameters of the tanks, which leads to the conclusion, that costs cannot be determined based only on simple functions.

3.1.1.6 Definition

As it turned out during the empirical research, the term function can be defined in the following way: “Function is the description of the overall task of the system, which defines the connection between the input and the output of the system without the technical solution.”[87] To clear up, if there is a correlation between theory and practice, the experts were asked to define the term function and to prove their standpoint with an example from their work.

All of them defined the meaning of functions similarly as it was written in the literature, however they remarked some important supplements. Firstly, functions must always satisfy the related requirements. Secondly, they are true only in a defined context, as in the beginning of a development process the pre- and boundary conditions – e.g. system environment – must be determined to clarify, what fulfillments are needed to realize the functionality. At last, the separation of software and hardware functions as well as clustering them into perspectives – e.g. activation/deactivation, charging, shut-down – is essential to create a transparent functional structure.

Clustering functions according to perspectives means, that they are interconnected to different units, like requirements or logical perspective. This is the principle of the RFLP (Requirement, Function, Logical, Physical) Systems Engineering approach. The experts agreed, that the using functions have a sense only in this framework.

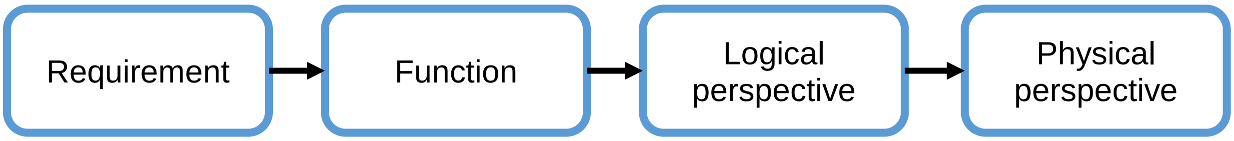


Figure 20: RFLP approach[88]

The expert from powertrain engineering drew an example to explain the practical meaning of functions. According to him each function of the entire vehicle describes what the system must do in order to fulfil customer requirements. Each of them is taken into consideration as a black box which has inputs and outputs and interactions with other functions. If this black box is opened, the main function of the vehicle is to drive. After opening the box of the main function, the vehicle can be disaggregated into more subsystems, e.g. powertrain, chassis, suspension. Following the chain, the main function of the powertrain is to provide propulsion power to support driving. This high-level function can also be divided into more sub-functions, e.g. electric drive, recuperation.

[87] This thesis, chapter 2.1.4

[88] Own illustration, based on: Interview with person A from ITS business unit, date: 18.09.2018; Zuccaro (2018), p. 61

Despite of describing the meaning of functions similarly to the theory, they had different opinions about the solution neutrality of functions. The solution neutrality depends on the degree of abstraction, which means, that it is true only at the highest structural level(s) of the system. Similarly, solution independency can be only ensured by applying top-down functional modeling, as on lower structural levels of the product more detailed functions are required. Based on these assumptions, solution independency of functions can be only ensured in the very beginning of the development process – when the first draft is made – but from cost estimation point of view it is rather useless, as costs are always dependent on the technical specifications of the system.

Although, if functions are used for development purposes, the higher the level of abstraction, the more space for solution is available. It means that if a hydrogen tank is taken into consideration as a system to be designed, the stored medium is already fixed, and the solution space is restricted, which is not beneficial from abstraction point of view. If another kind of energy would be taken into consideration, – e.g. electrical energy – it would be realized with a totally different technical solution. Following the systems engineering approach, in the first round of the development process, a very generic solution is figured out, after which, step by step more specific and more detailed solutions are evaluated. In this context, specific means that characteristics of the system are determined on the same hierarchal level, but not going into components´ and subsystems´ details; and detailed means that the sub-system and component characteristics are specified on a lower structural level too.

Based on this assumption, the main function of a hydrogen tank, formulated in the most abstract way would be ´to store chemical energy´. If the characteristics of the system would be more specific or functions would be addressed with attributes – e.g. store 10 kg of hydrogen – the solution space would be restricted. In this case, it can happen that the wrong solution will be realized, as it is not the appropriate one for the given functionality and its required characteristics. This is the reason why the following questions must be always asked when setting up a functional structure:

- Do I do the right things?
- Do I do the things right?

This can be checked with going forwards and backwards along the levels of abstraction and see if the distinct levels are fulfilling the customer requirements.

3.1.1.7 Functional structures

Regarding the detailedness of a functional structure, the interview partners shared similar opinions again. On one hand, by setting up a functional structure, the detailedness is highly influenced by the domain where it is used. If mechanical development is considered, not every single screw must be stated, but there is a level, until which it is beneficial to define and set up a functional structure. However, if the domain for control design is being considered, each small function must be captured to define the software components and, in this way, provide traceability for them. Moreover, functions can be observed as the reflections of customer requirements on a very high level. Coming from this, function-centric approach is needed where a communication is necessary between two or more people, because if the functionality of every single sub-component or component of the system – which is designed only by one person – would be specified, the effort would exceed the benefits. Only functions, with interaction to other functions with another responsible engineer needs to be explicitly specified and aligned among all of the affected stakeholders. Although, if the responsible person must communicate the solution, it must be clarified how the designed component is interacting with other components or sub-component in the whole system. This is the level, until which function-centric thinking is needed to obtain the same understanding on system level, hence cross-product-level. Furthermore, a functional structure is the opposite of a BOM list, as because of the hierarchical structure it is rather wide than deep. Functional hierarchies are very complex, and after a certain level they have rather academic sense than practical. It can be dangerous to set up a functional structure with a numerous of levels, because certain functions may overlap each other.

3.1.1.8 Purpose, advantages and disadvantages of the practical application of functions

The interview partners shared the same opinion in this topic. The practical application of functions is essential for a systematic approach, but it is always the question of the field where they are used. On areas, where product structure and functional structure have one-to-one allocations, functions can be used effectively, opposing with the fields, where an m-to-m connection is existing. Their application makes it possible to figure out better and more suitable solutions for engineering problems, furthermore it provides more space for innovation.

Challenges are the lack of understanding of engineers and the changed mindset, which is necessary to capture them in a right way. Changing the mindset from solution and component centric thinking to ´use case- & function centric thinking´ can be reached with training and guidance.

3.1.1.9 Conclusion

Although, they are coming from different disciplines, the experts mostly shared the same opinion about the questioned topics.

One target of the empirical research was to get a comprehensive overview about the difference between theory and practice. Comparing their thoughts with the theory proves, that the content of the literature is used in practice, however due to the field of application it is extended with some specific principles.

It can be seen, that their tasks and their customers they are dealing with, have totally different requirements, but the processes and principles they are pursuing, are very similar. Considering the requirement management process and communication tools of the different areas, it is obvious, that the basis of the processes – except for the document names – is the same in every case, however their communication tools are totally differing from each other.

This leads to the assumption, that in the frames of this project, the use of ´SysML´ models might be beneficial, because this model-based SE tool allows to capture more complex product- and functional structures, what is more, it is able to allocate attributes to product sub-systems, components and even functions. Besides that, exploiting the capabilities of the software, there might be an opportunity for creating a comprehensive framework for connecting functions and costs.

On the other hand, there are arguable opinions too, such as the usage of functions in case of cost estimation. It is true, that according to the academic description, single functions do not have attributes, which would serve as a basis of costing, furthermore, in case of a powertrain development functions can be allocated to many different components, creating an m-to-m connection, but with the help of ´SysML´, the complexity of such a complex system might be handled.

3.1.2 Cost engineering-related expert interviews[89]

In case of the cost engineering experts the questions addressed the following points:

- Demographic data,
- practical examples for application of cost engineering techniques,
- input and output data of projects in practice,
- cooperation between disciplines during cost calculation
- cost influencing parameters,
- accuracy of the calculated costs
- comparison of theoretical techniques with real processes.

3.1.2.1 Demographic data

The following interviews were taken with experts in the field of cost engineering. Although, they are working in the same department, they are dealing with different topics. One of them is active in projects regarding strategic costing, which means that he makes an approximate cost calculation for different parts of the powertrain system usually on the request of external customers (OEMs), which serves as decision criteria for a new development in most of the cases. Two of them are dealing with comprehensive, detailed cost calculation of different powertrain elements.

As they are coming from the same department and their main activity is to assess costs of different powertrain parts in different development phase, they are all active on engineering level in the development process. The expert from the field of strategic cost estimation, is also active in sales processes on the strategic management level. Their activities have connections to sales and operative management level, because they are not only responsible for cost estimation and calculation, but also for managing and organizing their projects with the customer.

As in the function-related interview session, the following figure shows the experts active areas.

[89] Cf. Interview with person D from PTE business unit, date: 16.11.2018;
Cf. Interview with person E from PTE business unit, date: 20.11.2018;
Cf. Interview with person F from PTE business unit, date: 29.11.2018

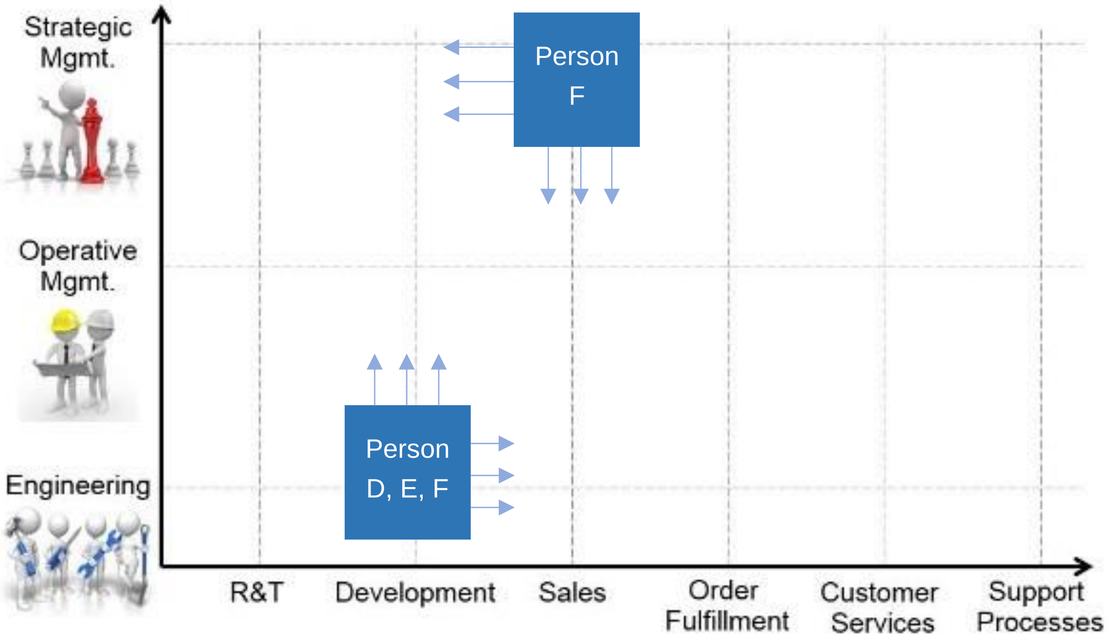


Figure 21: Management levels and processes of the interviewed experts[90]

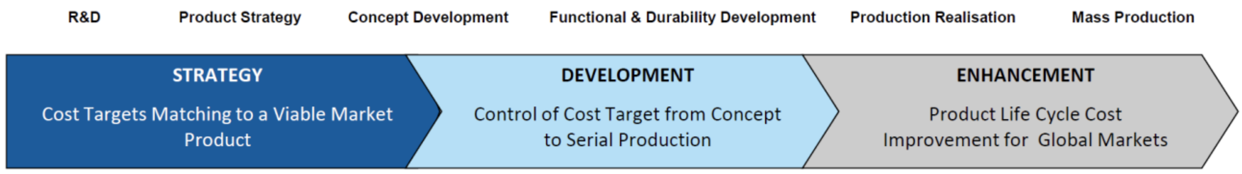
3.1.2.2 Practical examples for application of cost engineering techniques

The purpose of this section was to get a broad overview about the practical application of cost engineering methods, techniques to find out which of them could be used beneficially in the frames of this thesis.

During the interviews, it turned out that the widely used tool in the department for calculating costs and documenting results, is the Siemens Teamcenter. This software is capable of determining component costs, based on a virtual mockup and manufacturing processes. Besides this tool there are numerous – usually Excel-based – in-house supplementary software, such as a gear calculation tool or battery cell calculation tool, with which the costs can be determined for a specific group of products.

It was emphasized, that AVL offers cost engineering services in all phases of the product development, which can be seen on the following figure.

[90] Own illustration, based on: Interview with person D from PTE business unit, date: 16.11.2018;
Interview with person E from PTE business unit, date: 20.11.2018;
Interview with person F from PTE business unit, date: 29.11.2018;
Zingel (2015), p. 2



AVL Cost Engineering	Strategy	Development	Enhancement
Advanced Cost Studies	●		
Cost Benchmarking	●	●	●
Design to Cost	●	●	
Cost Analysis		●	●
Cost Reduction Studies		●	●
Cost Audit			●
Price Performance Analysis			●
Localisation Study		●	●
Make or Buy Analysis	●	●	
Cost Management Process	●	●	●

Figure 22: Cost engineering services at AVL[91]

Although, the figure localizes the stage of application of the techniques, all of the interviewed experts agreed on that cost engineering methodologies cannot be restricted strictly to only one development phase.

These services serve as a basis for the comparison of techniques in theory and practice, they are not being detailed in the frames of the interview section.

It was remarked that cost engineering services are applied during the whole product lifecycle, however until production, 95% of the product costs are settled. The following diagram depicts the Total Cost of Ownership (TCO) in the function of product lifecycle stages.

[91] Barna/Oswald/von Falck (2018) p. 6

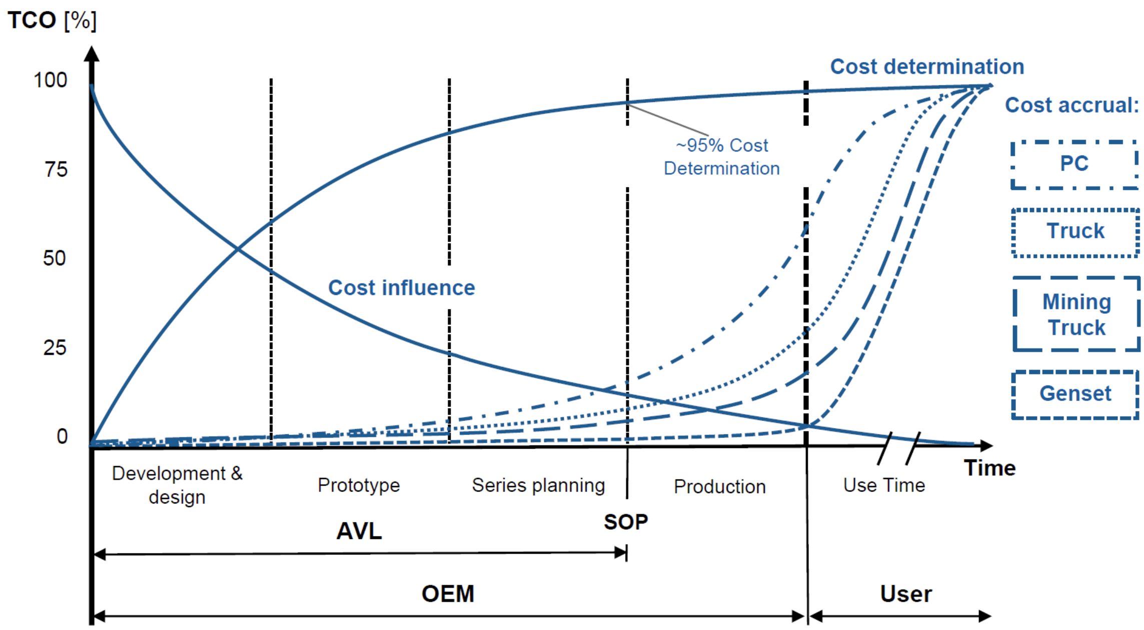


Figure 23: Cost determination and influence of costs during the development process[92]

In this paragraph, the emphasis lies on the application phase and sequence of these services to find out which of them are used in the early phase of the powertrain development. With this, the potential methods for connecting costs and functions can be revealed.

