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Improving incident-based maintenance in tunneling based on Systems Engineering

MASTER´S THESIS

to achieve the university degree of
Master of Science

Master´s degree programme: Production Science and Management

submitted to
Graz University of Technology

Supervisor

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Graz, November 2014

In cooperation with:

Marti IAV Solbakk DA

AFFIDAVIT

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Abstract

The objective of this thesis was to improve the efficiency of the machine maintenance process of the tunneling workshop at the 14.3km long Solbakk tunnel in Tau / Norway. Main objective of this work was to increase the overall efficiency of the service and repair processes of the underground vehicles and equipment – therefore the structured approach of Systems Engineering (SE) was used. Additionally, the analysis of existing maintenance processes and strategies significantly increased the understanding of the whole area for improvement. To improve the overall efficiency of the machine maintenance process various methods and tools of the SE theory were used, like the approach of systems thinking, the top-down approach and the building of variants according to the SE concept of Hall-BWI. This thesis is structured into defined project phases and various problem solving cycles had to be established. During the preliminary study the whole area of the machine maintenance was analyzed carefully, concerning difficulties or even problems of existing service and repair tasks. Cooperation at field work as well as process illustrations with BPMN led to a better overview of the overall situation of the current state. During the main study different possible solutions for an improved machine maintenance process were established and evaluated. The three best variants were analyzed and developed further in three “independent” detail studies. Finally, various prototypes were developed and implemented directly at the tunnel construction site Solbakk in order to support the ongoing tasks and therefore increase the efficiency of the current machine maintenance processes at this site. These implemented prototypes can be used on other tunnel construction sites as well and therefore they are very valuable for the maintenance sector in tunneling.

Kurzfassung

Ziel dieser Arbeit war es, eine Steigerung der Effektivität des Maschinenwartungs-Prozesses der Tunnelbau Werkstatt des 14.3km langen Solbakk-Tunnels in Tau / Norwegen zu erreichen. Das Hauptaugenmerk dieser Arbeit lag dabei an der Steigerung der gesamten Effektivität sämtlicher Service- und Reparaturarbeiten der verschiedenen Tunnelbaumaschinen. Dabei wurde das systematische Vorgehen des Systems Engineering (SE) Konzeptes angewandt. Auch die Analyse von bestehenden Wartungsprozessen- und Strategien diente dazu, das Gesamtverständnis für das vorliegende Projekt zu erhöhen. Um die Effektivität des Maschinenwartungsprozesses zu erhöhen, wurden verschiedene Methoden und Werkzeuge des Systems Engineering Konzeptes verwendet, wie zum Beispiel das Systemdenken, das Vorgehen vom Groben zum Detail und der Prozess der Variantenbildung laut dem SE Konzept von Hall-BWI. Die vorliegende Arbeit ist in verschiedene Projektphasen gegliedert und mehrere Problemlösungszyklen mussten erarbeitet werden. Während der Vorstudie wurde der gesamte Bereich der Maschinenwartung analysiert, um bestehende Probleme und Schwierigkeiten bei diversen Reparatur und Servicearbeiten zu erkennen. Direkte Mitarbeit auf der Baustelle sowie das Analysieren von Prozessen mittels BPMN erhöhten den Gesamtüberblick über die aktuelle Maschinenwartung deutlich. In der folgenden Hauptstudie wurden anschließend verschiedene Lösungsansätze bzw. Lösungsvarianten erarbeitet und bewertet. Danach wurden die drei besten Varianten der Hauptstudie in drei folgenden Detailstudien weiter analysiert und entwickelt. Schlussendlich wurden unterschiedliche Prototypen entwickelt und im Baustellenbetrieb implementiert, um bestehende Prozesse zu unterstützen und dadurch die gesamte Effizienz der Maschinenwartung der Tunnelbaustelle Solbakk zu erhöhen. Da diese implementierten Prototypen auch auf anderen Tunnelbaustellen verwendet werden können, stellen sie einen wertvollen Beitrag für den Maschinenwartungs-prozess im Tunnelbau dar.

Preamble

First of all I want to thank my parents for supporting me my whole life and for giving me the opportunity to study at the University of Technology in Graz. I also want to thank my twin brother Daniel for his inspiring and motivating support and for the perfect teamwork which we have developed together within the last few years at the University and also on different tunneling construction sites during our semester breaks. Additional I want to thank my older sister Manuela and my older brother Michael for encouraging me at every kind of problem which happened to me during the last few years and which we solved together as a family.

