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Benchmarking of automotive engines for application on a flight engine

Master Thesis

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Graz, February 2017

Statutory Declaration

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

Graz, 22.02.2017

IVAN GRGIĆ

Acknowledgement

I would like to thank my parents for their support and their trust they´ve gave me during my studies. Without this special believe in me nothing would be possible.

Thank you so much.

Graz, 22.02.2017

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Abstract

This thesis, Benchmarking of automotive engines for application on a flight engine, deals with the practical application of the benchmarking method in a product-development project. BRP-Rotax is developing an aircraft engine that should have the largest cylinder displacement and the highest performance of the actual aircraft engine portfolio. Because the market is saturated for BRP-Rotax in the performance range of 80hp to 150hp, the company wants a 180hp engine with which to step into a new market. The development process of aircraft engines at BRP-Rotax consists of five steps, which are called P0, P1, P3, Pilot run and Certified Engine. This thesis contributes to the P0 level, as the aircraft engine has this status. Because the project is in the concept phase, the company wants to review the actual concept by executing a benchmarking study and comparing modern automotive engines with the aircraft engine. Because no certified aircraft engines have yet been developed in this performance range, automotive engines with the same cylinder arrangement as the aircraft engine are used for the benchmarking study. The goal is to find ideas for the improvement of the actual concept and thereby make a more compact and light weight engine possible.

The method of benchmarking provides the basis for the optimization of the aircraft engine. Therefore, the first part of this thesis describes the benchmarking method. The second part focuses on the practical part of the thesis. In this second part, the process of benchmarking, which was used to execute the project, is explained and applied to the flight engine.

After suitable automotive engines were obtained, they were disassembled. Every part was measured and documented. Because the project is also intended to set up a general procedure for benchmarking projects in the company, the parts were split into functional groups. The breakdown of the parts into these groups was done to fit most potential future benchmarking projects. Excel was used for the documentation because of its simplicity and ready availability in the company. The automotive engines were scaled to see what dimensions the engines would have if they used the same bore and hub as the aircraft engine. This step made it possible to compare all of the engines at the same level.

After the automotive engines were compared with the aircraft engine, a list of disadvantages was created. Every value in which the aircraft engine performed “worse”, was documented separately in this list. This list was used to discuss ideas for improvements with responsible engineers in the company for every engine compared. During meetings, in which ideas for improvements were discussed, it was found that one method of optimization could involve changing production standards in the production line of the company. Because standardized bearing lengths are currently used, the aircraft

engine is not built as compactly as it could be. But, it further need to be determined whether the advantages to be obtained by changing production standards are worth the costs.

Kurzfassung

Die Masterarbeit „Benchmarking of automotive engines for application on a flight engine“ behandelt die praktische Anwendung einer Benchmarking-Methode in einem Produktentwicklungsprojekt. BRP-Rotax entwickelt momentan einen Flugmotor, der im Vergleich zum aktuellen Flugmotor-Portfolio den größten Hubraum und die größte Leistung haben soll. Da der Markt für die aktuellen Flugmotoren von 80-150PS für BRP-Rotax gesättigt ist, soll der neu entwickelte Flugmotor mit 180PS einen neuen Markt erschließen. Der Entwicklungsprozess von Flugmotoren besteht bei BRP-Rotax aus fünf Stufen, die P0, P1, P3, Pilot run und Certified Engine genannt werden. Weil sich das Projekt noch in der Konzeptphase (P0) befindet, will BRP-Rotax das aktuelle Konzept mittels einer Benchmarking-Studie überprüfen lassen, die den Flugmotor mit modernen Automobilmotoren vergleicht. Weil es momentan generell keine neu zertifizierten Flugmotoren in dieser Leistungsklasse gibt, werden für die Studie Automobilmotoren mit demselben Bauprinzip wie der Flugmotor verwendet. Das Ziel der Arbeit ist, Ideen für Verbesserungs- und Optimierungsmöglichkeiten für den Flugmotor zu finden, um eine kompaktere und leichtere Bauweise zu ermöglichen.

Die Benchmarking-Methode beschreibt die Basis für die Optimierung des Flugmotors. Der erste Teil der Arbeit beschreibt die Methode ausführlich, der zweite Teil beschäftigt sich mit der praktischen Anwendung des Benchmarking-Prozesses am ausgewählten Flugmotor.

Nach dem Erwerb passenden Automobilmotoren für die Studie, werden sie zerlegt. Jedes Bauteil wird vermessen und dokumentiert. Da dieses Projekt auch ein generelles Prozedere für Benchmarking-Projekte im Unternehmen entwickeln soll, werden die Bauteile in Gruppen geteilt und mittels Excel-Tabelle dokumentiert. Die Art der Unterteilung der Bauteile in Gruppen wird so gewählt, um den potentiellen zukünftigen Benchmarking-Projekten im Unternehmen zu genügen. Die Excel-Tabelle wird aufgrund ihrer einfachen Handhabung und ihrer generellen Verfügbarkeit im Unternehmen als Dokumentationstool verwendet. Alle Motoren werden in die gleichen Kategorien unterteilt und die Automobilmotoren werden zusätzlich skaliert. Diese Skalierung ist nötig um zu sehen, welche Dimensionen die Motoren hätten, wenn sie denselben Kolbendurchmesser und Hub wie der zu untersuchende Flugmotor verwenden würden. Dieser Schritt ist nötig, um alle Motoren miteinander vergleichen zu können.

Nachdem der Vergleich der Automobilmotoren mit dem Flugmotor abgeschlossen ist, werden die Abweichungen zueinander in einer Liste dokumentiert. Jedes Bauteil, bei dem der Flugmotor schlechtere Werte aufwies, wird separat in einer Liste dokumentiert. Diese Liste wird in weiterer Folge verwendet, um mit den verantwortlichen Ingenieuren

Verbesserungsvorschläge zu generieren. Während diverser Meetings, in denen mögliche Verbesserungen besprochen wurden, wurde festgestellt, dass der Flugmotor unter anderem durch die Änderung von Produktionsstandards optimiert werden kann. Das aktuelle Verwenden standardisierter Lagerlängen in der Produktionslinie verhindert eine kompaktere Bauweise des Flugmotors.

Es ist in weiterer Folge zu untersuchen, ob der potentielle Vorteil einer kompakteren Bauweise die Kosten rechtfertigt, die infolge einer Änderung der Produktionsstandards entstehen würden.

Table of Contents

1 Introduction

This thesis was done in cooperation with BRP-Rotax and was supported by the Institute of Innovation and Industrial Management (IBL).

After a description of BRP-Rotax, the initial situation is described. In the initial situation, the motivation of the company for wanting such a thesis is explained. This is followed by a description of the goals of the project, which ends with an explanation of the approach.

1.1 The company – BRP-Rotax

BRP-Rotax GmbH & Co KG is a subsidiary company of Bombardier Recreational Products Inc. (BRP). BRP split off from the parent company, Bombardier, in 2003. BRP is the market leader in the development, production and sale of motorised hobby vehicles. The products BRP offers include the following: snowmobiles (SKI-DOO, LYNX), roadster´s (CAN-AM), jet boats (SEA-DOO), side-by-side-vehicles (CAN-AM), outboard engines (EVINRUDE) and ATV´s (CAN-AM).[1]

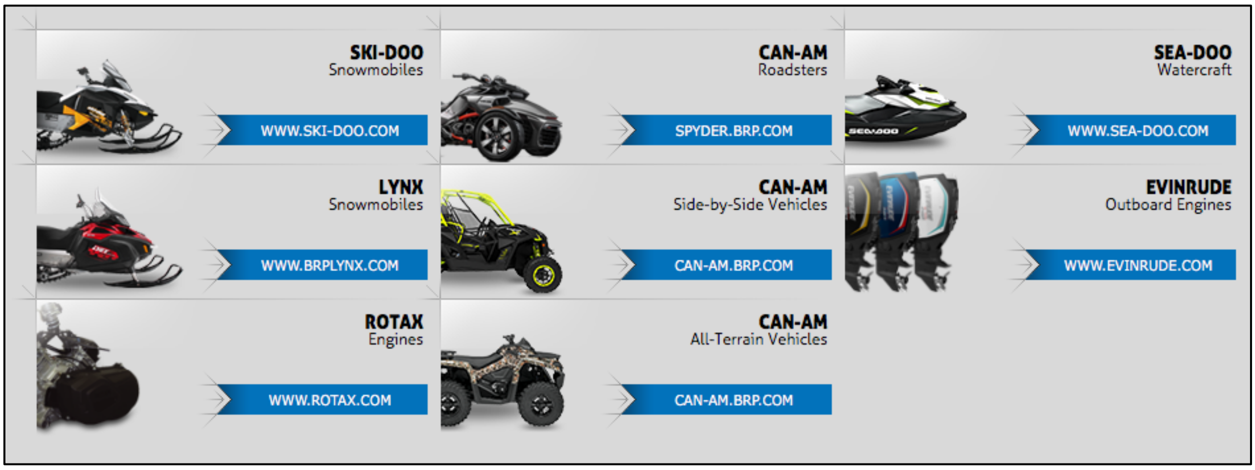

Fig. 1: BRP Products[2]

BRP-Rotax GmbH & Co KG is located in Gunskirchen, Upper Austria, and is specialized in the development and production of driving systems for the power sport branch. It is also responsible for the world-wide development of Rotax engines. These engines are

[1] Cf. http://www.brp.com/de-de, date of access: 15.09.2016

[2] Ibidem

installed in products such as SKI-DOOs, LYNXs, CAN-AMs, SEA-DOOs, Motorcycles, Karts and Light- and Ultralight Aircraft Engines.[3]

BRP-Rotax is located on three continents. In Europe, BRP-Rotax is located in Gunskirchen. In North America, BRP Mexico S.A. de C.V. is located in Querétaro, Mexico. In Asia, BRP Asia LTD. is located in Hong Kong.[4]

Fig. 2: BRP-Rotax in Gunskirchen, Upper Austria[5]

The history of BRP-Rotax in Gunskirchen begins in 1920 with the foundation of the so-called “Rotax-Werk AG” in Dresden, Germany. In 1930, the company was taken over from “Fichtel & Sachs AG” and the location moved from Dresden to Schweinfurt. After another movement, this time in another country, the company moved to Wels, Austria in 1943. In 1947 the company moved again. This time they stayed in the same city but moved to another part of it: Gunskirchen. Since the movement to Gunskirchen, new engines have been developed every year or more with the result that the portfolio of BRP-Rotax rose. In 1970, the “Rotax-Werk AG” was taken over from Bombardier and the

[3] Cf. https://www.rotax.com/de/unternehmen/ueber-uns.html, date of access: 15.09.2016

[4] Ibidem

[5] Cf. https://www.rotax.com/de/unternehmen/ueber-uns.html, date of access: 14.09.2016

official name was changed to “Bombardier-Rotax GmbH”. After the split of BRP from Bombardier in 2003, Rotax became part of BRP Inc.[6]

Of the 1100 employees who work at BRP-Rotax in Gunskirchen, only 50 work on aircraft engines. The reason so few people are connected with aircraft specific engines is that BRP sells more of other leisure products than aircraft engines. Only 6% of the sales are generated by aircraft engines at BRP-Rotax.[7]

1.2 Initial situation

BRP-Rotax aircraft engines are well known for their outstanding performance and high reliability. The company also aims to have the best value in fuel consumption and exhaust emissions. The number of aircraft engines sold is more than impressive. More than 175,000 aircraft engines have been sold since 1973, and more than 50,000 are from the well-known 912/914 series.[8]

The actual market, in the performance range of 80hp to 150hp, is saturated for BRP-Rotax. This is why the company wants to step in a new market with a higher-performing engine. For this new market, a new Rotax aircraft engine should be developed. The engine should have a displacement of 2.0 litres and a performance of 180hp, which would make it the highest-performing aircraft engine Rotax has ever built. The actual 912, 914 and 915 aircraft engines are built for the light- and ultralight branch, which is designed to transport the pilot plus one passenger. The new engine, which should be named Aircraft Engine 2017 (AE2017), should be able to transport the pilot and three passengers.

To successfully enter this new market, BRP-Rotax performed a market study. In this study, they calculated the size of the potential market and how many engines they would be able to sell. Also, the break-even point was calculated.

These facts and figures keep the motivation for inventing such an engine very high. BRP-Rotax envisions that the AE2017 will be the best in its class and that BRP-Rotax will again reach the status of market leader with the AE2017.

1.3 Goals and tasks of the benchmarking study

This thesis should determine how the actual concept of the AE2017 can be improved by use of the benchmarking method. To reach this goal the right benchmarking type must to

[6] Cf. https://www.rotax.com/de/unternehmen/geschichte.html, date of access: 15.09.2016

[7] Cf. Borchert (2013) pp. 88ff.

[8] Cf. https://www.rotax.com/de/produkte/rotax-flug.html, date of access: 16.09.2016

be investigated, as different types have different requirements. In this case, a combination of product benchmarking (Chapter 2.5.1) and branch independent benchmarking is chosen because of the comparison of similar products from different branches.

Because the European Aviation Safety Agency (EASA) hasn´t received new standards in recent years for the certification of high-performance, light aircraft Otto-Engines, other similar engines should be found for comparison. To realize the vision of building the smallest and lightest aircraft engine in the 180hp segment, the state-of-the-art technology of automotive engines should be compared with the concept for the AE2017, as these engines are very similar to combustion aircraft engines. During this comparison, potential performance gaps should be documented and discussed to provide the future project team with this information.

Summary of goals and tasks:

- Development of a benchmarking documentation tool
- Disassembly of chosen engines and documentation of them
- Comparison of automotive engines with AE2017
- Determination of improvements for AE2017

1.4 Approach

A plan for the approach of the project was set on March of 2016. Within this plan, the project begins with an analysis of literature on the benchmarking method. The method is to be studied briefly to gain knowledge about what it represents and how it proceeds. This step is to be followed by the obtaining of potential automotive engines for comparison. For these engines, the most important criterion is the order of the cylinders. Only Boxer-engines should be investigated, because the AE2017 has the same building principle. Focusing on the building principle makes the engines more comparable and thereby renders the benchmarking study more significant. Therefore, BRP-Rotax has chosen three automotive engines from three different automobile manufactures which are well known for their boxer engines. These are Porsche, Subaru and Alfa Romeo.

For the process of comparing the aircraft engine and the automotive engines, the parts in which BRP-Rotax is interested for comparison are split into groups.

The groups of scaled automotive engines are then to be directly compared with the AE2017 so that a positive/negative-list can be contrived. At the end of the project, the negative aspects relative to every benchmarked automotive engine are to be discussed. Reasons for these gaps are to be found and requirements for improvements are to be set.

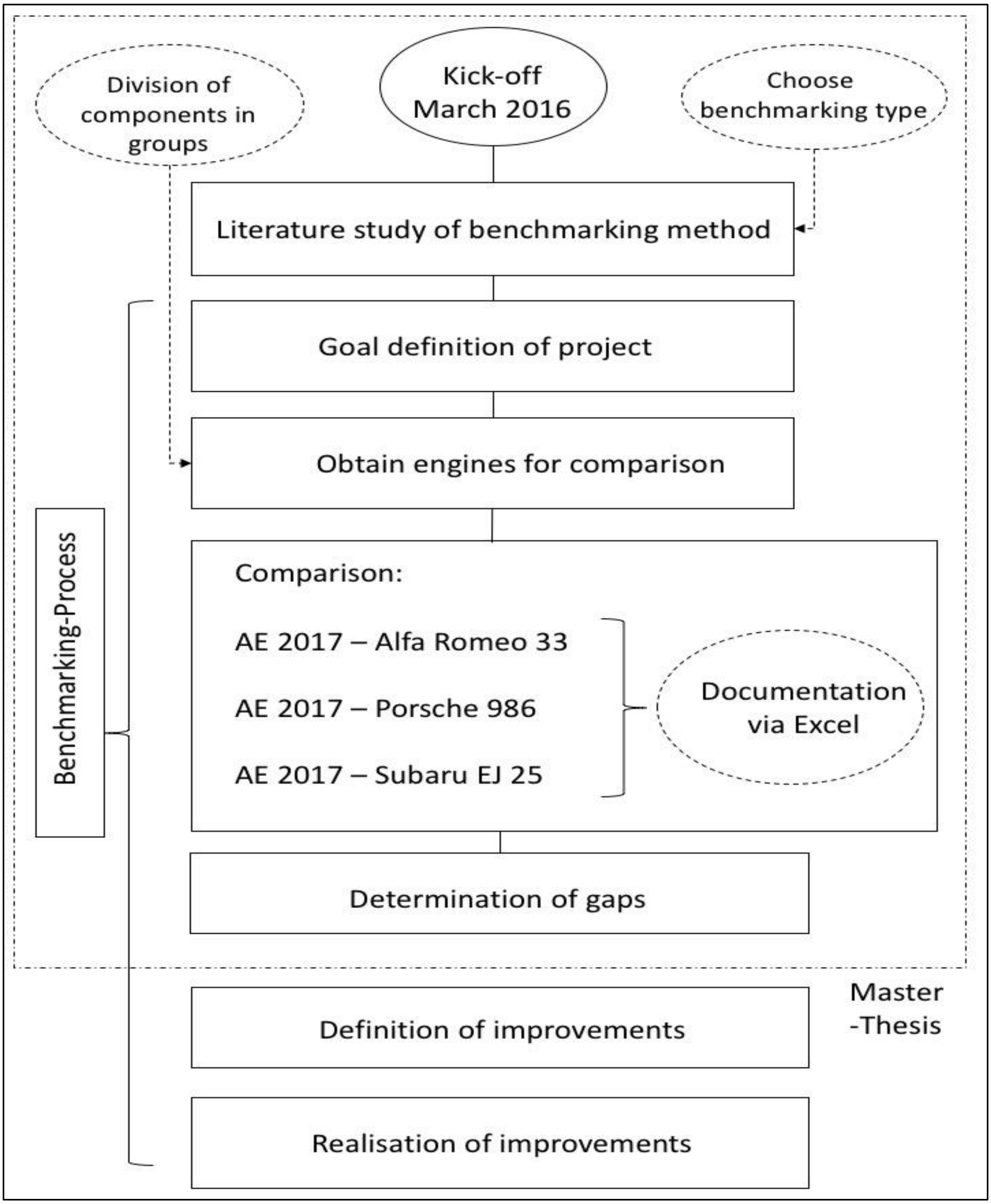

Fig. 3: Approach of thesis[9]

[9] Own illustration

2 The method of benchmarking

This chapter summarizes benchmarking as it is discussed in the literature. The chapter discusses where the term benchmarking comes from and how it is defined, and it discusses the overall goal or target of benchmarking. Different benchmarking methods are described with the aim of determining which method is best for this study. The benchmark process itself is described, and its description is followed by reflecting on the topic from a critical point of view.

2.1 **Development of benchmarking**

This chapter consider the term benchmarking from an historical point of view. It is explained where this method comes from and how it was transferred and implemented as a management tool.

2.1.1 History of benchmarking

The term *benchmark* comes from the surveying sector. It means a surveying point or mark from a predefined position. Benchmarks are used as reference points or standards against which something can be measured and evaluated.[10] *Benchmarking* is therefore a process or method for comparing values against a predefined scale or mark, which is the benchmark.[11]

For centuries, human beings have had two main principles of learning: “trial and error” or “learning by doing” and “learning by watching”. Learning by watching is the basic idea behind benchmarking. Watching the nature and deriving principles or formulas was one of the main tasks of scientists in the past and is today. At the beginning, the focus was on watching and investigating nature. With time, however, it became interesting to watch other humans and their principles. The basic idea behind this watching was always to win knowledge. For getting such knowledge, it is important to consider watching and learning from the right people. Only by watching better processes can knowledge be gained. This knowledge must be adapted and implemented if it is to yield advantage. Thousands of people use this principle every day—not only for business but also for private life -

[10] Cf. Camp (1994), p.15

[11] Cf. Sabisch & Tintelnot (1997), p.1

knowing that observed principles have been tested. The main difference in the benchmarking method is the strategic search for better processes.[12]

One of the best-known examples of the use of benchmarking principles is the invention of the band-conveyor process used in the automotive industry in 1916. Henry Ford became inspired by visiting a slaughterhouse. The hanged pig-half's moving from one work station to the next gave Henry Ford the idea to invent such a system for the production of cars. From this point on, cars were not manufactured at one location by all employees. Now, the working steps were split and different working steps were performed at different working places by different employees. After a period of time, because of this method, the number of cars produced rose significantly even as the price of the cars fell. So buying a car was no longer a privilege of the rich: the automobile became mainstream. By implementing the band-conveyor process after having observed it in a slaughterhouse, Henry Ford unwittingly tested the independent benchmarking method.[13]

To get the results and to implement the innovations Henry Ford did requires more than simple observing and imitating. The prevailing opinion concerning the great success of the Japanese economy in the 1960s is that the Japanese repeatedly copied management concepts and technologies from industrialized Western nations. But it is not that simple at all. The largest advantage the Japanese had was the ability not only to adapt learned methods and techniques but also to improve them. The Japanese never believed that simple imitation would make them competitive. They understood that new processes and methods they found had to be adapted to fit different conditions perfectly. This principle was the only way to get competitive advantage. For this reason, they started to search for best-practice methods and principles around the world, especially in the West, hoping to find transferable best-practice methods.[14]

2.1.2 Benchmarking introduced by Xerox

The term benchmarking first appeared in 1979. It was invented by the company Xerox along with the term *competitive benchmarking*.[15]

[12] Cf. Mertins/Kohl (2004a), pp.20–21

[13] Cf. Mertins/Kohl (2004a), p.22

[14] Cf. Mertins/Kohl (2004a), pp.22–23

[15] Cf. Camp (1989), p.6

Xerox is a company in the USA that was producing copiers at this time. They were very successful in the 1960s. Their profits jumped from 2.5 million USD in 1961 to 128 million USD in 1968.[16]

The introduction of the first benchmarking method was a necessity for Xerox despite the success and growth they enjoyed in the 1960s. In 1979, they found that Japanese competitors were selling copiers for less than Xerox could make them. Because of this, Xerox took a look at all of the copiers on the market and analysed them regarding production costs, design and other key indicators. Thus competitive benchmarking was born. With the results of the competitive benchmarking study, Xerox defined new company targets. By taking the results and adapting the new knowledge to the assembly department, Xerox succeeded. Because of the great success of the first benchmark study, Xerox management decided to use this special method in all departments of the company, starting in 1981. In the same year, by using the company L.L. Bean as a benchmarking partner, other benchmark projects were realized. This time Xerox wanted to see if they could achieve success upon comparing sector-independent departments. They focused on the company’s logistics and distribution departments. They succeeded again. With the investigation of sector-independent departments, they proved that benchmarking is not limited to the production department and that a benchmarking partner does not need to be from the same sector.[17]

2.1.3 Introduction of the first benchmarking institutions

Over time, the concept of benchmarking became more and more international. Single benchmarking projects in companies became more time and cost intensive. This fact led to the invention of benchmarking institutions. The institutions help companies by offering services that range from conducting complete benchmark projects to offering benchmark training. Choosing the right benchmark partner—i.e., finding the best possible process or product to learn from—is a core competence of such institutions.[18]

The first benchmarking institution was founded in 1992 by the American Productivity Quality Centre in the USA. It was named the International Benchmarking Clearinghouse (IBC). One year later, in 1993, the Strategic Planning Institute Council on benchmarking (SPIC) was also founded in the US. In the same year, the British benchmarking Centre was founded, which was followed by founders in the Scandinavian area. The first founding of a Benchmark Centre in a German-speaking area occurred in 1994, in Germany. The German industry and the “Frauenhofer Institut für Produktionsanlagen und

[16] Cf. Stapenhurst (2009), p.9

[17] Cf. Mertins/Kohl (2004a), pp.23–24

[18] Cf. Mertins/Kohl (2004a), pp.25–26

Konstruktiontechnik IPK-Berlin“ founded the “Informationszentrum Benchmarking (IZB)“.[19]

2.2 **Benchmarking in literature**

This chapter offers a clear definition of the term of benchmarking. It shows how this term is defined in literature and what its advantages are.

2.2.1 Definition of benchmarking

To be competitive on the global market, every company needs to constantly improve its performance. To become or stay a market leader, the products or services a company offers should differ from those of its competitors. Every product or service must have something unique and should be associated with the company that produces or offers them in a positive way. To implement these elementary principles, clearly defined company targets are not just needed, they are unavoidable. These targets can be defined satisfactorily by analysing internal and external needs and demands with the highest grade of accuracy. Only if there is knowledge of what is needed and where the strengths and weaknesses are can clear targets and satisfying products be defined or developed. Modern management methods like benchmarking make it possible not just to close the gap on market leaders but even to overrun them to become the new market leader.[20]

The specific method of comparing called benchmarking, was first named by Robert C. Camp, a manager at Xerox. He defined benchmarking as follows: [21]

“Benchmarking is the search for industry best practices that lead to superior performance.”

In the literature, the term *benchmarking* is defined differently.[22] The definitions mostly build on the work of Camp and Watson.[23] Watson defines benchmarking as follows: [24]

“A systematic and continuous evaluation process; a process where the sequences of a company are permanently compared and evaluated with the world´s leading companies, to get information’s, which help the company, to increase their performance.”

[19] Cf. Mertins/Kohl (2004a), p.26
[20] Cf. Sabitsch/Tintelnot (1997), p.11
[21] Cf. Camp (1989), p.12
[22] Cf. Anand/Kodali (2008), p.25; Cf. Spendolini (1992), p.21; Cf. Moriarty/Smallman (2009), p.485
[23] Cf. Hastreiter/Buck/Jehle. (2015), p.66
[24] Cf. Watson (1993), pp.223–224

The definition used in this thesis is taken from the German benchmarking centre called "Deutsches Benchmarking Zentrum (DBZ)": [25]

"Benchmarking is the methodical comparison of:

- Strategies
- Processes
- Organizational structures
- Products and services
- Performance indicators
- Methods, instruments and systems.

During benchmarking, a comparison is made with exchange partners that are considered superior. These comparison partners are found through analogies of their own or another organisation. The target of the benchmarking method is to increase performance through the example of the comparison partner."

Besides their differences, the definitions agree in treating benchmarking as a continuous process of measuring and comparing with best practices with the aim of implementing the improvements to achieve better performance.[26]

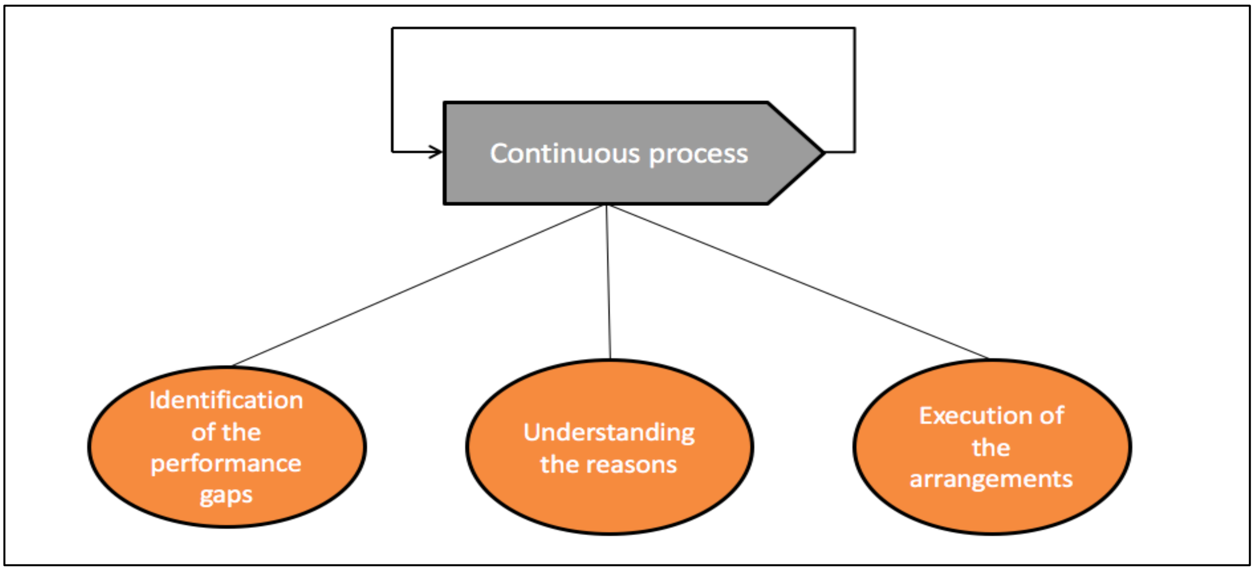

Fig. 4: Benchmarking as a continuous process[27]

Benchmarking can be summarized as a systematic search for transferable best-performance methods from different branches that results in implementation of adapted

[25] Cf. http://benchmarkingforum.de/benchmarking-wissen/benchmarking-grundlagen/, date of access: 11.07.2016

[26] Cf. Hastreiter/Buck/Jehle. (2015), p.66

[27] Cf. Hastreiter/Buck/Jehle (2015), p.67

solutions, in a new field. The main statement of this principle is that simple copying does not represent or replace the making of innovations.[28]

2.2.2 Advantages of benchmarking

One of the critical points of the benchmarking method is the clear evaluation of the benefits. This does not mean that it is critical to gain advantages with this method; it means that it is hard to measure advantages in a benchmarking project. The problem of effective measuring of the benefits is also described by Balm.[29] He connects this topic with return on investment (ROI), which is an important value for management to hold when planning investments. In the end, there is no absolute value where the effort and the benefits of a benchmark project can be measured. Knowledge of internal problems, with the combination of the appreciation of external solutions, makes benchmarking unavoidable.[30]

Balm describes this principle in his own words: [31]

"There is no absolute assurance. But can you afford not to do?"