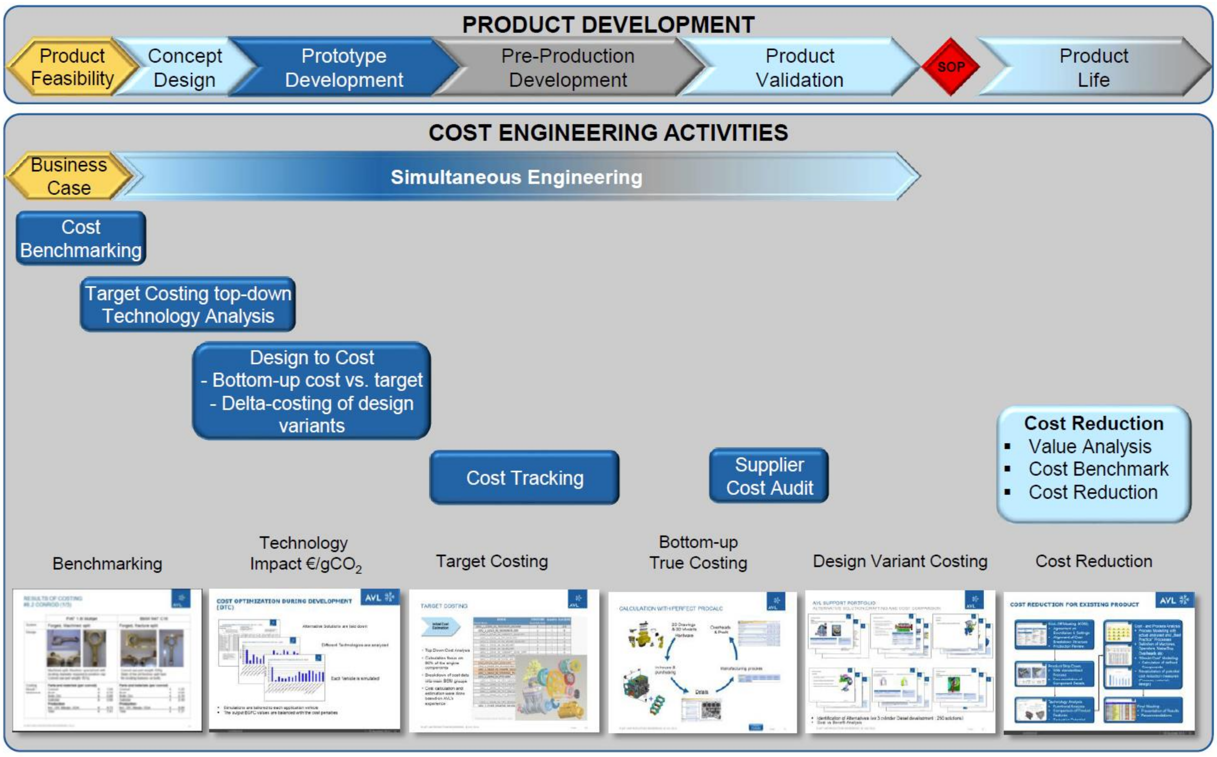


Figure 24: AVL cost engineering methods during development and production[93]

[92] Sams (2015), p. 32
[93] Barna/Oswald/von Falck (2018) p. 8

Based on Figure 24 and on the opinion of the experts, it can be stated, that a cost analysis and top-down technology analysis are done in the first row. It means that in the very first phase the developed product is analyzed from a technological point of view and compared with an existing one. Based on this comparison, the rough manufacturing costs of the new product can be estimated. The following step is a detailed cost calculation, where the exact manufacturing costs are determined with the help of bottom up analysis. Within this basic costing process there are many special variants, such as target costing, design variant costing, cost reduction.

The partners suggested, that in the evaluation of the final approach, the mentioned approach might be suitable as a starting point. They assumed, that this process can be partly stated as case-based reasoning, as the past experience is also used for determining the costs.

3.1.2.3 Input and output data of projects in practice

In order to come closer to the solution and to get an overview about the most common cost engineering projects, the partners shared information about their personal experiences.

It turned out that there are numerous scenarios, which can be distinguished according to the maturity of the project. In the concept phase, AVL customers communicate the boundary conditions – main requirements – of the product to be developed. In this early stage, strategic costing is applied, where the costs are determined based on assumptions and similar previous projects. This is a crucial step in the development process, as the customer makes the decision about the continuation or cancellation of the development usually based on these roughly estimated values. The interviewed expert from the field of strategic costing drew an example about a project in which he is currently involved. In this project, the emphasis lied on the cost assessment of internal combustion engine-based powertrains, which fulfills emission legislation in 2025. During the project, technical experts from different fields are involved, such as exhaust aftertreatment or electrification. Different variants of powertrain systems are investigated to see if there is a possibility to leave the conventional propulsion away and replace it with a hybrid or compressed natural gas (CNG) driven engine. The customer wants to preserve the original behavior of the propulsion system, such as power or torque. The task is to assess the cost of all the possible combinations of powertrain systems which can substitute the original one. At the final decision besides costs, other factors are also taken into consideration by the OEM, such as the applicability of the drivetrain to other vehicles within the same platform. The input data for this project were the parameters of the baseline engine´s behavior. The interview partner remarked, that the degree of freedom in this maturity of the project is extremely high, as the customer did not set strict and limiting development targets.

In the subsequent stages of product development usually most of the cost influencing parameters are already known, however they are never communicated comprehensive enough to finish the development without the client. This will result, that cost estimation and calculation is always an iterative process. In these stages of product development, the information shared by the customer is rather two-sided – there are cases, when the customer gives only requirements, however it can happen, that 3D CAD model or the real hardware is also provided to determine the costs.

3.1.2.4 Cooperation between disciplines during cost calculation

Product Design, Production Engineering and Cost Engineering are disciplines, which cannot exist without each other when it comes to cost calculation. To clear the interdependencies between these knowledge branches, the cost engineer experts described how they cooperate with professionals from these fields.

They shared the same opinion and assumed that there is a continuous and proactive communication between these disciplines in case of development projects. Depending on project type, internal as well as external customers of the DOP department are experts from fields of Cost Engineering, Purchasing, and Research and Development. Therefore, the most common case from external side is that the designer gets the proposal from the customer to design the part. During elaborating the project, the designer has more options regarding numerous parameters, which results in alternative designs. As next, the cost engineer determines the manufacturing processes and calculates the costs for different variants and sends them back to the designer, who informs the customer about the opportunities. The customer decides, and the project goes further with the solution which was chosen by the customer. The most decisive factors are usually the mass and the costs in choosing the final solution. As cost engineers are familiar with basic principles and methods of manufacturing processes, the role of a manufacturing engineer in such a project is that when it comes to problems about feasibility and manufacturing processes in details, their expertise required.

3.1.2.5 *Cost influencing parameters*

According to the experts, one usual approach for detailed cost assesment of a certain part is the ´bottom-up´ calculation where manufacturing costs and raw material costs are calculated to determine the ´Production Costs´. To get the ´Sales Price´, overheads, like ´Selling, General and Administrational Costs (SG&A)´ and ´Profit´ must be summed and added to ´Production Costs´.

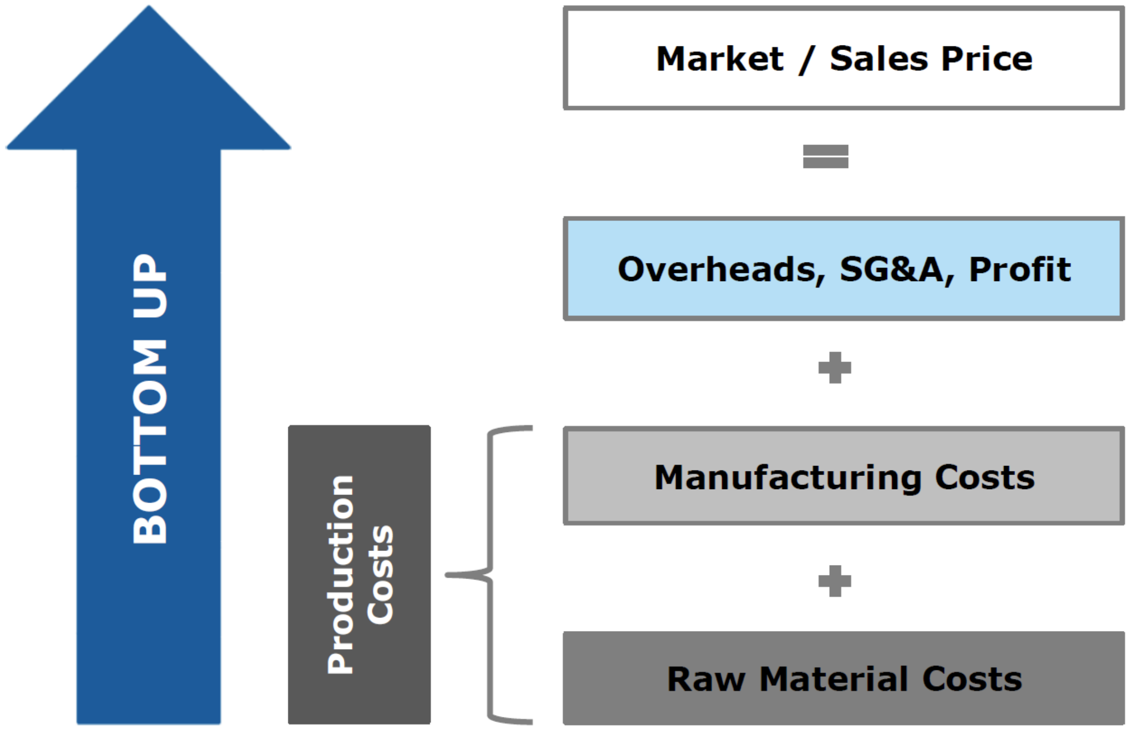


Figure 25: The sum of market/sales price[94]

Those cost influencing factors which have a significant impact on our calculated results can be summarized in terms of ´general boundary conditions´. They have a significant effect not only on the manufacturing technology, but even on choosing semi-final products. For example, in case of different annual production volumes, the approach is not the same and the considered manufacturing processes are disparate. This will show up in cost calculation too. The classification of the general boundary conditions can be seen below.

[94] Barna/Gruber (2018), p. 13

General boundary conditions:[95]

- "Base currency, exchange rates,
- production site,
    - countries and regions,
    - hourly wages according to qualification,
    - interest rate,
    - leasing fee production area and offices,
    - energy costs,
- annual volume,
- production lifetime,
- shift model,
- number of manufacturing lots,
- tooling approach (one-time payment or allocated to part price),
- initial conditions,
    - greenfield production approach,
    - brownfield production approach."

Beside general boundary conditions, the applicable raw material costs must be determined too, which are influenced by the following parameters.

Raw material costs:[96]

- "Production site (region),
- form of the material (bar, sheet metal, casting material),
- volume,
- quality of the material."

There are several costs which are not calculated in the detailed cost calculation but only considered with a percentage rate. These are overheads, namely material overhead, manufacturing overhead or the selling and general administration costs.

[95] Cf. Barna/Gruber (2018), p. 28 et seq., Barna/Oswald/von Falck (2018) p. 43
[96] Ibidem

Overhead costs:[97]

- "Production site (region),
- size of the company (revenue),
- place in the entire supply chain (OEM, Tier 1 or Tier 2 etc. Supplier),
- quality level of the production,
- industry branch (e.g. plastics-injection molding or metals-turning),
- the ratio of material cost to revenue."

It was remarked that these parameters are not calculated in detail in the beginning of the development process but must be taken into consideration according to the best practices of the engineer.

3.1.2.6 Accuracy of the calculated costs

From this project´s point of view, it is essential to know the accuracy of the costs, estimated in different stages of the development process, to target the best possible accuracy in the early phase. Each of the interview partners were on the same opinion about this topic, as they mentioned that in the very early stage the certainty is approximately 70-75% and in the final stage, when the decision is made on minor technical solutions, the proximity is around 95%. In the followings, the admitted accuracy by the DOP department in different time phases of the development is represented:

Rough Estimation:[98]

0. "´Rule of thumb´ estimation,
1. personal-history based estimation,
2. interpolation from previously analyzed data,
3. estimation of differential costs to reference data."

Fine estimation:[99]

4. "Adjustment of existing process model to known boundary conditions,
5. supplier quotation without a cost breakdown,
6. supplier quotation with a cost breakdown,
7. AVL CE detail calculation based on detail specification and best practice processes."

[97] Cf. Barna/Gruber (2018), p. 28 et seq., Barna/Oswald/von Falck (2018) p. 43
[98] Barna/Gruber (2018), p. 11
[99] Ibidem

Benchmark calculation:[100]

8. "Negotiated calculation/offer,
9. purchase price,
10. supplier quotation verified by AVL CE with assumed boundary conditions, process details,
11. supplier quotation validated by AVL CE with agreed boundary conditions, process details,
12. product in production (supplier) price/costs fully validated by AVL CE under agreed and fully described boundary conditions, change management, reliability."

Verified/validated data:[101]

13. "Benchmark calculation verified by AVL customer."

[100] Ibidem
[101] Ibidem

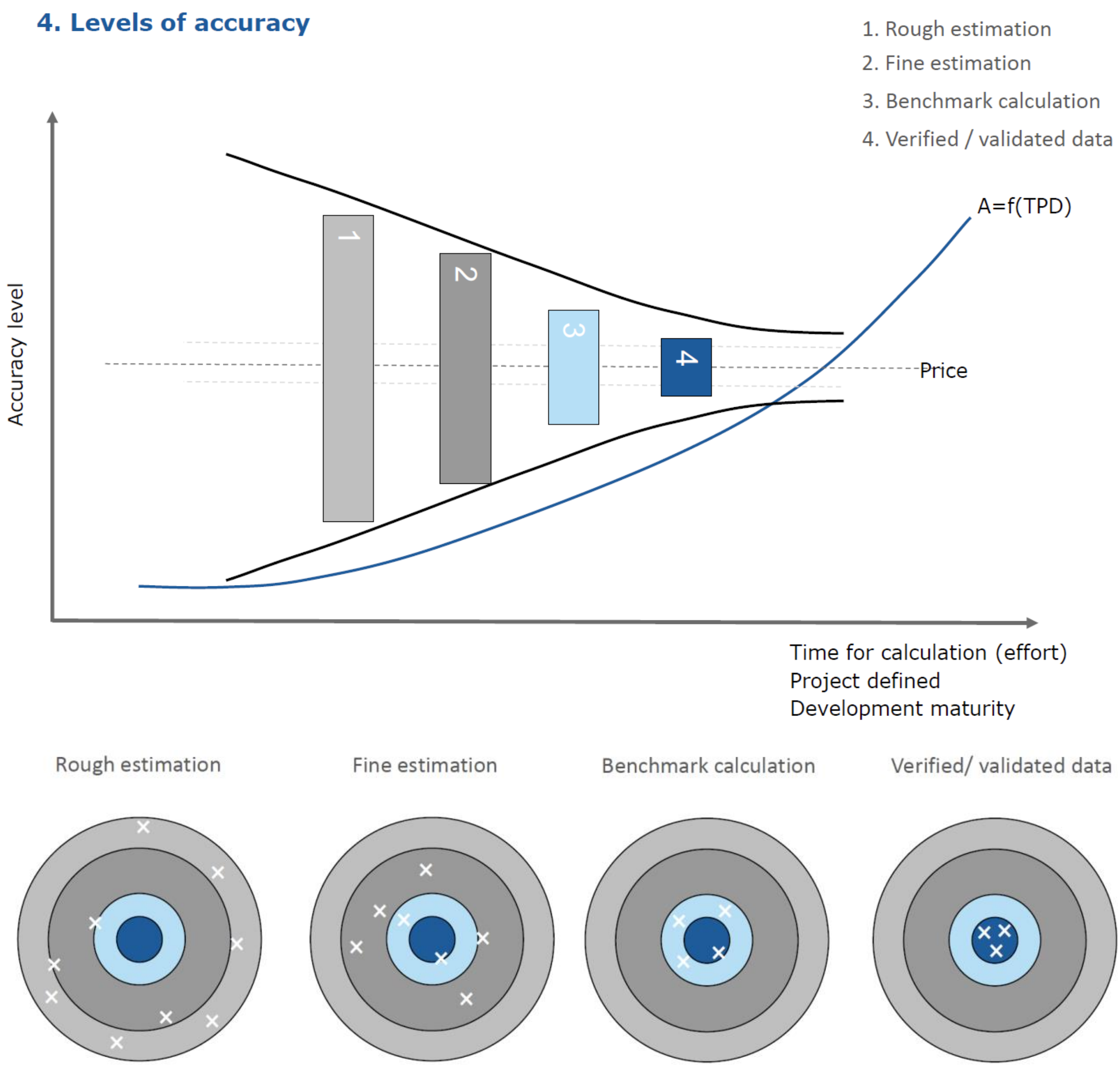


Figure 26: Levels of accuracy in the DOP department[102]

[102] Barna/Gruber (2018), p. 8 et seq.