Regarding to this thesis I want to give special thanks to Mr. Ralf Schreitmüller (commercial manager), Mr. André Pas (project manager) and Mr. Andreas Jakobitsch (workshop manager) from the Marti AG to initiate and finance this thesis and for enabling me this great chance to work on the Solbakk tunnel project in Tau / Norway. Additional special thanks to Mr. Gerald Lichtenegger and Mr. Dietmar Neubacher from the institute of Engineering- and Business Informatics at the University of Technology in Graz for supporting me with their experience and knowledge and for giving me the opportunity to write this thesis on their institute. I am very thankful and proud that I had such great supervisors and that I could learn very much from them not only for my thesis. Finally I want to thank all my coworkers and at the construction site Solbakk as well as all of my friends for their close friendship. At the conclusion of this preamble I want to express one of the best statements which I have learned from Mr. Lichtenegger:

Most people work solution-oriented and therefore they focus only on appropriate solutions for existing problems. But to work solution-oriented does not change the circumstances which caused the problems. Therefore it is very important to work problem-oriented as well in order to achieve sustainable results.

This statement accompanied me every day at the construction site Solbakk and extended my view quite a lot due to the fact that this is a very uncommon way of thinking especially at a tunneling construction site.

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1 Introduction

A tunnel is a manmade built passage which is crossing underground mountains, bodies of water or other barricades. Most common tunneling constructions are built for traffic (road tunnels for cars or trains, tunnels for metros) and utility devices (tunnels for fluids e.g. fresh water and sewage water, tunnels for pressure pipes of water power stations, tunnels for oil / gas pipelines or for electricity cables). Road tunnels can be built single-lane, double-lane or multi-lane. If a tunnel is very long it is common to work with two excavations – from each tunnel portal towards each other. This causes additional costs for equipment and the need of additional workers, but on the other hand it reduces the building time of the tunnel tremendous. The building of a tunnel construction is very cost expensive and a big challenge for every construction company.

A tunnel is usually built with the conventional excavation process or with the mechanized excavation process. Most common examples for conventional excavations are the drill and blast excavation process and the excavation with special tunnel excavators. A mechanized excavation is usually done with tunnel boring machines (TBM`s). Depending on the rock conditions it can be necessary to perform special rock consolidation tasks with shotcrete. An additional usage of wire fabric reinforcements, steel mats, anchors or the usage of steel arches supplementary to the shotcrete can be required too. Tunnel boring machines often use segmental lining for rock consolidation.

No matter if there is a conventional or a mechanized excavation – the key for an effective built tunnel project is always the well working machinery in operation. It is very important to have the appropriate machines for the special required tasks on site. The proper performed maintenance of these machines is a very important factor and essential for the success of every project to guarantee a long lifetime of all machines and to prevent abrupt machine downtimes which can cause tremendous problems and huge costs for the construction company. To improve the maintenance process itself various actions can be executed – the challenge is to find out and implement the most effective measures. To deal with this complex task the theory of Systems Engineering is a very helpful tool to work out and develop different variants for improvement of the maintenance process for the tunnel excavation machines and following to evaluate them – concerning the guidelines and regulations of Systems Engineering.

1.1 Motivation

Already with the age of 15 years I made my first working experiences during my summer holidays at the building site as a mechanic and blacksmith. Every summer I gained important experiences at different construction sites at home and abroad. During this time I found my passion for technic and my education at the Secondary College of Engineering in Lienz provided also important knowledge for the different tasks on site. In 2007 I started to work at the quality management for Liebherr household appliances in Lienz for 13 months. But I realized quite fast that I will not stick to this industry sector forever. This was the reason why I started to study mechanical engineering and economics at the University of Technology in Graz in 2008. I was starting to work every summer on different tunnel construction sites in e.g. Germany, Switzerland and Austria during the summer semester breaks because I had to finance my studies by myself. I was working on some tunnel construction sites with drill and blast excavation process as well as on a tunnel construction site with mechanized excavation by the usage of a gripper TBM. My responsible working areas were among other things tunneling mechanist, machine operator, mechanist and metalworker in the machine shop, surveyor and member of the maintenance team for all kind of machines. The service, repair and maintenance tasks for these machines were counted to my daily routine jobs. I made a lot of experiences in all of these sectors and I have learned to cooperate in teams and to tackle any kind of problem. I have also learned to understand the importance of connecting theory and practice.

Due to the fact that I worked in a lot of different areas at various tunnel construction sites I received a good overview about the whole process and related tasks. This is the reason why I have recognized a lot of potential for improvement at these areas, especially at the field of the machine maintenance. In November 2013 I got a call from a former mechanic chef of me for developing a better and more efficient machine administration for a drill and blast excavation construction site in Norway – where he was actually involved. This tunneling project was located in Tau / Norway and the responsible construction company was the Swiss-based Marti IAV. So the idea of this master thesis was born.