In the literature, the general advantages of benchmarking can be summarized as follows:

- Self-analysis through a benchmarking project leads to the questioning of existing practices. If processes are recorded the first time by going through the value chain, the company is faced with unknown strengths and weaknesses.[32]
- Benchmarking is not only about identifying gaps in top performances. It also involves determining the procedures that lead to best performances.[33]
- The performances of the benchmarking partners are real values that represent real opportunities for the improvement of the company.[34]
- Benchmarking allows the integration from branch independent best practice methods in the investigated company processes or functions.[35]
- Benchmarking drives the motivation and training of employees. The implementation of the employees in the changing process and the division of responsibility on employees is raising the motivation and minimizing the fear of

[28] Cf. Mertins/Kohl (2004a), p.23
[29] Balm (1992), pp.38ff.
[30] Cf. Tucher (2000), p.85
[31] Balm (1992), p.38
[32] Cf. Leibfried/McNair (1993), p.31
[33] Cf. Camp (1994), p.160
[34] Cf. Tucher (2000), p.86
[35] Cf. Camp (1994), p.12

changes. By using the creativity of involved employees, the integration of best practices can be optimized. This creativity can lead to innovations.[36]

- Breaking of internal resistance over changes because of using methods and principles from other branches. Employees are more open to new ideas and processes if they come both from outside the company and from outside the branch.[37]
- Comparing a company's own processes with state-of-the-art technologies leads to a change in the corporate culture, which is based on changes and continuous improvements.[38]
- Benchmarking results in technological innovations that had not previously been noticed.[39]
- Benchmarking raises the personal values of a company's employees because it involves making professional contact with other companies that are the best in their branch.[40]
- With the collection and addition of external data concerning best-practice processes, a higher grade of objectivity is generated. Employees who generally focus on internal procedures often lack a sense of competition. With benchmarking, these employees learn how important competition is.[41]
- One of the largest benefits of benchmarking is that the products or processes that are investigated for comparison are already proven. The products chosen for the benchmark study are on the market, and the processes are implemented.[42]

To gain a good overview of the advantages offered by a process, it is best to categorize them. It is possible to categorize the advantages in terms of direct and indirect advantages. With direct advantages, concrete values can be compared. Indirect advantages involve finding reasons for differences. Camp uses another categorization of the benefits and splits the advantages into five categories. He states that the main advantages can be described by knowing the customer's needs, setting the right goals and targets, determining the actual productivity of the company, getting competitive and ensuring usage of best practices.[43]

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[36] Cf. Balm (1992), p.37; Cf. Zairi (1992), p.8
[37] Cf. Camp (1994), p.12
[38] Cf. Zairi (1992), p.8
[39] Cf. Camp (1994), p.12
[40] Cf. Camp (1994), p.12
[41] Cf. Hegele/Walgenbach (1999), p.14
[42] Cf. Mertins/Kohl (2004a), p.16
[43] Cf. Camp (1994), p.35

Without benchmarking	**With benchmarking**
Actual customer´s needs	
Based on past values	Based on actual market
Perception or intuition	Objective determination
Not high conformity of actual needs	High conformance of actual needs
Definition of goals and targets	
No focus on external values	Closer to reality
Reaction; not be the first	Action; proactive approach
Always behind the branch	Market leader
Determination of true measures of productivity	
Strengths/weaknesses not good known	Understanding process performances
Take route of least resistance	Best practices
Getting Competitiveness	
Internal point of view	Best understanding of competitors
Small, evolutional changes	Proven processes leads to new ideas
Best Practices	
“Not-invented-here” syndrome	Active search for changes
Small number of solutions	Large number of solutions and options
No large steps in terms of progress	Inventions and breakthroughs
Catch up to industry leaders	Set best performance

Table 1: Division of benchmarking advantages in groups[44]

[44] Cf. Camp (1989), pp.29–34; Cf. Boxwell (1994), p.15

To obtain the best possible results and highest profit from the listed advantages, every benchmarking project need to meet requirements. Only by considering these requirements satisfying results be reached.[45] These requirements are the following: [46]

- The team that conducts the benchmark study needs to be able to completely handle the benchmarking method. This means that they must have a clear understanding of the benchmarking method and have internalized the benchmarking principles.
- The benchmark team needs to know the product or process that is going to be investigated with all its advantages, disadvantages and key indicators.
- The company management must be the main driving force of a benchmark study. Hierarchical input is essential to clarifying the importance of the project. Every employee should appreciate this importance.
- The benchmark team must have enough time to execute the benchmark study; benchmark studies are not "by-the-way" projects.
- Changes must be implemented; the results of a benchmark study must be desired and accepted.

2.3 Benchmarking compared to other management methods

Besides benchmarking, there are several other management methods. This chapter discusses the most important alternatives and compares them to the benchmarking method. This should make it possible to differentiate the benchmarking method from other management tools.

2.3.1 Demarcation of benchmarking to existing management methods

Andrall Pearson of Harvard Business School, former CEO of Pepsi, once said, *"I´ll take solid execution over brilliant strategy any day."*[47] And Arthur Rock, the venture capitalist who helped companies like Apple and Intel said, *"Strategy is easy. Tactics are hard."*[48] Benchmarking is one of the tools that are used for tactics and execution. Therefore, it does not replace strategic planning but rather supports it.[49] Benchmarking is also not a method for reducing costs. Though cost reduction could occur—because many

[45] Cf. Mertins/Kohl (2004a), p.17
[46] Ibidem
[47] Boxwell (1994), p.14
[48] Rock (1987), p.63
[49] Cf. Rock (1987), p.14

departments and operations do not use best practices—benchmarking does not necessarily yield cost reduction.[50]

Benchmarking is not a remedy for actual solving of any kind of actual business problems or issues. It is more like a continuous management process that requires constant updating if it is to yield consistently satisfying results. Industry-best practices must influence decision making and communication at all levels of a company. The benchmarking process needs to be repeatable and adaptable and should continuously support employees with newest information about new methods and processes.[51]

2.3.2 Total Quality Management (TQM)

The vision of TQM is the total orientation on the quality target. This vision is built up of basic elements, including customer-orientation, process-orientation, employee-orientation, and prevention and constant improvement.[52]

The main goal of TQM is quality improvement. But quality is determined by customers. Therefore, customer satisfaction is one of the main goals of this method. This can be achieved by offering the highest possible level of quality by going through all phases of the value chain with customer satisfaction in mind.[53]

To execute the method, it is important to set organizational, personal and technical boundaries. The organizational boundaries involve splitting the company procedures into processes and sub-processes. High-quality targets can be reached by introducing self-performable test processes in which all employees and managers are asked to take responsibility for quality in their area of authority.[54]

Benchmarking is one of the most important elements in TQM. Burckhardt states that the function of benchmarking in TQM is to provide comparisons to companies that have best-practice methods in terms of quality and thereby to provide input concerning quality improvements for those companies.[55]

2.3.3 Kaizen

Kaizen refers to the permanent improvement of the status quo in small steps. To implement this philosophy on a daily basis, a process for continuous improvement and

[50] Cf. Camp (1989), p.14
[51] Cf. Camp (1989), pp.14–15
[52] Cf. Siebert/Kempf (2008), pp.24–25
[53] Cf. Töpfer/Mehdorn (1995b), pp. 8ff.
[54] Cf. Siebert/Kempf (2008), pp.24–25
[55] Cf. Burckhardt (1995), p.517

optimization must be generated that involves all employees.[56] Innovation, in contrast, refers to the drastic improvement of the status quo via the introduction of a new technology.[57]

By spreading responsibility for decision-making to a large number of employees, employee-empowerment is generated. This empowerment is the basis for the sustainable generation and implementation of ideas for continuous improvement, because employees from hierarchically lower positions have the power to make improvements to the system.[58]

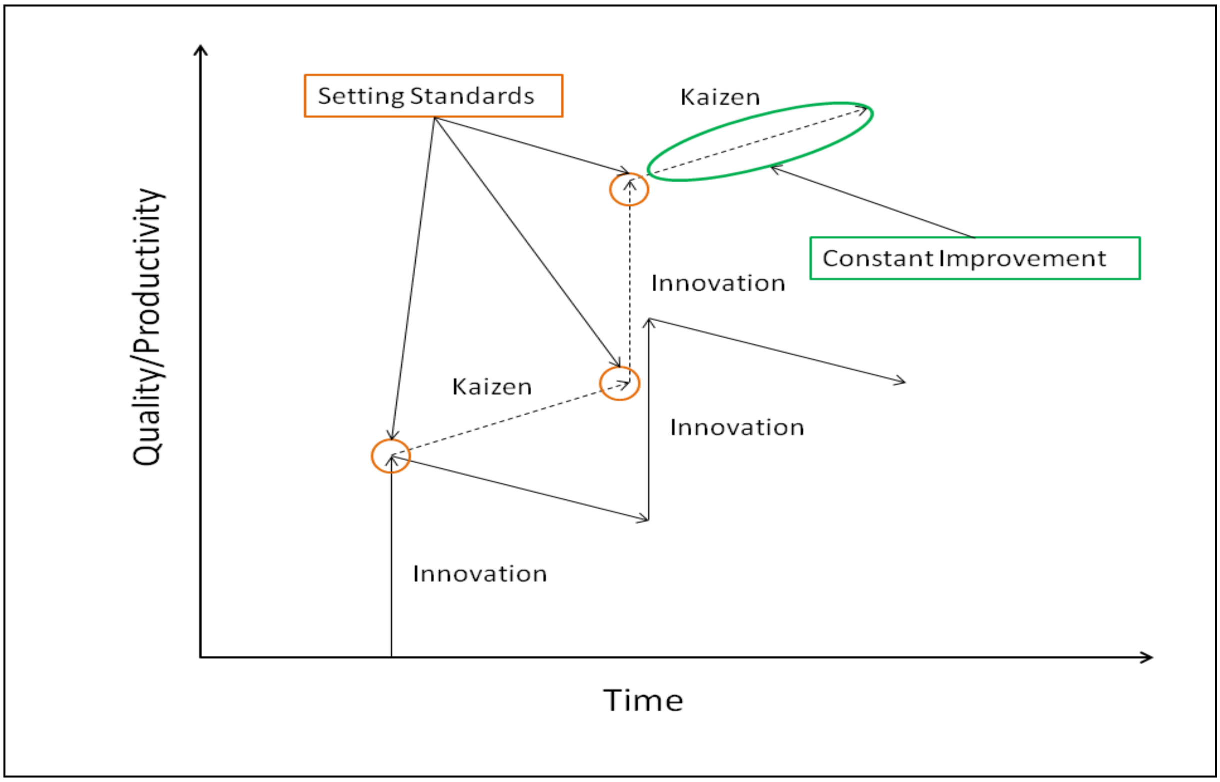

Fig. 5: Comparison/Combination of Kaizen and Innovation[59]

The mission of Kaizen is simple: let no day pass without improvement.[60] Because every employee has his or her own area responsibility and therefore his or her own place in the continuous-improvement process, everyday improvements can be set. Everyone must guarantee and control the quality of work. This can only be ensured if the employees are highly qualified and motivated.[61]

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[56] Cf. Imai (1992), pp.23–27

[57] Cf. Siebert/Kempf (2008), p.26

[58] Cf. Töpfer/Mann 1997, p.42

[59] Own illustration

[60] Cf. Siebert/Kempf (2008), p.26

[61] Cf. Töpfer/Mann (1997), p.42

To get desired results, Kaizen requires that employees and management are willing to improve. Improvements must be standardized to prevent them from being lost over time.[62]

The difference between benchmarking and Kaizen is that changes in Kaizen are executed in small steps whereas benchmarking forces more rapid changes. This is why benchmarking is more closely related to innovation than Kaizen. Kaizen therefore does not replace innovations.[63]

2.3.4 Reengineering

Reengineering involves the drastic reorganisation of the business processes in a company. It involves ignoring all the knowledge generated in the past to create a new structure for the business process that is more customer- and process-oriented.[64]

Reengineering should not be confused with restructuring, in which existing structures are optimized rather than built from scratch. Reengineering pursues the strategy of strategic reorientation oriented on its core competences. New procedures are developed that perform better and are more cost efficient and transparent.[65]

Hammer and Champy describe reengineering as a pack of activities.[66] These activities can have several different inputs, and their results have a value for the customer.[67] The most common business processes are the following:[68]

- Production
- Product development
- Sales
- Order transaction
- After-sales service

To profit from a restructuring, business process must be investigated. The aim is to determine and examine the unspoken rules or assumptions that directly or indirectly influence processes. Radical redesign, therefore, is understood as an organizational restructuring of the company.[69]

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[62] Cf. Siebert/Kempf (2008), pp.26–27
[63] Ibidem
[64] Cf. Hammer/Champy (1994) pp.51ff.
[65] Cf. Töpfer/Mann (1997), p.41
[66] Cf. Hammer/Champy (1994), p.56
[67] Ibidem
[68] Cf. Mertins/Edeler/Schallock (1995), p.4
[69] Ibidem

Satisfying results can be reached with the reengineering method, but it is very risky.[70] Some of the risks are the following:[71]

- Knowledge and results from previous management methods are not considered.
- Structures and processes that work well are given up.
- The position of the competition needs to be reached again with the new structure and processes.
- Employees may be unmotivated if they were not involved in the reengineering process from the start.

One reason to begin a reengineering can be to make an internal comparison of processes or structures with other departments or a company benchmarking with companies from the same or different branch. A benchmarking study, therefore, can be the driving force behind a Reengineering.[72]

2.4 **Benchmarking targets**

Benchmarking, in its simplest form, is a goal-setting process. Benchmarks, for business processes, are statuses from points in the future. The best practices, which need to be split into measureable values, help companies reach these future points. The benchmarks can be seen as indicators that influence the future direction of the company strategy rather than as specific internal targets which can be reached immediately. By taking the benchmarks and deriving internal company targets from them, long-term strategic plans directly influence the actual processes.[73]

Because benchmarking always follows the improvement of performance, there are two different categories in which improvements can be divided. One is evolutionary improvement, which is continuous improvement in small steps. Another is revolutionary improvement. Revolutionary improvement refers to the development of completely new products or procedures by using new principles of problem solving. benchmarking focuses on revolutionary improvement. But sometimes benchmarking can also result in evolutionary improvements.[74]

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[70] Cf. Siebert/Kempf (2008), p.28
[71] Ibidem
[72] Cf. Siebert/Kempf (2008), p.29
[73] Cf. Camp (1994), pp.19–20
[74] Cf. Sabisch/Tintelnot (1997), p.17

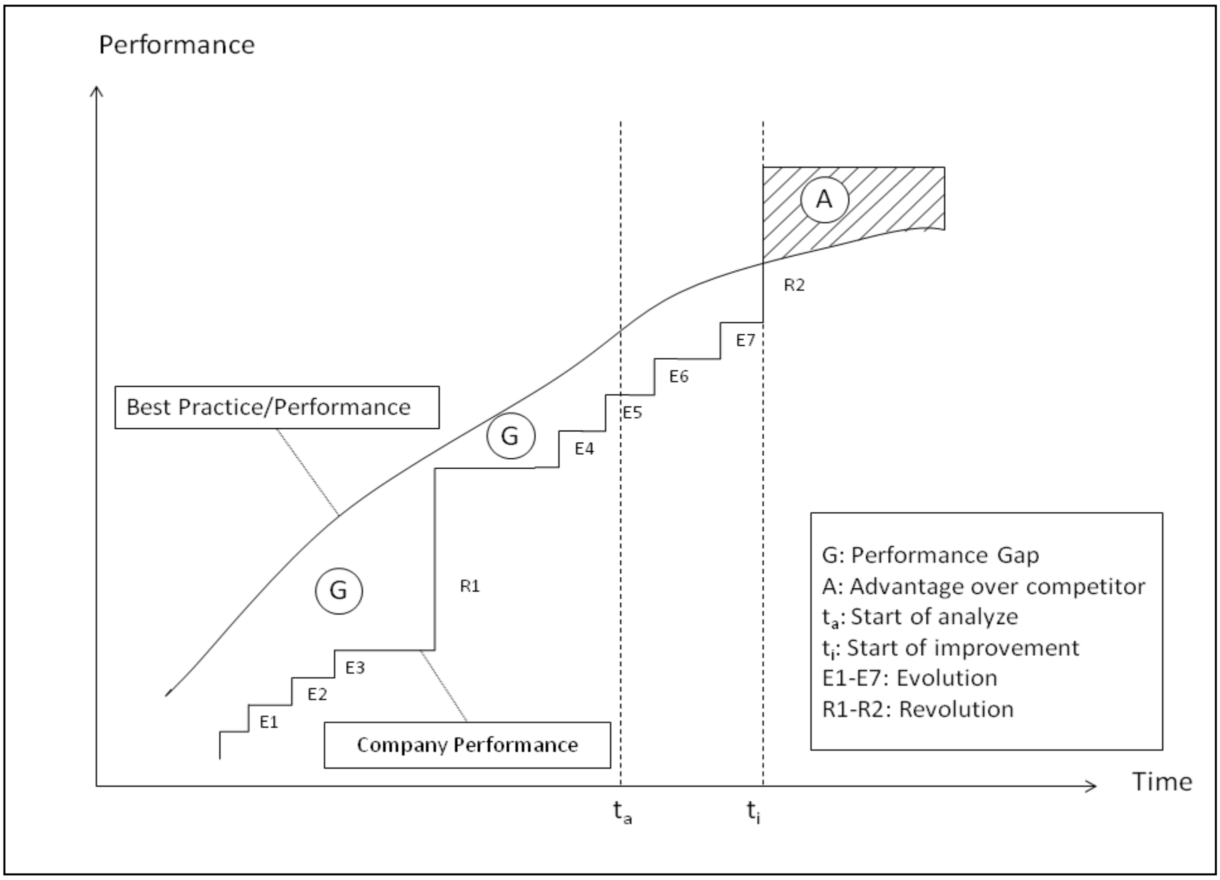

Fig. 6: Evolution and Revolution Steps in benchmarking[75]

Executing a benchmarking study often leads to particular effects in a company. These effects further lead to the desired goals of a benchmarking project. The effects are as follows:[76]

- Continuous orientation with respect to market requirements and customer needs.
- Determination of factors that influence effectiveness and efficiency.
- Determination of weaknesses.
- Higher transparency in case of processes and procedures.
- Increased flexibility for implementing adapted processes.
- Determination of possibilities for improvement.
- Start of innovation processes.
- Possible start of reengineering process.
- Support of quality management.

[75] Cf. Sabisch/Tintelnot (1997), p.17 (own illustration)
[76] Cf. Sabisch/Tintelnot (1997), p.18

- Support of the philosophy of permanent learning and of making organizations and departments self-learnable.

The goals of benchmarking can be summarized as follows:[77]

- Identifying method that are industry-best practices and determining performance gaps by comparing these best practices with company's actual value.
- Determination of reasons for existing gaps.
- Understanding and integration of adapted industry-best practices for reaching company targets.
- Search for further ideas and practices for elimination of the performance gaps.
- Improvement of the position on the market by following the benchmark method.

2.5 **Benchmarking types**

Benchmarking, according to Mertins and Kohl, can be divided into three main groups: the benchmarking of companies, the benchmarking of sectors and the benchmarking of frameworks. Benchmarking of companies can be further divided into three groups.[78]

Benchmarking is split into different types is done in very different ways in the literature. Pieske, for example, splits benchmarking into four categories: comparable partner, time horizon, object and target category. Comparable partners is further split into internal, competition, functional and generic benchmarking.[79]

Robert C. Camp also splits the types of benchmarking into four groups. He focuses on internal benchmarking, competition benchmarking, benchmarking against external companies that are industry leaders (which he also calls functional benchmarking) and generic benchmarking. This division is similar to that of Pieske.[80]

Considering the differentiations, benchmarking can be divided generally into internal and external benchmarking, depending on whether the benchmarking partner comes from the same or another company. External benchmarking can be further divided into competition oriented or not-competition oriented. The not-competition oriented benchmarking is therefore functional or generic.[81]

For this thesis, the division of Mertins and Kohl is used. Therefore, the benchmarking of companies is to be discussed. The focus is on the first two sub-groups, which are

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[77] Cf. Hastreiter/Buck/Jehle (2015), p.68

[78] Cf. Mertins/Kohl (2004a), p.28; Cf. Mertins/Kohl (2004b), pp.75–85

[79] Cf. Pieske (1995), p.41

[80] Cf. Camp (1994), p.77

[81] Cf. Watson (1993), pp. 108ff.

differentiated in terms of objects and partners, whereas the group of differentiation in parameters is not mentioned.[82]

2.5.1 Differentiation in objects

The benchmarking of companies is the most used group when talking about different benchmarking types. In this group, companies learn directly from one another by comparing key figures and benchmark objects. By comparing the definition of single benchmark objects, best performances are identified.[83]

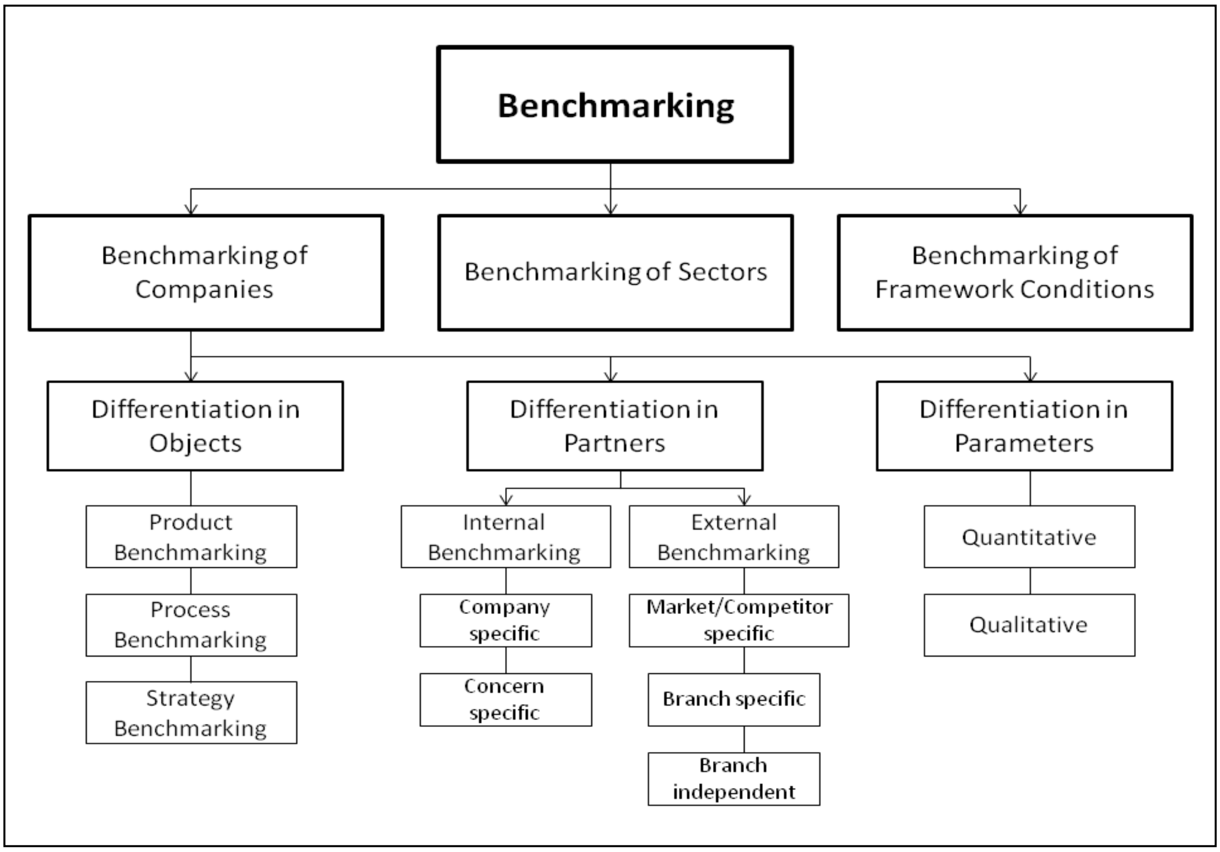

Fig. 7: benchmarking types[84]

The differentiation of objects has similar subdivisions in other literature. The major difference is that Mertins and Kohl see this group as a sub-group of benchmarking of companies and others do not. The differentiation of objects is therefore a major group, with objects for comparison in it like products, services, processes, functions and companies.[85]

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[82] Cf. Mertins/Kohl (2004), pp. 89-94

[83] Cf. Mertins/Kohl (2004a), p.27

[84] Cf. Mertins/Kohl (2004b), pp.75–92 (own illustration)

[85] Cf. Tucher (2000), pp.91–95; Cf. Pieske (1995), p.41; Cf. Faßhauer (1995), p.30

When talking about benchmarking of objects, there is a separation into three further terms, which are products, processes and strategies. Product benchmarking is a major topic in this thesis, because it was used to practice the benchmark project. The aim of the project is to compare two different products from different companies and consider product-specific values.[86]

Product benchmarking

Definition

The DBZ defines product benchmarking as follows:[87]

“Product benchmarking improves the performance of products. The focus is on the design, the product components and the type of production. Product benchmarking is also applied on services where then the focus is on the individual performance components and on the service.

Gerry Angeli described product benchmarking in a very uncommon way: [88]

“Most people think of product benchmarking as elementary biology – just dissecting a frog to see what the parts are. But product benchmarking is really like archaeology, where you dig to find out as much as you can about civilization.”

General

In product benchmarking, the company’s product and the competing products are completely dismantled and the parts are compared. The differences of the products are listed and evaluated. The evaluation can be related to costs, production techniques or simple dimensional data like length, width or mass. For costs, the basis for calculation is how much it would cost the company to implement the competitor’s technical solution. Also, implementation of a competitor’s techniques for production can influence the cost function. The results can lead to a review and rethinking of the company’s product, which is reengineering, as mentioned in Chapter 2.3.4. Costs are often reduced with the redesign of the product, which is one of the largest benefits of product benchmarking. The adaption and implementation of new principles would not occur if the costs were

[86] Cf. Mertins/Kohl (2004a), pp.76–77
[87] Cf. http://benchmarkingforum.de/benchmarking-wissen/benchmarking-arten/, date of access: 22.01.2017
[88] Miller/Mexer/Nakane (1992), p.20

significantly higher. This would be the case if buying new machines for production is necessary.[89]

Another advantage of product benchmarking over process benchmarking is that product benchmarking can occur without the benchmarking partner. The competitive product can be legally bought on the market before starting the comparison. So the focus is more on finding only the right product for comparison rather than on finding the right company/benchmarking partner.[90] Only recognized products should be used as comparison products. Selection criteria may include the technical performance, the market position, and the market price of the product.[91]

Product benchmarking sets tasks in the specification sheet for product development. The result of the product development then is compared with internal or external benchmarks. Therefore, the main task of product benchmarking is to provide product-development engineers with appropriate, market-specific data and to acquire external know-how.[92]

With product benchmarking, parameters like price and quality can be determined from the competitor's product. These parameters are significant to a customer's decision whether or not to buy a product, and they are accordingly very important for commercial success. Therefore, it is important to know these parameters from competitors for comparison. Product benchmarking often occurs before the invention of a new product, because in many branches, product benchmarking is a part of product development.[93]

The disadvantage of product benchmarking is that it is limited to competitive products. Potential for improvement can only be derived from a competitor´s product. Also, it is sometimes hard to implement technical solutions from other branches for the company's own product because of the different requirements of the branches. The implementation of the results of product benchmarking often leads to similarity with a competitor´s products. This must be avoided, because the goal is to improve on the competitor's product.[94]

Procedure

In the first step of product benchmarking, the product is divided into groups for investigation. These can be product components or product functions. Product functions

[89] Cf. Kleinfeld (1997), p.117
[90] Cf. Mertins/Kohl (2004b), pp.76–77
[91] Cf. Kleinfeld (1997), p.117
[92] Cf. Sabisch/Tintelnot (1997), p.58
[93] Cf. Pieske (1995), pp. 61ff.
[94] Cf. Mertins/Kohl (2004b), pp.75–76

are often used for separation if the product has a larger amount of software included. The division into product components is more common. Though differentiation functions are used at the beginning, these often end with a component division in further levels. In the next step, every comparison group is described in detail. Important indicators in this step could include considerations of the building of the product, the materials used, production technologies, dimensions, tolerances and performance indicators. The values determined from the competitive product are always directly compared with those of the company's own product. Further, the differences in the two products are evaluated. The differences should at least be split up into production costs. To compare only material costs does not yield a fair comparison. In maintenance-intensive industries, service costs must also be mentioned.[95]

The market-oriented evaluation of single components or function groups is the last step of the process. The price differences are often caused by technical differences. Not existing technical features, at the comparison product, is often a reason for its cheaper price. This fact is therefore often used to vindicate the company's own product. In this phase, however, the performance benefits are often said to be due to over-engineering. This means that customers are getting more performance than they really wish to pay for. Only by investigating all components is it possible to determine what technical performance the customer is willing to pay for.[96]

Process benchmarking

To understand process benchmarking, the process must be defined:

"A process describes the flow and transformation of material, information, operations and decisions. Business processes are characterised through the grouping and the structured order of activities with a beginning and an end with clear defined inputs and outputs."[97]

Process benchmarking involves the comparison of processes. By examining processes that are assumed to be better, significant improvements and process optimizations can be made. To render processes comparable, it is necessary to define them and their processes clearly. Splitting the processes into measurable values is therefore also needed. During the investigation of other processes, it is necessary to determine why a process value is better. To obtain these answers, measurable process values are split into primary and secondary values. The primary process values reveal differences between the processes, whereas the secondary values explain why a value is better. The

[95] Cf. Kleinfeld (1997), p.117
[96] Ibidem
[97] Cf. Osterloh/Frost (1996), p.31

secondary values can reveal the boundary conditions of the compared process or expose reasons for differences. Primary values may include tact times or cycle times, for example, whereas secondary values may include quality indicators like failure rate or indirectly influencing values like the number of employees who work on a process. The question of why a process is better can be fully answered by determining primary and secondary values.[98]

The term of the process benchmarking can be defined as follows: [99]

“Process benchmarking is the comparison of similar processes with the aim of process optimization. Without considering competition- or branch boundaries, the comparison refers to company internal, branch internal or branch independent processes. Thereby the differences, the reasons and options for improvement are determined.”