3.2 Evaluation

In this chapter, the evaluation of the project will be discussed in detail. This means that an approach will be worked out, which is expected to help the cost assessment process in the early development phase, possibly with the interaction of functions. The approach will be demonstrated with the help of a Proof of Concept (PoC).

3.2.1 Meaning of early development phase

Before starting to work out the solution, some boundary conditions must be cleared, which have significant effect on the outcome. They can be stated as requirements from the side of the DOP department.

The first boundary condition to be cleared is the exact meaning of ´early development phase´. As it is a broad area on the schedule of powertrain development and cannot be separated by events, the desired place can be seen on the next figure:

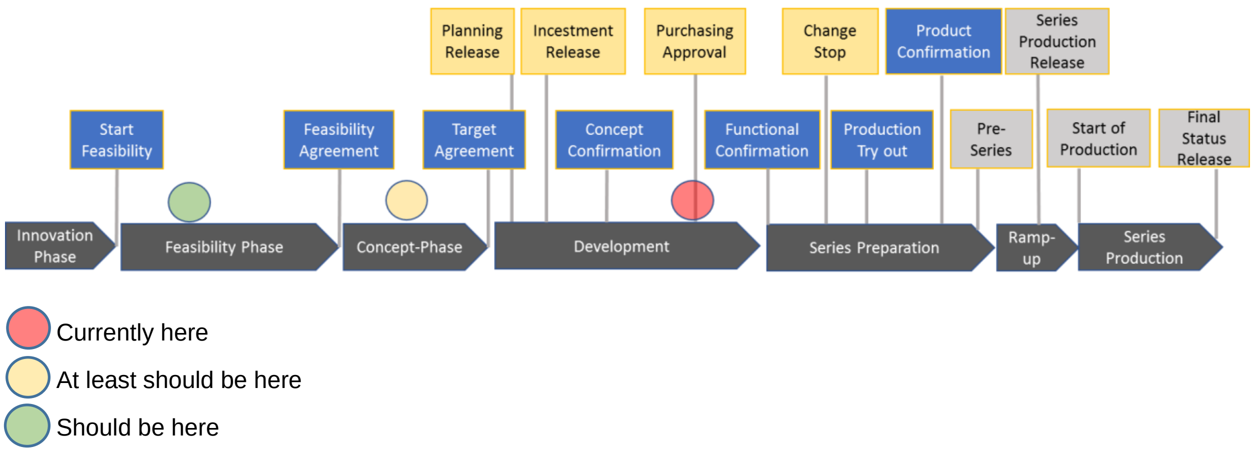


Figure 27: Product development process at AVL[103]

As it can be seen in Figure 27, the cost assessment process takes place currently at the end of the ´development phase´. The target is to bring it forward and be able to assess the costs in the first quarter of the ´feasibility phase´, but at least until the end of the ´concept phase´.

The opinion of the experts during the interview sessions mostly showed that functions themselves do not have added value when it comes to Cost Engineering. This statement seems to be true, because it is quite a difficult task to assess costs without being familiar with the technical solution itself. For instance, it is not possible to assess the cost of the function ´store energy´, without aware of any product parameters, such as the amount or

[103] Own figure, based on AVL Internal Homepage, date of access: 18.12.2018

the stored medium. Therefore, the solution, which was suggested by the interview partners is to attach attributes to these verb and noun connections. This would enable cost calculation with the assistance of functions, as the connected parameters would serve as a basis in cost assessment processes.

As it was stated in the empirical research section, the difference between benchmark calculation and rough estimation (strategic costing) lies in the phase of application in the development process. This effects the detailedness of product features and with this the accuracy of the cost influencing factors too.

In most of the cases, strategic costing is based on experience, which means that the newly developed or adjusted product is compared with similar products from the past, containing many assumptions. A relatively substantial proportion of strategic costing projects are based on determining the costs of different variants of powertrain, which fulfill the same requirements. These can be stated as totally different variants or an adjusted variant of the same product. As an example, certain powertrain performance – which is determined by the customer – can be fulfilled by various types of engines, such as Diesel engine, Otto engine, electric engine. In this case, these engine types would count as different variants. However, if the desired performance would be satisfied only by Otto engines, differing in certain technical modules – e.g. camshafts with different functionalities, or chargers based on different principles – the new version would count as an adjusted variant of the same product.

Taking these facts into consideration, it can be concluded that usage of functions makes only sense if the project is based on comparison of product variants, but not in case of detailed cost calculation. A simple example to prove this statement is that in case of detailed cost assessment, where bottom-up approach is applied, all the technical parameters, such as geometry data, tolerances, production methods must be known for the cost engineer to get a precise value as an output. Whereas, in case of a comparison-based rough cost assessment, component functions, as well as overall powertrain functions play an important role, because they display in which direction are product features changing and how these changes are influencing product costs in case of different setups.

Based on the above-mentioned facts and the opinion of the experts, in the frames of this thesis the principles and approaches of strategic costing must be applied. However, the separation of detailed cost calculation and strategic costing is not that easy at all, because product costs in the early stage cannot be estimated, without being familiar with some of the technical parameters and adherent costs from previous projects.

3.2.2 Initial vision

The vision, which was formed in the beginning of the project was, to use the existing product and component cost database from Siemens Teamcenter and connect it with a standardized functional structure. Based on these functions and customer (OEM) requirements, the functional structure of the desired product could be determined with functions chosen from the standard structure. Furthermore, the most similar products from previous projects would be used for the cost assessment of the desired system. This would result in a comprehensive database, containing fuzzy connections between functions, components and their costs.

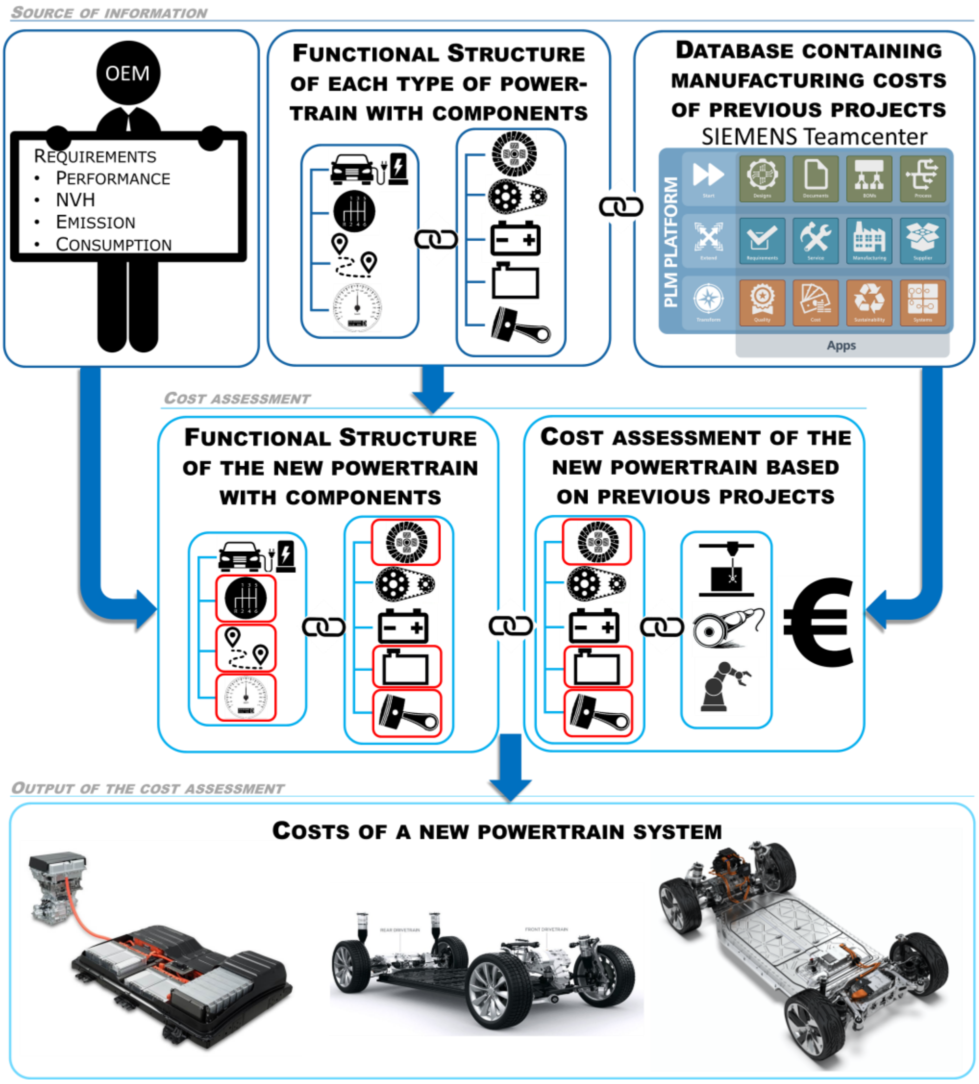


Figure 28: Initial vision[104]

Following these thoughts, in the following chapter the connection between different functional structures will be examined.

[104] Own figure, Rákos (2018)

3.2.3 Detailed functional structures in strategic costing

Based on the above-mentioned assumption, the product architecture was traced back to the detailed component level to observe, if there is a possibility to find dependency between functions and costs and to shift strategic costing in the background to a more detailed level. As the piston is one of the simplest core parts in a conventional powertrain, it was chosen as a demonstrating example.

Firstly, the system structure of the whole vehicle based on an internal document was set up, to be able to position the demonstrating counterparts – piston, piston ring and piston pin – in the entire system. Figure 29 depicts the vehicle as a system with its subsystems and system borders.

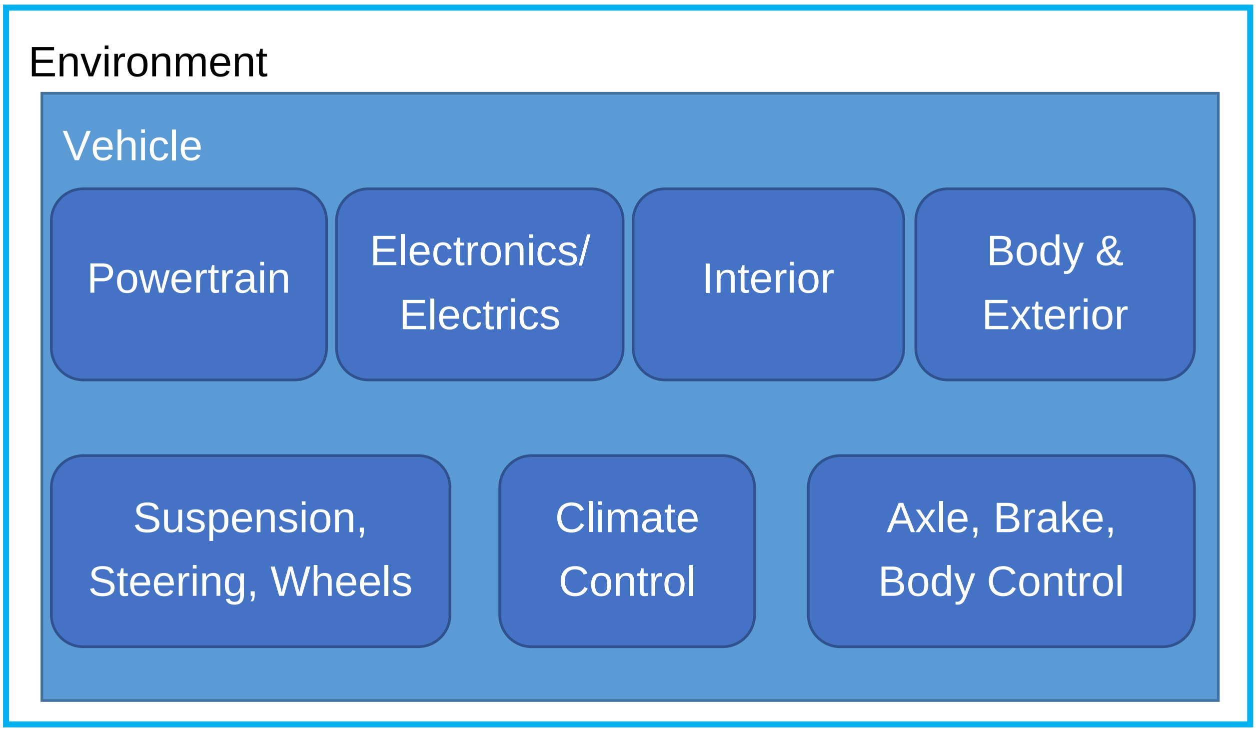


Figure 29: Vehicle System Structure[105]

In the next step, the disaggregation of the ´powertrain´ subsystem was continued to reach the component level and to position the piston and its parts – piston rings, piston pin – in the whole powertrain system. The powertrain layout was derived from [56], in which the piston and its components were positioned according to Table 2. It must be remarked that this example focuses on an internal combustion engine and for this reason other powertrain parts, other types of propulsion systems and some engine parts are not represented here.

[105] Own figure, based on Fischer (2018), p. 67

Powertrain					
	Engine				
		IEC			
			Engine Structure		
				Cylinder Block	
				Cylinder Liner	
				Cylinder Head	
				Cylinder Head Cover	
				Cylinder Head Gasket	
				Cylinder Head Bolt	
				Piston	
				Piston Ring	
				Piston Pin	
				Connecting Rod	
					Connecting Rod Bolt
					Connecting Rod Bush
				Connecting Rod Bearing	
				Variable Compression	
				Crankshaft	
					Front PTO
				Balance Shaft	
					Balance Shaft Gear
				Engine Bearing Cap	
				Main Bearing Caps	
				Oil Pan	

Table 2: Powertrain Layout (detail)[106]

As it can be seen in Table 2, the piston, the piston ring and the piston pin are on the same structural level and an extra level is created for standard parts, such as bolts and washers. This structural disposition proves the expert´s opinion about the number of levels and the detailedness of the structure in case of such a classification. Components which do not require significant communication from the development point of view, are on the last level in the structure.

According to the opinion of the interviewed experts, the application of functions in cost engineering is only possible, if functions are addressed with measurable attributes, to serve as a basis for the cost calculation. During detailed cost assessment processes, the calculation is always based on specific cost influencing parameters of the part. To be able to detect the interdependency between functions and costs on component level, the cost influencing attributes, component functions, and development requirements of the piston must be determined. These properties were derived from [25], created by AVL, according to which the cost influencing parameters of the exemplary components can be seen in Table 3, Table 4, and Table 5.

[106] AVL Internal Homepage, date of access: 17.01.2019

Material		
	Aluminum	
	Steel	
Production method		
	Forging	
	Casting	
Geometry		
	Diameter	
	Total length	
	Skirt length	
	Top land height	
	Number of rings	
	Crown thickness	
	Offset of bowl	
	Valve pocket diameter	
	Valve pocket depth	
	Ring groove widths	
	Land widths	
	Compression height	
	Pin bore diameter	
Surface treatment		
	Skirt	
	Groves	
	Crown	
		Tin Plating
		Graphite layer
		Anti-friction layer
		Anodizing
		Ferrostan
		Chrome plating
		Nickel plating
Tolerances		
	Piston diameter	
	Piston crown flatness	
	Piston crown roughness	
	Piston crown inclination	
	Offset of bowl	
	Valve pocket depth	
	Valve pocket diameter	
	Inner groove diameter	
	Groove chatter marks	
	Groove perpendicularity	
	Groove top/bottom face parallellity	
	Groove roughness	
	Groove root corner radius	

	Groove heights	
		1st groove
		2nd groove
		3rd groove
	Skirt roughness	
	Skirt profile	
	Skirt wall thickness	
	Pin bore diameter	
	Pin bore roughness	
	Pin bore cylindricity	
	Pin bore roundness	

Table 3: Piston cost influencing parameters[107]

Geometry		
	Shape (profile)	
	Width	
	Height	
	Diameter	
Material		
Coating		

Table 4: Piston ring cost influencing parameters[108]

Type		
	Floating	
	Fixed	
Geometry		
	Length	
	Diameter	
	Wall thickness	
Material		
	Case hardening steel	
	Nitriding steel	
Tolerances		
	Surface finish	
	Roundness	
	Cylindricity	
	Inner diameter	
	Front ends	

Table 5: Piston pin cost influencing parameters[109]

Component functions of powertrain counterparts will be always the same, because their working principle cannot be changed. However, it is not true in another way around, because one function can be satisfied by more technical solutions, especially when it comes to innovation. The only parameter which is varying from powertrain to powertrain is the cost influencing parameter, with which single component functions are addressed.