This project proved to be a great opportunity for me to use and combine my gained theoretical and practical knowledge. Because of the high complexity of the whole machine maintenance and administration tasks of such a machine park I decided together with my supervisors from the TU Graz to use the concept of Systems Engineering. Various systematic methods should ensure the best possible result for this very responsible task. Therefore the topic of Systems Engineering is also considered as a core part of this thesis.

1.2 Mannerisms in tunneling

The maintenance process for the machines of a tunnel construction site is in general very different from “common” maintenance processes which most people first think about. Close to scratch machines can get damaged by e.g. roof collapse of rocks or by accidents and crashes with other tunneling vehicles. Another problem is that with increasing length of the tunnel the service and maintenance tasks of the machines become much more difficult. Sometimes it is hard or even impossible to drive damaged underground vehicles to the machine workshop outside of the tunnel and to perform the repair or maintenance tasks there. Then these works have to be performed directly in the tunnel. This is of course much more difficult because of missing equipment for maintenance and shortage of space.

Occasionally these broken machines can block the ongoing excavation process for other machines and miners. This complicates the drill and blast process for all involved workers. Reasons for these, mostly unpredictable, accidents are e.g. the dark and dirty underground working conditions as well as the high noise and dust level. Also ingress of water can cause huge problems. Sometimes there is even not enough time to perform proper service and maintenance tasks on the machines because of urgent need of them for the excavation process. Exceeded service intervals can cause subsequent damages and high additional costs. Another problem is the abolition of the manufacturer warranty for these machines due to wrong or insufficient maintenance.

To work in a tunneling project is a big challenge for all involved employees and all used machines and equipment because of the extreme rough environment. No day is passing by like the day before, because new problems and challenges appear which have to be solved. Therefore the miners and mechanics have to be very flexible at all performing tasks. It is obvious that the whole maintenance process differs very much from “common” maintenance tasks in ordinary workshops which are located in relatively friendly environments. “Improvisation” and “teamwork” are the buzzwords for this underground working area. It is a tough but diversified job for all participants.

1.3 Project Solbakk Tunnel

The drill and blast excavation process for the project Solbakk tunnel started already in August 2013. This tunnel is built as a double-pipe tunnel with a total length of about 14,3 km. The tunnel is excavated from the portals at two different sites – one site is located in Stavanger (South site) and the other one is located in Tau (North site). The building owner of this project is the Norwegian Public Roads Administration – Statens Vegvesen.

The Marti IAV is a Swiss-based company of the Marti Holding and the headquarter is located in Moosseedorf (CH). The Marti Holding consists of about 80 subsidiaries and has about 5000 employees in total.

The contingent of the Marti IAV includes the 2 tunnels at the northern section starting in Tau with 8km length each and the construction of access roads and landfill engineering. The diameter of these tunnels is about 11,4m. The transport of the excavated material is performed by a conveyor belt system and with conventional dumpers. Afterwards this material is mucked directly into the sea. The contract value for the Marti IAV is about 206 million CHF and some important technical specifications are:

Face advance material: 1,3 Mio m^3
Injection material: 4,3 Mio kg
Drill hole length for injections: 130 000 m
Anchors: 470 000 m
Shotcrete: 57 000 m^3

At the completion of the project in 2018 this tunnel will be the world's longest subsea-auto-tunnel with the deepest point about 290m below sea-level. About 80 employees from all over Europa are working 24 hours a day to finish this project for the company Marti IAV. The employees at the site are mainly from Slovakia, Switzerland, Iceland, Germany, Sweden, Norway, Poland, Denmark and Austria. The drill and blast excavation team is working with a day- and a night shift to cover the needed manpower. A third shift is meanwhile always staying at home. Most workers are staying in Norway with a 4 weeks working-time followed by 2 weeks off-time at home. Figure 1 shows the portal area of the Solbakk tunnel in Tau / Norway.

Figure 1: Portal area of the Solbakk tunnel (North side)

When the tunnel is finished it will link the city Stavanger with the village Tau. Until today the people have to use the ferry connection of Nordled to travel between these two places. This transport with the ferry takes about 40 minutes for driving into one direction. This route of the ferry can be seen in figure 2 and the distance is about 15km. In 2018 the travel time will be drastically reduced through this new tunnel connection.