Tucher describes process benchmarking in a different way. He states that the significant value for the comparison of processes is the output. Most popular outputs include costs, quality and time or productivity. The main idea is that processes need resources and that the resources used are responsible for the success of the process. By benchmarking processes, these resources can be identified.[100]

The need to search for the right benchmarking partner is one of the disadvantages of process benchmarking. It may be hard to gain access to sensitive internal data of the comparison company, especially if the partner is in the same branch. Problems can also appear if the benchmarking partner exhibits a general misunderstanding of product benchmarking and process benchmarking.[101]

Process benchmarking is an important management tool not only because other processes are investigated but also because a company’s own processes become better known in the process. It was Mr. Deming who said that someone who cannot handle processes cannot handle a company either.[102]

Strategy benchmarking

To describe strategy benchmarking, the term strategy must first be described. This term is introduced from the Greek, where it refers to the ability to lead an army.[103]

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[98] Cf. Siebert/Kempf (2008), pp.44–45
[99] Cf. Siebert/Kempf (2008), p.45
[100] Cf. Tucher (2000), p.95
[101] Cf. Mertins/Kohl (2004b), p.79
[102] Töpfer/Mann (1997), p.39
[103] Kreikebaum (1987), p.24; Ulrich/Fluri (1992), p.114

When strategy is spoken of in economic or management terms, corporate strategy is often meant.[104] Corporate strategy was defined by Hofer and Schendel in the 1970s as a: [105]

“Fundamental pattern of present and planned resource deployments and environmental interaction that indicates how the organization will achieve its objectives”

There are two different ways to define the term *corporate strategy*. One refers to the process of determining company goals; the other does not. Hofer and Schendel do not include this process in their definition. But Chandler or Andrews do.[106] Chandler defines corporate strategy as,[107]

“The determination of the long-term goals and objectives of an enterprise, and the adoption of courses of action and the allocation of resources necessary for carrying out these goals.”

Both strategy definitions include reference to a method for reaching goals and targets.[108] Strategy can be defined as follows: [109]

“The essence of strategy is choice”

Benchmarking can also be used for strategy planning and developing. Strategy benchmarking follows the principle of improving company strategies. The aim is to gain competitive advantage through better strategy. To change or adapt a strategy to be more future oriented is to develop success factors and to improve competitive advantage.[110]

Mertins and Kohl defined strategy benchmarking as follows: [111]

“Strategy benchmarking is a tool for determination and orientation of future key areas, which are core competences, and it is also a tool for the improvement of core processes. It is an objective early warning instrument to recognize long-term developments, which result from external and internal changes in order to react on these in time. Strategy benchmarking is the search for best strategies, which lead to best performances. To achieve this, the requirements for the best strategies, need to be known.”

[104] Tucher (2000), p.39
[105] Hofer/Schendel (1978), p.25
[106] Tucher (2000), pp.10–11
[107] Chandler (1995), p.13
[108] Hofer/Schendel (1978), p.25; Chandler (1995), p.13
[109] Porter (1991), p.101
[110] Cf. Mertins/Kohl (2004b), p.79; Cf. Siebert/Kempf 2008, pp.51–52
[111] Cf. Mertins/Kohl (2004b), p.79

Sabisch and Tintelnot describe strategy benchmarking as a long-term instrument that facilitates the planning of research tasks and aids in the preparation of new procedures for research and development.[112]

The two definitions agree in defining strategy benchmarking as a long-term tool in which yet set choices the company can benefit from in the future.[113]

Compared to process benchmarking, strategy benchmarking is more about determining the position of a company on the market. Using knowledge about the strategy of competitors to gain insight into their behaviour is also an aspect of strategy benchmarking. Process benchmarking, on the other hand, is the investigation of the internal procedures of a company.[114]

2.5.2 Differentiation in partners

Differentiation in partners can be further split into internal and external benchmarking. In internal benchmarking, following Mertins, there is a separation between the benchmarking of a company or of a concern, whereas external benchmarking is divided into market and competition, branch-dependent and branch-independent, and related sub groups.[115]

Internal benchmarking

Internal benchmarking can be seen as the very first step required by an external-benchmarking project. The comparison of internal objects yields a better understanding of the benchmarking method itself, of the company, and of the processes involved. On the other hand, internal benchmarking can also be seen as a separate process for improving performance with internal best practices. It is one of the simplest benchmarking types because it has few restrictions and encounters few limitations from outside. The procedure uses only the internal view for the learning process.[116]

Internal benchmarking can be defined as follows: [117]

“Internal benchmarking is the comparison between similar activities or functions within a company or with associating organisations for determination of the performance level, which within of this common frame represents the best practice.”

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[112] Sabisch/Tintelnot (1997), p.53

[113] Mertins/Kohl (2004b), p.79; Sabisch/Tintelnot (1997), p.53

[114] Töpfer/Mann (1997), p.39

[115] Cf. Fig. 7: benchmarking types, p.42

[116] Cf. Mertins/Kohl (2004a), pp.28–29; Cf. Siebert/Kempf (2008), pp.34–35

[117] Cf. Mertins/Kohl (2004b), p.29

Watson defined internal benchmarking in a more detailed manner: [118]

“An approach to benchmarking where organizations learn from sister companies, divisions, or operating units that are part of the same operating group or company (e.g., the study of internal research and development groups to determine best practices that recuse time to market for the new product introduction process). In this type of study, performance information is compared for the same work process or business function within the same organization (perhaps looking at unique production lines, different plants, separate divisions, of distinct business units).”

Internal benchmarking exists because of differences within a company. These differences may include different processes, different problem-solving procedures, different marketing strategies, or different sales strategies. The differences may occur as a result of different locations or different historical developments within an area of concern.[119]

One large advantage of internal benchmarking is also the availability of needed data. The execution of a benchmark study is often connected with the use of sensible, company-specific data. This is not an issue with internal benchmarking because access to the needed data is more easily obtained.[120]

The negative aspect of internal benchmarking is its small potential for improvement. Given an exclusively internal view, there is no guarantee of finding the world´s best practices. And because processes are improved only with reference to an internal view, there is no guarantee that even the best internal processes can be achieved because of a lack of optimization in considering market trends.[121]

Typically, managers have difficulty making improvements from the outside. They think that their company is very specific and that many procedures that are identified as best practices cannot be applied. Internal benchmarking counteracts this thinking because only internal procedures and processes are investigated.[122]

External benchmarking

Comparison presupposes the basic similarity of the objects compared. The objects for comparison need to be investigated and defined so that their similarity can be confirmed. Therefore, external benchmarking also requires preparation.[123]

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[118] Watson (2007), p.11
[119] Cf. Rau (1996), p.43
[120] Cf. Tucher (2000), p.97
[121] Cf. Bendell/Boulter/Kelly (1993), p.96; Cf. Siebert/Kempf (2008), pp.34–35
[122] Cf. Siebert/Kempf (2008), p.35
[123] Cf. Mertins/Kohl (2004a), pp.34–35

The more abstract the benchmarking partner, the higher the potential for the failure of the benchmarking project. The level of improvement is also directly connected with the desired change in the company. This can be a problem, considering the motivation of the employees. During the project, processes are investigated and performance gaps are determined. The reasons for gaps are often found in the persons responsible for the departments in which the gaps exist. This lead to specific sanctions in which department leaders often lose power. In special situations, whole departments are closed or restructured.[124]

External benchmarking can be divided into three sub groups:[125]

- Competitor-specific benchmarking involves the comparison of a company's own objects with those of a direct competitor.
- Branch-specific benchmarking involves the expansion of potential objects for comparison to the whole branch.
- Branch-independent benchmarking involves expanding the potential objects for comparison on several branches.

Competitor-specific benchmarking

Competitor-specific benchmarking involves comparing a company's own objects with those of direct competitors.[126] Management is generally more interested in and focused on projects with direct competitors.[127] If the objects of investigation are not competitive specific, like safety procedures or training activities, it is easier to get direct cooperation with a competitor.[128]

Competitor-specific benchmarking projects are often performed by third parties. These third parties, such as benchmarking centres, can separate competition-relevant information from performance-relevant information and can therefore guarantee that only performance data is published. The data analysis is published as a case study with the performance values of several different companies that participate. This gives the case study enough reference values and splits the costs of such projects among the participating companies. These case studies can also be used to inform the decision-making process concerning what objects need to be investigated.[129]

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[124] Cf. Tucher (2000), p.96
[125] Cf. Fig. 7: benchmarking types
[126] Cf. Siebert/Kempf (2008), p.39
[127] Cf. Wild (1995), p.89
[128] Cf. Siebert/Kempf (2008), p.39
[129] Cf. Mertins/Kohl (2004a), p.35

The problem with competitor-specific benchmarking is that it often makes it possible only to catch up with competitor because of a lack of information of the processes that lead to the performance values.[130]

When using third parties to execute competitive-benchmarking projects, sceptical points of view can be minimized. Another method for minimizing trust issues is to find benchmarking partners from the same branch that are not direct competitors. In this case, benchmarking partners can be found from other regions or countries in which direct competition is unlikely.[131]

Branch-specific benchmarking

Branch-specific benchmarking involves more than just comparing direct competitors. It involves searching for trends within a branch. It also involves the investigation of functions in a branch. Therefore, the group chosen for investigation is larger than in competitive-specific benchmarking.[132]

To differentiate competitor benchmarking from branch-specific benchmarking, the view of a company is important. Every company can have a few competitors for every product. But, considering a company as a whole, with its production lines, processes and market shares, many more companies can be used for comparison. This is also the case if they are not direct competitors.[133]

The borders between these two methods are not ultimately very clear because a clear answer to where target-oriented benchmarking ends and trend research begins cannot ultimately be given.[134]

A major advantage of branch-specific benchmarking over competitor-specific benchmarking is that no direct competition occurs. This leads to a less complicated information flow. In addition, the comparability of processes and methods within a branch is higher because business units of companies within the same branch are similar because companies from same branches have usually the same market boundaries and therefore have similar strategies and goals.[135]

Benchmarking within a branch is still not the best method to choose, however. The comparability of companies is high, but the effort in terms of competition benefits still has

[130] Cf. Siebert/Kempf (2008), p.40
[131] Cf. Tucher (2000), p.98
[132] Cf. Mertins/Kohl (2004b), pp.34–35
[133] Cf. Leibfried/MacNair (1995), p.142
[134] Cf. Siebert/Kempf (2008), p.40
[135] Cf. Mertins/Kohl (2004b), p.36

potential for improvement. Considering not only direct competitors but even the whole branch makes it possible to achieve more extensive and better solutions, but significant competition benefits still cannot be reached. The best method for getting a performance boost is to orient with respect to best practices worldwide, which this method does not consider. It cannot be guaranteed that such methods are used in the company's own branch.[136]

Branch-independent benchmarking

According to Camp, Watson and Spendolini, branch-independent benchmarking can be seen as a mixture of functional and generic benchmarking.[137]

Functional benchmarking involves the investigation of processes or procedures and the realization of functions of companies that may or may not be direct competitors.[138] The goal of functional benchmarking is to identify the best practices in any branch with respect to a specific function or area.[139]

Generic benchmarking uses the principle that some processes are the same, no matter which branch they occur in. This could be, for example, the order processing. Many companies, from different branches, need to proceed this function.[140]

Branch-independent benchmarking searches for best practices outside the company's own branch. This fact needs to handle the ability to define success with external criteria. Therefore, a clear understanding of what best practices or best performances are, is unavoidable.[141]

Searching from outside one's own branch also means that the potential for finding innovations is very high because of the worldwide orientation. The worldwide orientation also means that the process of generating values for companies is similar, no matter which branch or market is investigated. This fact leads to the result that branch-independent benchmarking is the benchmarking of business processes. A clear definition of business processes is therefore unavoidable.[142]

Besides the more open exchange of data, the benefit of branch-independent benchmarking is that innovations from other branches can be transferred to the

[136] Cf. Mertins/Kohl (2004b), p.36

[137] Cf. Camp (1994), pp.79–82; Cf. Spendolini (1992a), pp.20–22; Cf. Watson (2007), pp.107–109

[138] Cf. R. Pieske (1995), p.52; Cf. Spendolini (1992a), pp.20–21

[139] Cf. Spendolini (1992a), p.21

[140] Cf. Camp (1994), p.81

[141] Cf. Kohl (2004), p.123

[142] Cf. Mertins/Kohl (2004b), p.37

company's own branch within the company. All innovations found from outside are used and therefore have also proven.[143] This is why this type of benchmarking is often used for the investigation of branches that are classified as innovative with a fast technological cycle.[144]

It is very difficult to get this kind of benchmarking accepted and applied within a company, but for just this reason, this kind of benchmarking is perhaps most likely to increase performance.[145]

2.6 **Process of benchmarking: The 5-phases model**

The process of benchmarking can be described in different ways. Standardization does not yet exist for it.[146] The different types of processes can be differentiated with respect to the number of included steps and the activities within their process. But they are mostly comparable because of their similar meaning. This thesis uses the 5-phases model of Mertins, Siebert and Kempf.[147]

Mertins, Siebert and Kempf define the benchmarking process as a process of five phases. In practice, the 5-phases model is often extended by adding steps. It is no problem to adapt the model to company-specific working flows so long as the principle of the adapted model stays the same.[148]

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143 Cf. Wild (1995), p.90; Cf. Camp (1994), p.82
144 Cf. Siebert/Kempf (2008), p.41
145 Cf. Camp (1994), p.82
146 Cf. Yasin (2002), p.217
147 Cf. Camp (1989) pp. 18ff.; Cf. http://benchmarkingforum.de/benchmarking-wissen/nutzen/, date of access: 11.07.2016; Cf. Moriarty/Smallman (2009) pp. 490ff.
148 Cf. Mertins/Kohl (2004b), p.39

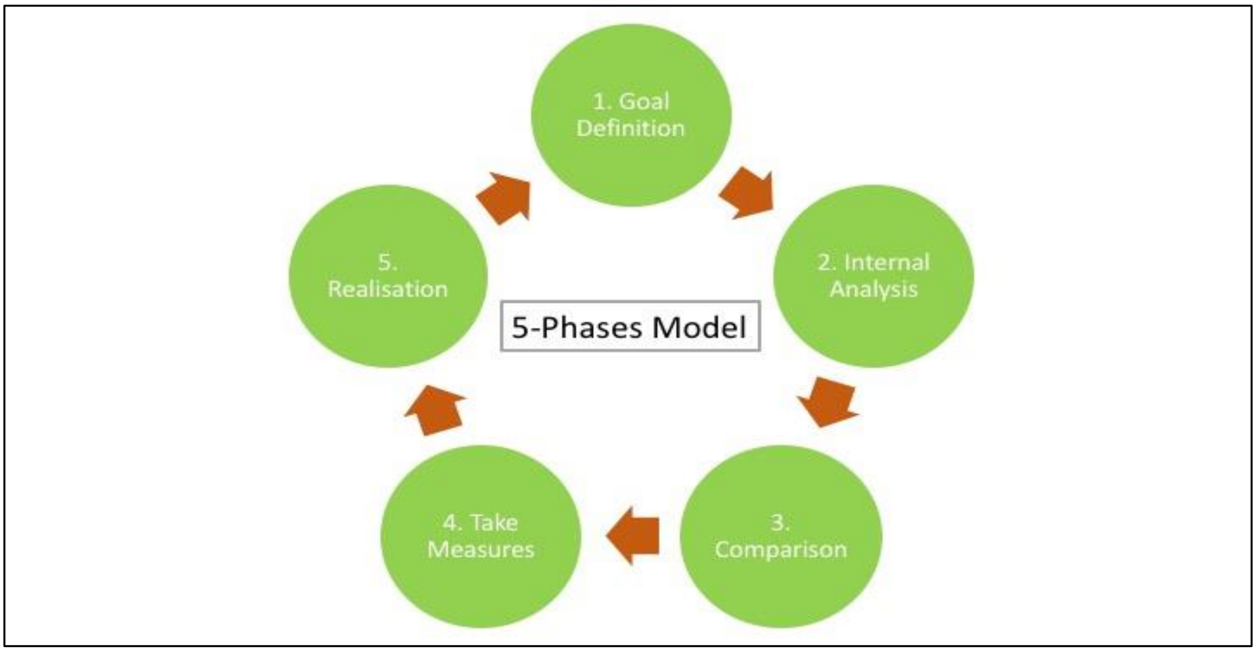

Fig. 8: 5-phases model[149]

Before the process can start, preparation should be made. One must determine whether sufficient resources—such as manpower and budget—are available and decide which type of benchmarking project is to be carried out. Employees with benchmarking experience can be involved in the new project, and the option of using consultants should be discussed with the management.[150]

Also, the pre-collection of data should be considered a part of proper preparation. Any information that can be gained before the project starts does not need to cost time during the project and therefore minimizes stress. The market position, the strengths and weaknesses of the parent company, and a rough time and cost schedule constitute such information. This information can be used to determine a benchmarking objective in which improvements have the highest potential for success.[151]

Goal-definition phase

Every benchmarking project begins with the definition of goals and targets. The goals must be compatible with the strategy of the company. Focusing on a wrong target leads to useless results and renders the project useless. This is why it is important that the management of a company is already involved in this phase of the process. The goal-

[149] Mertins/Siebert/Kempf (1995), p.XVII
[150] Cf. Siebert/Kempf (2008), pp.73–75
[151] Cf. Siebert/Kempf (2008), pp.73–75

finding process can be handled through a workshop in which all participants define, structure and prioritize goals.[152]

In the first step of the goal-definition phase, the benchmarking object is selected. All information about competition and market positions are used to select the right object. After the best object for the study is determined, the goals are defined. This step is followed by deciding how many employees are to work on the project. The last step is to calculate a time and cost schedule, which is based on previous knowledge about the object, the goal definition and the planned resource consumption. It will take time to execute the steps of the goal-definition phase. This time consumption is legitimate because it makes it possible to avoid failures in later project phases that might otherwise have significantly negative impact on the project.[153]

Internal analysis

With the information and knowledge generated in the first phase, the second phase starts with an internal analysis of the company's own processes and procedures. As mentioned in Chapter 2.5.2, the first step when executing a benchmarking project should be to perform an internal analysis.[154] The internal analysis phase can be summarized as follows:[155]

- Analysis of the benchmarking object and the associated processes.
- Reduction on benchmarking-related topics.
- Definition of the measurement unit.
- Determination of the influences that lead to the actual performance of the benchmarking object.

The clear definition of the measurement unit against which the benchmarking object is rated is important. The same terms are often understood differently, even in the same company and especially in different companies.[156]

The business processes that are responsible for the benchmarking object should be identified and understood. These processes are often modelled with software tools to gain a better understanding and overview of them.[157] This modelled process represents

[152] Cf. Mertins/Kohl (2004b), p.40
[153] Cf. Siebert/Kempf (2008), p.76
[154] Cf. Mertins/Siebert/Kempf (1995), p.XVII
[155] Cf. http://benchmarkingforum.de/benchmarking-wissen/nutzen/, date of access: 11.07.2016
[156] Cf. Mertins/Kohl (2004b), p.45
[157] Cf. IPK n.d.

the basic understanding for the team, from which further questions, strengths and weaknesses or potential for improvement can result.[158]

Internal analysis can occupy most of the time of a benchmarking project. The company 3M determined that it spent 45% of the time in the second phase.[159]

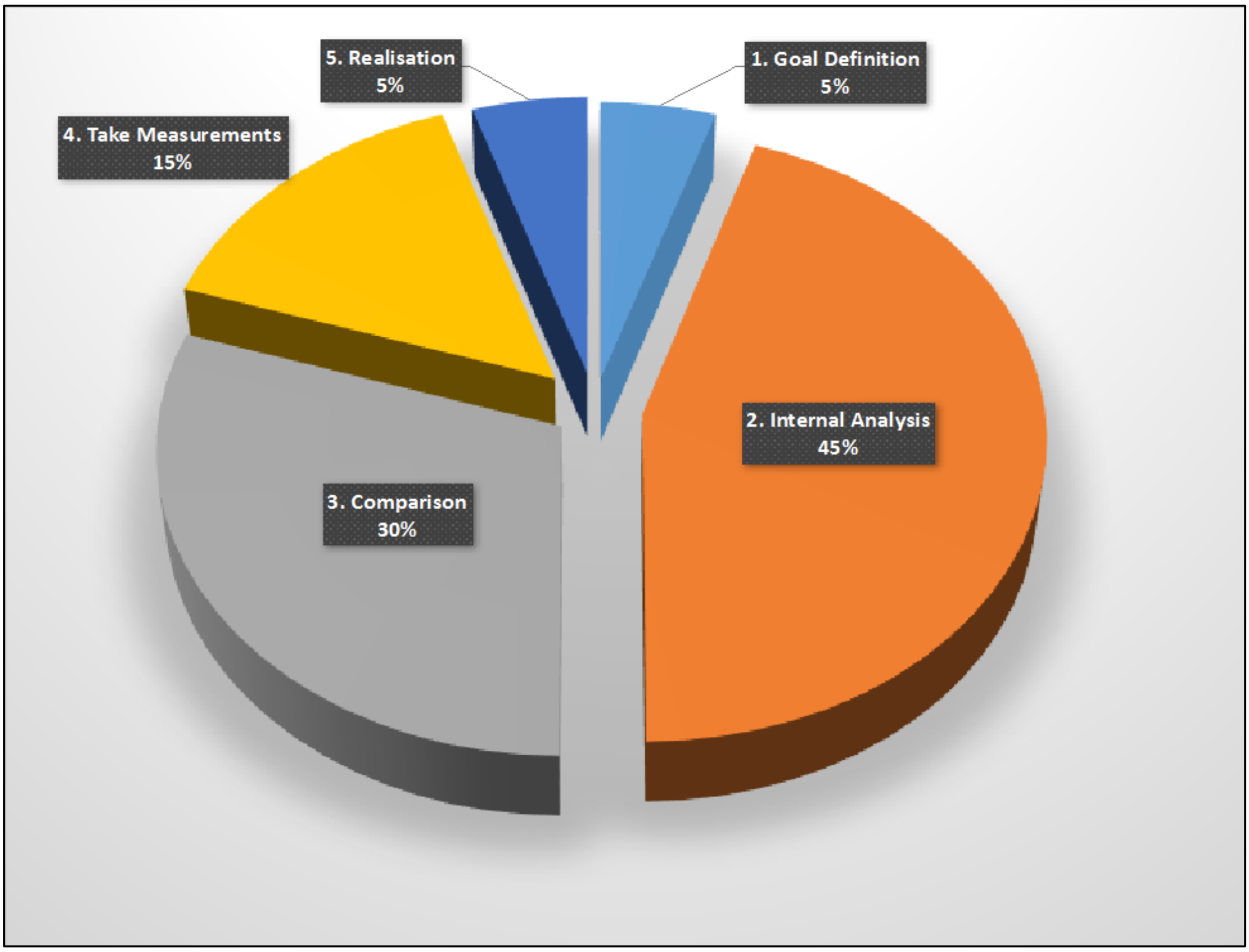

Fig. 9: Time segments of a benchmarking project considering 3M[160]

Comparison phase

The data and knowledge generated by the internal analysis are very useful when it comes time to look for the best possible benchmarking partner.[161]

[158] Cf. Mertins/Kohl (2004b), pp.42–46
[159] Cf. Siebert/Kempf (2008), p.66
[160] Cf. Mertins/Siebert/Kempf (1995), p.26
[161] Cf. Mertins/Kohl (2004b), p.46

The steps in the comparison phase can be summarized as follows:[162]

- Selection of best possible benchmarking partner
- Comparison of objects
- Interpretation of results
- Determination of sources for results

The selected object reduces the number of potential partners because different partners are usually the best in class for different objects.[163] The integration of employees with experience in other branches or with benchmarking in general can be of significant advantage to the project.[164]

Companies that are identified as potential benchmarking partners are often the best at only one activity or process. A market leader is not necessarily the best possible partner for the project.[165] This is why the focus should be on the benchmarking object and not on the number of awards a company has.[166]

The criteria for choosing the best possible benchmarking partner are as follows:

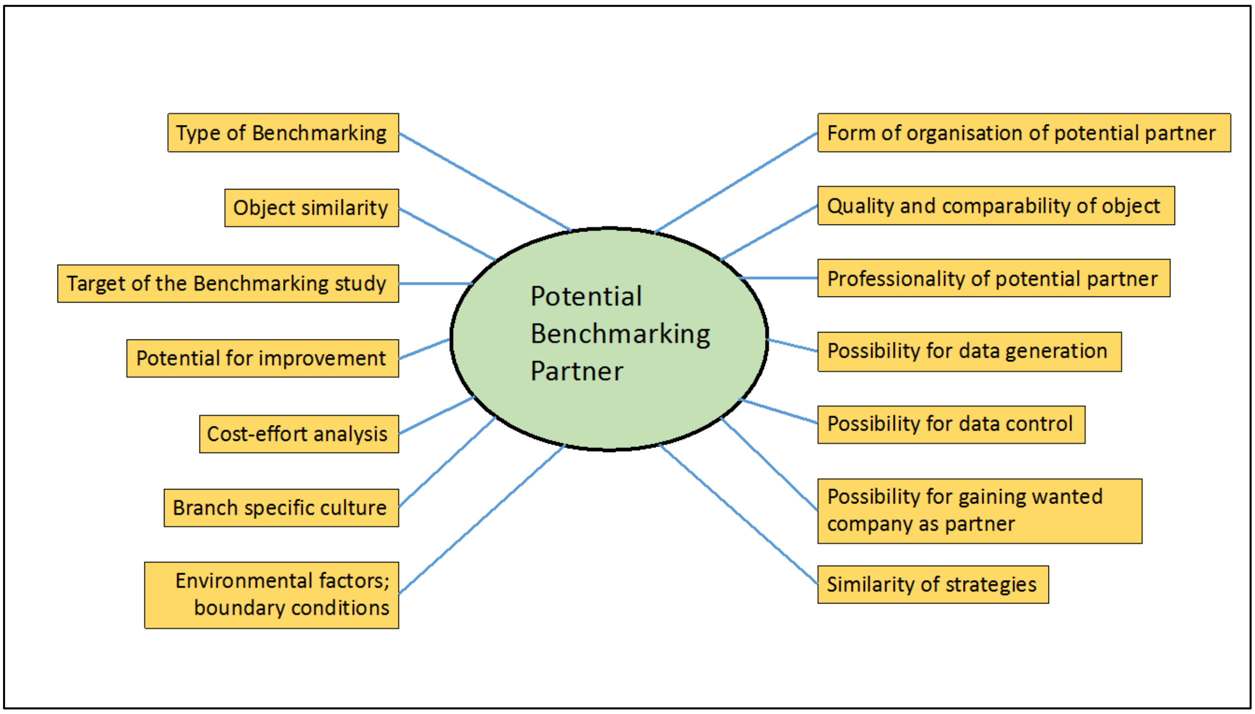

Fig. 10: Influencing factors for finding benchmarking partner[167]

[162] Cf. Mertins/Kohl (2004b), p.46
[163] Cf. Tucher (2000), p.117
[164] Cf. Balm (1992), p.139
[165] Cf. Balm (1992), p.83
[166] Cf. Watson (1993), p.79
[167] Cf. Tucher (1998), p.118 (own illustration)

After the right partners for the project have been chosen, the next step is to make first contact with them. Knowledge about the processes is a requirement for making contact. With the send of a questionnaire, which can be generated in the steps before, first direct data is determined. This data only can be read correctly by consulting the partner, which makes a meeting with the partner unavoidable.[168]

When the collection of data is completed, evaluation occurs. For comparison and evaluation of the data, the question "How?" is more important than the question "How much?"[169] The analysis occurs by comparing company performance indicators with those of the partner. For the best possible comparison, the indicators of the partner need to be set in relation to the actual internal and environmental situation. Short-term major contracts or government projects can render the indicators unreliable.[170]

Take measurements

With the results of the comparison phase, appropriate recommendations for reaching best possible performance values in the own company are set. Realistic and measureable methods for the realisation of improvements are therefore determined in this phase. [171]

Realisation phase

Benchmarking requires the constant implementation of pre-defined measurements for reaching benchmarking goals. This fact makes the end of the benchmarking method rest on the beginning of an innovation process.[172]

During implementation, the progress of the improvement process can be controlled by inventing a measuring system. The progress-control-system should be integrated in the improvement-implementation process of the company. Because of constant change caused by the invention of improvements in the companies involved in the study, it is necessary to determine whether the compared best practices still are best practices. This requirement also results from the constant changing of processes and methods in the benchmarking partner´s company, which is also progressing. This fact makes the benchmarking method a continuous process of self-renovation and improvement.[173]

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[168] Cf. Mertins/Kohl (2004b), pp.47–48

[169] Cf. Boxwell (1994), p.110

[170] Cf. Mertins/Kohl (2004b), p.48

[171] Cf. Faßhauer (1995), p.34

[172] Cf. Sabisch/Tintelnot (1997), p.40

[173] Cf. Mertins/Kohl (2004a), pp. 49ff.