[107] Cf. Melde (2009), p. 5 et seq.
[108] Ibidem
[109] Ibidem

Component functions of a piston:[110]

- Convert pressure to force,
- compress air-fuel mixture,
- eject exhaust gas from the cylinder.

Component functions of piston rings:[111]

- Seals against the piston,
- controls Lube Oil Consumption (LOC),
- controls blow-by gas flow.

Component functions of a piston pin:[112]

- Transmits piston force to the connecting con-rod,
- supports piston crown against deflection.

Development requirements which must be determined to start piston design:[113]

- Power load,
- peak firing pressure,
- bore and stroke,
- liner design,
- cooling,
- number of rings and ring packs,
- number of valves,
- combustion bowl shape.

Despite of taking very common and simple parts of the powertrain into consideration, it can be seen, that there are numerous cost influencing parameters in case of every part. On the other hand, it can be also stated, that the number of component-associated functions and development requirements is relatively low. Based on these facts, it can be doubted, if establishing a connection between cost influencing parameters and component functions on this structural level is possible, or does create a value for the following reasons:

[110] Cf. Melde (2009), p. 5 et seq.
[111] Ibidem
[112] Ibidem
[113] Ibidem

- In this example, many of the cost influencing parameters cannot be unambiguously addressed with a component function, because they are influenced by other properties or functions of the engine or the powertrain. For instance, type and the place of surface treatment on the piston is highly dependent on engine characteristics, such as operating temperature, operation related to knocking limit, fuel quality. These detailed properties are determined after a long, iterative discussion with the customer.[114]
- In the early phase of the powertrain development process, where strategic cost calculation is applied, these detailed technical parameters and properties are not known, neither by the piston, nor by the engine.
- Value creation is a question of customer type, because setting up such a system would be only beneficial, if the customer is a component designer and manufacturer company – e.g. a piston designer company –, who supplies the parts for the developed engine. In the frames of the thesis, it is assumed that most of the contracts are being made with OEMs, who would not benefit from such a detailed system.
- As it was mentioned by [31] during the interview sessions, functional structures can be very complex and after a certain level, the enormous complexity can cause problems in creating interconnections between functions from different hierarchical levels. Such a deep functional structure has rather academic than practical sense.[115]
- Such a detailed functional description of a component is limiting the space for the possible solution as it is clearly determining the final design of the part.
- From AVL customer´s perspective it does not create value to assess the cost of a function which is describing the operating principle of the product.

Taking these reasons into consideration, the establishment of such a detailed functional structure does not create a value from the strategic cost calculation point of view. Therefore, it is essential to jump to a higher functional hierarchical level and examine if there is a potential to connect costs with functions.

[114] Cf. Melde (2009), p. 8 et seq.
[115] Cf. Interview with person B from ITS business unit, date: 27.09.2018

3.2.4 General functional structures in strategic costing

After proving that component functions are hardly applicable in practice from strategic cost calculation point of view, the next step is to examine the functional structure of the main units in the powertrain.

To explore, if a general functional structure creates a value in case of using it as a part of strategic costing, the functional structure of an internal combustion engine was chosen as a demonstrating example.

Thanks to the continuous communication with experts inside the company, they provided the documentation of another previous internal project [23], in which the applicability of Systems Engineering to traditional development processes was investigated. In a more detailed way, the influence of a crankshaft oiling borehole´s function on other components of the engine was analyzed. This documentation contained the whole functional structure of an internal combustion engine, which can be seen in the following table.

ICE Functions		
Transform chem. energy to pressure and mechanical rotational energy	provide air	absorb air
		compress air
		ingest air
	provide fuel	compress fuel
		store fuel
		inject fuel
	combust fuel-air mixture	generate fuel-air mixture
		compress fuel-air mixture
		ignite fuel-air mixture
		channel pressure of expanding gas
	release exhaust	
	convert pressure to torque	convert pressure to force
		transmit force
		convert force to torque
		transmit torque
Minimize friction at contact areas	provide fluid lubrication	collect and store lubrication fluid
		(pre-) filter lubrication fluid
		generate lubrication fluid pressure
		temper (cool/pre-heat) lubrication fluid
		transport lubrication fluid to friction contact
	lubricate friction contacts	disperse lubrication fluid
		build-up oil film
		dissipate lubrication fluid
		sealing against clean-bearing
	bearing of friction contacts	ball-/roller-bearing
		slide bearing
Optimize fuel-mixture generation and combustion	produce turbulent flow	
	atomize fuel	

Balance cyclic irregularities	damp/balance vibrations	
	damp/balance torsional vibrations	
Exhaust aftertreatment	filter particles	
	oxidize carbon molecules	
Provide optimal operating temperature	provide cooling fluid	store cooling fluid
		provide cooling fluid flow
		cool cooling fluid
		transport cooling fluid to heat dissipating systems
	cool	cool internal combustion engine
		cool electric motor/generator
	heat isolation of ICE	
Provide penetration of pollutant	sealing of bearing seats	
	sealing of piston against cylinder wall	
	filtering of intake air	
	filtering of lubrication fluids	

Table 6: Functional structure of ICE[116]

In case of this structure, it can be realized that these functions are describing the operating principle of the engine. The assumption of the double diamond is proved here, because these functions will remain the same in case of any reciprocating internal combustion engine. Applying this approach in the development of a totally new system is very beneficial, as designers and developers may find a technical solution for a function – necessary for the engine´s operation – which is better or cheaper than the existing one. However, it can be argued if the application of this functional approach is beneficial from cost engineering point of view in the early phase of the development, because of the following reasons:

- In most of the cases, AVL´s customer (OEM) has requirements regarding development targets, such as performance, emission, range, fuel- and energy consumption. The difficulty lays in connecting these requirements to a functional structure which describes the operation principle of the engine, as none of these functions will fulfil the mentioned customer requirements directly.
- The OEM is not interested in the cost of a function which describes the operation principle of a powertrain element, he rather cares about the cost of the function which directly fulfills his requirements, what is more he wants to decide among the possible technical solutions according to his preferences.
- An approach, in which functions, describing the operating principle of powertrain components are considered, would work mostly in case of innovation processes, where engineers are looking for a new and better solution for a certain problem. However, in case of this project, the task is to assess the cost of the already existing, but at least pre-determined solutions, and not to invent a whole new thing

[116] Cf. Maletz (2011), p. 14 et seq.

for the customer. The task of the cost engineer is to offer a solution concept, which satisfies the requirements of the customer and calculate the costs of these solutions in the very early phase of the development.

- Estimating the costs only on functions would not work in practice, because the technical solution with its determinative parameters must be known to estimate some costs. If it would be so, a sportscar and a B-segment car would cost the same amount of money, as the functional structure of the two is the same.

Based on these facts, it can be assumed, that functions are useful for classification of different technical solutions with the same task and for detecting the possibilities for functional transfer – reducing the number of components and costs –, while preserving the original functionality of the system.

With this in mind, it can be stated that another viewpoint should be considered regarding the nature of functions, with which AVL´s customer requirements can be unambiguously satisfied, and technical solutions can be directly addressed.

3.2.5 Changing the nature of functions

According to the specialized literature and the interviewed experts, function is a description of the overall task of the system, which defines the connection between the input and the output of the system without the technical solution. In other words, it is describing, what the system should do.[117] This means, that they do not have to be formulated in a different way, only their nature should be changed from operating principle oriented to solution oriented to make it applicable to cost assessment in the early phase of the development.

To do so, customer requirements are considered as a starting point. It is obvious that every AVL customer wants to improve something when a new development contract is made. This willingness for improvement shows up in form of requirements. Coming from this, the nature of functions must be formulated so, that they fulfil the requirements, given by the customer. This will allow that each requirement will be fulfilled directly by a function and indirectly by a technical solution.

[117] See also chapter 2.1.4

But why is the usage of functions still important? As it was mentioned before, the benefit of functions in this approach is the unambiguous classification of those technical solutions, which can fulfil customer requirements. It also creates potential for functional transfer, which makes it possible to exclude a component and fulfil its function by another one.

Based on this hypothesis, an approach was determined, which considers functions as improvement potentials to satisfy requirements directly. In this way, the method seems to be applicable for cost estimation in the beginning of new customer (OEM) projects.

To show the details of the idea, in the following chapter, the steps of a new development project will be discussed:

3.2.5.1 Initial steps of starting a new customer project

1st step: Determining the car segment and cost engineering related boundary conditions

Each project starts with an iterative discussion with AVL´s customer, therefore there are some determining factors which are fixed already in the beginning. Information regarding car segment is one, that belongs to these factors. It already specifies or reveals some powertrain requirements and boundary conditions, which serve as development targets, such as NVH, performance, weight, dimensions. For example, NVH requirements are totally different in B- and F-segment cars.

In the beginning, the cost engineering related boundary conditions must be also cleared to be able to give an accurate estimate. These boundary conditions are the volume to be produced and the production site.

2nd step: Development targets

During discussing the development targets with AVL´s customer, the question of ´what the customer is willing from the vehicle to do´ will be answered. These high-level requirements cannot be tied directly to functions, which is the reason for indicating them as development targets. At this step, all targets are determined, which has an influence on the possible outcomes of the next steps, such as performance, range, emission, NVH.

3rd step: Specifying the type of the powertrain

The type of the powertrain is cleared also at the beginning of the development process, as it strongly depends on the emission standards and respectively on the wish of the customer. It can also happen that more powertrain types can satisfy the standards, therefore the costs for each of them must be assessed. The specification of powertrain type in the beginning of the development is extremely beneficial, as it sets the direction towards targets regarding development and cost calculation.

4th step: Powertrain layout

In the next step, the layout, especially high-level technical details are fixed with AVL´s customer, such as engine, transmission and gearbox configuration. These details are strongly dependent on the outcome of the previous steps, as the boundary conditions of the vehicle decreases the number of possible variants. For example, the probability of building an inline 6 engine in a B-segment car is rather low due to the available space under the bonnet.

5th step: Powertrain-related boundary conditions

Finally, those parameters are discussed, which are strongly related to the chosen powertrain system, such as engine volume or the number of gears in the transmission. The outcome of this step can result in going back to previous steps again, as the whole development process is characterized by continuous and iterative communication.

These steps are not separated from each other significantly in time, they are part of a continuous iterative discussion with AVL´s customers. They help to understand and record the wishes of the customer systematically and provide a direction for the development and cost calculation of the desired powertrain.

3.2.5.2 Base propulsion layout

The outcome of this iterative process is one or more base propulsion systems, which are the closest to fulfil the requirements of the customer in the first draft. To be able to respond to the wishes of the customer as quickly as possible, a standard, modular product portfolio is needed, according to which the base propulsion system(s) can be set up. This means that the product portfolio must involve standard modules with standard set of parameters to serve as a repository for the modular assembly.

After aggregating the base propulsion layout from the repository of standardized modules, the fulfilment of requirements must be examined and communicated to the customer. It is obvious that this initial powertrain assembly is set up according to the cost engineer´s best knowledge and only approximates the required system values. At this point, the investigation and communication of potentials for improvement to the customer is necessary. To be able to do this, the possible potentials for improvement must be collected and categorized according to development targets (2nd step).

3.2.5.3 Improvement potentials

The basis of a ´field of improvement potential´ is always an initiation for enhancement from the side of AVL´s customers – e.g. satisfy emission standards or increase the performance of the vehicle – to meet the expectations of the legislation, end-user, etc. They can be detected with the question: ´What can be optimized or improved? ´ For this reason, requirement can be stated as ´field of improvement potential´, because it determines the area, which is affected by the wishes of the customer – e.g. decrease fuel consumption.

Going further with this thread, it can be declared that ´improvement potentials´ are the equivalent of functions in this case, because on one hand, they describe the principle of technical solutions with verb-noun connections, on the other hand they characterize the solution for the problem so, that they can satisfy the requirements of the customer. They are answering also the question: ´How can it be optimized or improved?´ This means that they can establish a direct and unambiguous medium between requirements and technical solutions. Coming from this, it is obvious that the theory of the ´double diamond´ can be applied as a basis in this approach.

As the function-related requirements of AVL customers are not varying significantly in case of a certain powertrain type, a standardized list of ´field of improvement potentials´ together with the corresponding ´improvement potentials´ can be set up with the purpose of classification of technical solutions. Coming from this, not only the ´improvement potentials´ must be summarized in a list, but also those technical solutions, which have an impact on the affected ´field of improvement potential´. As ´improvement potentials´ describe the solution for the problem independently from the concrete technical realization, technical solutions give answer to the question: ´How can be the improvement potential realized?´

For example, the wish of the customer is to reduce the NO_x emission of the engine. This affects emission requirements from the list of ´field of improvement potentials´. In this case the question of how to decrease the NO_x emission of the engine must be posed to reveal the functions in form of ´improvement potentials´. It can be decreased as an instance by ´decreasing the temperature of the combustion´, respectively with the sub-function ´decrease the oxygen content of the intake air´. The technical solution for this function can be revealed by posing the question: ´How to decrease the oxygen in the cylinder?´ From this point on, already existing technical solutions are proposed that are able to fulfill the requirements. In this case it can be e.g. EGR, VVT, VVL.[118]

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[118] Cf. Bosch (1998), p. 6 et seq.

3.2.5.4 Interdependencies

There are some cases, when one technical realization provides solution for more functions, or two customer requirements exclude each other in a system. For this reason, in the frames of a follow-up project, the final solution might be a comprehensive database, in which improvement potentials, having influence on each other must be connected. Such a linkage helps to reveal interdependencies and contradictions between functions and draws the user´s attention to them.

3.2.5.5 Higher-level powertrain areas

Continuing this thread, the concrete technical solutions are required to be linked together with higher level technical divisions of the powertrain. This will make it possible to reveal the influences of certain technical solutions on different areas of the powertrain. It helps the cost engineers to recognize the influencing connections between technical solutions and to speed up the cost assessment process.

3.2.5.6 Expected benefits

With this approach, the main requirement of the department will be fulfilled, namely to assess the costs based on functions in a systemized way. Functions in the new interpretation allow to link requirements with the technical solutions as they provide a direct linkage between them.

It allows to assess the cost of AVL customer wishes directly, such as reducing the NOx emission of the engine or improving the acceleration of the car and reveals interdependencies or contradictions between them. For these reasons, it provides evidence for negotiation – in case of contradictions and interdependencies – with the customer (OEM) and helps to make decision about the final technical solution easier and quicker.

With the help of this connected lists of requirements, functions, technical solutions and powertrain areas, the approach makes the work for cost engineers much simpler and quicker, as they will not require the intervention of technical experts in the very early development phase, which often takes a lot of time and effort.

This approach makes functional transfer realizable, as interdependencies and possible technical solutions for the required functions will be visible. This makes the examination of certain powertrain components possible, if their functions can be taken over by other counterparts with the purpose of cost reduction.

3.2.6 Proof of Concept (PoC)

As fuel consumption is one of the most important issues in the development of today´s powertrain systems, the proof of concept will be limited exclusively to this area. In the followings, certain improvement potentials, technical realizations and their linkage will be discussed.

3.2.6.1 Revealing possible improvement potentials

To satisfy the wishes of the customer, the potentials for improvement in the field of fuel consumption must be revealed and addressed with technical solutions. To do so, a system is needed, which contains all those improvement potentials and technical solutions in a systemized way, which are relevant for the field of fuel consumption. For setting up such a system, the help of experts in the affected field would be necessary, but in case of this demonstration only few instances are represented, based on a quick research.

Looking at the engine-level general functional structure, which is represented in Table 7, it can be realized that its content can serve as a very good basis for revealing all improvement potentials regarding fuel consumption, as it describes the operation principle of an ICE engine. To do so, only the corresponding part of Table 6 is considered:

ICE Functions		
Transform chem. energy to pressure and mechanical rotational energy	provide air	absorb air
		compress air
		ingest air
	provide fuel	compress fuel
		store fuel
		inject fuel
	combust fuel-air mixture	generate fuel-air mixture
		compress fuel-air mixture
		ignite fuel-air mixture
		channel pressure of expanding gas
	release exhaust	
Minimize friction at contact areas	provide fluid lubrication	collect and store lubrication fluid
		(pre-) filter lubrication fluid
		generate lubrication fluid pressure
		temper (cool/pre-heat) lubrication fluid
		transport lubrication fluid to friction contact
Provide optimal operating temperature	provide cooling fluid	store cooling fluid
		provide cooling fluid flow
		cool cooling fluid
		transport cooling fluid to heat dissipating systems

Table 7: Functional structure of ICE (detail)[119]

[119] Maletz (2011), p. 14 et seq.