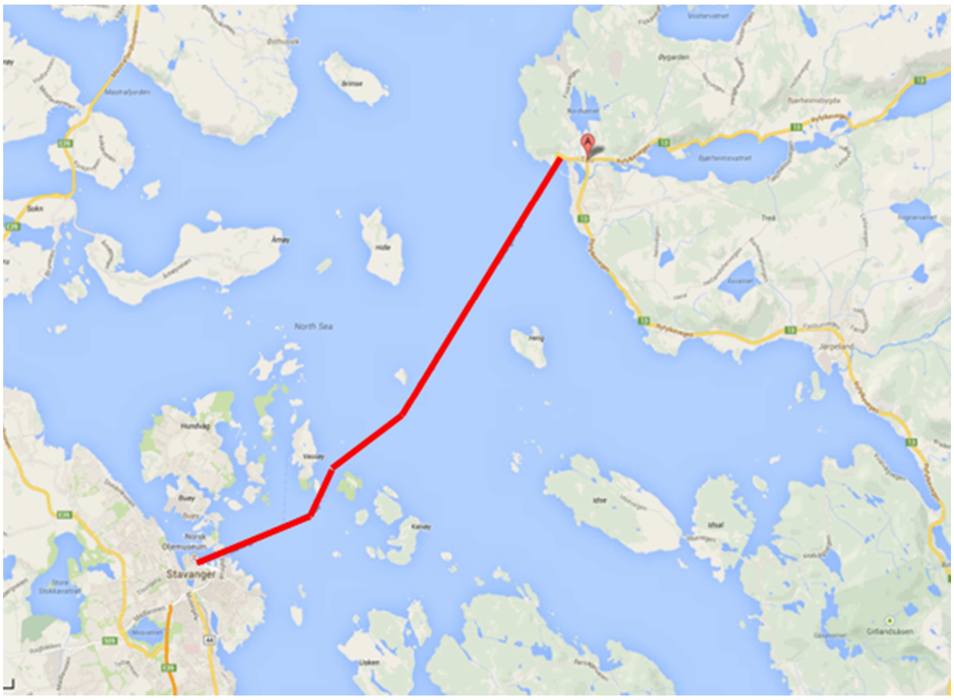

Figure 2: Route of the ferry between Stavanger and Tau (Google maps)

1.4 Initial situation

The initial situation at the construction site Solbakk tunnel is an already ongoing drill and blast excavation process with two separate excavations working in parallel. A big challenge for the workshop manager and the whole maintenance team at this site is the appropriate performed service and maintenance task of all machines and equipment due to many unexpected problems which can occur – this mannerism in tunneling is already explained a little bit in more detail in chapter 1.2. A critical point, especially for this construction site, is that the tunnel is going to underrun the sea and therefore the ingress of salt water can cause additional problems at the tunneling machines, especially at all electric sockets and connections due to the fact that salt water is very aggressive. To prevent electrical failures special protective measures have to be considered.

Some key facts about the used machines at the site: There are four Sandvik drilling jumbos for drilling the holes in the face of the tunnel as well as for drilling the holes for the anchors and injections. The face is the area of the tunnel where the drill and blast excavation takes place. Two Red Devil Explosive vehicles are used to charge the face with the two component reaction explosive agent. After the blasting process the wheel loaders are starting to muck the material away from the face. Therefore five Volvo wheel loaders are in use. The excavated material is then mucked directly into a stone crusher. This Gipo stone crusher breaks the rocks to an appropriate size so that the material can be transported with the continuous material conveyor belt. This conveyor belt is mounted quite on top of the tunnel and transports the material directly out of the tunnel. Outside of the tunnel the material is mucked into the sea via transfer stations and a special swimming station.

Sometimes for the transport of the material some conventional dumpers can also be used e.g. when there are service or repair tasks at the crusher or at the conveyor belt system. Three Belloli dumpers can be utilized for that discontinuous material transport. For the machine scaling and cleaning tasks of the face diverse Volvo excavators are used. In total six special excavators are available at this site. A further very important step is the rock consolidation – therefore two Meyco shotcrete machines are used as well as two AMV grouting rig trucks for injections. The needed concrete for the rock consolidation is delivered by external concrete mixer trucks.