One of the largest problems encountered during the realisation phase is that this phase is not taken as seriously as the phases before it are taken. During the comparison and measurement phases, many ideas are discussed and are taken over into the company. The euphoria and enthusiasm is very high in these phases because of the confrontation with something new. The measurements that are defined for reaching better performance are accepted in the group and appear very solid. And because it seems that nothing bad can happen anymore, interest in the actual realization of the goals diminishes. Support from the top management also decreases. This often results in the cancellation of the project because of a failure to integrate the procedures. [174]

2.7 **Benchmarking in Research and Development**

The quality of a research and development (R&D) department directly influences the technical and economic success of innovations. While innovations lead directly to new products or processes, it is important to integrate the benchmarking method in the R&D department. This means integrating the benchmarking principle in the innovation and product-development process.[175]

This chapter considers the connection between innovation, product development and benchmarking. It shows how the benchmarking method influences the innovation process and how it can be used for product development.

2.7.1 Benchmarking and innovation

Benchmarking is also a method for planning new problem-solving principles. If the method of best practices is used during idea generation and conception of new features, the best possible potential for improvement can be reached. This means that benchmarking can be an important tool for innovation management.[176]

When the term *benchmarking* is connected with the term *innovation* or *innovation management*, the two terms should first be defined.

Innovation does not mean just a good idea. *Innovation* is more the invention of an idea for a new product, procedure or service with a promise of economic success due to using this invention.[177]

[174] Cf. Mertins/Kohl (2004a), pp. 49ff.
[175] Cf. Sabisch/Tintelnot (1997) pp. 45ff.
[176] Cf. Sabisch/Tintelnot (1997), p.45
[177] Cf. Weis (2014), pp.37–38

While innovation involves the successful integration of an idea on the market, *innovation management* means the systematic development of ideas to yield innovations within a company or organisation. Innovation management therefore aims to make economicly successful products, processes or services out of ideas.[178]

Benchmarking has the following tasks within innovation management:[179]

- Definition of the goals of an innovation considering the market competition. This involves the definition and explanation of what performance the innovation should have in the specification sheet.
- Selection of the best possible variety of product development with consideration of the desired competition advantages.
- Support of creativity in the R&D department by providing the R&D team with actual best practices.

Different innovation processes are described in the literature for making successful objects out of ideas. Cooper has developed the stage-gate process, which can be used either for the process of innovation or for product development. Different steps are made in the stages, whereas a decision is made every time whether the process should go on or not in the gates. After every stage, therefore, a gate must be passed.[180]

Oliver Gassmann and Philipp Sutter describe their own innovation process, which is split into two categories. In the first phase, the cloud phase, creativity occurs. The second phase, the building phase, requires structure and process management.[181]

The principle of using the benchmarking method in the innovation process is described best by Sabisch and Tintelnot. They split the innovation process into six levels, starting with problem identification and analysis up to the launch of the new product or service. Every step or level in their process is supported by the benchmarking method. This goes from the demonstration of performance gaps at the level of problem analysis up to finding and using the best possible strategy for market launch in the last step.[182]

[178] Cf. Weis (2014), p.156
[179] Cf. Sabisch/Tintelnot (1997), pp.45–46
[180] Cf. http://wirtschaftslexikon.gabler.de/Definition/stage-gate-modell.html, date of access: 31.08.2016
[181] Cf. Gassmann/Sutter (2008) pp. 44ff.
[182] Cf. Sabisch/Tintelnot (1997), p.46

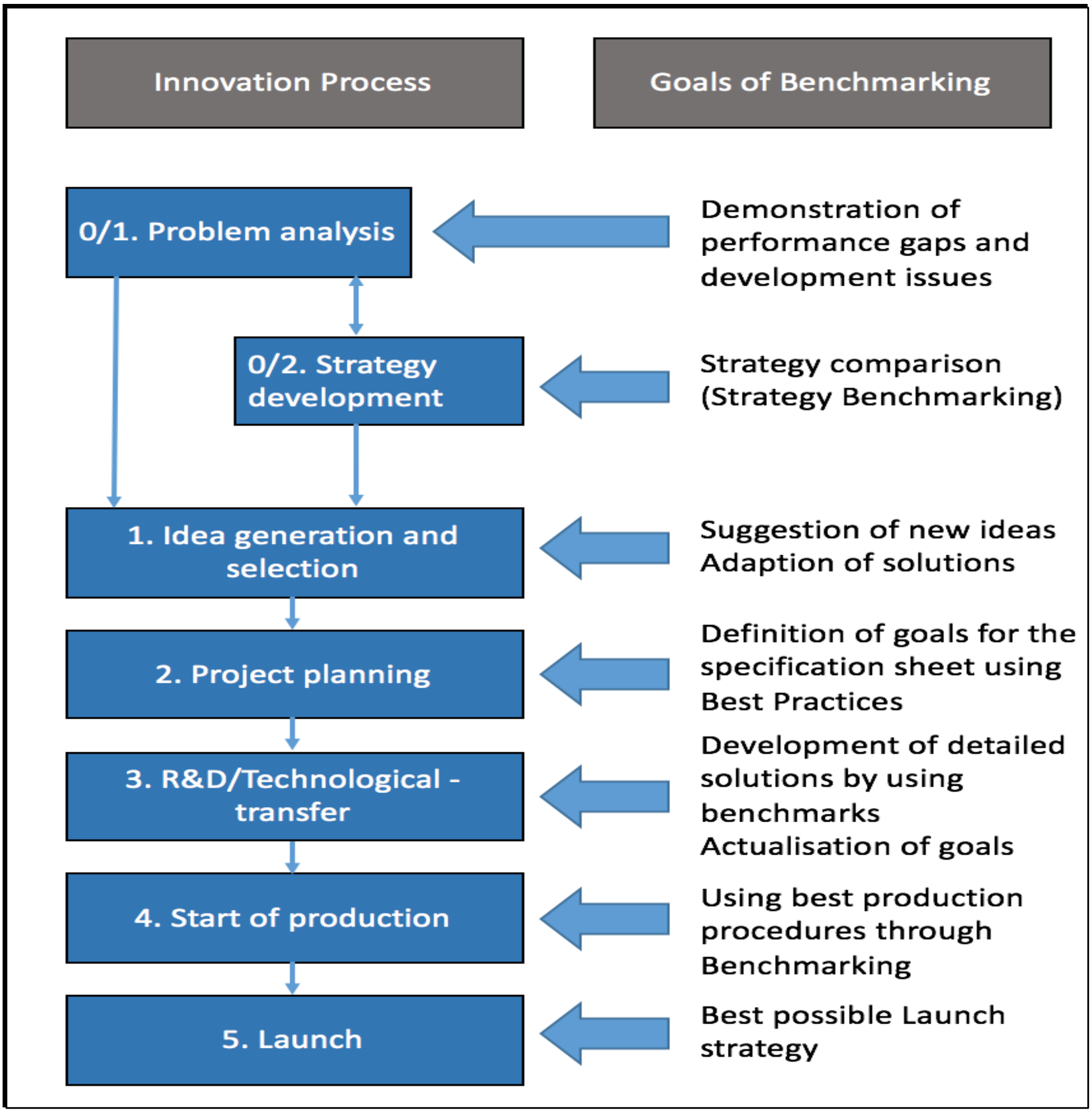

Fig. 11: Innovation process including benchmarking[183]

2.7.2 Benchmarking in product development

The production of a product, from the first idea to the launch, can be illustrated as a process that ends at the market release. This leads to the fact that, for the process of developing a product, the same principles prevail as in the process of benchmarking, which was described in Chapter 2.5.1. The fact that benchmarking in general is a

[183] Cf. Sabisch/Tintelnot (1997), p.46 (own illustration)

process-oriented method also helps to integrate this management tool in the product-development process.[184]

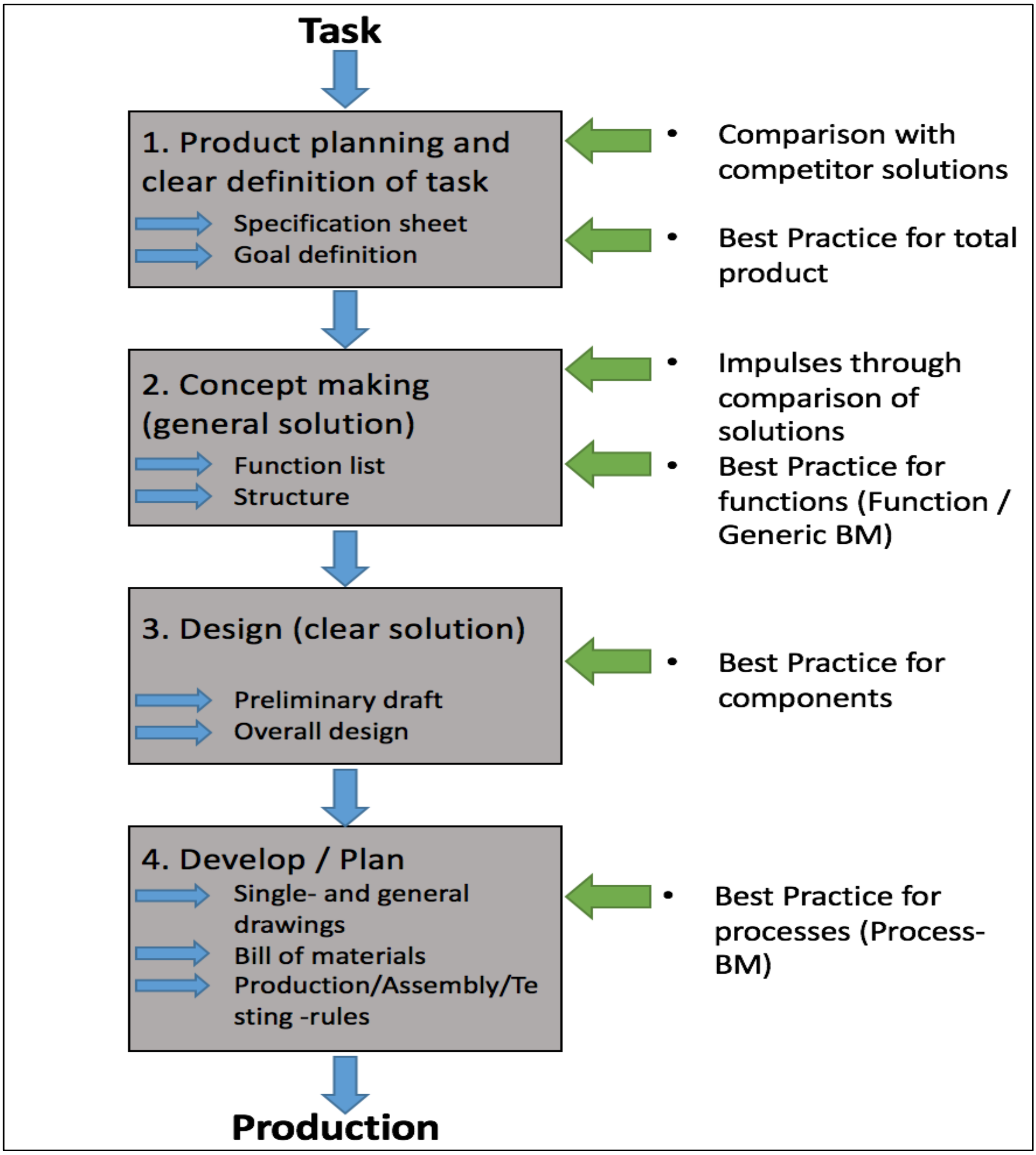

Fig. 12: benchmarking in Product Development[185]

[184] Cf. Jackstien/Vajna (2014), p.79

[185] Cf. Sabisch/Tintelnot (1997), p.54

To master the challenges of the modern industry, companies are becoming more and more process oriented. This means splitting work procedures into single functions.[186] While process-oriented thinking represents the future of the industry, companies still work in management functions such as marketing, production, sales, etc., in which working steps and responsibilities are delimited.[187] This kind of thinking seams easier for employees because of the clear responsibility and defined work steps. But processes are cross-functional with inputs and outputs. The thinking in management functions contradicts the process orientation of the benchmarking method. It seems obvious that the colour of a prototype should be arranged by the marketing team to get representative results on the market test of the new product. This example suggests that process orientation in general is the right way and that the single steps and procedures in the product development also need to interact with more than one department.[188]

Sabisch and Tintelnot connect the product development process with the benchmarking method such that the product-development process can best profit from the method. In every step of the process, they added the basic principles of the benchmarking method so that the company can improve the product before it exists. This implies an active implementation to achieve the best possible customer satisfaction and economic success.[189]

2.8 **Common criticism of benchmarking**

Some management experts say that the benchmarking method contradicts the principle of free-market economy because it involves cooperation between companies. But this is not true. A closer look at this specific management method shows that these experts suffer from a fundamental misunderstanding: If companies do not fight for market shares, then there is no reason for these companies not to work together. In this case they can even improve their own market positions and thereby increase the competition in their specific branch.[190]

Not everyone believes in this method. And it is true that benchmarking can do more harm than good if it is practiced poorly. This can happen because some managers think that a

[186] Cf. Ulrich/Fluri (1992) pp. 173ff.
[187] Cf. Burckhardt (1995), p.522
[188] Cf. Sabisch/Tintelnot (1997), p.61
[189] Cf. Sabisch/Tintelnot (1997), p.54
[190] Cf. Watson (1993), p.36

simple phone call to a company to request a number represents the benchmarking method, which is not true at all.[191]

There are, however, three common criticism of benchmarking that can be dubbed the spying, the copycatting and the "not invented here" criticisms.[192]

Spying

When Xerox first published its benchmarking method, some journalists reported it as a form of industrial espionage. The company was named the master of espionage and the method was associated with something illegal.[193]

But this is not true. This method is neither immoral nor unethical, because there is a significant difference between espionage and benchmarking. And this difference represents the degree of openness between the companies. If a company wants to spy on another company then it does so secretly. But with benchmarking, what is desired is open communication and open transfer of data. Both companies know exactly what data is transferred when and to whom. This fact makes the term *industrial espionage* ridiculous and shows the benchmarking method in another light.[194]

Copycatting

Another widespread criticism of benchmarking is that it results in copycatting. This means that it reduces the creativity of the employees and therefore is counterproductive in the long run. But this is not true at all. Benchmarking truly supports creativity in a company because processes and procedures are not just copied; they are adapted. Adaptation requires a lot of creativity.[195]

"Not invented here"

The "not invented here" criticism" is often issued by managers who believe that, given the uniqueness of their company, potential best practices cannot be invented anywhere else. This excuse can simply be disproven when executing an internal benchmarking project. Searching for best practices within a company and adapting these practices to

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191 Cf. Boxwell (1994), pp.47–48

192 Cf. Boxwell (1994), p.48

193 Cf. Dumaine (1988)

194 Cf. Watson (1993), p.37

195 Cf. Boxwell (1994), pp.48–49

departments that perform poorly simply reveals the falsity of the “not invented here” criticism.[196]

2.9 Benchmarking summary

Benchmarking is a proven instrument for handling the challenges of modern competition. This means that it is not only able to react quickly to changing competition boundaries, but also that it provides the company with the best possible procedures to get ahead of competitors. Benchmarking means comparing objects with the world´s best products, processes or services, which are called best practices. It is a continuous process in which best practices are compared, investigated and adapted so that they fit the company the best.[197]

Benchmarking is performed in different ways depending on the type of benchmarking. It can be used to differentiate between objects and partners, depending on the desired targets. Generally, internal benchmarking is the first step to take when confronting a company with this topic. With internal benchmarking, the method itself and the company become better known, which leads to better results for the real project.[198]

Internal benchmarking differs from common management methods like TQM or *kaizen*. If TQM represents a focus on quality, benchmarking can represent an important tool in TQM for comparing companies with best practices in terms of quality. Also, marking represents larger and fewer changes than *kaizen*, which strives after improvements every day.[199]

Nevertheless, benchmarking represents a powerful management tool for improving competitiveness. The criticism of this method is not justified unless is not carried out well, which needs to be avoided in any case. This only can be handled if the team members understand the philosophy and the process of this method.[200]

Benchmarking is of course not to be done only once. It is more a process of single steps that is rerun again and again, because best practices change. It therefore means constant learning and the aspiration for best performances.[201]

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[196] Cf. Siebert/Kempf (2008), p.35

[197] Cf. Watson (1993), pp.223–224; Cf. Hastreiter/Buck/Jehle (2015), p.67

[198] Cf. Mertins/Kohl (2004b), pp.75–92; Cf. Siebert/Kempf (2008), pp.34–35

[199] Cf. Burckhardt (1995), p.517; Cf. Siebert/Kempf (2008), pp.26–27

[200] Cf. Boxwell (1994), pp.47–48

[201] Cf. Leibfried/MacNair (1995), p.371

3 Benchmarking in practice

This chapter describes the practical part of this study. At the beginning, the adapted 5-phases model is described. This is followed by a detailed description of every single phase of the adapted model. After the description, the aircraft engine and the automotive engines are described.

The chapter ends by comparing the engines and explaining the performance gaps between the aircraft engine and the automotive benchmarks.

3.1 The adapted 5-phases model

Chapter 2.6.2 introduces the 5-phases model, which was defined by Mertins, Siebert and Kempf. The 5-phases model is only one of the benchmarking process principles described in literature. This model is often used and modified to fit a company in the best way.[202]

This thesis uses a modified 5-phases model that is inspired by the model of Füser:

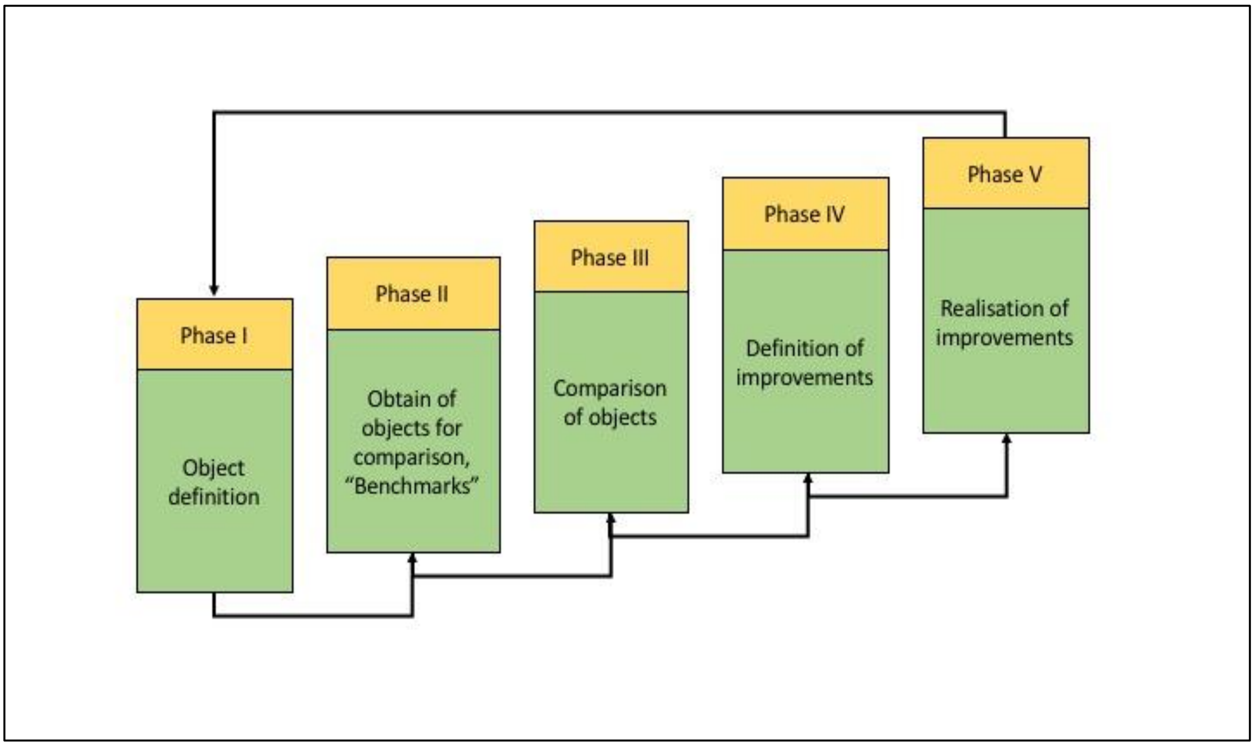

Fig. 13: Modified 5-phases model[203]

[202] Cf. Mertins/Kohl (2004b), p.39; Mertins/Siebert/Kempf (1995), p.XVII

[203] Cf. Füser (1997), p.91

Phase I

When comparing the initial 5-phases model with the modified model, some differences are noticeable. The first difference is that the object-definition phase stands at the beginning instead of the goal-definition phase. Setting the right goals with the management is a necessity for further steps. Because the definition of the object is a part of the goal-definition phase, there is no large difference between these two steps.[204]

Instead of setting specific goals and finding a product to which these goals can be applied, the object in this case is defined first. The goals therefore are defined according to the chosen object.

Phase II

In the original model, the internal analysis follows the goal-definition phase. In this phase, the defined benchmarking object should be analysed and reduced with respect to benchmarking-related topics. The determination of influencing factors which lead to the actual performance is also a part from the initial Phase II.[205]

In the actual model, these points went into the third phase. The benchmarking object should not be analysed before objects for comparison are found. The idea is to analyse and measure all engines at the same time. The goal is to make it possible to set appropriate functional groups and to assign the measured parts to the right groups. Therefore, it is necessary to obtain the benchmarking objects before the analyse can start and Phase II can be reduced on the obtaining of benchmarking objects.

Phase III

The third phase of the two models is very similar. The comparison of objects and the interpretation of the results occurs in both of the third phases. The only difference is that, in the initial model, the process of finding benchmarking partners is also set in the third phase, whereas this task is done in the second phase in the actual model. Because the automotive engines are obtained in Phase II, Phase III does not include this task. [206]

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[204] Cf. Mertins/Kohl (2004b), p.40

[205] Cf. http://benchmarkingforum.de/benchmarking-wissen/nutzen/, date of access: 11.07.2016

[206] Cf. Mertins/Kohl (2004b), p.46; Cf. Füser (1997), p.91

Phase IV

The fourth phase determines the improvements to be made for reaching the goals, which were defined in the first phase. This is done by using the data generated in the first three phases. The initial and adapted 5-phases model do not differ in this phase.[207]

In this project, the results from the third phase were discussed in several meetings. For every measured value in which the automotive engines exhibit better results, a meeting was hold with the employees responsible for the values generated on the aircraft side. During these meetings, employees discussed why the automotive engines performed better. Answering these questions led to improvements in the best case or to the insight that no better values can be generated at this moment given the specific machines used for processing at BRP-Rotax for the single parts of the aircraft engine.

Phase V

The Phase V is about realizing the improvements identified in the previous phase. Therefore, the initial Phase V and this Phase V are the same.

The last phase should also be supported with adequate time and manpower, as the phases before. The problems, which are often described in literature, should be taken seriously and should be considered while executing the last task. The motivation of the top management need to be guaranteed until the end, to prevent a cancellation of the project at the finish.[208]

3.2 Object definition: The BRP-Rotax AE2017

This chapter describes the AE2017. Because the management decided to benchmark this product, the concept of this engine is shown here, as are the facts and measures fixed at this moment.

3.2.1 General information and basic data

The development of new engines at BRP-Rotax is a process that should be described differently for different prototype levels. The levels go from Status P0, which represents a first dummy, up to a certified engine, which can be built in a new aircraft.[209] Every

[207] Cf. Faßhauer (1995), p.34
[208] Cf. Sabisch/Tintelnot (1997), p.40; Cf. Mertins/Kohl (2004a), pp. 49ff.
[209] Cf. BRP-Rotax (2014), p.27

prototype of a new engine starts with Status P0. The statuses, according to the design organisation exposition (DOE) of BRP-Rotax, are the following:

Status	Description
P0 Prototype	First dummy for making a feasibility study.
P1 Prototype	Development pattern based on design drawings and sketches but not manufactured under production conditions. Mostly used as sand casting. Dimensional documentation of critical components with testing and reporting of results.
P3 Prototype	Development pattern for series production with a full dimensional and technical documentation that is manufactured and mounted under production conditions.
Pilot Run	At least five engines are mounted on the series assembly line at least four weeks before the start of the series assembly to determine the availability of parts and devices and to avoid starting problems. Documentation and tracking by the quality assembly.
Certified Engine	An engine that has been type tested by an accredited standards manual.

Table 2: Statuses of BRP-Rotax Engines[210]

The actual concept of the AE2017 has the status P0. This means that a digital dummy exists that needs to be tested for feasibility. During the feasibility study, the engine is compared with automotive boxer engines to gain knowledge about potential improvements, before the first sand casting is build.

Table 7 presents a rough overview of the basic size and the performance values of the AE2017 engine. Though it is beyond the scope of this chapter to depict all of the measured data of all parts of the AE2017, all of the data can be found in the Appendix.

[210] Cf. BRP-Rotax (2014), p.27 (own illustration)

Description	Value [ ]
Length without transmission, frame and generator	339 [mm]
Width	666 [mm]
Height	351 [mm]
Weight	37,10 [kg]
Bore	88 [mm]
Hub	80 [mm]
Displacement	1946,28 [mm^3]
Max. Torque	217 [Nm]
Rotation speed at max. torque	5800 [1/min]
Max. Performance	132 [kW]
Rotation speed at max. performance	5800 [1/min]
Torque at max. performance	217 [Nm]

Table 3: Basic data of AE2017[211]

The air intake and exhaust systems of the AE2017 are not shown in Fig. 20 because the calculation of the air-intake system is not yet finished. This system works with an air-box, which is placed on the upper side of the crank case.

The calculation of the exhaust system is also not yet finished. The boundary conditions are that the exhaust gases are used to increase performance values via a turbo charger. This exhaust system, with the turbo charger and the included pipes, is t be mounted on the bottom side of the crank case.