To reveal all the ´improvement potentials´, all the 2nd and 3rd level general functions are being considered and elaborated based on the following sample:

- Provide air: This function includes all the components, which are contributing to the airflow from the air filter until the combustion chamber.
  - Absorb air: It is obvious that in this case, the function could be taken into consideration, but the related components do not make a significant deviation from cost engineering point of view in the early phase of the development.
  - Compress air: this function though, can be decisive from costing point of view – especially in the early development phase – because the related components can have a huge impact on costs.

At this point, the importance of the function ´compress air´ must be examined. The following picture represents the Brake Specific Fuel Consumption (BSFC) in the function of engine torque, speed and Brake Mean Effective Pressure (BMEP). Based on this map, the BSFC at low RPM-range can be decreased by increasing the torque and respectively the BMEP.

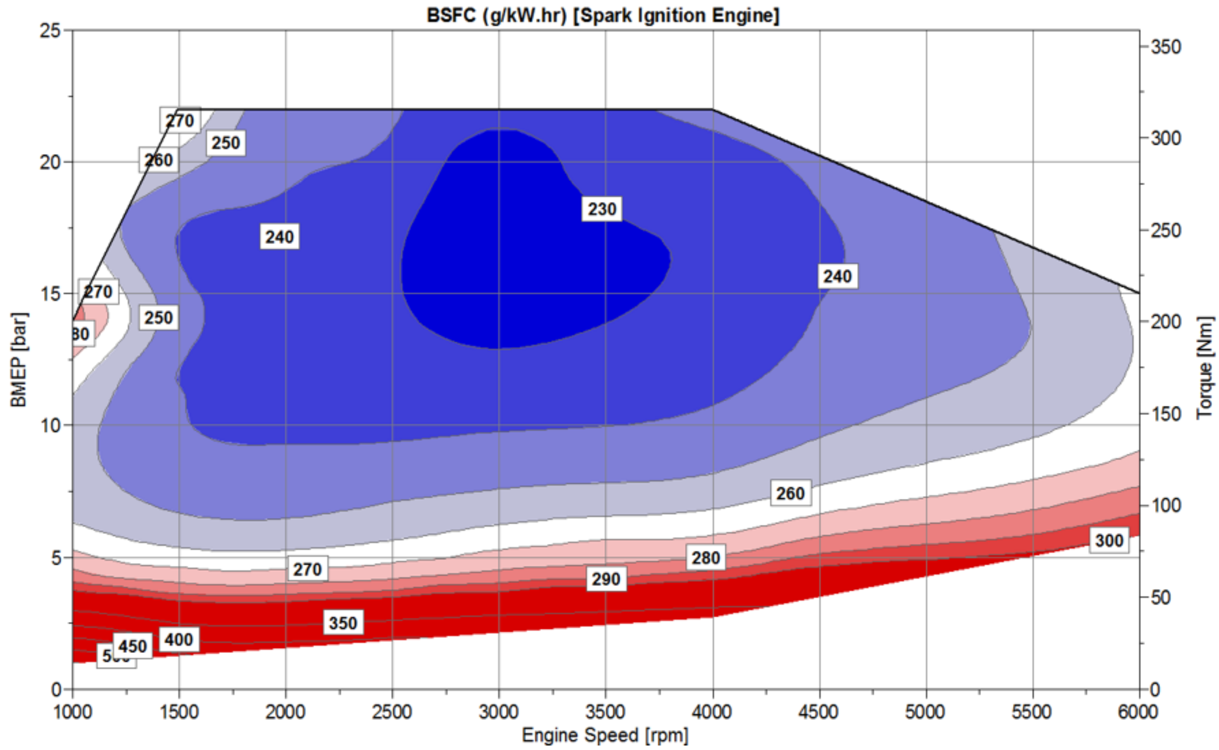

Figure 30: Brake Specific Fuel Consumption Map[120]

120 http://www.engineknowhow.com/, date of access: 18.04.2019

But what are those technical solutions which can provide higher BMEP or engine torque? According to [8], the Brake Specific Fuel Consumption at low RPM-range can be decreased by charging the engine, as it results in higher BMEP and torque and with this less burned fuel. There are numerous technologies to charge an engine, such as a Variable Turbine Geometry turbocharger (VTG), electrified turbocharger, Wastegate turbocharger (WG). These must be listed in the costing system and provided for AVL customers as options for decision.

Engine charging unambiguously corresponds with the function ´compress air´, however the Brake Specific Fuel Consumption map suggests an other way to satisfy the requirements. To decrease the fuel consumption at low RPM-range, the load on the ICE must be reduced. The easiest way to do so, is adding an alternative propulsion system, which can take over partly or fully the energy generation of the ICE. Taking today´s trend into consideration, the most widespread solution is the variety of electric drivetrains. To demonstrate the diversity of hybrid powertrains, the following table was compiled from different neutralized AVL projects. All the listed variants are applicable for a D-SUV segment.

Type	Measure	Technology
Mild Hybrid	P0: Belt Starter Generator (BSG) 12V	▪ BSG (5 kW), double belt tensioner, wiring harness, with conventional starter ▪ Li-ion battery
	P0: BSG 48V 10 kW	▪ BSG (10 kW), double belt tensioner, 48V wiring harness, with conventional starter ▪ 400 Wh Li-ion battery ▪ Adapted FEAD, tensioning system ▪ DC/DC converter
	P1: ISG 48V 10 kW	▪ E-machine high torque (10 kW), modular solution, wiring harness ▪ 400 Wh Li-ion battery ▪ DC/DC Converter
	P1: Side mounted 48V 10 kW	▪ E-machine high speed (10 kW), gear drive, modular solution, wiring harness ▪ 400 Wh Li-ion battery ▪ DC/DC Converter ▪ Electrical water pump

Full Hybrid	P2: Coaxial 48V 20 kW	▪ E-machine high torque (20 kW), modular solution, wiring harness ▪ 800 Wh Li-ion battery ▪ DC/DC Converter
	P2: Side mounted 48V 20 kW	▪ E-machine high speed (20 kW), gear drive, modular solution, wiring harness ▪ 400 Wh Li-ion battery ▪ DC/DC Converter ▪ Electrical water pump
	P2: 450V 40 kW	▪ E-machine (40kW), modular solution ▪ HV wiring harness, appropriate battery ▪ Inverter ▪ DC/DC Converter
	P4: 20 kW and P0: 48V 5 kW	▪ iBSG (5 kW), ▪ E-machine high speed (20 kW), gear drive, modular solution, wiring harness ▪ 800 Wh Li-ion battery ▪ DC/DC Converter
	Dedicated hybrid transmission 70 kW	▪ Housing, shafts, differential, electromechanical actuation, wiring and sensors ▪ 2 E-machines
Plug-In Hybrid	P2: 100 kW	▪ E-machine (100 kW), modular solution, HV wiring harness, ▪ Battery (10 kWh) ▪ Inverter ▪ DC/DC Converter
	P0 & P4: 100 kW	▪ E-machine (15kW) ▪ E-machine (85kW), modular solution, HV wiring harness ▪ Battery (10kWh) ▪ Inverter ▪ DC/DC Converter

Table 8: Levels of D-SUV Segment electrification[121]

[121] Own table, based on various neutralized AVL projects

As the purpose of this work is to figure out only a methodology, the technological background of the remaining improvement potentials is not being discussed in such a detailed way. Based on this way of thinking, the following general function – improvement potential pairs were used during the project:

Field of improvement potential		**Improvement potential Level 1**	**Improvement potential Level 2**	**Functions in general interpretation[122]**
Consumption	Fuel consumption	Decrease pumping losses	Change opening and closing timepoint of valves	Compress air-fuel mixture, inject air, inject fuel
			Change lifting height of valves	Compress air-fuel mixture, inject air, inject fuel
			Recirculate exhaust gas	Compress air-fuel mixture
		Generate more homogenous air fuel mixture	-	Generate air-fuel mixture
		Increase compression ratio	-	Compress air-fuel mixture
		Decrease the load on engine	Apply additional propulsion	Electrification
		Decrease the load on engine	Decrease mechanical losses	Provide cooling fluid, provide fluid lubrication, generate vacuum
		Generate extended discharge in the combustion chamber	-	Ignite fuel-air mixture
	Brake Specific Fuel Consumption at low end of the rpm-range	Decrease the load on engine at low rpm	Apply additional propulsion	Electrification
		Increase engine torque at low rpm	Increase the pressure of intake air	Compress air

Table 9: Pairs of general functions and improvement potentials

[122] Cf. Maletz (2011), p. 14 et seq.

It can be clearly realized that without applying improvement potentials, functions in the general interpretation would not work, as they are not exact enough to encompass specific groups of technical solutions. Table 9 shows that the same general function encloses numerous improvement potentials, and for this reason they would not create value from functional classification point of view. What is more, the general functional structure does not contain functions regarding hybrid or alternative powertrains, despite of looking at today´s automotive industry, electrification is one of the issues that plays the most important role. On the other hand, improvement potentials can help cost engineers to reveal the necessary technical solution based on the preferences of AVL customers, which results in less necessity for intervention of technical experts. It means that the assumption in chapter 3.2.4, according to which, the general functional structure is not applicable from cost engineering point of view, is confirmed by this part of the PoC.

3.2.6.2 Connecting improvement potentials and technical solutions

In this chapter, the linkage between the previously determined improvement potentials and their corresponding technical solutions are introduced.

The side of technical solutions contains most of the technologies, which were already offered or used by AVL in external projects with the purpose of reducing the fuel consumption of a vehicle.

Staying with the previously introduced example, the idea can be easily demonstrated. The torque of the engine can be increased at low RPM-range by increasing the pressure of the intake air. At this point, it must be examined, which are those technical solutions, which can be applicable for the new engine, to increase the pressure of the intake air. After a brief research, the possible technical solutions in case of this example can involve a WG turbocharger, VTG turbocharger, or an electrified turbocharger.

This arrangement of data is rather beneficial, as with the help of improvement potentials, the technical solutions can be grouped and can be stored in a systemized way, what is more, the structure is easily expandable, which means that newly invented or developed solutions can be added with a slight effort.

As in the previous chapter, the rest of the pairs are not discussed, hence Table 10 summarizes matching of improvement potentials and technical solutions.

Improvement potential Level 1	**Improvement potential Level 2**	**Technical solution**
Decrease pumping losses	Change opening and closing timepoint of valves	Variable Valve Timing (VVT)
	Change lifting height of valves	Variable Valve Lifting (VVL)
	Recirculate exhaust gas	Exhaust Gas Recirculation (EGR)
Generate more homogenous air fuel mixture	-	Direct Injection
Increase compression ratio	-	(+2) Compression Ratio increase
Decrease the load on engine	Apply additional propulsion	P0: Belt Starter Generator (BSG) 12V
		P0: BSG 48V 10 kW
		P1: ISG 48V 10 kW
		P1: Side mounted 48V 10 kW
		P2: Coaxial 48V 20 kW
		P2: Side mounted 48V 20 kW
		P4: 20 kW and P0: 48V 5 kW
		P2: 450V 40 kW
		Dedicated hybrid transmission 70 kW
		P2: 100 kW
		P0 & P4: 100 kW
Decrease the load on engine	Decrease mechanical losses	Electric Water Pump 12V
		Electric Water Pump 48V
		Electric Vacuum Pump 12V
		Electric Vacuum Pump 48V
		Electric Oil Pump 12V
		Electric Oil Pump 48V
Generate extended discharge in the combustion chamber	-	High frequency ignition
		Plasma ignition
		Pre-chamber ignition
Increase engine torque at low RPM	Increase air pressure of intake air	VTG turbocharger
		WG turbocharger
		Electrified TC

Table 10: Grouping of technical solutions[123]

[123] Own table, based on various neutralized AVL projects

3.2.6.3 Affected powertrain area

The next main section of the system is the affected area of the powertrain by the required technical solution. With the help of this feature, it can be unambiguously monitored, which main powertrain part must be changed during the development. This is really important for AVL customers, as it can provide an overview about the necessary modifications. The following table represents the feature through the example from the previous chapters:

Technical solution	Affected Powertrain Area
Variable Valve Timing (VVT)	Valvetrain
Variable Valve Lifting (VVL)	Valvetrain
Exhaust Gas Recirculation (EGR)	Exhaust System
Direct Injection	Injection System
(+2) Compression Ratio increase	Engine Structure
P0: Belt Starter Generator (BSG) 12V	Transmission
P0: BSG 48V 10 kW	
P1: ISG 48V 10 kW	
P1: Side mounted 48V 10 kW	
P2: Coaxial 48V 20 kW	
P2: Side mounted 48V 20 kW	
P4: 20 kW and P0: 48V 5 kW	
P2: 450V 40 kW	
Dedicated hybrid transmission 70 kW	
P2: 100 kW	
P0 & P4: 100 kW	
Electric Water Pump 12V	Engine Cooling System
Electric Water Pump 48V	
Electric Vacuum Pump 12V	Vehicle Vacuum System
Electric Vacuum Pump 48V	
Electric Oil Pump 12V	Engine Lubricating System
Electric Oil Pump 48V	
High frequency ignition	Ignition System
Plasma ignition	
Pre-chamber ignition	
VTG turbocharger	Charging System
WG turbocharger	
Electrified TC	

Table 11: Affected powertrain area[124]

[124] Own table, based on various neutralized AVL projects

3.2.6.4 Description of reference project

To prove that the invented approach works, a currently running external project was taken as a proof of concept. In this project, the early-stage powertrain cost assessment of a D-segment SUV is implemented. Although, the project is not fully following the steps of the introduced methodology, it was the most suitable one to demonstrate the approach. It must be remarked that the used data do not fully represent the reality in all cases. They were either neutralized due to confidentiality agreements or taken from AVL publications.

Following the previously determined initial steps of the approach, the first thing is to determine the considered car segment. As it was mentioned earlier, the subject of the project is a D-SUV segment vehicle. This already suggests, that the sufficient power for such a car would be approximately 130 kW - 200 kW. Of course, this is not limiting the space for the solution yet, but already restricts the list of corresponding powertrains.

As next the main boundary conditions must be cleared with AVL´s customer. In case of this project the annual volume to be produced, is 200 000 vehicles per year.

As it was mentioned earlier, the proof of concept considers only the area of fuel consumption, which means that the subject of the 2nd step is limited to this field.

In case of this project, the base engine was already determined by the car manufacturer. This means that the powertrain layout as well as the powertrain-related boundary conditions are already determined, and the proposed powertrain serves as a ´base propulsion layout´. Their requirement was to reveal all the possible configurations, which can decrease the fuel consumption of the vehicle at reasonable costs. After determining the possible technical solutions, they required their costs and impact too.

The source of energy in this powertrain is a 2.0-liter Double Overhead Camshaft (DOHC) gasoline engine. It is already equipped with some of the technical solutions which can reduce the fuel consumption of the vehicle, such as Variable Valve Timing (VVT), Start-Stop System and a WG turbocharger. The vehicle has a 12 V electric system, electric power-steering and the fuel supply is included too, namely high-pressure fuel pump, fuel rail and injectors on the engine side. Besides these the water-, oil- and vacuum pumps are working mechanically. The transmission and drive shafts are also determined by the OEM, namely an automatic transmission with 8 gears and 500 Nm of peak torque. However, in case of a new development, when the OEM is not stick to an existing powertrain, other solutions can be suitable too. For this reason, the technical solutions of the base engine must be considered in connection with the list of corresponding improvement potentials. As it was already discussed, the intake air pressure can be increased with engine charging, which in case of the reference base engine is solved by a WG turbocharger. However, there are more, already existing realizations, which can satisfy the improvement potential with higher efficiency, such as a VTG turbocharger or an electrified turbocharger. It is important to remark, that not only the more efficient solutions must be listed among the new variants, but also the same or less efficient ones, to provide the possibility for downgrade too.

Improvement potential Level 1	**Improvement potential Level 2**	**Base engine technical solution**	**New variant technical solution**
Decrease pumping losses	Change opening and closing timepoint of valves	With VVT	without VVT
			with VVT
	Change lifting height of valves	Without VVL	without VVL
			with VVL
	Recirculate exhaust gas	Without EGR	without EGR
			with EGR
Generate more homogenous air fuel mixture	-	Intake port Injection	Intake port Injection
			Direct Injection
Increase compression ratio	-	Compression ratio 12	Compression ratio: (+2)
Decrease the load on engine	Apply additional propulsion	Without electrification	without electrification
			P0: Belt Starter Generator (BSG) 12V
			P0: BSG 48V 10 kW
			P1: ISG 48V 10 kW
			P1: Side mounted 48V 10 kW
			P2: Coaxial 48V 20 kW
			P2: Side mounted 48V 20 kW
			P4: 20 kW and P0: 48V 5 kW
			P2: 450V 40 kW
			Dedicated hybrid transmission 70 kW
			P2: 100 kW
			P0 & P4: 100 kW
Decrease the load on engine	Decrease mechanical losses	Mechanical Water Pump	Mech Water Pump
			Electric Water Pump 12V
			Electric Water Pump 48V
		Mechanical Vacuum Pump	Mech Vacuum Pump
			Electric Vacuum Pump 12V
			Electric Vacuum Pump 48V
		Mechanical Oil Pump	Mech Oil Pump
			Electric Oil Pump 12V
			Electric Oil Pump 48V

Generate extended discharge in the combustion chamber	-	Standard ignition	Standard ignition
			High frequency ignition
			Plasma ignition
			Pre-chamber ignition
Increase engine torque at low RPM	Increase air pressure of intake air	WG turbocharger	VTG turbocharger
			WG turbocharger
			Electrified TC
			Without TC

Table 12: Base engine and new technical solutions[125]

The ´base engine technical solution´ column contains the technical solutions of the initial engine. With the help of this approach, a straightforward customization of the new engine is possible, what is more the system makes the difference between the standard and new variant clearly visible.

3.2.6.5 Impact of the new technical solutions

Another requirement of the OEM was to visualize and make the impact of the new technical solutions obvious. For this reason, the effects of technical solutions, represented in Table 12, are gathered regarding the questioned vehicle segment for 2.0-liter engines, based on various neutralized AVL projects. Unfortunately, due to confidentiality agreement, this information cannot be shown in the thesis, but they are used for further calculations. It must be remarked that the measures are not based on real measurement data, but they are representing real condition values, based on best engineering judgement.

[125] Own table, based on various neutralized AVL projects

3.2.6.6 Sample data generation

For the cost assessment task, a dataset was generated by combining best engineering judgement, and a random number generator with the consent of the project stakeholder. The steps of data generation were the following:

- Firstly, an upper and a lower limit was determined with the help of AVL experts and internal documents for the cost of each technical solution.
- As next, costs were generated between the given range by a random generator for the components of 2.0-liter engines for six different hypothetic car manufacturers.
- The generated costs of the base engines are different in case of each car manufacturer and vary between 1490 € – 1780 €.
- In the following step, the proportion of technical solution costs from the overall costs of the base engine was calculated. This proportion is represented as percentage.
- From the randomly generated component costs, as well as from the proportions, an average was calculated.
- This average proportion can be used for the cost assessment of technical realizations in new projects.

The method can be easily represented through the following example:

The costs of a 2.0-liter base engine in the D-SUV segment for the six car manufacturers:

- $CBe_A = 1550$ €
- $CBe_B = 1670$ €
- $CBe_C = 1490$ €
- $CBe_D = 1510$ €
- $CBe_E = 1780$ €
- $CBe_F = 1615$ €

The cost of a Variable Turbine Geometry turbocharger for the mentioned engines:

- $C_{VTGA} = 350$ €
- $C_{VTGB} = 351$ €
- $C_{VTGC} = 365$ €
- $C_{VTGD} = 334$ €
- $C_{VTGE} = 361$ €
- $C_{VTGF} = 335$ €

Proportion of technical solution – VTG turbocharger – from base engine cost:

$$P_{VTGA} = \frac{C_{VTGA}}{CBe_A} \cdot 100 = \frac{350\ €}{1550\ €} \cdot 100 \cong 22{,}6\ \% \qquad (3.2.6.1)$$

Where:

- P_{VTGA} – cost proportion of VTG turbocharger ´A´ from base engine ´A´ cost [%]
- C_{VTGA} – cost of VTG turbocharger ´A´ [€]
- CBe_A – cost of base engine ´A´ [€]

Proportion of the other turbochargers:

	A	**B**	**C**	**D**	**E**	**F**
$\boldsymbol{CBe_n}$	1550 €	1670 €	1490 €	1510 €	1780 €	1615 €
$\boldsymbol{C_{VTGn}}$	350 €	351 €	365 €	334 €	361 €	335 €
$\boldsymbol{P_{VTGn}}$	22,6 %	21,0 %	24,5 %	22,1 %	20,3 %	20,7 %

Table 13: Price proportion of VTG turbochargers

As next, the average of these proportions must be determined:

$$\overline{P_{VTGn}} = \frac{1}{n}\sum_{i=1}^{n} P_{VTGi} = \frac{1}{6}\sum_{i=1}^{6} P_{VTGi} \cong 21{,}9\ \% \qquad (3.2.6.2)$$

Where:

- $\overline{P_{VTGn}}$ – average proportion of VTG turbochargers from base engines costs [%]
- P_{VTGi} – cost proportion of VTG turbocharger ´i´ from base engine ´i´ cost [%]

This means that based on the considered data, a VTG turbocharger costs about 22% of the overall base engine cost, if it does not have a turbocharger. If the base engine would have a turbocharger, but not a VTG one, then the proportional difference between the standard and the VTG turbocharger must be considered.

On the pattern of Table 13, the following table shows the costs of a WG turbocharger:

	A	B	C	D	E	F
$\boldsymbol{CBe_n}$	1550 €	1670 €	1490 €	1510 €	1780 €	1615 €
$\boldsymbol{C_{WGTGn}}$	240 €	259 €	251 €	259 €	239 €	240 €
$\boldsymbol{P_{WGTGn}}$	15,5 %	15,5 %	16,9 %	17,2 %	13,4 %	14,9 %

Table 14: Price proportion of WG turbocharger

Average of WG turbocharger price proportions:

$$\overline{P_{WGTGn}} = \frac{1}{n}\sum_{i=1}^{n} P_{WGTGi} = \frac{1}{6}\sum_{i=1}^{6} P_{WGTGi} \cong 15{,}6\ \% \qquad (3.2.6.3)$$

Where:

- $\overline{P_{WGTGn}}$ – average proportion of WG turbocharger from base engines costs [%]
- P_{WGTGi} – cost proportion of WG turbocharger ´i´ from base engine ´i´ cost [%]

In the reference project, the OEM offered an engine, which was already equipped with a WG turbocharger however in the new engine variant, the application of a VTG turbocharger was intended with the purpose of BSFC reduction. Based on the previous assumptions, in this case the difference between the average proportions of the two turbochargers must be taken into account.

$$\overline{P_{VTGdiff}} = \overline{P_{VTGn}} - \overline{P_{WGTGn}} = 21{,}9\ \% - 15{,}6\ \% \cong 6{,}3\ \% \qquad (3.2.6.4)$$

Where:

- $\overline{P_{VTGdiff}}$ – proportion difference of VTG turbocharger related to WG turbocharger [%]
- $\overline{P_{VTGn}}$ – average proportion of VTG turbochargers from base engines costs [%]
- $\overline{P_{WGTGn}}$ – average proportion of WG turbocharger from base engines costs [%]

This means, that a VTG turbocharger instead of a WG turbocharger would cost for the OEM about 6 % more in case of this project. At this point the generation of sample data is finished, in the following steps the cost assessment of the reference project is discussed.

3.2.6.7 Cost assessment of reference project

As the thesis focuses only on the engine, the components, which costs must be considered, are represented in Table 15. Unfortunately, because of confidentiality reasons, the costs of the listed powertrain components cannot be displayed in detail in this thesis.

	Name	Costs
Base engine	D-Suv 2.0 TGDI (CBe_{REF})	1.550 €
Additional vehicle elements	LV wiring	XXX €
	Transmission	XXX €
	Fuel supply	XXX €
	HVAC	XXX €
	Main Cooling System (radiator & fan, no extra water pumps)	XXX €
	Exhaust system (muffler & pipe)	XXX €
	EAS system	XXX €
Cost of additional vehicle elements ($C_{Add.E}$)		**2.940 €**

Table 15: Costs of additional powertrain components

Going further with the example of the turbocharger, the costs of the base engine will increase by 6,3 %, because in (3.2.6.4) the calculated proportion is $\overline{P_{VTGdiff}} = 6{,}3\ \%$.

Coming from this, the extra costs coming from changing the turbocharger:

$$C_{VTGdiff} = \overline{P_{VTGdiff}} \cdot CBe_{REF} = 6{,}3\ \% \cdot 1550\ € \cong 98\ € \qquad (3.2.6.5)$$

Where:

- $C_{VTGdiff}$ – cost difference of VTG turbocharger related to WG turbocharger [€]
- $\overline{P_{VTGdiff}}$ – proportion difference of VTG turbocharger related to WG turbocharger [%]
- CBe_{REF} – reference base engine cost [€]

In this phase of the project, the given cost values are only estimations, for this reason the final costs cannot be predicted with accuracy of the detailed cost calculation. Nevertheless, agreed upon with the project stakeholder, the results´ deviation between this approach and the traditional cost assessment process in this early project phase (see rough and fine estimation in chapter 3.1.2.6) should fit in the range of $\pm\ 5\ \%$.

Based on this assumption, the range in which the cost of the final turbocharger can fit:

$$C_{VTGdiff(\min)} = C_{VTGdiff} - C_{VTGdiff} \cdot 5\% = 98\text{ €} - 98\text{ €} \cdot 5\% \cong 93\text{ €} \qquad (3.2.6.6)$$

$$C_{VTGdiff(\max)} = C_{VTGdiff} + C_{VTGdiff} \cdot 5\% = 98\text{ €} - 98\text{ €} \cdot 5\% \cong 103\text{ €} \qquad (3.2.6.7)$$

Where:

- $C_{VTGdiff(\min)}$ – minimum cost difference of VTG turbocharger related to WG turbocharger [€]
- $C_{VTGdiff(\max)}$ – maximum cost difference of VTG turbocharger related to WG turbocharger [€]
- $C_{VTGdiff}$ – cost difference of VTG turbocharger related to WG turbocharger [€]

It means that the cost of the new VTG turbocharger will be between 93 € - 103 €. This cost must be added to the overall cost of the base engine, together with the costs of other new components.

Based on this example, the following table contains the costs of new engine components:

Base engine technical solution	New variant technical solution	Cost increase / decrease	Average cost	Minimum costs	Maximum costs
With VVT	without VVT	-4,8%	-75 €	-71 €	-78 €
	with VVT	-	-	-	-
Without VVL	without VVL	-	-	-	-
	with VVL	8,8%	137 €	130 €	144 €
Without EGR	without EGR	-	-	-	-
	with EGR	6,0%	94 €	89 €	98 €
Intake port Injection	Intake port Injection	-3,4%	-53 €	-51 €	-56 €
	Direct Injection	-	-	-	-
Compression ratio 12	Compression ratio: (+2)	2,0%	31 €	29 €	32 €
Without electrification	without electrification	-	-	-	-
	P0: Belt Starter Generator (BSG) 12V	22,3%	346 €	329 €	363 €
	P0: BSG 48V 10 kW	34,4%	533 €	506 €	559 €
	P1: ISG 48V 10 kW	41,8%	648 €	616 €	680 €
	P1: Side mounted 48V 10 kW	39,2%	607 €	577 €	637 €
	P2: Coaxial 48V 20 kW	77,9%	1.208 €	1.148 €	1.269 €
	P2: Side mounted 48V 20 kW	73,0%	1.132 €	1.075 €	1.188 €
	P4: 20 kW and P0: 48V 5 kW	60,6%	939 €	892 €	986 €
	P2: 450V 40 kW	240,5%	3.728 €	3.541 €	3.914 €

	Dedicated hybrid transmission 70 kW	130,0%	2.015 €	1.914 €	2.115 €
	P2: 100 kW	345,7%	5.359 €	5.091 €	5.627 €
	P0 & P4: 100 kW	351,2%	5.444 €	5.172 €	5.716 €
Mechanical Water Pump	Mech Water Pump	-	-	-	-
	Electric Water Pump 12V	1,6%	24 €	23 €	25 €
	Electric Water Pump 48V	1,9%	29 €	28 €	31 €
Mechanical Vacuum Pump	Mech Vacuum Pump	-	-	-	-
	Electric Vacuum Pump 12V	1,3%	19 €	18 €	20 €
	Electric Vacuum Pump 48V	1,6%	24 €	23 €	25 €
Mechanical Oil Pump	Mech Oil Pump	-	-	-	-
	Electric Oil Pump 12V	1,6%	24 €	23 €	25 €
	Electric Oil Pump 48V	1,9%	29 €	28 €	31 €
Standard ignition	Standard ignition	-	-	-	-
	High frequency ignition	3,1%	48 €	46 €	51 €
	Plasma ignition	3,0%	46 €	44 €	49 €
	Pre-chamber ignition	3,1%	48 €	46 €	50 €
WG turbocharger	VTG turbocharger	6,3%	98 €	93 €	103 €
	WG turbocharger	-	-	-	-
	Electrified TC	8,0%	125 €	118 €	131 €
	without TC	-15,5%	-241 €	-229 €	-253 €

Table 16: New powertrain component costs

The applied technical solutions are highlighted with green letter colour. All the measures, which are contained by Table 16, are rounded, as high accuracy would not make sense in such an early phase of the development.

The requirement of the representative AVL project is the following:

A comprehensive comparison must be made among powertrains, containing different technical solutions to have an overview about component costs and their impact on fuel consumption, taking the standards of the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) cycle into consideration.

At this point, the potential future design of powertrains must be considered, to provide the most suitable solutions for the car manufacturer. The following diagram represents an estimated forecast about the different ICE technical solutions, which can be applied to reduce the overall fuel consumption. This is highly important for cost engineers, as based on this prediction, they can foresee and offer the technology to be applied, already in the very first stages of customer discussions.

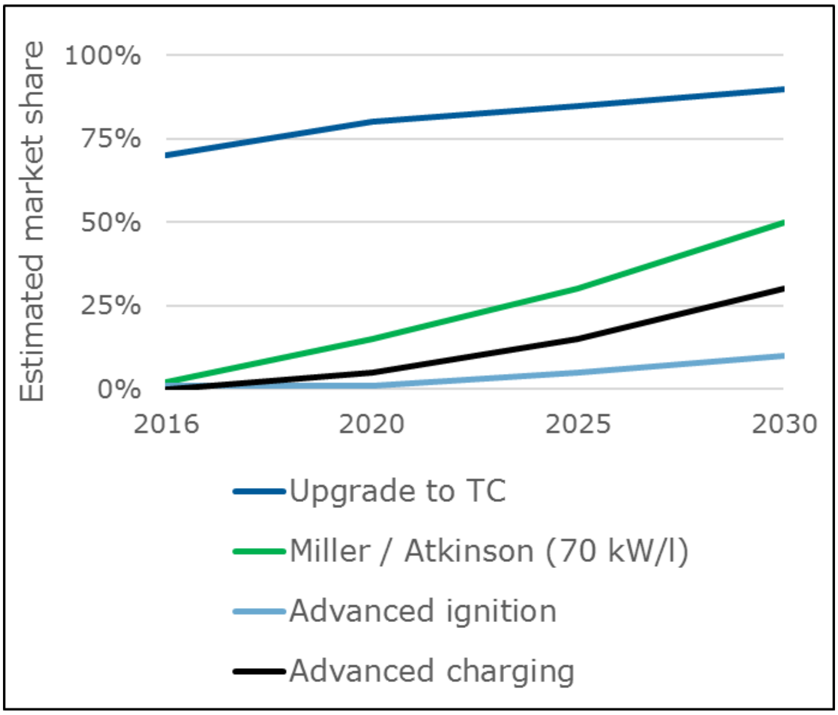

Figure 31: Estimated market share of ICE fuel consumption reducing technical solutions[126]

The figure let us draw the following conclusions:[127]

- Generally, upcoming RDE legislation will have a major impact on the future technology distribution as well as the complexity and cost of the technical realizations.