[211] Own illustration

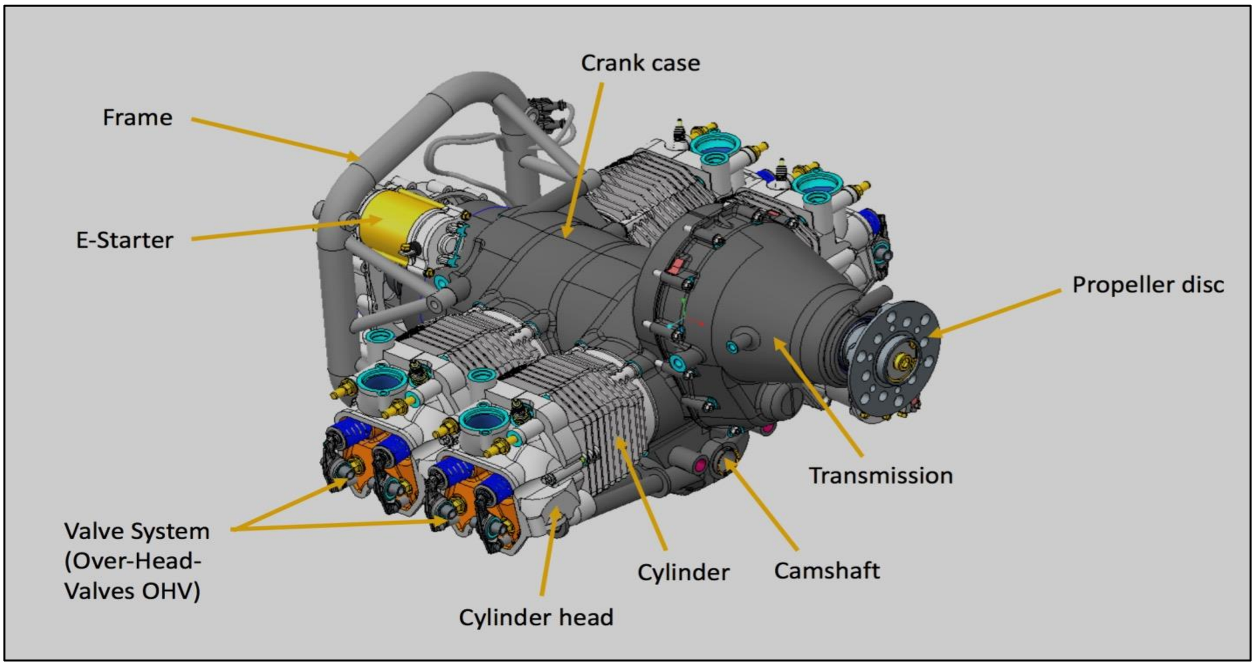

Fig. 14: P0 Concept of the BRP-Rotax AE2017[212]

Also, the valve covers are displaced to show the actual valve system, which is an over-head-valve system (OHV).

Cooling of the engine is accomplished with two separate systems. The cylinders are manufactured with ribs and use the existing airstream during flight for cooling. The cylinder heads, on the other side, are cooled with a water-cooling system.

For the piston displacement, BRP-Rotax uses four single cylinders. This is important to mention as mostly every automotive four-cylinder boxer engine uses two cylinder pairs. This is characteristic of the BRP-Rotax engines and is also used in the 912, 914 and 915 series. Therefore, same parts can be produced and used, and the fact that there is no casting material between the cylinders or cylinder heads saves a lot of weight.

3.2.2 Crank train

The crankshaft of the AE2017 is 460mm long and weighs 8,95kg. The largest value, in terms of width, is measured at the counterweight. It is 141.8mm. A five-bearing system is used for the bearing of the crankshaft, as it is used in modern automotive engines.

[212] BRP-Rotax (2016)

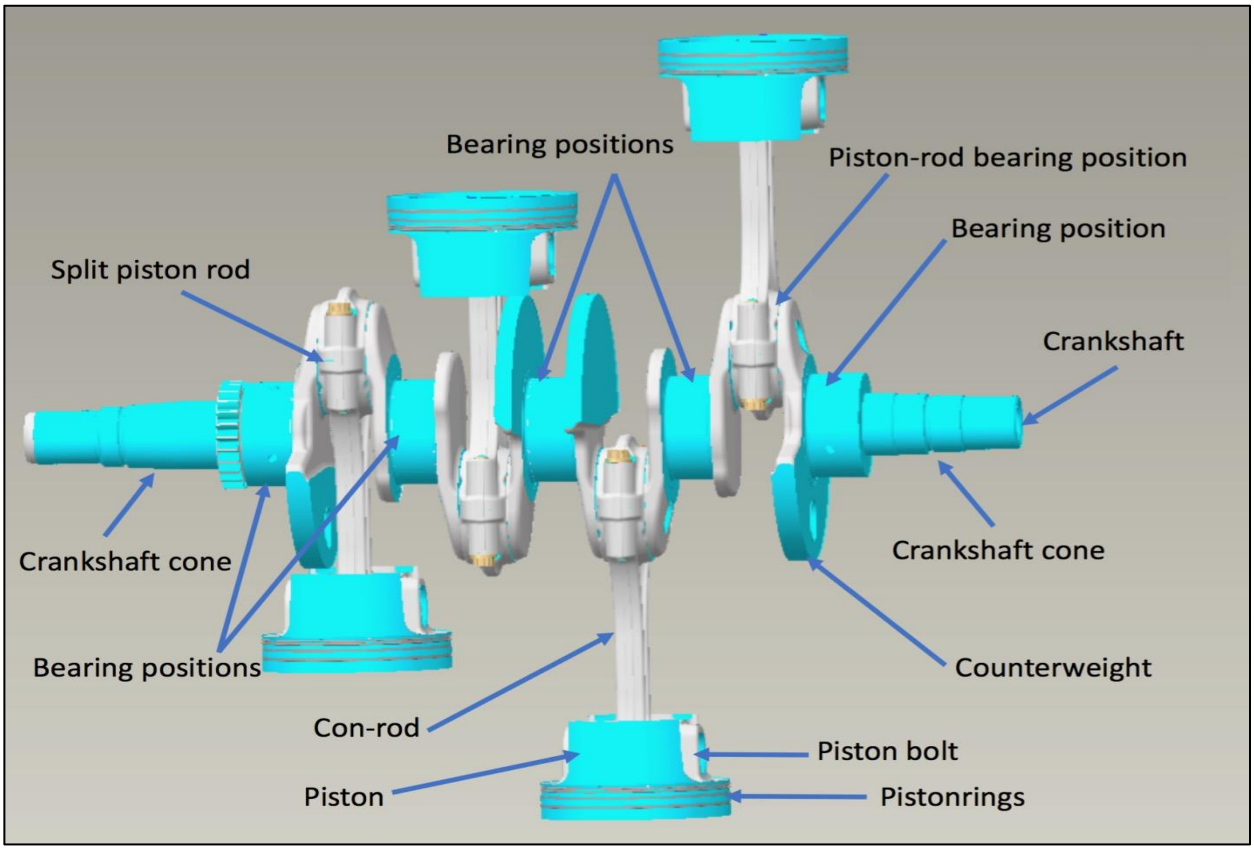

Fig. 15: Crank-train of AE2017[213]

The piston rods are 132mm long and are split at one end to make it possible to mount them on the crankshaft via two M8 x 50mm screws. The pistons are connected via a 20mm diameter bolt with the rod.

The crankshaft itself is a forged part. For the benchmarking study, the length values from the first counterweight to the last one were also determined. The cones of both ends of the crankshaft can be used for different purposes, depending on the branch and the application of the engine. So the distance between the outer walls of the counterweight represents the absolute core of the engine, which should be compared to other engines. This value is 238.8mm.

The counterweights, the con rods, and the bearings for the con rods and the crankshaft were calculated. The bearing diameter of the crankshaft bearings is 60mm and the con rod bearings are 46mm.

[213] BRP-Rotax (2016)

3.2.3 Timing drive

The valve system of the AE2017 is an OHV-system. In the AE2017, the camshaft is placed centrally at the bottom of the crank case.

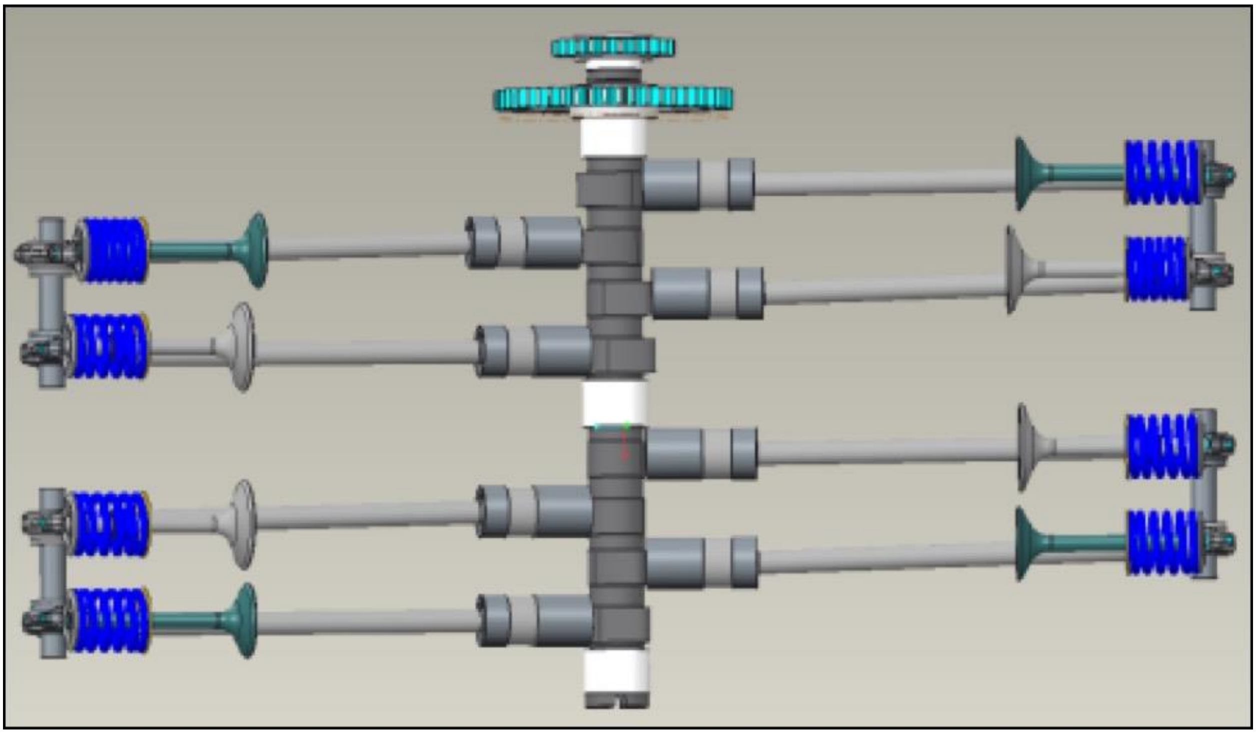

Fig. 16: Timing drive of AE2017[214]

The specific tilting system of the AE2017 is also used on other aircraft engines at BRP-Rotax. Because of the higher performance of the AE2017, the whole engine is larger than others. The largest differences in the tilting system are the longer rods and the increased diameter of the valves, which were used to reach the desired performance.

The camshaft is connected with the crankshaft via a sprocket that is directly mounted on the camshaft. The camshaft, with the necessary sprocket for rotation, is made from one piece and weighs 0,747kg.

Compared to modern automotive engines, this is a low value, especially considering that most automotive engines use the OHC-system, which requires a camshaft on every side of the cylinder head. Separate camshafts are often used for the intake and the exhaust systems, so two camshafts are placed on the side of every cylinder-head, at automotive engines. This is not the case at the AE2017.

[214] BRP-Rotax (2016)

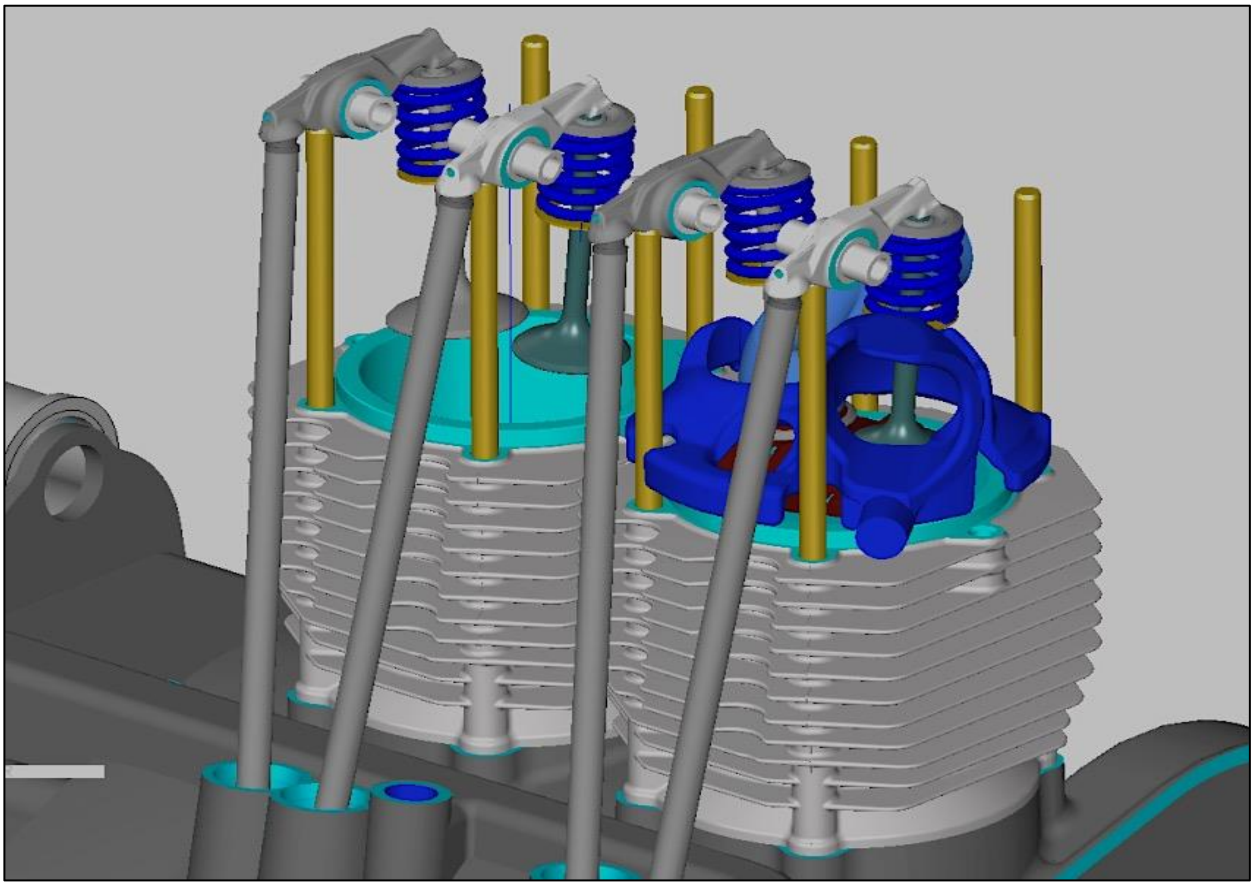

Fig. 17: Tilting system at AE2017[215]

3.2.4 Crank case

The crank case is made of Aluminium and is a chilled-casting part. It is split along the longitudinal axis into two parts. These two parts are almost completely equal; the only difference is in the part on the back side where the flange for the starter is and in the position of the cylinders.

Because the cylinders are not parts of the crank case, the crank case is very light compared to other crank cases, especially with automotive crank cases. The crank case of the AE2017 weighs 7,82kg. Even with the four cylinders without the cylinder heads but including the screws for mounting the cylinders on the crank case, the weight is only 13.15kg.

[215] BRP-Rotax (2016)

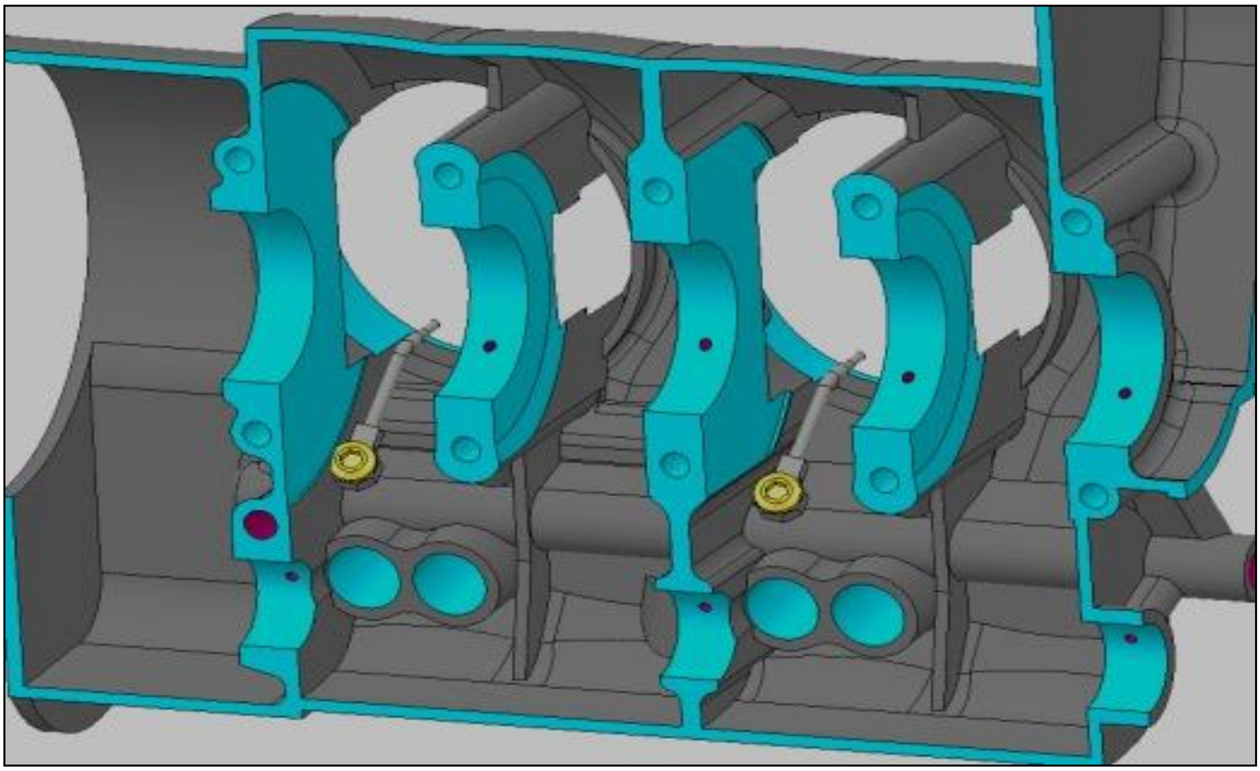

Fig. 18: Crank case of AE2017[216]

The crank case has five bearing positions. The screw connection between the two crank case parts consist of four M8 x 163 screws, six M8 x 139 screws, 16 threaded sleeves that are M8 x 32 and two M8 nuts. The sleeves, which have an internal and external screw thread, are screwed into one half of the crank case, which means that there are eight threaded sleeves for one side (four for every cylinder position). The second crank case part is mounted on the first one. The thread rods are putted through the second case part and screwed into the threaded sleeves, which were previously mounted in the first crank case part. These thread rods are again fixed with threaded sleeves, which are screwed from the outside of the second crank case part.

The cylinders are screwed with the cylinder head on the crank case. They are mounted via eight M8 x 186 screws and eight M8 x 200 screws. The long screws are putted through the cylinder head and through the whole cylinder, and they are screwed into the threaded sleeves, which have internal and external threads on both sides. The cylinder heads are also connected to the cylinders with two M8 x 55 screws per cylinder head.

[216] BRP-Rotax (2016)

3.3 Benchmarks: Selected automotive engines

After the object for comparison was defined, appropriate benchmarking objects were obtained from BRP-Rotax. From the beginning, BRP-Rotax management wanted to work with automotive engines as benchmarking objects. There were two significant reasons for this.

- **EASA certification:**

  Every newly developed aircraft engine must be certified by the responsible aviation regulatory before it can enter into operation. Since 2003, EASA has been responsible for the certification of aircraft in the European Union (EU). The certification testifies that the aircraft meets the safety requirements set by the EU. Some non-EU countries also work with EASA.[217]

  Since there have been no new developments for high-performance light-aircraft engines, in terms of EASA-certified Otto-Combustion-Engines, in recent years, BRP-Rotax decided to step out of the branch and work with modern automotive engines instead of aircraft engines. There are no new developments in boxer engine constructions for aircraft engines in the last years. All of the newer developments of boxer engine constructions, as far as BRP-Rotax knows, are from the automotive industry.

  Because state-of-the-art technology of boxer engine constructions is well known in the aircraft industry has encouraged BRP-Rotax to see itself as one of the innovation drivers in this branch. This fact supports the thinking of stepping out of the branch.

- **Costs:**

  BRP-Rotax is producing aircraft engines for private customers rather than for commercial pilots. This means that these engines need to be developed such that private customers can afford them.
  Because the automotive industry requires larger quantities, the parts the automotive industry is producing are cheaper and easier to manufacture. For this reason, the company wanted to investigate automotive engines.

[217] Cf. https://www.easa.europa.eu/easa-and-you/aircraft-products/aircraft-certification, date of access: 07.10.2016

In the automotive industry, only a few brands use boxer engines. The brands which have produced successful boxer engines with a good reputation are Alfa Romeo, Porsche and Subaru. These brands are not only successful in motorsports; they also offer boxer engines to standard consumers who use their cars every day.

It is therefore quite reasonable to search for suitable engines among these brands. It is clear that it would not be possible to find engines that completely fit the performance and measurement values of the AE2017. For the project therefore, it is important to find engines with similar dimensions in terms of bore, cylinder distance, crankshafts and crank case.

Only the engine block with its crankshaft, pistons, piston rods, crank case and cylinder heads were studied.

3.3.1 Alfa Romeo 33

The Alfa Romeo 33 is a four-cylinder boxer engine. It has a bore of 80mm, a hub of 67,2mm and a cylinder distance of 119mm. The main bearings have a diameter of 59,75mm, which is almost exactly the same as the AE2017 with 60mm. The engine offers 90hp at 6000min^{-1} and a torque of 116Nm at 4500min^{-1}.[218] A two-valve per cylinder system is used. The same system is used in the aircraft engine.

The Alfa Romeo 33 is a completely water cooled aggregate that was measured without the intake manifold and the water and oil pumps. These things are not fixed at the AE2017 and were therefore not comparable in the end.

[218] Cf. http://www.auto-data.net/de/?f=showCar&car_id=1376, date of access: 11.10.2016

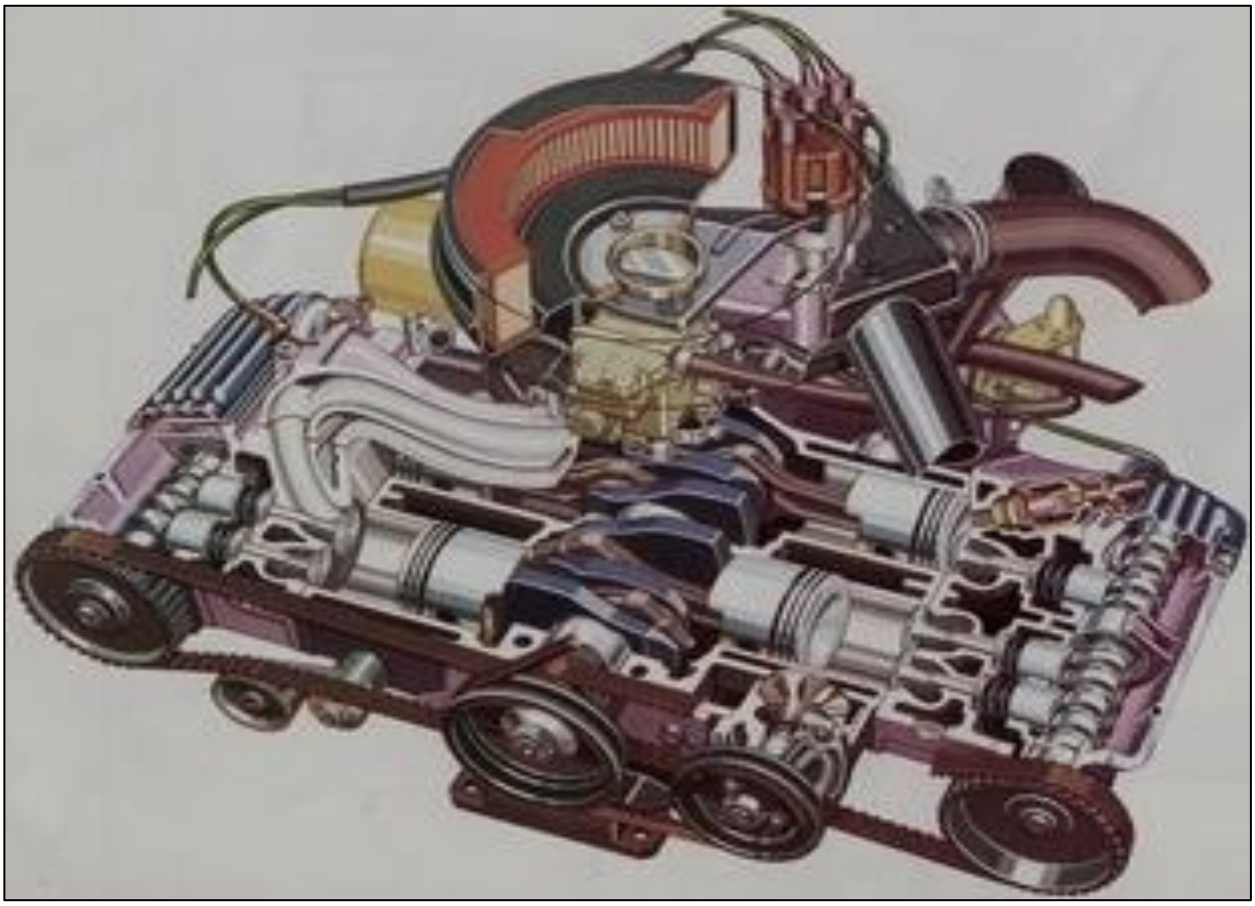

Fig. 19: Alfa Romeo Type 33 engine[219]

Besides the similar values mentioned before, the chosen motor is also interesting because it uses the three position-bearing system of the crankshaft instead of the five position-bearing system. With the investigation of this system, the company wanted to get know whether it is possible to build a shorter crankshaft with fewer bearing positions, because every bearing position needs space such that two positions fewer would mean a shorter crankshaft. This fact can also lead to a shorter crank case, which could also make it possible to save weight.

Caused to the used three position bearing system it was expected to find a shorter and therefore also lighter crankshaft in the Alfa Romeo 33. The scaling process, which is explained in Chapter 4.4 and which is important and necessary for a fair comparison, could bring even better values in terms of the length of the crankshaft at the Alfa Romeo 33. Therefore, reasons for these better values could be found, in system or process operations at Alfa Romeo, which probably could be implemented at BRP-Rotax.

[219] Cf. http://alfasud.alfisti.net/astd.html, date of access: 10.10.2016

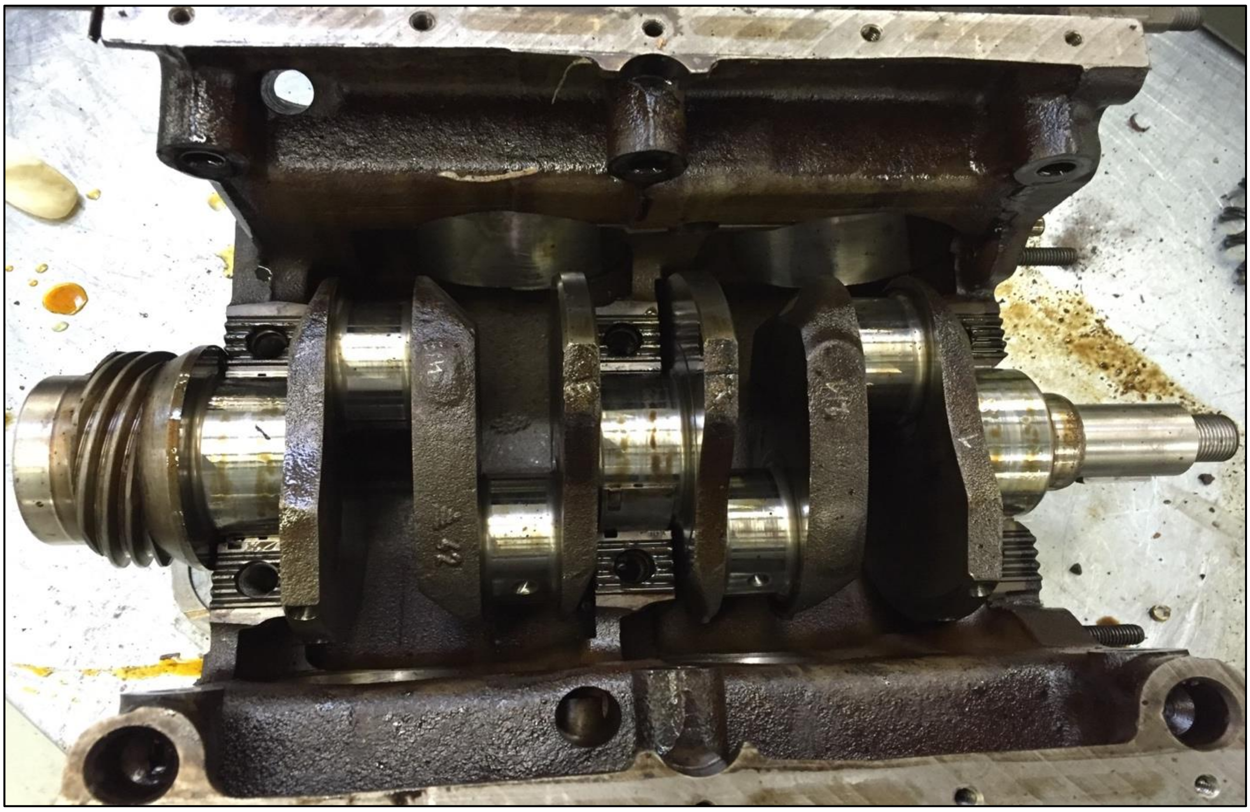

Fig. 20: 3-position bearing system at Alfa Romeo 33

Besides the length-, width- and height values, also weight was a important indicator for comparison. Because of the compact construction of this engine, it would be interesting to see if such a compact automotive engine could reach the weight values the AE2017 can reach. Therefore, the weight of the whole engine and all single parts had to be investigated.