[126] Derived from Schoeffmann et al. (2019a), p. 5; Prevedel et al. (2019), p. 8; Grebe/Rothbart (2019), p. 9; Interview with person F from PTE business unit, date: 29.04.2019
[127] Ibidem

- Miller and Atkinson tend to become widespread technology for most segments as they offer a very good ratio between fuel consumption improvements and cost to be invested.
- Advanced engine charging and ignition will follow this trend to further improve efficiency.
- In larger vehicle segments such as D and E generally the highest willingness to invest more into advanced technology features is expected.

In the election of the necessary technical solutions not only the predicted market share estimation plays an important role, but also their costs and benefits. The following figure represents these values for each ICE technologies.

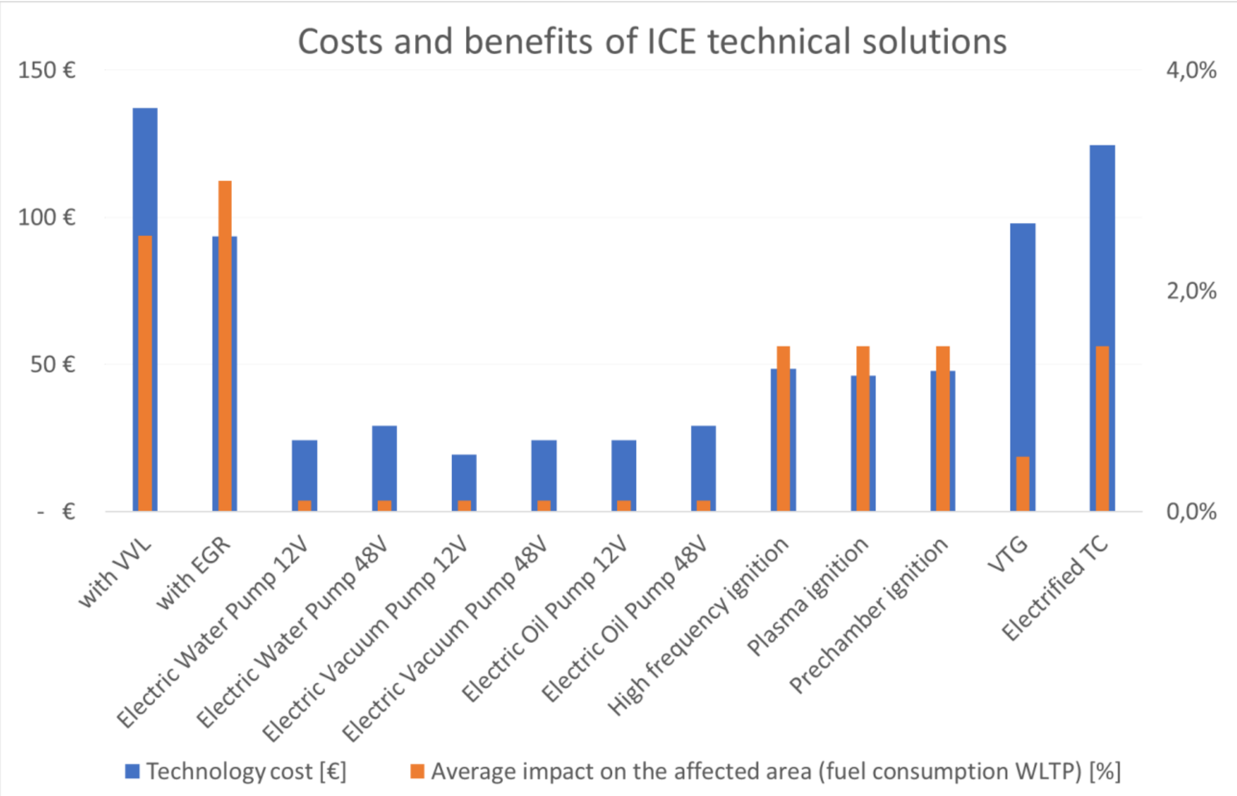

Figure 32: Costs and benefits of fuel consumption reduction technologies[128]

It can be seen that with the application of common technologies, the fuel consumption of the engine can be made more favorable with only a minor investment. Unfortunately, advanced ignition technologies, and electrified turbocharger are under further development, and the customer do not want to risk a delay in its powertrain development or any uncertainties in the field of reliability. For this reason, these technologies will not be considered during the project.

[128] Own figure, based on various neutralized AVL projects; Brendel et al. (2018), p. 8 et seq.; Pels et al. (2018), p. 3 et seq.; Schöffmann (2019b), p. 46 et seq.; and Table 16

Based on the assumptions of future market share of technologies, the OEM provided gasoline engine was extended with the following technical solutions:

Standard variant	New variant	Average cost increase / decrease	Ave-rage cost	Average impact on the affected area	Affected power-train area
without VVL	with VVL	8,8%	137 €	XXX%	Valvetrain
without EGR	with EGR	6,0%	94 €	XXX%	Exhaust System
Compres-sion ratio: 12	Compres-sion ratio: (+2)	2,0%	31 €	XXX%	Engine Structure
Mech. Water Pump	Electric Water Pump 12V	1,6%	24 €	XXX%	Engine Cooling System
Mech. Vacuum Pump	Electric Vacuum Pump 12V	1,3%	19 €	XXX%	Vehicle Vacuum System
Mech. Oil Pump	Electric Oil Pump 12V	1,6%	24 €	XXX%	Engine Lubricating System
WG-TC	VTG-TC	6,3%	98 €	XXX%	Charging System
Results					
Average cost increase / decrease in %		**27,6%**			
Average cost increase / decrease in €			**427 €**		
Average impact on the affected area (fuel consumption % WLTP)				**10,3%**	
Final powertrain cost					**4917 €**

Table 17: Sum of applied technology costs in the new engine variant

Overall powertrain cost:

$$C_{ICEPT} = CBe_{REF} + C_{Add.E} + C_{incr.ICE} = \\ = 1550\ € + 2940\ € + 427\ € = 4917\ € \qquad (3.2.6.8)$$

Where:

- C_{ICEPT} – overall cost of the gasoline driven powertrain with fuel consumption reductive technologies [€]
- CBe_{REF} – reference base engine cost [€]
- $C_{Add.E}$ – cost of additional powertrain equipment [€]
- $C_{incr.ICE}$ – average engine cost increase / decrease [€]

This means that the overall cost of a gasoline engine driven powertrain in a D-SUV segment vehicle with fuel consumption reduction technologies would cost **4671 € – 5163 €** with the 5% tolerance.

Powertrain electrification:

As next, the forecast of market share of electrified powertrains in the D-SUV segment is considered to serve as a basis for offering the right hybrid system for the customer.

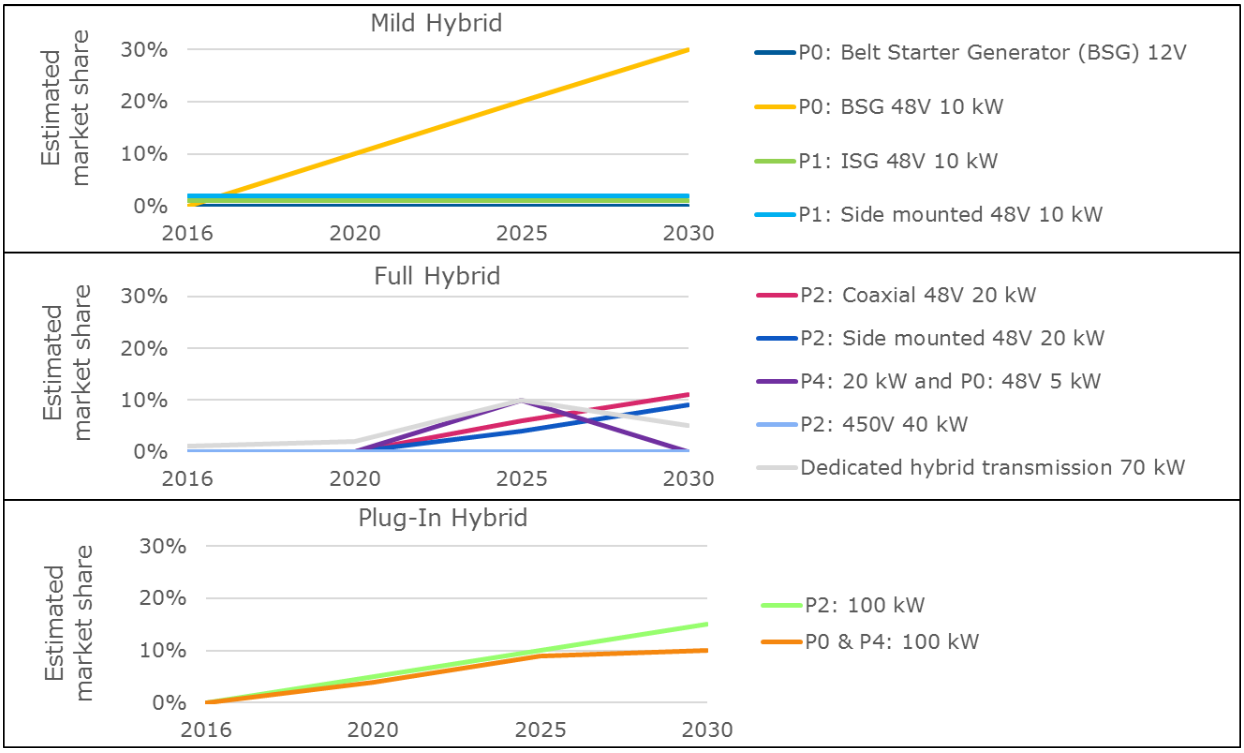

Figure 33: Forecast of electrified powertrain systems in D-SUV segment[129]

[129] Derived from Grebe/Rothbart (2019), p. 14; Schoeffmann et al. (2019b), p. 5; Brendel et al. (2018), p. 8 et seq.; Interview with person F from PTE business unit, date: 29.04.2019

As in case of ICE technologies, the costs and benefits of hybrid technologies are considered again.

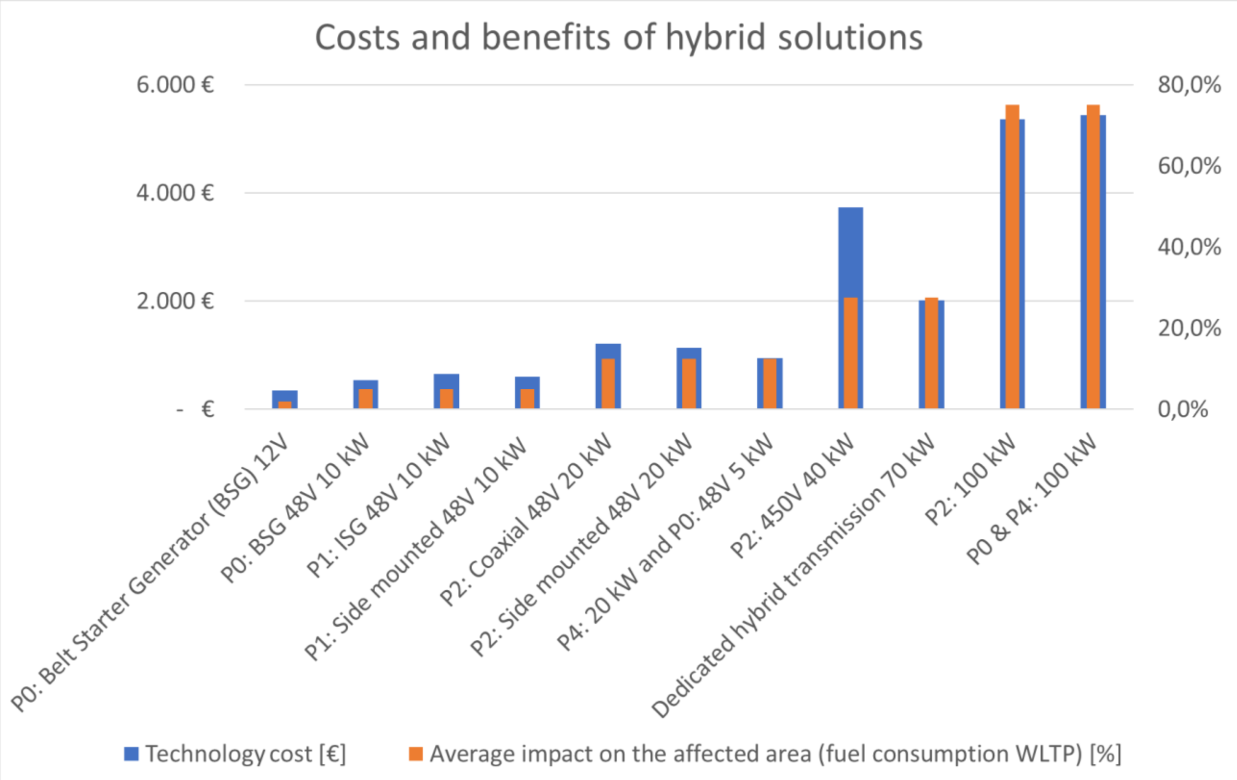

Figure 34: Costs and benefits of hybrid systems[130]

Based on the estimated market share and costs and benefits diagram, it can be concluded that among mild hybrid configurations the ´P0: BSG 48 V 10 kW´ variant seems to be promising, because the technology was predicted to have a higher market share in the D-SUV segment, furthermore its benefit is the highest among mild hybrid variants.

From the range of full hybrid systems, ´P2: Coaxial 48V 20 kW´ turned to be the most adequate to apply, because according to the estimated market share it is showing a continuously growing tendency for application.

On the diagram of estimated market share, both of the plug-in hybrid technologies are pointing upwards, however the relatively low complexity made the ´P2: 100 kW´ module the best choice.

[130] Own figure, based on various neutralized AVL projects; Brendel et al. (2018), p. 8 et seq.; Pels et al. (2018), p. 3 et seq.; and Table 16

To sum it up, the following electrified powertrain configurations will be offered for the customer with their costs and impact on fuel consumption:

- base gasoline engine with extended technical solutions and a P0: BSG 48V 10 kW mild hybrid system
- base gasoline engine with extended technical solutions and a P2: Coaxial 48V 20 kW full hybrid system
- base gasoline engine with extended technical solutions and a P2: 100 kW plug-in hybrid system

In the followings, the summary of overall powertrain costs will be represented. It must be remarked that the cost of all additional powertrain equipment, which is needed for electrification, are involved by the final powertrain cost. The voltage of electric parts, such as oil- vacuum- and water pump must be changed depending on the voltage of the alternative propulsion system. Besides these, ICE technologies are the same for all electrified system. Some values are hided due to confidentiality reasons.

P0: BSG 48 V 10 kW mild hybrid powertrain costs:

Standard variant	**New variant**	**Average cost increase / decrease**	**Ave-rage cost**	**Average impact on the affected area**	**Affected power-train area**
without VVL	with VVL	8,8%	137 €	XXX%	Valvetrain
without EGR	with EGR	6,0%	94 €	XXX%	Exhaust System
Compres-sion ratio: 12	Compres-sion ratio: (+2)	2,0%	31 €	XXX%	Engine Structure
Mech. Water Pump	Electric Water Pump 48V	1,9%	29 €	XXX%	Engine Cooling System
Mech. Vacuum Pump	Electric Vacuum Pump 48V	1,6%	24 €	XXX%	Vehicle Vacuum System
Mech. Oil Pump	Electric Oil Pump 48V	1,9%	29 €	XXX%	Engine Lubricating System
WG-TC	VTG-TC	6,3%	98 €	XXX%	Charging System

Without electrifi-cation	P0: BSG 48 V 10 kW	34,4%	533 €	XXX%	Trans-mission
Results					
Average cost increase / decrease in %		**62,9%**			
Average cost increase / decrease in €			**974 €**		
Average impact on the affected area (fuel consumption % WLTP)				**15,3%**	
Final powertrain cost					**5464 €**

Table 18: Sum of applied technology costs in the P0: BSG 48 V 10 kW mild hybrid powertrain

Overall powertrain costs:

$$C_{P0\,BSGPT} = CBe_{REF} + C_{Add.E} + C_{incr.P0\,BSG} = \\ = 1550\,€ + 2940\,€ + 974\,€ = 5464\,€ \tag{3.2.6.9}$$

Where:

- $C_{P0\,BSGPT}$ – overall cost of the gasoline driven powertrain with fuel consumption reductive technologies, extended with a P0: BSG 48 V 10 kW mild hybrid system [€]
- CBe_{REF} – reference base engine cost [€]
- $C_{Add.E}$ – cost of additional powertrain equipment [€]
- $C_{incr.P0\,BSG}$ – average engine cost increase / decrease extended with a P0: BSG 48 V 10 kW mild hybrid system [€]

This means that the overall cost of a gasoline engine driven powertrain in a D-SUV segment vehicle with fuel consumption reduction technologies and electrification would cost **5191 € – 5738 €** with the 5% tolerance.

P2: Coaxial 48V 20 kW full hybrid powertrain costs:

Standard variant	New variant	Average cost increase / decrease	Ave-rage cost	Average impact on the affected area	Affected power-train area
without VVL	with VVL	8,8%	137 €	XXX%	Valvetrain
without EGR	with EGR	6,0%	94 €	XXX%	Exhaust System
Compres-sion ratio: 12	Compres-sion ratio: (+2)	2,0%	31 €	XXX%	Engine Structure
Mech. Water Pump	Electric Water Pump 48V	1,9%	29 €	XXX%	Engine Cooling System
Mech. Vacuum Pump	Electric Vacuum Pump 48V	1,6%	24 €	XXX%	Vehicle Vacuum System
Mech. Oil Pump	Electric Oil Pump 48V	1,9%	29 €	XXX%	Engine Lubricating System
WG-TC	VTG-TC	6,3%	98 €	XXX%	Charging System
Without electrifi-cation	P2: Coaxial 48V 20 kW	77,9%	1208 €	XXX%	Trans-mission
Results					
Average cost increase / decrease in %		**106,4%**			
Average cost increase / decrease in €			**1650 €**		
Average impact on the affected area (fuel consumption % WLTP)				**22,8%**	
Final powertrain cost					**6140 €**

Table 19: Sum of applied technology costs in the P2: Coaxial 48V 20 kW full hybrid powertrain

Overall powertrain costs:

$$C_{P2\,CoaxialPT} = CBe_{REF} + C_{Add.E} + C_{incr.P2\,Coaxial} = 1550\text{ €} + 2940\text{ €} + 1650\text{ €} = 6140\text{ €} \qquad (3.2.6.10)$$

Where:

- $C_{P2\,CoaxialPT}$ – overall cost of the gasoline driven powertrain with fuel consumption reductive technologies, extended with a P2: Coaxial 48V 20 kW full hybrid system [€]
- CBe_{REF} – reference base engine cost [€]
- $C_{Add.E}$ – cost of additional powertrain equipment [€]
- $C_{incr.P2\,Coaxial}$ – average engine cost increase / decrease extended with a P2: Coaxial 48V 20 kW full hybrid system [€]

This means that the overall cost of a gasoline engine driven powertrain in a D-SUV segment vehicle with fuel consumption reduction technologies and electrification would cost **5833 € – 6447 €** with the 5% tolerance.

P2: 100 kW plug-in hybrid powertrain costs:

Standard variant	New variant	Average cost increase / decrease	Ave-rage cost	Average impact on the affected area	Affected power-train area
without VVL	with VVL	8,8%	137 €	XXX%	Valvetrain
without EGR	with EGR	6,0%	94 €	XXX%	Exhaust System
Compres-sion ratio: 12	Compres-sion ratio: (+2)	2,0%	31 €	XXX%	Engine Structure
Mech. Water Pump	Electric Water Pump 12V	1,6%	24 €	XXX%	Engine Cooling System
Mech. Vacuum Pump	Electric Vacuum Pump 12V	1,3%	19 €	XXX%	Vehicle Vacuum System
Mech. Oil Pump	Electric Oil Pump 12V	1,6%	24 €	XXX%	Engine Lubricating System
WG-TC	VTG-TC	6,3%	98 €	XXX%	Charging System

Without electri-fication	P2: 100 kW	345,7%	5359 €	XXX%	Trans-mission
Results					
Average cost increase / decrease in %		**373,3%**			
Average cost increase / decrease in €			**5786 €**		
Average impact on the affected area (fuel consumption % WLTP)				**75,0%**	
Final powertrain cost					**10276 €**

Table 20: Sum of applied technology costs in the P2: 100 kW plug-in hybrid powertrain

Overall powertrain costs:

$$C_{P2\ Plug-inPT} = CBe_{REF} + C_{Add.E} + C_{incr.P2\ Plug-in}$$
$$= 1550\ € + 2940\ € + 5786\ € = 10276\ € \quad (3.2.6.11)$$

Where:

- $C_{P2\ Plug-inPT}$ – overall cost of the gasoline driven powertrain with fuel consumption reductive technologies, extended with a P2: 100 kW plug-in hybrid system [€]
- CBe_{REF} – reference base engine cost [€]
- $C_{Add.E}$ – cost of additional powertrain equipment [€]
- $C_{incr.P2\ Plug-in}$ – average engine cost increase / decrease extended with a P2: 100 kW plug-in hybrid system [€]

This means that the overall cost of a gasoline engine driven powertrain in a D-SUV segment vehicle, with fuel consumption reduction technologies and electrification would cost **9762 € – 10790 €** with the 5% tolerance.

To conclude the results obtained, the following diagram represents the mean cost of each powertrain variant.

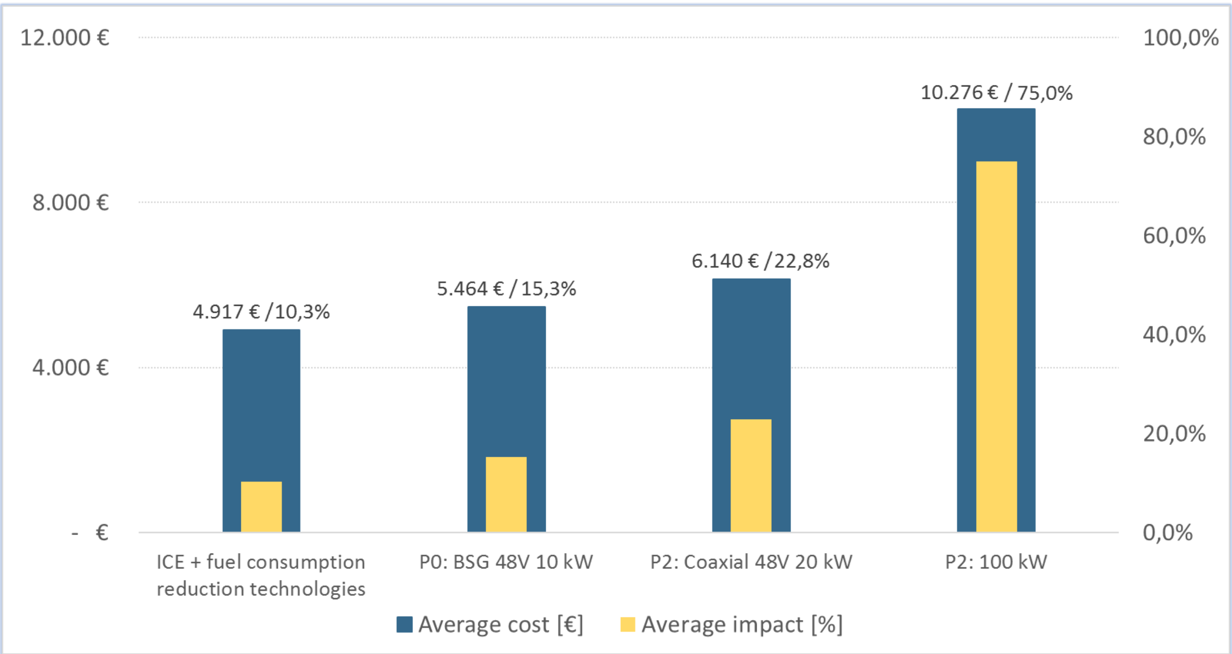

Figure 35: Cost comparison of powertrain variants

It can be clearly seen that the plug-in hybrid variant has the biggest impact on the fuel consumption, however its overall cost is the highest among all. On the other hand, it can be also recognized that the impact on fuel consumption is far the highest in case of the plug-in hybrid version. With the help of such a diagram the customer can have an overview about the most important aspects and can be supported in the decision-making process about the most suitable variant.

3.2.6.8 Evaluation of results

In the previous chapter, the principle of the approach was demonstrated with the help of the generated dataset. However, the authenticity of results obtained must be investigated, to prove the credibility of the whole approach.

During the progression of the thesis, the external project also reached a high maturity, which made it possible to compare the results obtained, with the results of the traditional cost estimation process. The details of the traditional calculation will not be discussed in the frames of this thesis, only the final costs of the involved powertrains are displayed. The following table and diagram represent the differences between the results.

	ICE + fuel consumption reduction technologies	P0: BSG 48 V 10 kW	P2: Coaxial 48 V 20 kW	P2: 100 kW
Thesis approach results	4.917 €	5.464 €	6.140 €	10.276 €
Traditional cost assessment results	4.750 €	5.320 €	5.950 €	8.810 €
Difference	***167 €***	***144 €***	***190 €***	***1.466 €***
Deviation	***3,4%***	***2,6%***	***3,1%***	***14,3%***

Table 21: Comparison of cost estimation results

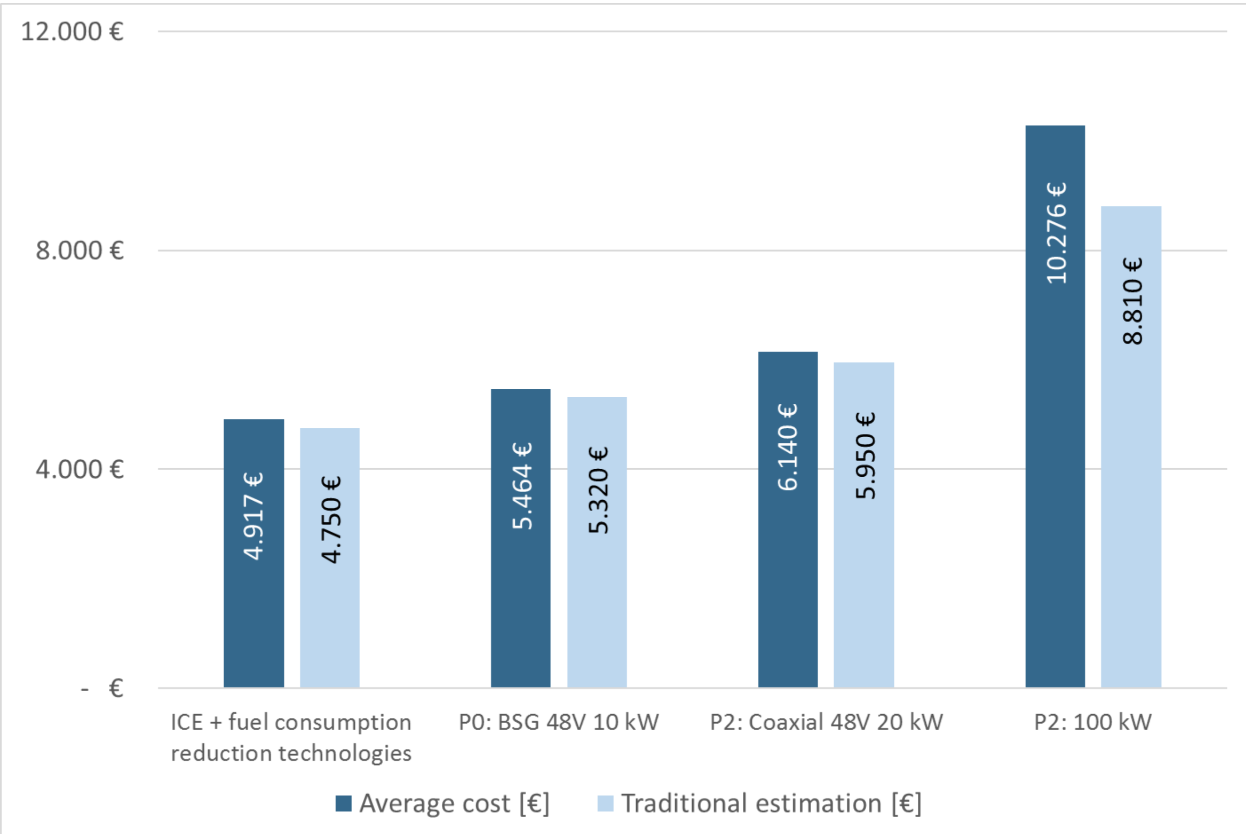

Figure 36: Comparison of cost estimation results

The interviewed experts in chapter 3.1.2.6, confirmed that the accuracy of the estimated costs is around 95%, if the minor technical solutions are decided. This means that the range of uncertainty is 5%, in other words, the deviation between the result of the implemented approach and the traditional cost estimation (in rough and fine estimation in the early development phase) must not be bigger than 5%. Based on Table 21 and Figure 36, besides the plug-in hybrid version, all powertrain variants are within this range. The explanation for this huge difference is that during the project, the stakeholder has changed its requirements and a powertrain with slightly different attributes was considered than in the generated dataset. The propulsion systems are differing in their power, especially instead of 100 kW, the output of the new version is only 80 kW. Another major difference which can be the reason for this huge contrast, is that in the external project some electrical powertrain components were not considered during the cost estimation.

This means that the plug-in hybrid powertrain must be excluded from the comparison, because its results are not relevant for proving the authenticity of the approach. However, it can be declared that all the results of the other powertrain systems are meeting the expectations and do not exceed the range of accuracy.

To sum it up, the authenticity of the approach is proved which means that it can be applied in the future as a very effective tool for cost engineers in the early development stage and can provide support when the technical expertise is not fully available.

4 Conclusion and Outlook

The result of the thesis provides an approach, which serves as a suggestion for an expert system, containing a comprehensive database about the existing technologies with their corresponding ´fields of improvement potential´ and ´improvement potentials´.

During the elaboration of the approach, a theoretical research was done on functions and cost engineering techniques to get an insight into their academical sense. Furthermore, an empirical research was conducted with AVL´s technical experts in the same topics, to observe their practical application too.

Based on the research information, it was realized that functions in their traditional interpretation cannot be used effectively in the cost assessment of powertrain elements. The reason for this was that they could not be connected unambiguously and directly with customer requirements and technical solutions so, that they would have created value in costing processes. For this reason, they were reformulated and stated as ´improvement potentials´ of certain technical solutions.

The final approach was demonstrated with the help of a reference external AVL project, in which the client´s main requirement was to reduce the fuel consumption of an existing ICE without changing its basic structure. It was also demanded to provide information regarding the cost and impact of all applicable technologies, furthermore a suggestion for the most beneficial powertrain configurations.

To make benefit from the already existing AVL ICE functional structures, improvement potentials of the ICE were revealed, which served as an excellent basis for collecting the corresponding, and currently available consumption reducing technologies. Afterwards, this dataset was inserted into an initial database, together with their estimated impact. Due to confidentiality reasons, a dataset was randomly generated, to be able to proof the concept.

In summary, the result is a demonstrating database in form of an Excel file, which can serve as a robust starting point for a follow-up project, in which the database will be extended and involved in an expert system, which considers all those suggestions that were described during the elaboration of the final approach.

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7 List of Figures

8 List of Tables

9 List of Abbreviations

AI	Artificial Intelligence
BEV	Battery Electric Vehicle
BMEP	Brake Mean Effective Pressure
BPNN	Back-Propagation Neural-Network
BSFC	Brake Specific Fuel Consumption
BSG	Belt Starter Generator
CE	Cost Engineering
CNG	Compressed Natural Gas
DOHC	Double Overhead Camshaft
DSS	Decision Support System
EGR	Exhaust Gas Recirculation
ETO	Engineer-to-Order
HEV	Hybrid Electric Vehicle
HV	High Voltage
ICE	Internal Combustion Engine
ISG	Integrated Starter Generator
ITS PA	ITS Person A
ITS PB	ITS Person B
ITS	Instrumentation and Test Systems
KBS	Knowledge-based System
KE	Knowledge Engineering
LOC	Lube Oil Consumption
OEM	Original Equipment Manufacturer
PCE	Product Cost Estimation
PD	Product Development
PoC	Proof of Concept
PTE PC	PTE Person C

PTE	Powertrain Engineering
PTO	Power Take-Off
RDE	Real Driving Emissions
RFLP	Requirement-Function-Logical-Physical
RPM	Revolutions per Minute
SE	Systems Engineering
SG&A	Selling, General and Administrational
SUV	Sport Utility Vehicle
SwE	Software Engineering
TC	Turbocharger
TCO	Total Cost of Ownership
VTG-TC	Variable Turbine Geometry Turbocharger
VVL	Variable Valve Lifting
VVT	Variable Valve Timing
WG-TC	Wastegate Turbocharger
WLTP	Worldwide Harmonized Light Vehicles Test Procedure