The Alfa Romeo 33 does not use a longitudinal split crank case like that of the AE2017. Instead, it uses a flat U-shaped crank case that is split horizontally in height. This leads to the fact that bearing bridges are used with a metallic cover that goes over the whole top of the crank case.

Fig. 21: Bearing bridges at Alfa Romeo 33

For the timing drive, this engine uses a OHC system with one camshaft per cylinder head. The driving of the camshafts is done by two separate toothed belts.

3.3.2 Porsche 986

The Porsche 986 is a water cooled six-cylinder boxer engine that was used in the Porsche Boxster. It has a bore of 85,5mm, a hub of 78mm and a cylinder distance of 118mm.[220] The main bearings have a diameter of 59,7mm, which is similar to that of the AE2017: 60mm. The engine offers 228hp at 6300min^{-1} and a torque of 260Nm at 4700min^{-1}.[221] The Porsche 986 uses a four-valve system instead of a two-valve system, which means that two valves are used separately for input and output.

The 986 model was designed with a 2.5, 2.7 and 3.2 litre cylinder capacity. We investigated the 2.7 litre model. This model has an engine output per unit of displacement like that of the AE2017. The Boxster 986 has 62,52kW/l, whereas the AE2017 have 67,82kW/l.

[220] Cf. http://www.auto-data.net/de/?f=showCar&car_id=6710, date of access: 11.10.2016

[221] Cf. http://www.auto-data.net/de/?f=showCar&car_id=6710, date of access: 11.10.2016

Fig. 22: Porsche Boxster 986 engine[222]

The bearing system of this engine uses seven bearing positions for the crankshaft due to the six cylinders. If the same engine had two fewer cylinders and used the same bearing system, it would have a five-position bearing system like the AE2017. This fact made this engine interesting to the benchmarking project, especially because, through the scaling process, the engine was reduced to four cylinders with five bearing positions.

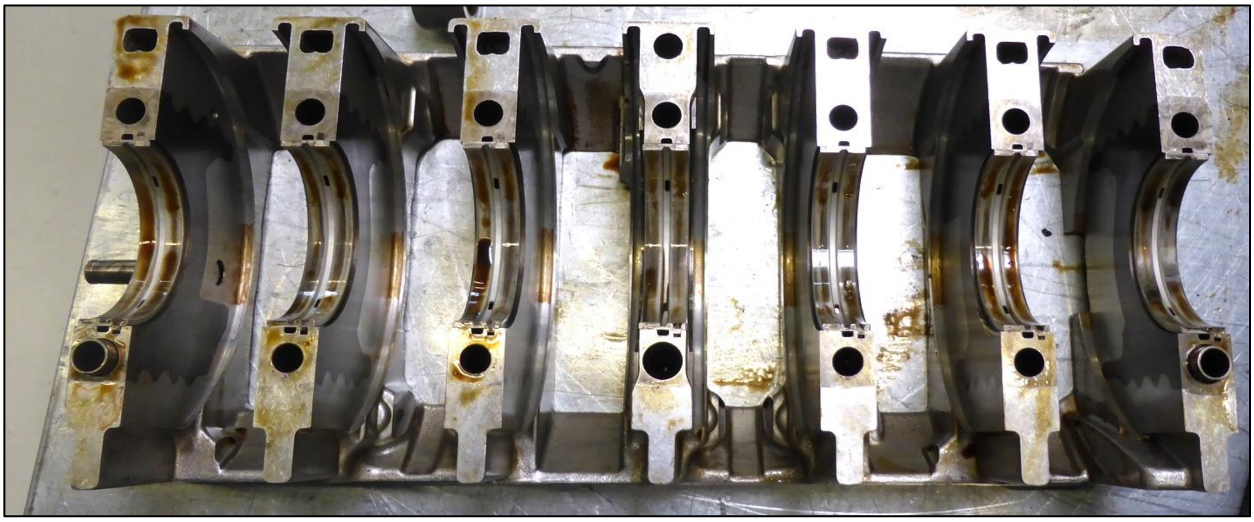

Fig. 23: Seven position bearing system of Porsche 986

[222] Cf. http://programming4.us/multimedia/24424.aspx, date of access: 11.10.2016

The length of the crankshaft is also very interesting for this project. While the complete crankshaft is a little bit longer than that of the AE2017, the scaled crankshaft length is shorter.

Another interesting fact about the crankshaft is that Porsche was able to use thinner counterweight thicknesses for performance.

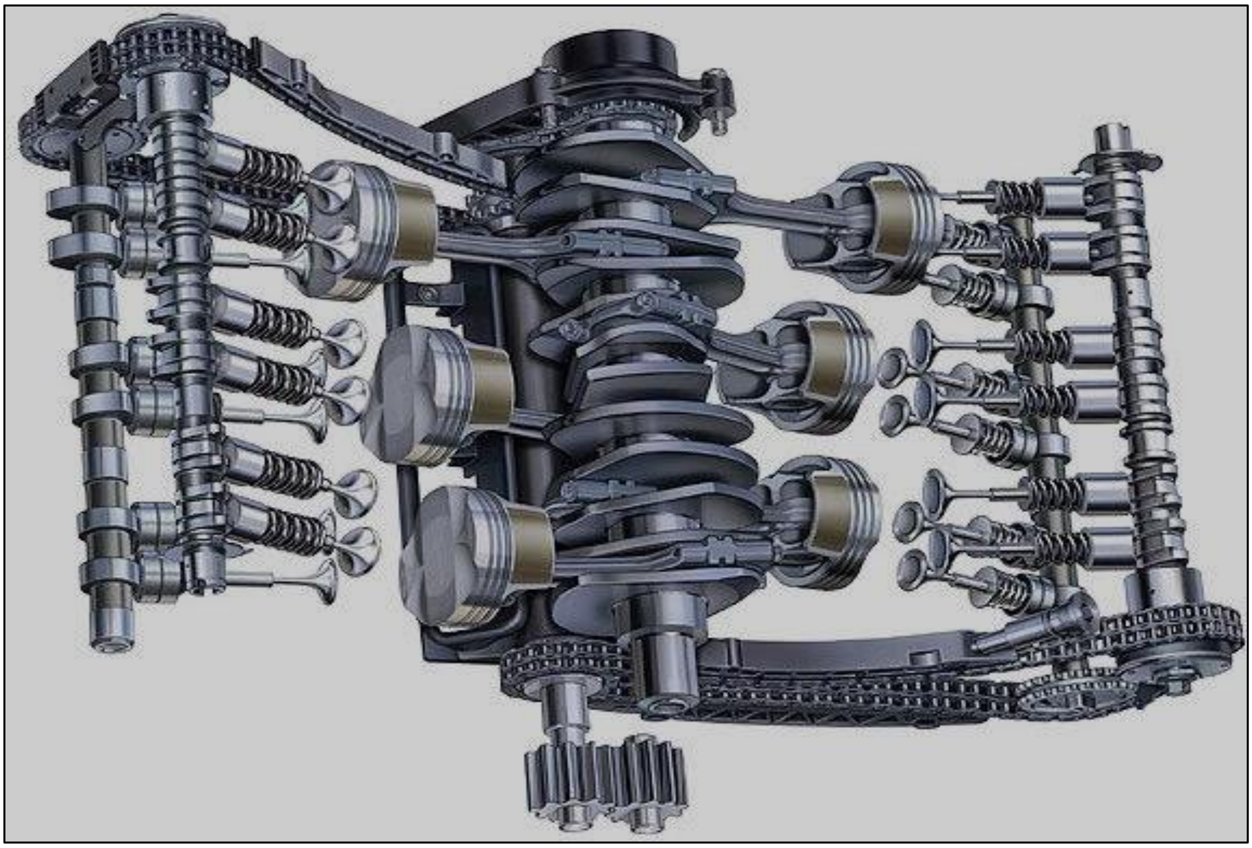

Fig. 24: Crank train and timing drive of Porsche 986[223]

The crank train of the Porsche 986 is a Double Over Head Camshaft (DOHC). The Porsche 986 uses also an intermediate shaft for the driving of the camshafts. This intermediate shaft is placed directly under the crankshaft and does not have any mass-balance function. It is just a straight rod with interlocking’s at the beginning and end. These interlocking’s are used to place the chains that drive the camshafts. The intermediate shaft itself is driven via another, wider chain, by the crankshaft. The three chains and the intermediate shaft produce a lot more weight, especially when this system is compared with the AE2017, which has neither an intermediate shaft nor driving chains.

[223] Cf. http://boxsterguide.blogspot.co.at/2010/09/intermediate-shaft-ims-bearing-info-and.html, date of access: 11.10.2016

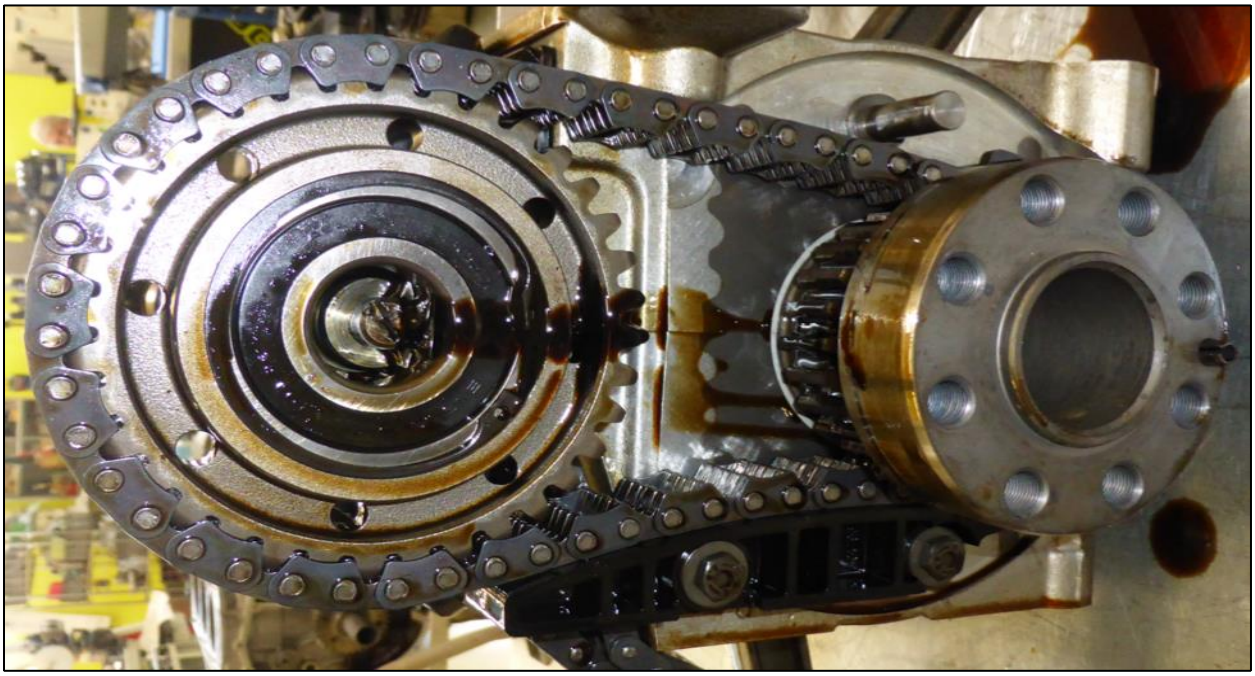

Fig. 25: Driving of the intermediate shaft by the crankshaft

Fig. 26: Crank train with intermediate shaft at Porsche 986

The crank case of the 986 is also especially interesting. What it makes special is not the case itself but how the crankshaft is placed in the crank case. The Porsche Boxster 986 uses an internal cage for bearing the crankshaft. This cage is split longitudinally and connected via screws. The cage is made from Aluminium, but the bearing positions are made from in-moulded steel to handle the forces on the crankshaft.

The cage, with its mounted pistons and rods, is placed in the crank case and fixed with screws that go through the cylinder head and that therefore fix the cylinder head to the crank case and the cage. This is done from both cylinder head sides.

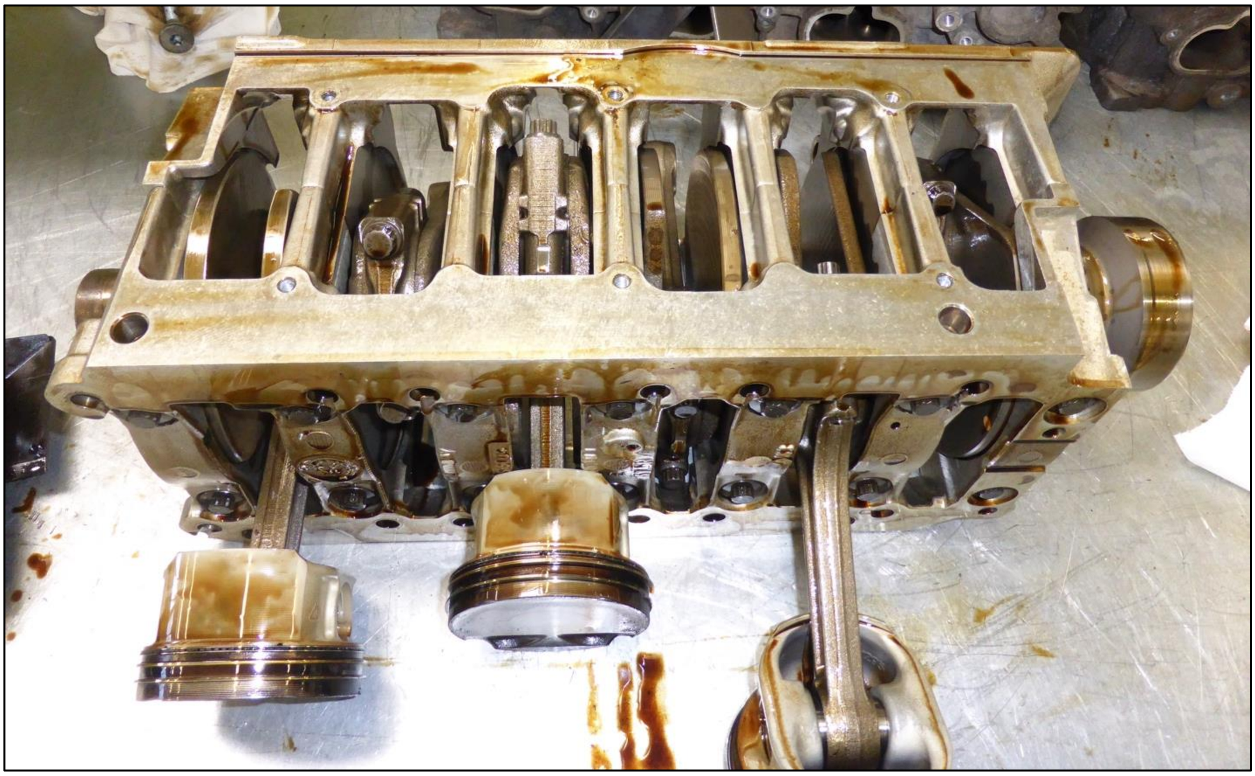

Fig. 27: Internal crankshaft cage

3.3.3 Subaru EJ 25

The Subaru EJ 25 is a water cooled four-cylinder boxer engine. The engine was used in the well-known Subaru Impreza, which is very successful at rally competitions. It has a bore of 99,6mm and a hub of 79mm, which creates a cylinder displacement of 2,46 Litres.[224] The distance between the cylinders is 113mm, which is 15mm less than the cylinder distance of the AE2017. This makes for a shorter building with almost same performance, and these results make the engine interesting.

The Subaru EJ 25 has a diameter of 60mm at the main bearing positions, which is the same as in the AE2017.

[224] Cf. http://www.auto-data.net/de/?f=showCar&car_id=16108, date of access: 20.10.2016

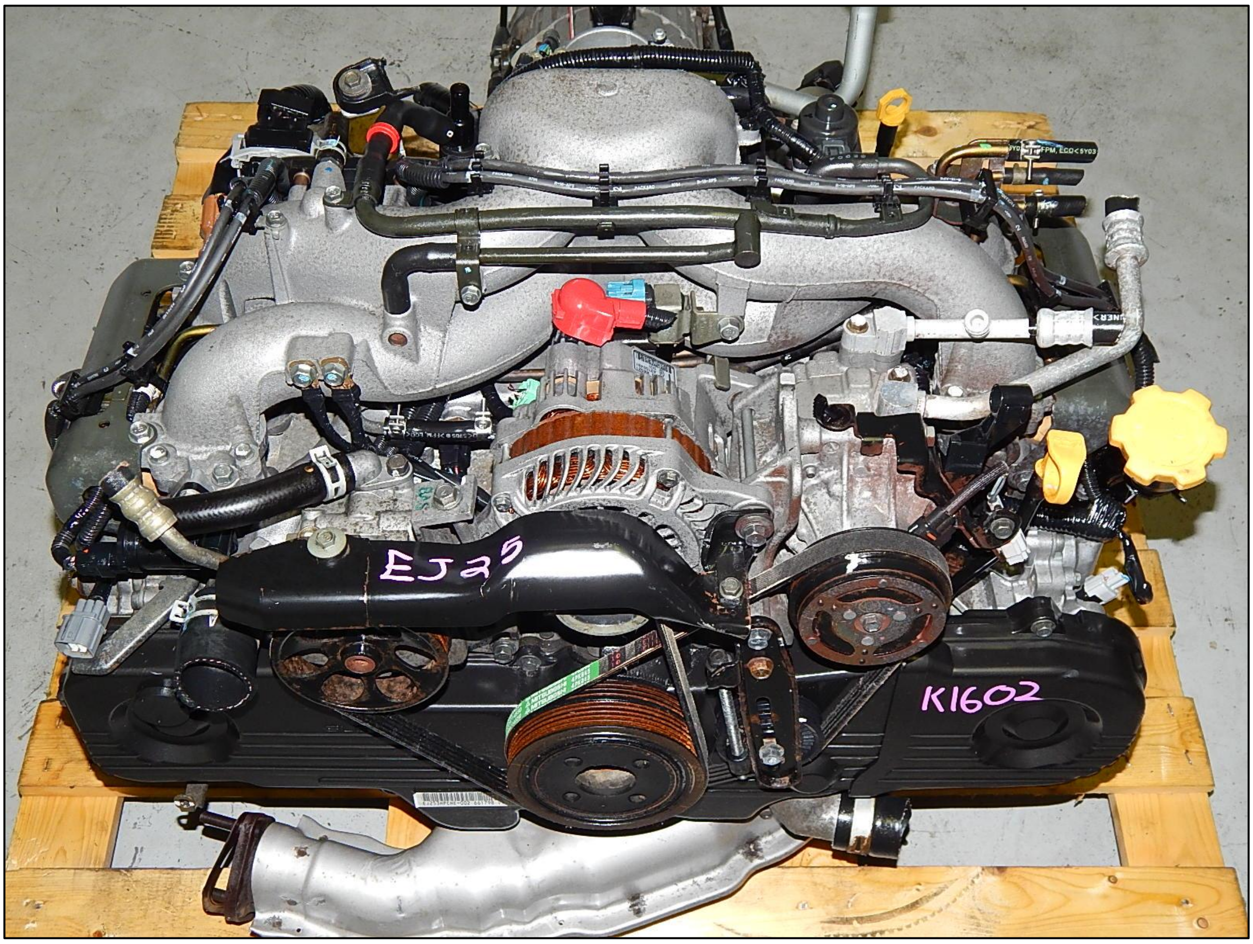

Fig. 28: Subaru EJ 25[225]

As mentioned before, the performances of these engines are very similar. As the Subaru EJ 25 offers a performance value of 167hp at 5600min^{-1}, the AE2017 offers 180hp at 5800min^{-1}. The torque is 225Nm at 4000min-1, which is higher than that of the AE2017 which is 217Nm at 5800min^{-1}. The compression value of the EJ 25, at 8,4 is also similar to the compression value of the AE2017 at 8,5.[226] The valve system of the Subaru is the same as that of the Porsche: it is a DOHC with four valves per cylinder.

[225] Cf. https://jdmracingmotors.com/en/subaru/forester-legacy-ej25-engines-ej20x-ej20y-eg33-ez30-motors/934/, date of access: 20.10.2016

[226] Cf. http://www.auto-data.net/de/?f=showCar&car_id=16108, date of access: 20.10.2016

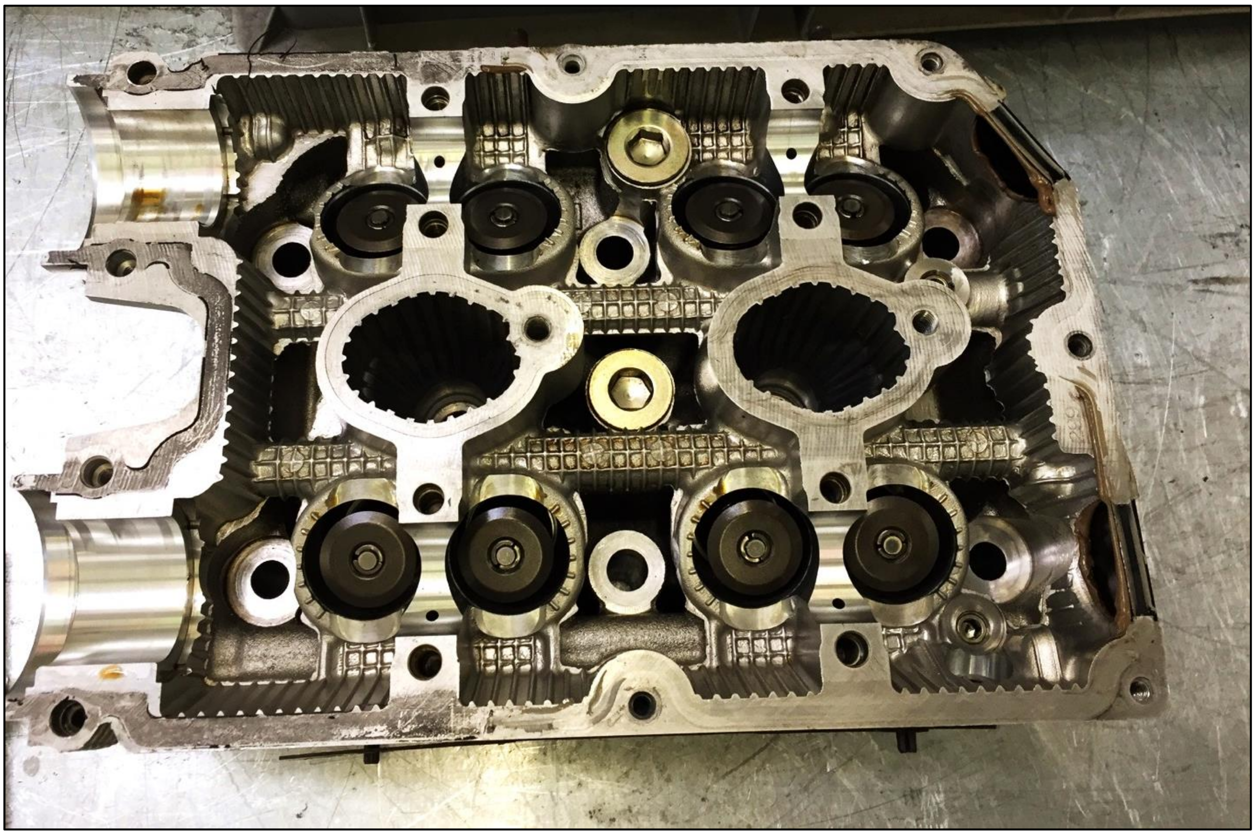

Fig. 29: Cylinder head with DOHC system at Subaru EJ 25

The size of the crank case of the Subaru also made it interesting for comparison. The crank case of the Subaru is made from pressure die-cast Aluminium and has a length of 335mm and a width of 410mm, without cylinder heads. The AE2017 has dimensions of 339mm x 420,2mm.

These similar, small, values are unusual for the automotive industry. The Subaru EJ 25 is one of the engines that best fit the AE2017 requirements, not only in performance but also from a dimensional point of view.

The second interesting fact about the crank case dimensions is that they become smaller after the scaling process, which means that the crank case of the Subaru would be even more compact.

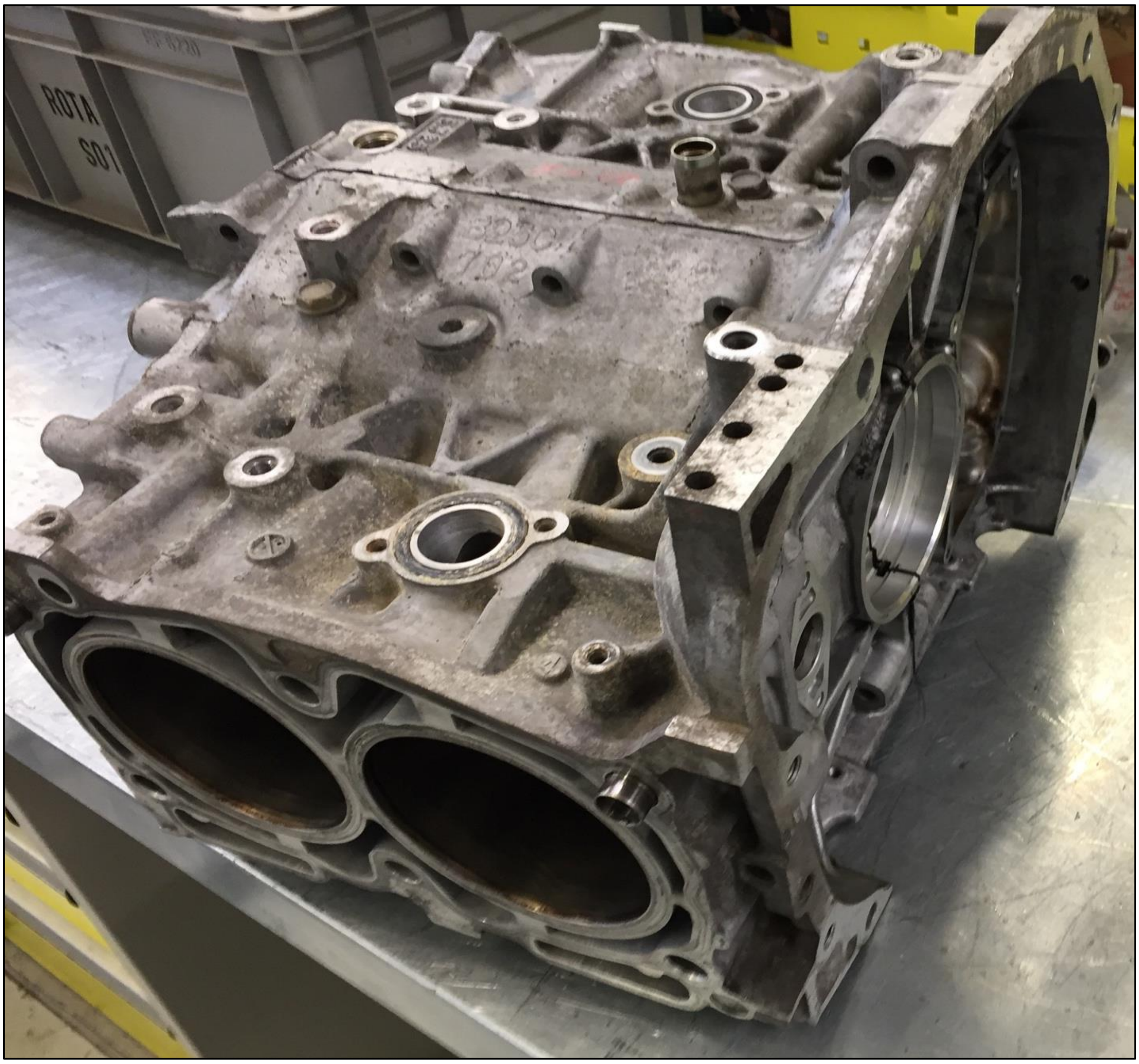

Fig. 30: Crank case of Subaru EJ 25

The bearing of the crankshaft in the crank case is achieved by a five-position bearing system. As mentioned, this system has the large advantage of offering higher stiffness to the crankshaft, which is needed at higher performances.

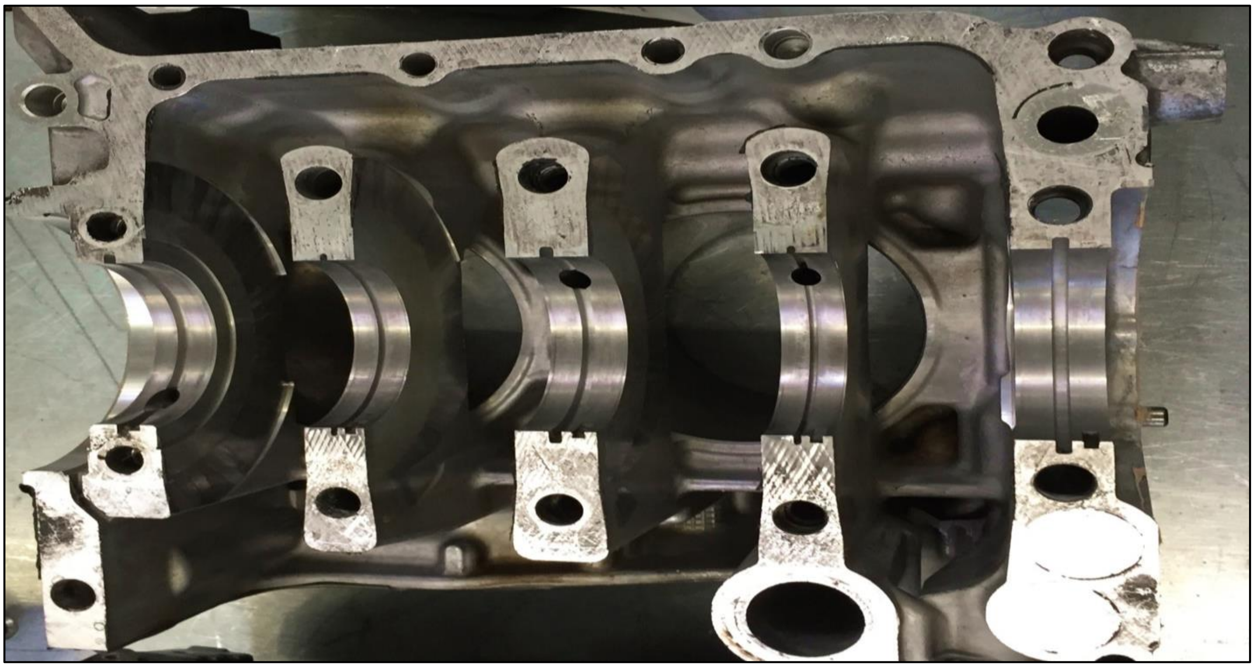

Fig. 31: 5-position bearing system of Subaru EJ 25

The crankshaft of the EJ 25 is very compact and light weight. It is better in almost all respects than the crankshaft of the AE2017. Only the weight is higher.

The thickness of the counterweights in the crankshaft of the Subaru must also be mentioned. Whereas the AE2017 has eight times the same thickness, the EJ 25 uses two different values for the thickness of the counterweights, and both are smaller than that of the AE2017.

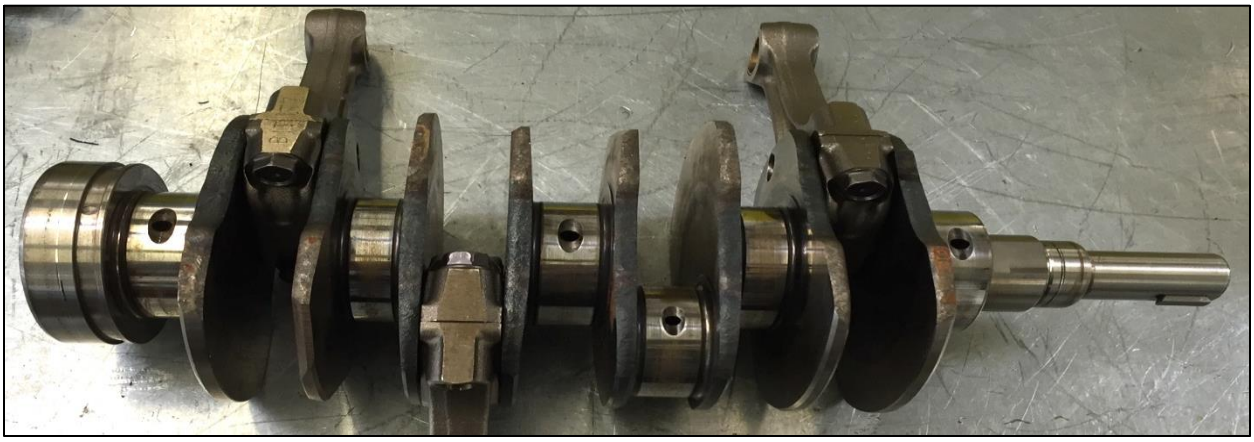

Fig. 32: Crankshaft with piston rods of Subaru EJ 25

3.4 Comparison of Objects

This chapter presents the results of the comparison phase.

At first the structure of the data collection tool, the Excel sheet, is explained. This is followed by a detailed explanation of the scaling process. At the end, the data which was gained during disassembling and measuring is presented.

3.4.1 Dividing the Engines into Systems

Before we could start to disassemble the Benchmark engines, a system for recording the data had to be fixed. The data collection tool should be a database with which further benchmarking projects could be conducted. We therefore chose to use Microsoft Excel for data collection. This has the benefit that everyone in the company can handle with it and access it.

BRP-Rotax splits its engines into several different categories. These categories help to divide the responsibility and to keep the overview. The categories are as follows:

- Crank case
- Crank train
- Cylinder/Cylinder head
- Timing drive
- Electric components
- Gear transmission
- Engine sealing
- Induction system
- Fuel system
- Lubrication system
- Cooling system
- Exhaust system
- Engine management system SW
- Engine calibration
- Turbo

For the project, only the dimensions and weight of mechanical components were investigated. This is why a few of these categories were cancelled. The focus for the benchmarking study is on the first categories: the crank case, the cylinder head, the crank train and the timing drive. The category cylinder, which in BRP-Rotax aircraft engines is a separate part, was implemented in the category crank case so that the measurements taken in this category can be compared to those of the crank cases in the automotive engines. Another category, basic data, was additionally used to give a rough overview of the performance specifications of the benchmarked engine when opening the file.

By using these five categories, the single automotive benchmarks are rendered comparable with the AE2017.

The Excel Sheet was produced in German, as the working language at BRP-Rotax is German. The first engine to be disassembled, digitally, measured and split into the categories is the AE2017. Therefore, the following chapter offers an overview of the measurement system used by showing the measured values of this engine.

The Excel sheet of the whole benchmarking study can be found in Appendix.

Basic data

The basic data of the AE2017 is mentioned in Chapter 4.2.1. The basic-data table in the Excel sheet was extended by the cylinder distance and by the number of cylinders. Also the compression value was added. The other values entered into the table of the basic data—such as performance per displacement, the speed of the piston or the power-to-weight ratio—are calculated values.

Crank case

The crank case was measured once without the cylinders and again with the cylinders. The measurement with the cylinders makes the crank case wider and heavier. The length did not change, as the cylinders are placed on the side of crank case. The weight of this category, with all included parts, is 13,15kg.

The weight of the screw connections for the crank case was determined separately to create one more value for comparison. This was done for all categories that mention a screw connection. The value of the screw connection at the crank case is 0,871kg and is included in the total weight.

Crank case (including cylinders)	Value
Total length [mm]	339
Total width [mm]	420,2
Total height [mm]	255
Total weight [kg]	13,15

Cylinder length [mm]	115,1
Distance cylinder walls (Y) [mm]	29
Distance between cooling ribs (Z) [mm]	2

Table 4: Measurement of the crank case of AE2017[227]

The total width of the crank case is 420,2mm. This value results from taking the width of the blank crank case, which is 190mm, and adding twice the length of the cylinder, which is 115,1mm.

The measured values between the walls and the ribs of the cylinders, which are identified as Y and Z, are discussed later.

Cylinder head

The length of the cylinder head of the AE2017 is represented by the length of two cylinders when they are mounted on the crank case. The gap between two cylinders is therefore also a part of the length. This gap is labelled Z. This measurement makes sense, because at the automotive engines the cylinder heads were also always two connected cylinders.

The cylinder head weight of 1,39kg represents the weight of one single cylinder without valves, springs and valve cover. The weight for comparison was measured again from the whole cylinder head side, which means the addition of two single cylinder heads with the including valves, springs and screwing connection for both of them. This value is 4.56kg.

[227] Own illustration

Cylinder head	Value
Total length [mm]	267,4
Total width [mm]	163,7
Total height [mm]	123,7
Total weight (per side) [kg]	4,56
Valve cover weight [mm]	0,18

Table 5: Measurement of the Cylinder head of AE2017[228]

The screw connection, which connects the cylinder head and the cylinder with the crank case, is mentioned in the category of the cylinder head and not in the category of the crank case. This has the reason cause only through the mounting of the heads, both cylinder heads and cylinders are connected with the crank case.

The construction of the valve cover of the AE2017 was not yet finished. The 0,18kg value for the weight of the valve cover was taken from previous engines like the 912iS. Because the valve cover of the AE2017 should not have excessive weight, the cover of the 912 yields a good value for comparison.

Crank train

The category of the crank train is split into three parts. To create the movement, which is transferred to the transmission, the crankshaft, the piston rods and the pistons are necessary.

The measurement of the crank train is one of the most important measurements, because the crank train represents the beginning of the construction of the engine. The crank case, cylinders and cylinder heads are built around the crank train. The limits in construction are set by the crank train, especially by the bore and the hub.

What the engine is to be used for determines what performance the engine should have. This performance is physically generated through the torque and the rotational speed. The torque is generated through the force which occurs when the fuel explodes in the cylinder and presses the piston downwards, which is multiplied by the distance the force has to the pivot point and is represented through the con rod bearing. The distance to the

[228] Own illustration

pivot point is determined by the length of the piston and therefore also through the length of the hub.

The torque is thermodynamically calculated through the bore and the hub, which represents the beginning of the calculation of the engine. When this two values are set, the bearing of the crankshaft and the crankshaft itself can be calculated. This is followed by the calculation and construction of the crank case and the other necessary parts.

Crankshaft

Crankshaft	**Value**
Total length [mm]	460
Core length between bearing: 1-5 [mm]	290
Core length of outer walls of counterweights [mm]	238,8
Maximum width [mm]	141,8
Total weight [kg]	8,95
Thickness of counterweights [mm]	8,7
Hardening of bearing positions [mm]	Inductive hardening
Bearing diameter main bearing positions [mm]	60
Bearing diameter piston bearing positions [mm]	46
Bearing lengths main bearing positions [mm]	25,1 / 22,2 / 22,2 / 22,2 / 25,1
Bearing length piston bearing positions [mm]	22,2

Table 6: Measurement of the crankshaft of AE2017[229]

As mentioned in Chapter 4.2.2, the length of the crankshaft was measured in different ways. The core value of 238,8mm represents the most important value for comparison. In this value, the lengths of the first and the last bearing position are not implemented.

[229] Own illustration

Adding these two values would yield a total weight of 290mm, which can also be used for comparison.

The maximum width of the crankshaft is represented through the width of the counterweights, which is 141,8mm.

The first and last bearing positions of the crankshaft are 25,1mm long, whereas the bearing positions in the centre are 22,2mm long.

The bearing shells of the crankshaft and the piston rods were not mentioned in the study because they are not calculated yet.

Piston rod

Piston rod	**Value**
Total length [mm]	132
Total width (Head/Eye) [mm]	32,2 / 75,9
Piston rod shaft width [mm]	22
Piston rod thickness Eye [mm]	22
Piston rod thickness Head [mm]	19
Piston rod inner diameter Head [mm]	22
Piston rod inner diameter Eye [mm]	49
Piston rod screw connection	M8x50
Total weight [kg]	0,484

Table 7: Measurement of the piston rod of AE2017[230]

The length of the piston rod was measured from the centre of the circle where the piston rod is mounted on the crankshaft and the centre of the circle where the piston bolt connects the rod with the piston. This value is 132mm.

The diameter of the top and bottom of the piston rod is with 22mm and 49mm, respectively, as measured without bearing shells. Because the bearing diameter of the

[230] Own illustration

con rod at the crankshaft is 46mm, the bearing shells should have a thickness of 1,5mm. The screwing connection of the piston rod is M8x50.

Piston

Piston	**Value**
Piston bolt length [mm]	51,2
Piston bolt diameter [mm]	20
Total piston weight (including bolt) [kg]	0,434

Table 8: Measurement of the Piston of AE2017[231]

The most interesting fact about the piston for BRP-Rotax is the weight of the piston, including the piston bolt and the piston rings. Therefore, this value was measured.

Timing drive

The category of the timing drive consists of the valves, the springs, the tilting system, with its necessary parts, and the camshaft. The whole timing drive, including the camshaft, has a total weight of 3,51kg.

Timing drive	**Value**
Number of valves per cylinder	2
Intake valve diameter [mm]	42
Outtake valve diameter [mm]	35
Valve cup weight [g]	108
Tilt rod weight [g]	50,3
Return pipe weight [g]	24
Toggle lever weight [g]	53,4

[231] Own illustration

Toggle lever bolt weight [g]	17,3
Sprig weight [g]	32,5
Intake valve weight [g]	68,5
Outtake valve weight [g]	51,6
Camshaft total length [mm]	295,15
Camshaft total weight (including sprocket) [kg]	0,747

Table 9: Measurement of the Timing drive of AE2017[232]

Unlike the automotive engines, the AE2017 uses the same valve cups for intake and outtake. This is because the most automotive engines use a DOHC system which therefore often need two different valve cups.

The camshaft is almost 300mm long and weighs 0,747kg, including the sprocket. The system does not have any other camshaft and does not need any toothed chains or belts.

3.4.2 Scaling Process

After the engines were disassembled and their measurements entered in the Excel sheet, every engine except the AE2017 was scaled. The scaling process is intended to bring all engines to the same level. Because the AE2017 is the object to be improved, the dimensions of the Alfa Romeo 33, the Porsche 986 and the Subaru EJ 25 were up-, or downscaled to reach its dimensions. The goal of the project is not to see what dimensions the engines actual have but to determine what dimensions the engines would have if they had the same bore and hub as the AE2017 and used the same principles of cooling, bearing, etc. Only by implementing the scaling process in the benchmarking study can allow the study to have a representative value.

The basis of the scaling process is represented through the bore and the hub. Because these two parameters are mostly responsible for the generated performance, as mentioned in Chapter 4.4.1, all three benchmarking engines should be adapted to a bore of 88mm and a hub of 80mm, which are the values of the AE2017. The assumption is that, with these parameters, the engines would be thermodynamically able to bring in the right amount of fuel and air to generate the right combustion and offer the same performance. This means that, for example, the Subaru EJ 25 would still be able to offer

[232] Own illustration

167hp with a diameter of 88mm instead of 99.5mm. The scaling of the benchmarking engines must be calculated and simulated when the project of the AE2017 is continued. But, after a discussion with the thermodynamic expert at BRP-Rotax and my supervisor, I conclude that this assumption can be used for the first comparison of the engines.

Because bore represents the core of the crankshaft construction, everything changes upon adaptation. The bore changes the cylinder distance, which again changes the whole crank case. The change in size leads to a corresponding change in weight.

The scaling process will be shown by the scaling of the Subaru EJ 25 in the previously fixed categories.

Basic data

By changing the bore and hub, the piston displacement sunk almost to 2,0 Litres. The scaled cylinder distance was calculated by multiplying the quotient of the two bores with the initial cylinder distance. This yields a new cylinder distance of 99,94mm. It is obvious that the cylinder distance on smaller bore would be less.

The performance per Litre of cylinder displacement and the performance per weight, changes to better values as the cylinder displacement and the total weight of the engine sunk, caused by the changed values.

Crank case

The width of the crank case changes in the same relation as the hub changes. So the hub was factorized with 80/79, and this value was multiplied by the 410mm of width. The assumption is that the engine would need more than the 1mm more per side.

Because the cylinder distance of an engine directly influences the length of the crank case, the decision was made to multiply the crank case length with the quotient of the scaled and the primary cylinder distance. As the scaled cylinder distance is smaller than the primary cylinder distance, the length of the crank case sunk.

The height of the crank case was calculated on the assumption that it would change in the same relation as the quotient of the two different bores. The scaled height is therefore calculated by taking the height of 236mm and multiplying it with 88/99,5. The scaled height is therefore 208,72mm.

The height of the crank case of the Subaru EJ 25 was measured without the flange for the gear transmission. This was done with all engines, including the AE2017.

As the scaled values of the length, the width and the height were calculated, they were used to determine the weight. The crank case was treated as a box with a specific weight.

Knowing the weight and the dimensions of the initial crank case made it possible to calculate the theoretical density of the crank case. Knowing the density of the crank case, the weight of the scaled crank case could be calculated. This is done by multiplying the theoretical density with the scaled length values on the assumption that the initial and scaled crank case have the same density. Because the scaled crank case sunk in its dimensions, the weight also became less.

The screwing connections were not scaled because the screws are standard parts and because the changing factor would not make a large difference. So the weight of these connections was not adapted.

These principles for scaling the length, the width, the height and the weight, were used for all categories for all benchmarking engines.

Cylinder head

The length and the width of the cylinder head of the Subaru EJ 25 were scaled like the values reported above. Only the scaled height value did not change compared to the initial height, because it was assumed that the changing of camshafts in the cylinder head would not change significantly the height, especially considering that the height depends on the valve cover, which would not change in shape but only in length and therefore in weight. So the height stays 180mm.

Crank train

In the crank-train category, the crankshaft width remains the same after the scaling process. The width of the crank shaft was measured at the counterweights. Because these counterweights were calculated and simulated for to allow the engine to offer the desired performance, they were not to be changed. The thickness could not be adapted either.

For these fundamental parts, as the counterweights or the bearing positions are, it was decided to do not scale them, as a simple scaling of these values, as it was done with the other terms, was not possible and was not necessary for a first comparison.

The length of the piston rod was not scaled with the quotient of the different cylinder distances, as other length values were; it was instead adapted by the quotient of the different hubs, because the piston rod is directly influenced by the size of the hub.

The width of the piston at the piston eye and the piston head did not change because it is not possible to determine the scaling of these values at this stage of the project without resorting to simulation. This is also why neither the thickness nor the shaft width of the con rod are changed for scaling, only the weight changes for the scaled value with the quotient of the initial and scaled length.

The piston changed in weight by the quotient of the initial and the scaled bore.

Timing drive

The diameters of the valves were scaled by setting the area of the diameters in relation to the area of the piston. The quotient of these two values was used to calculate the scaled valve diameter, as the scaled bore is known. The assumption is that the relation between the valve and the piston areas must stay the same. Also, the EJ 25 uses two separate valves for intake and two separate valves for outtake for the process.

The change of the weight of the two different valves and springs was not mentioned, as the change would be minimal. The valve cups were not scaled either to facilitate comparison.

The length of both intake and outtake camshafts was scaled by the quotient of the cylinder distance, as was the weight of the camshafts.

The camshafts were driven by a toothed belt with a weight of 306 grams, which was not mentioned in the scaling process.

3.4.3 Comparison of scaled Alfa Romeo 33 with AE2017

When starting to scaling the Alfa Romeo 33, by changing the bore and the hub, it was obvious that this engine could not be used for comparison. The gaps in the diameter and the hub were too large for us to make reasonable interpretations of the scaled values. The assumption—that the engine would still be able to bring the right amount of fuel and air into the combustion chamber after the scaling process—could no longer be maintained.

After a discussion with the supervisor and the thermodynamic department at BRP-Rotax, the decision was to cancel this engine from the benchmarking study.

The measurements of this engine remain in the Excel sheet, but the results are not mentioned in any later discussion of the project.

3.4.4 Comparison of scaled Porsche 986 with AE2017

The comparison data can be found in Appendix A.

3.4.5 Comparison of scaled Subaru EJ 25 with AE2017

The comparison data can be found in Appendix A.

3.5 Discussion of gaps

As mentioned in Chapter 1.3, Phase IV involves discussion of the performance gaps AE2017 has compared to the chosen automotive engines. For the discussion, a list of every negative aspect of comparison between two engines was generated. This list provides an overview of which aspects of the aircraft engine need to be improved.

This chapter goes through the points of this list and documents what information was generated in the different meetings. Only those parameters for which the AE2017 exhibits worse values, are mention.

The breakdown of the values has the same structure as the values of the measuring and comparison phases. The only change is that the different categories are separated into engine length, engine width, engine height and engine weight.

As a basis for the information about the percentage differences, the values of the AE2017 are taken as 100%.

3.5.1 Discussion of performance gaps to Porsche 986

The first and most important value—the value by which almost all other values are influenced—is the cylinder distance. Porsche was able to achieve an almost 6% shorter cylinder distance for its engine. This means that the scaled value of the cylinder distance of the Porsche 986 is 120,5mm compared to the 128mm on the AE2017. The shorter distance is also reflected in the length of the crank case, which is 6% shorter, and in the different length values of the crankshaft, which are between 7% and 26% less.

Engine Length Parameters

The value of the cylinder distance of the Porsche 986 is generated through different length values of the crankshaft. These values are as follows:

- 2 x ½ of the length of the bearing position of the piston rod (20mm)
- 2 x the length of the bearing position of the main bearings (44mm)
- 4 x the thickness of the counterweights (33,2mm)
- 1 x additional the length of bearing position of the piston rod (20mm)

The addition of these values, considering small measurement errors, results in the actual cylinder distance of 118mm.

Summing up the same values of the AE2017 also results in the cylinder distance. This means that these single values are, besides other factors, responsible for the difference in the length of the cylinder distance.

Engine-Length-Parameters	**Porsche 986 scaled**	**AE2017**	**[%]**	
Basic data:				
Cylinder distance [mm]	121,45	128	5,12	negativ
Crank case:				
Crank case length [mm]	321,12	339	5,27	negativ
Crank train:				
Crankshaft				
Total length of crankshaft[mm]	341,02	460	25,86	negativ
Crankshaft core length bearing: 1-5 [mm]	256,62	290	11,51	negativ
Crankshaft core length of outer walls of counterweights [mm]	228,49	238,8	4,32	negativ
Maximum width (measured at counterweights) [mm]	140	141,8	1,27	negativ
Counter weights thickness [mm]	8,3	8,7	4,60	negativ
Bearing length of main bearings [mm]	21,5/22/22/22/22/22/19	25,1/22,2/22,2/22,2/25,1	-	negativ
Bearing lengths of piston bearings [mm]	20	22,2	9,91	negativ
Piston rod				
Piston rod thickness Eye [mm]	20,2	22	8,18	negativ

Table 10: Negative list of comparison of Porsche 986[233]

The difference in the length values may not seem very large, but given that the AE2017 has a total weight of 37,10kg at a total length of 339mm, the aircraft engine has an

[233] Own illustration

average weight value of 0,2kg/mm. This means that an only 10mm shorter crankshaft results in 2kg less weight, which represents 5% of the total weight. Taking into account that every kg is important in the aircraft industry, especially in the light-weight sector, one can understand the desire to build a shorter crankshaft.

Porsche was able to generate shorter bearing positions for the piston rod, and shorter bearing positions for the main bearings. They were also able to make the thickness of the counterweights almost 5% shorter. This means that the calculation, simulation and construction of the crankshaft, resulted in better values. The question for BRP-Rotax is therefore not only why the others can produce shorter crankshafts etc., but why BRP-Rotax is not able to produce better values assuming that the actual values of the AE2017 are the best values they could generate.

During the meetings, a few reasons were discussed for the gaps in the length values, especially for the cylinder distance. These are the reasons:

- Bearing system of crankshaft at Porsche 986
- Actual crank case screwing concept of AE2017
- Usage of same cylinders and cylinder heads at AE2017
- Standardized bearing lengths at BRP-Rotax
- Air cooling system of cylinders at AE2017

Bearing system of crankshaft at Porsche 986

Porsche uses a sophisticated bearing system for the bearing of the crankshaft. The internal cage with the in-moulded steal bearings increases the stiffness of the crankshaft. It is assumed that, because of the internal cage, a shorter crankshaft can be achieved.

Given the weight of the cage concept in the Porsche 986, the system cannot be taken over. The internal cage plus the screws that it needs to connect both sides weighs over 11kg. This value was measured without the crankshaft, the pistons and piston rods. It is not an option for the AE2017 to generate a shorter cylinder distance but while gaining more weight.

In addition, the length of the crank case of the Porsche 986, which is directly influenced by the cylinder distance, is 6% shorter. But a weight reduction cannot be found here either. The crank case of the Porsche 986, without the internal cage, weighs more than twice as much as the crank case of the AE2017.

The 6% length saving is also reflected in the intake camshaft. Because of the DOHC timing drive concept with its four camshafts, the Porsche 986 weighs almost 14kg compared to the 3,5kg of the AE2017. Again, it was not possible to consider changing the concept at this point.

In general, it can be said that the price Porsche is paying for a more compact engine is too high for BRP-Rotax. This does not mean that Porsche has a bad concept, only that it would not be used if the role of weight was more important.

Actual crank case screwing concept of AE2017

The actual screwing connection of the crank case is described in Chapter 3.2.4. This concept uses six screws per cylinder. Four of them connect the cylinder and cylinder head with the crank case, and two more screws connect the cylinder head with the cylinder.

This concept influences the cylinder distance, not directly, but through the crank case length. The screws require a minimal amount of space in the crank case, which is reflected in the cylinder distance.

The six screws concept also is used to generate the sealing of the cylinder and the cylinder head. Because the AE2017 does not use a multi-layer gasket, the sealing of the cylinder head must be generated through two screws. One option for reducing the cylinder distance is to use a multi-layer gasket, which leads to a through connected four-screws concept of the cylinder and cylinder head. This would reduce the cylinder distance as the two screws which connect the cylinder head with the cylinder are placed along the longitudinal axis of the engine. Every saved millimetre means saved weight, which is always wanted in the aircraft industry.

Another fact that is directly connected with the six-screws concept is the principle of using single cylinders and cylinder heads for the construction. Connected cylinders, as used in modern automotive engines, could lead to a shorter cylinder distance. The principle behind this idea is to reduce the distance of the walls of the cylinders, which is now 29mm, to a minimum. The Subaru EJ 25 engine uses this principle and has a distance of only 13,5mm between the cylinder walls, which would mean a saving of 15,5mm, compared to the value of the AE2017.

This idea, of course, also has disadvantages. The cylinders would most likely need to be cooled by water instead of by air stream, except it would be possible to build a connected cylinder head with cooling ribs, which could reduce the temperature enough. The other disadvantage would again be the weight. The construction would mostly have more weight, as both the Porsche and Subaru engines have more weight in the category of the crank case, where the cylinders are included.

Nevertheless, a change in the concept of the cylinders should be considered. A new concept could be calculated and simulated to see if better values can be generated.

Usage of same cylinders and cylinder heads at AE2017

The BRP-Rotax aircraft engine AE2017 uses four similar cylinders and cylinder heads. This results in many benefits in the production, considering the lean philosophy in the company, where standardized parts are desirable.

In terms of calculation of the cylinder distance, this philosophy is a disadvantage. Not every piston requires the same cylinder and cylinder head, considering the cooling of the cylinders. Given that same parts are used, the orientation in construction was on that piston, which needs the largest cylinder and cylinder head. This therefore means that some cylinders could be oversized.

Talking with the responsible engineers lead to the fact that the concept of same cylinders was a point which was set on the beginning of the project, as the company is using this principle since years. Given the positive experience BRP-Rotax had with this principle, they decided to use it again. Because this engine is still in the concept phase, it may be possible to recalculate with adapted cylinders and cylinder heads to see which new length values could be generated. An investigation should also be made of the additional costs in the production line that will accrue as a result of using different cylinders and cylinder heads.

Standardized bearing lengths at BRP-Rotax

As mentioned, standardisation is part of the lean principle, which is a very large topic at BRP-Rotax. This principle is used not only for parts, but also for processes. One aim of the company is therefore to use standardised length values for the bearing positions at the crankshaft process. This offers the large benefit that the production of the crankshaft is easier and faster. Also, retooling of the process and the number of tools needed can be minimized with such principles. But this also means that some bearing lengths are oversized.

BRP-Rotax has to perform a cost-benefit analysis of the fact for using different, but not oversized, bearing length values for the crankshaft.

Air cooling system of the cylinders at AE2017

While disassembling and measuring the AE2017, the distance between the cylinder walls and the distance between the ribs was measured. The Y-value, which represents the distance between the walls, is 29mm, and the Z-value, which represents the distance between the ribs, is 2mm. These two values are not only higher because of single cylinders are used, as mentioned; they are also higher compared to air-cooled single-cylinder engines like the 912iS and the 915iS. Both of the named engines have smaller

Y-values. On both of them, this value is 19mm. The Z-value is 2mm for both engines. So this means that BRP-Rotax is actually able to build and mount cylinders where the distance to the cylinder walls is 10mm less. This shorter value can be directly transferred to a 10mm shorter crankshaft.

Of course, both of these engines are smaller engines with less performance. Nevertheless, this is a fact worth further investigation.

Another reference value is an older, air-cooled Porsche 911 Carrera. It is a six-cylinder boxer engine with 210hp and a 2,7 litre cylinder displacement with a cylinder distance of 118mm. The engine has a Y-value of 14.7mm, which is almost the half the value of the AE2017, and a Z-value of 2,3mm. The Porsche 911 Carrera is not a part of this benchmarking project. The data was provided by a machinist at BRP-Rotax. The data was noticed in the Excel sheet as well.

Engine Width Parameters

The only negative aspect in the width-parameter category is in the difference in the diameters of the main bearing positions. Because the difference is only in 0.3mm, it was discussed no further.

Engine Height Parameters

No negative aspects were generated in the width category.

Engine Weight Parameters

No negative aspects were generated in the weight category.

3.5.2 Discussion of performance gaps to Subaru EJ 25

The most important reference value for the Subaru engine is also the cylinder distance. Because the Subaru has a compact building, it has a 22% smaller cylinder distance than the AE2017: i.e., a distance of almost 100mm compared to 128mm. This distance is again reflected in many other length terms of the scaled Subaru EJ 25, as discussed in this chapter.

Engine-Length Parameters

The length of the cylinder distance is a sum of the same parameters but with different values, as with the Porsche 986. Therefore, the same parameters must be investigated.

Engine-Length-Parameters	Subaru scaled	AE2017	[%]	
Basic data:				
Cylinder distance [mm]	99,94	128	21,92	negativ
Crank case:				
Total crank case length [mm]	296,28	339	12,60	negativ
Crank train:				
Crankshaft				
Total crankshaft length [mm]	314,85	460	31,55	negativ
Crankshaft core length bearing: 1-5 [mm]	219,34	290	24,37	negativ
Crankshaft core length of outer walls of counterweights [mm]	181,31	238,8	24,08	negativ
Maximum width (measured at counterweights) [mm]	1x8,5mm/7x6,8mm	8,7	-	negativ
Bearing lengths main bearing positions [mm]	23/18/22,5/18/20	25,1/22,2/22,2/22,2/25,1	-	negativ
Bearing lengths piston bearing positions [mm]	21,80	22,2	1,80	negativ
Bearing shells length of main bearings [mm]	19(23)/15/19/15/19	does not exist yet	-	negativ
Bearing shells length of piston bearings [mm]	16,4	does not exist yet	-	negativ
Timing drive:				
Camshaft intake total lengths (without sprocket) [mm]	E1: 283,9; E2: 270,86	295,15	-	negativ

Table 11: Negative list of lengths parameters at Subaru EJ 25[234]

Subaru was able to build a crankshaft which, in sum of the length values of the main bearing positions, is 15,3mm shorter than the AE2017. The main reason for this value is

[234] Own illustration

that it uses four different bearing lengths. BRP-Rotax uses only two different values for the AE2017. Therefore, it seems that Subaru does not standardize its length as BRP-Rotax does. One of the reasons is the quantity Subaru had with the EJ 25 compared to the quantity of the AE2017. The higher number of pieces could also mean that Subaru uses a standardized length but that they have more standardized length than BRP-Rotax does. Nevertheless, the length saving in the bearings is one of the main reasons for the shorter crankshaft, but only for the main bearing positions. The bearing lengths of the piston rods are almost equal.

The use of standardized length is also a topic at the counterweights. As BRP-Rotax uses the same values for the thickness, Subaru uses two different values, both of which are smaller than those of the AE2017. The major difference is that Subaru uses two counterweights per piston whereas the AE2017 crankshaft uses only one.

In general, it can be said that the longer bearing lengths are the reason for the longer crankshaft.

Also the points offered as reasons for the cylinder distance value in the AE2017 one chapter before can also be applied here.

Engine Width Parameters

The calculated negative points in the width parameters are minimal. A further investigation was not necessary, especially considering that the AE2017 generated better width values except for the crank case width and the maximum width at the counterweights.

Engine-Width-Parameters	Subaru scaled	AE2017	[%]	
Crank case:				
Total crank case width (without cylinder head) [mm]	415,19	420,2	1,19	negativ
Crank train:				
Crankshaft				
Maximum width (measured at counterweights) [mm]	138,7	141,8	2,19	negativ

Table 12: Negative list of width parameters at Subaru EJ 25[235]

Engine Height Parameters

The only negative aspect found by the investigation of height values is in the height of the crank case.

Engine-Height-Parameters	Subaru scaled	AE2017	[%]	
Crank case:				
Total crank case height (without gearbox flange) [mm]	208,72	255	18,15	negativ

Table 13: Negative list of height parameters at Subaru EJ 25[236]

The height of the crank case is directly influenced by the eccentricities the counterweights of the crankshafts have. Because the counterweights need to make full rotations within the crank case, the crank case needs to offer this space in all dimensions. Because the counterweights of the AE2017 are 3mm longer, a higher crank case value results. Also the eccentricity value of the bearings of the con rods have to the middle axis of the crankshaft, could be a reason for the higher value. The crankpins also need to make full rotations within the crank case. Unfortunately, this value was not measured in the comparison phase. It can nevertheless be investigated for further discussions.

[235] Own illustration

[236] Own illustration

If the two reasons mentioned are responsible for the height difference, it would again show that the calculation of the crankshaft needs to be adapted. It should be determined whether a smaller crank case could be generated with smaller eccentricity values of the counterweights. This could again be the case if standardized lengths were not used. A weight reduction through a smaller height value would be the result.

Engine Weight Parameters

The only weight parameter for which the Subaru EJ 25 generated a better weight value is in the weight of the crankshaft. The crankshaft of the AE2017 weights 600 grams more than the crankshaft of the EJ 25. The reason is the length of the crankshaft. Because the Subaru has a shorter crankshaft, it also has less weight. Looking at the core length values of the crankshafts, a difference of 24% is the result. This means that the crankshaft of the Subaru EJ 25 is 24% shorter but only 600 grams lighter. Looking at the density, by taking the quotient of the length of the crankshaft and the weight, a smaller value is generated by the AE2017. This again means that only the length must be adapted to eliminate this negative aspect.

3.5.3 Value Analysis of the AE2017 compared to Subaru EJ 25

The Subaru EJ 25 is most similar to the AE2017 of the engines used in this study. It not only uses a five-position bearing system; it is also turbo charged and has a very similar performance to the aircraft engine, with only 13hp difference. The compact construction of the engine is also similar. Because of these facts, this engine was additionally investigated through a value analysis. For this value analysis, the engine was split into six main categories. These categories are the following:

- Crank case (including cylinders)
- Cylinder head
- Crankshaft
- Con rod
- Piston
- Timing drive

Every of these categories was investigated in which processes of production and materials were used. The same was done for the AE2017. Then the categories were compared to see which the cheaper process is. The goal is to find a cheaper way to produce the AE2017. The results are demonstrated in percentage to display by how many percentage points a category is cheaper than the other.

Because the AE2017 is still in the P0 status, and no finished engine is available, the next smaller aircraft engine was used, which is the 915iS. This engine is completely equal in construction to the AE2017 except that it has smaller dimensions and the crankshaft is made not from one part but from a few parts, which are built together. This is mentioned in the value analysis.

The volume of production was set at 1000 produced pieces per year, on the assumption that this amount of the AE2017 are sold per year, as mentioned in Chapter 1.2. The costs of the analysis were reduced from the in-house costs, which are declared as variable costs. The assumption is that, for the production of the AE2017, no additional investment costs are necessary and that the engine can therefore be produced with the existing machines.

The analysis proceeded internally with the value analysis department. This department is specialized to calculate costs of different parts, whether prototypes or standard parts. Therefore, all costs of the 915iS are truly existing costs, whereas the costs of the single parts of the Subaru are estimated costs, due to the expertise of the value analysis department.

Crank case

The production of the Subaru crank case would be 28% cheaper than the production of the crank case of the 915iS.

Fig. 33: Comparison of crank cases

The variable costs for the 915iS are 205,5€ compared to the 147,92€ of the Subaru engine. As mentioned, the AE2017 is a chilled-casting part, as is the 915iS. The crank case of the Subaru is a pressure-casting part. Considering the two different casting processes and the fact that the category of crank case at Subaru consists of two parts whereas the crank case of the 915iS consists of six parts, the difference in the production costs of the Subaru is no surprise. The fact that the cylinders not only need to be produced but also mounted on the blank crank case further supports the higher production costs.

The disadvantage of the Subaru is its higher weight of 21.5kg, which includes the weight of the cylinders and all necessary screw connections. This means that 28% higher production costs are compared with almost 40% less weight, especially considering that aircraft engines are in a higher price segment.

Nevertheless, it could be investigated whether the production costs would sink if a different casting procedure was used.

Cylinder head

The production of the cylinder head of the Subaru EJ 25 is 35% more expensive.

Because the cylinder head of the Subaru uses four valves per cylinder and a DOHC system instead of an OHV system as in the 915iS and AE2017, higher production costs are expected. The camshaft itself is not brought up in this category, but the lubrication of the camshaft is done in the cylinder head, which again means a higher effort at the EJ25.

Fig. 34: Comparison of cylinder heads

One major difference at the cylinder heads is the number of spark plugs per cylinder. The Subaru EJ 25 uses one spark plug per cylinder, as does almost every combustion engine. The 915iS and the AE2017 use two spark plugs per cylinder. The reason for the second spark plug is that aircraft engines are required to be redundant. If the aircraft engine loses one ignition circuit, another should be able to run the engine. During flight both circuits are used. Before every start, both of them must be tested separately.

Crankshaft

The investigation of the crankshaft suggests that the Subaru EJ 25 is 55% less expensive to produce than the 915iS. Taking into account that the crankshaft of the 915iS is built from five parts, this analysis value is not representative.

Con rod

The value analysis of the con rod found that the con rod of the Subaru EJ 25 is 25% more expensive than the con rod of the 915iS. The main reason for this value is that the built crankshaft of the 915iS leads to a non-split con rod.

The con rod on the AE2017 is split, which make the value analysis in this category also not representative.

The con rod of the 915iS can be produced for 24€ in house. The 25% difference leads to the 30€ cost of the Subaru EJ 25 con rod. Considering that the con rod of the AE2017 is also split and has very similar dimensions, this 30€ value can be taken as producing reference for the con rods of the AE2017, taking into account that these need to be produced in the future.

Fig. 35: Comparison of con rods

Piston

The result of the piston comparison revealed that the piston of the Subaru EJ 25, which is seen on the right side of the picture, can be produced for 40% less than the piston of the 915iS.

Fig. 36: Comparison of pistons

The production costs of the piston of the 915iS were calculated to be 48,50€. This means that the variable production costs of the piston of the Subaru engine would be 29,1€. The reason for the higher cost of the 915iS piston is its sophisticated adjustments. More bores for cooling the rings, a special inflow lamination, valve pockets on the piston floor and a lubrication groove for the piston bolt at the 915iS are the main reasons for the cost difference.

The design of the piston at the AE2017 and the Subaru EJ 25 is very similar. This could have the result that, for the production costs of the cylinder of the AE2017, the actual cost value of the Subaru can be taken as reference. Perhaps, the not existing bores for the cooling ribs and the not existing lubrication bolt, could be discussed at the AE2017 considering that the Subaru is offering mostly the same performance without these things.

Timing drive

The value analysis found that the OHV concept of the 915iS and AE2017 is more than 50% cheaper than the timing drive concept of the Subaru EJ 25.

Fig. 37: Comparison of the timing drive

The concept of the timing drive of the 915iS and the AE2017 is equal. Only the dimensions of the camshaft and the valves are different, but the principle stays the same. The large cost difference results from the different system. The DOHC needs four camshafts whereas the AE2017 needs only one. Also, the Subaru needs a toothed belt, four belt pulleys and a belt tensioner.

The large benefits in weight are therefore also obvious. It is not an option to change the used OHV concept. One of the things that could be further investigated is the cost analysis of the single camshafts. Perhaps the production costs of the single camshafts can fulfil the requirements of an aircraft engine, such that these parts could be taken over to the AE2017.

3.6 **Realisation of improvements**

The phase of realisation of improvements for the AE2017 is not a part of this thesis.

3.7 **Summary of the practiced part**

The beginning of this chapter introduced the adapted 5-phases model of the benchmarking process. From the beginning of the project, it was clear that the AE2017 should be investigated. To understand the principle and the function of the engine, it was split into different categories.

In the special market of light aircraft engines, the costs are not the most important factor. It is more important to have a light weight concept. Therefore, the costs for buying an BRP-Rotax aircraft engine would be higher than the costs for buying an automotive engine in the same performance level.

The comparison phase shows that, in terms of weight, the AE2017 is better in almost every investigated term. There are even dimensional terms for which the AE2017 engine exhibited worse values but is still lighter. This shows that the aircraft engine is fulfilling its light-weight requirements. Of course, the weight value also depends on the dimensions of the engine. The engine weighs an average of 0,2kg/mm, which means 2kg for every centimetre. Therefore, BRP-Rotax wants to minimize the length values, especially at the crankshaft, as the crankshaft represents the heart of the engine. All other parts are built around it.

The discussions held with team members of the AE2017 project pointed out that the crankshaft is partially oversized. The principle of using standard lengths for the main bearings and con rod bearing led to a longer-than-necessary crankshaft. Also, the screwing concept used for the crank case and the screwing concept of the cylinders are bottle necks for the total length of this engine.

To improve the length values and therefore also the weight values, an investigation should be made to determine whether the benefits of the production are worth the smaller size the engine could have.

The value analysis shows that there is a potential to save future production costs for the AE2017. It should be investigated if it is possible to use a cheaper casting principle without losing quality. It should also be investigated whether it is possible to connect the two single cylinders per crank case side with the blank crank case during casting. This would save the mounting procedure and screwing connections. Also, the option for using externally parts by buying automotive parts, such as the crankshaft, or camshaft, should be calculated. The automotive industry has a higher quantity and therefore can most likely produce cheaper shafts. If they can fulfil the requirements, a saving of costs would result.

4 Conclusion

This thesis provides an overview of the topic of benchmarking. After the first, theoretical part, the practice of benchmarking is described. The aim of the benchmarking study is not only to find out how good or bad the dimensional and weight values of the single parts of the aircraft engine are in comparison to modern automotive engines. The question was more on why the AE2017 perform worse. The goal therefore is to adapt the actual concept of the AE2017, with the help of the generated data in the comparison phase, to make it more compact and less in weight. The project was also used to create a general procedure, set measurement requirements and generate a tool with which future benchmarking investigations can be performed.

The project shows that aircraft engines can generally be compared with automotive engines as long as all engines use the same building principle. In this case, all the engines were Boxer engines. This similarity made a benchmarking study possible. The results, by comparing those engines, are only reprehensive if the engines are also brought on the same level by adapting the bore and the hub. Therefore, a scaling of the engines is unavoidable.

The study also shows that, where the AE2017 is worse, decisions made in the production line, are responsible. Due to the lean philosophy of the company, where only two different lengths for the bearings are used, a shorter building of the crankshaft yet is not possible. This means that the AE2017 is partially oversized and that it can be optimized if these standards were not used. Because the project is focused on generating data for afterwards improvement decisions, the cost benefits of using standards in the production, especially in this project, were not investigated.

Therefore, a new concept of the crankshaft, by using not oversized bearing values, need to be developed. The crank case and other parts need to be adapted during the recalculation and the difference in production costs by not using standard lengths must be investigated.

One of the biggest competitions for BRP-Rotax will be the transfer of the benchmarking method in a continuous process. The comparison of engines is neither process oriented nor standardized at this moment. Engines are bought intuitively by inputs of mechanics and therefore no best practice comparison is guaranteed. Also the fact that those who are executing the comparisons, are not having any theoretically benchmarking background, is a thing which must be changed for future investigations.

Another fact worth mentioning is that generated data is noticed in simple Word-files and is saved under the specific project folder. No database with directly access to benchmarking related values, from all projects, exists.

To stay competitive and use the benchmarking method with the highest possible benefit, a benchmarking team must be implemented. This team should have team members with benchmarking experience, in the best case, and should act like an interface between the product development and the production. Only by staying up to date with the newest technologies and newest best practice methods, best possible products at BRP-Rotax can be generated. Therefore, implementation of a database where the product development as well as the production not only have access to it but also need to orientate on those values, is necessary.

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Table of Abbreviations

AE2017	Aircraft Engine 2017
APQC	American Productivity and Quality Centre
BRP	Bombardier Recreational Products Inc.
CEO	Chief Executive Officer
DOE	Design Organisation Exposition
DOHC	Double Over Head Camshaft
EASA	European Aviation Safety Agency
EFQM	European Foundation for Quality Management
EU	European Union
FY	Financial Year
IBC	International benchmarking Clearinghouse
IPK	Institut für Produktionsanlagen und Konstruktionstechnik
IZB	Informationszentrum benchmarking
KMU	Klein-und Mittelunternehmen
OHC	Over Head Camshaft
OHV	Over Head Valves
PSM	Production Science and Management
R&D	Research and Development
ROI	Return on Investment
SPIC	Strategic Planning Institute Council
US	United States
USA	United States of America
TQM	Total Quality Management
TU-Graz	Technical University of Graz

Appendix A: Comparison Table

	Engine 2 Porsche 986	**Engine 2 scaled** Porsche 986 scaled	**Engine 3** Subaru EJ 25	**Engine 3 scaled** Subaru EJ 25 scaled	**Engine 4** AE2017
Basic data					
Brand	Porsche	Porsche	Subaru	Subaru	Rotax
Type	Boxster	Boxster	Impreza EJ 25	Impreza EJ 26	AE2017
Year of production	2004	2004	1998	1998	2016
Turbo charged	No	No	Yes	Yes	Yes
Bore [mm]	85,5	88	99,5	88	88
Hub [mm]	78	80	79	80	80
Cylinder displacement [cm³]	2687	1946,3	2457,1	1946,28	1946,28
Displacem/Cylinder [dm³]	0,4	0,5	0,6	0,487	0,487
Cylinder distance [mm]	118	121,45	113	99,94	128
Relation Bore/Hub	1,10	1,10	1,26	1,10	1,10
Max. Torque [Nm]	260	173,33	225	225	217
Rotation at max. Torque [1/min]	4700	4700	4000	4000	5800
Max. Performance [kW]	168	112	123	123	132
Max. Performance [PS]	228,48	152,3	167,28	167,28	179,52
Rotation at max. Perf. [1/min]	6300	6300	5600	5600	5800
Torque at max. Performance [Nm]	254,65	169,77	209	209	217
Cooling system []	Water cooled	Water cooled	Water cooled	Water cooled	Water/Air
Num. cylinders []	6	4	4	4	4
Compression []	11:1-0,6	11:1-0,6	1/8,4	1/8,4	1/8,5
Power ratio [kW/l]	62,52	57,55	50,06	63,20	67,82
Total weight [kg]	130,40	95,08	70,35	58,29	37,10
Power to weight ratio [kW/kg]	1,29	1,18	1,75	2,11	3,56

Crank case

Total crank case width (without cylinder head) [mm]	436	447,18	410	415,19	420,2
Total crank case length [mm]	468	321,12	335	296,28	339
Total crank case height (without gearbox flange) [mm]	435	447,7192982	236	208,72	255
Crank case screwing connection []	14*M10x127	10*M10x127	8*M10x158+2*M10x106,5	8*M10x158+2*M10x106,5	4*M8x163+6*M8x139
Crank case screwing connection weight [kg]	0,86	0,61	0,94	0,94	0,87
Total crank case weight [kg]	56,78	41,12	24,74	19,79	13,15
Production type of crank case (casting, forging etc.)	See value analysis	See value analysis	See value analysis	See value analysis	See value analysis
Crank case characteristics	In moulted steal bearings	In moulted steal bearings	see "Subaru" Table	see "Subaru" Table	Chill casting

Cylinder head

Total cylinder head length [mm]	433	297,11	320	283,02	267,4
Total cylinder head width [mm]	330	339,65	208	183,96	163,7
Total cylinder head height (incl. valve cover) [mm]	220	220	180	180	123,7
Total cylinder head [kg]	17,63	9,68	12,59	10,18	4,56
Valve cover weight (two covers) [kg]	2,11	1,448	1,03	0,911	0,36
Cylinder head screwing connection	24*M10x230	16*M10x230	12xM11x173	12xM11x173	8*M8x186+8*M8*200
Cylinder head screwing connection weight [kg]	3,25	2,17	1,68	1,68	1,33

Crank train

Crankshaft

Total length crankshaft [mm]	497	341	356	314,85	460
Core length between bearing: 1-5 (without cone) [mm]	374	256,62	248	219,34	290
Core length betw. outer walls of counterw. [mm]	333	228,49	205	181,31	238,8
Maximum width (measured at counterw.) [mm]	140	140	138,7	138,7	141,8
Total weight of crankshaft [kg]	16	10,98	9,31	8,23	8,95
Thickness of counterw. [mm]	8,3	8,3	1x8,5mm/7x 6,8mm	1x8,5mm/7x 6,8mm	8,7
Number of bearings for crankshaft []	7	5	5	5	5
Hardening of bearing positions []	Moulted steal bearing in alu cage	Moulted steal bearing in alu cage	Hardened inductively	Hardened inductively	Hardened inductively
Bearing diameter of main bearing positions [mm]	59,7	59,7	60	60	60
Bearing diameter of piston bearing positions [mm]	53	53	52	52	46
Bearing lengths of main bearing positions [mm]	21,5/22/22/22/22/22/19	21,5/22/22/22/22/22/19	23/18/22,5/18/20	23/18/22,5/18/20	25,1/22,2/22,2/22,2/25,1
Bearing lengths of piston bearing positions [mm]	20	20,0	21,8	21,80	22,2
Bearing shells length of main bearing positions [mm]	15,4	15,4	19(23)/15/19/15/19	19(23)/15/19/15/19	Not existing yet
Bearing shells length of piston bearing positions [mm]	15,4	15,4	16,4	16,4	Not existing yet

Piston rod					
Piston rod length (measured between Eye and Head) [mm]	145	148,72	130,5	132,15	132
Piston rod width (at Head/Eye) [mm]	34/83,8	34/83,8	36/81	36/81	32,2/75,9
Piston rod shaft width [mm]	24	24	21,3	21,3	22
Piston rod thickness at Eye [mm]	20,2	20,2	21,3	21,3	22
Piston rod thickness at Head [mm]	20,7	20,7	21,4	21,4	19
Piston rod inner diameter at Head (incl. Bearing shells) [mm]	22,1	22,1	23	23	22
Piston rod inner diameter at Eye (incl. Bearing shells) [mm]	53,2	53,2	52	52	49
Total Piston rod weight (incl. Bearing shells and screw connection) [kg]	0,64	0,66	0,63	0,64	0,484
Piston rod screwing connection	M10x57	M10x57	M9x47	M9x47	M8x50
Piston					
Total piston weight (incl. Piston rings and bolt) [kg]	0,47	0,51	0,59	0,44	0,43
KH [mm]	31,5	31,5	30	30	33,26
Timing drive					
Number of valves per cylinder []	4	4	4	4	2
Valve intake diameter [mm]	34,5	35,51	36	31,84	42
Valve outtake diameter [mm]	28,7	29,5	32	28,3	35
Camshaft intake type []	4 camshafts each as one part	4 camshafts each as one part	Build camshaft, pressed cams	Build camshaft, pressed cams	One camshaft made from one part
Total camshaft intake length [mm] (without sprocket etc.)	406	278,58	E1: 321, E2: 306	E1: 283,9; E2: 270,86	295,15

Total camshaft intake weight [kg] (without sprocket etc.)	1,87	1,28	E1: 1,39; E2: 1,31	E1: 1,23; E2: 1,16	0,565
Total camshaft intake length [mm] (incl. sprocket etc.)	453	310,83	-	-	295,15
Total camshaft intake weight [kg] (incl. sprocket etc.)	3,11	2,13	Not measured	Not measured	0,747
Camshaft outtake type []	Made from one part	Made from one part	Build camshaft, pressed cams	Build camshaft, pressed cams	Not existing
Total camshaft outtake length [mm]	395	271	A1: 297, A2: 287	A1: 262,67; A2:253,8	Not existing
Total camshaft outtake weight [kg]	1,53	1,05	A1: 1,37; A2:1,31	A1: 1,21; A2: 1,16	Not existing
Camshaft driving []	Two chains	Two chains	Toothed belt	Toothed belt	Via sprocket and crankshaft
Chains/Toothed belt weight [kg]	1,72	1,72	0,31	0,31	Weight included in camshaft
Intermediate shaft diameter [mm]	42	42	Not existing	Not existing	Not existing
Intermediate shaft weight [kg]	2,48	1,70	Not existing	Not existing	Not existing
Intermediate shaft chain weight [kg]	0,64	0,64	Not existing	Not existing	Not existing
Total weight of timing drive (incl. all chains, camshafts etc.)	16,40	13,63	7,82	7,2	3,51

Appendix B: Negative list Porsche 986 / AE2017

Engine-Length-Parameters	Porsche 986 scaled	AE2017	[%]	
Basic data:				
Cylinder distance [mm]	121,45	128	5,12	negative
Crank case:				
Crank case length [mm]	321,12	339	5,27	negative
Crank train:				
Crankshaft				
Total length of crankshaft[mm]	341,02	460	25,86	negative
Crankshaft core length bearing: 1-5 [mm]	256,62	290	11,51	negative
Crankshaft core length of outer walls of counterweights [mm]	228,49	238,8	4,32	negative
Maximum width (measured at counterweights) [mm]	140	141,8	1,27	negative
Counter weights thickness [mm]	8,3	8,7	4,60	negative
Bearing length of main bearings [mm]	21,5/22/22/22/22/22/19	25,1/22,2/22,2/22,2/ 25,1	-	negative
Bearing lengths of piston bearings [mm]	20	22,2	9,91	negative
Piston rod				
Piston rod thickness Eye [mm]	20,2	22	8,18	negative
Timing drive:				
Intake camshaft total length (without sprocket) [mm]	278,58	295,15	5,61	negative

Engine-Width-Parameters	**Porsche 986 scaled**	**AE2017**	**[%]**	
Crank train:				
Crankshaft				
Bearing diameter main bearing positions [mm]	59,7	60	0,50	negative
Piston				
KH [mm]	31,5	33,26	5,29	negative
Engine-Weight-Parameters	**Porsche 986 scaled**	**AE2017**	**[%]**	
Crank case:				
Crank case screwing connection []	10*M10x127	4*M8x163+6*M8x139	-	-
Crank case screwing connection weight [kg]	0,615	0,871	29,39	negative

Appendix C: Negative list Subaru EJ 25 / AE2017

Engine-Length-Parameters	Subaru scaled	AE2017	[%]	
Basic data:				
Cylinder distance [mm]	99,94	128	21,92	negative
Crank case:				
Total crank case length [mm]	296,28	339	12,60	negative
Crank train:				
Crankshaft				
Total crankshaft length [mm]	314,85	460	31,55	negative
Crankshaft core length bearing: 1-5 [mm]	219,34	290	24,37	negative
Crankshaft core length of outer walls of counterweights [mm]	181,31	238,8	24,08	negative
Maximum width (measured at counterweights) [mm]	1x8,5mm/7x6,8mm	8,7	-	negative
Bearing lengths main bearing positions [mm]	23/18/22,5/18/20	25,1/22,2/22,2/22,2/25,1	-	negative
Bearing lengths piston bearing positions [mm]	21,80	22,2	1,80	negative
Bearing shells length of main bearings [mm]	19(23)/15/19/15/19	does not exist yet	-	negative
Bearing shells length of piston bearings [mm]	16,4	does not exist yet	-	negative
Piston rod				
Piston rod thickness Eye [mm]	21,3	22	3,18	negative

Timing drive:

Camshaft intake total lengths (without sprocket) [mm]	E1: 283,9; E2: 270,86	295,15	-	negative

Engine-Width-Parameters	**Subaru scaled**	**AE2017**	**[%]**	

Crank case:

Total crank case width (without cylinder head) [mm]	415,19	420,2	1,19	negative

Crank train:

Crankshaft

Maximum width (measured at counterweights) [mm]	138,7	141,8	2,19	negative

Piston

KH [mm]	30	33,26	9,80	negative

Engine-Height-Parameters	**Subaru scaled**	**AE2017**	**[%]**	

Crank case:

Total crank case height (without gearbox flange) [mm]	208,72	255	18,15	negative

Engine-Weight-Parameters	**Subaru scaled**	**AE2017**	**[%]**	

Crank train:

Total crankshaft weight [kg]	8,23	8,95	8,00	negative