Of course many supporting processes have to be performed simultaneously to the excavation process e.g. the extension of the air tube and water hoses, extension of the water pipes, building ditches and so on. For these tasks special machinery is used at the construction site e.g. two Dieci hoisting machines, two Kramer forklifts, one Volvo truck with a truck-mounted crane and some smaller additional machines. For the foremen and the surveyor six special Puch G cars are used as transport cars. The workshop manager is responsible for the service and maintenance tasks of all these machines and vehicles. He is supported by his workshop team which consists of three foremen and six mechanics. So every shift (day or night) is operating with one foreman and two mechanics. At the dayshift the workshop team is additionally supported by one storekeeper, one all-rounder and one worker for greasing and tanking of the machines. A main overview of the most important machines at the construction site Solbakk can be seen in figure 3. The major categories of the machines are: drill and blast machines, lifting machines, material handling machines and machines for rock consolidation. According to this classification it can be seen that the material transport can be continuous or discontinuous.

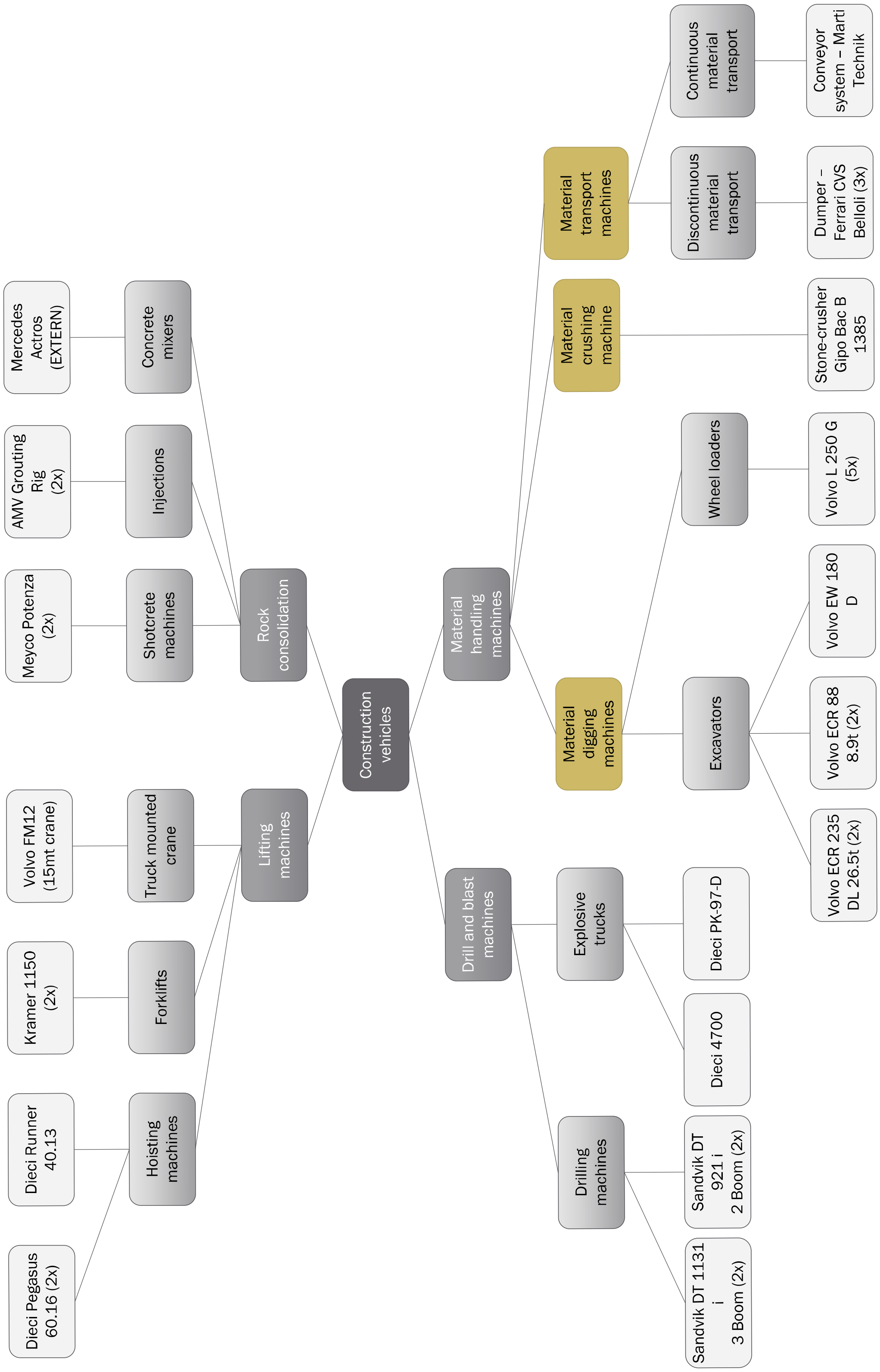

Figure 3: Classification of the construction vehicles at the site

1.5 Objective target

Objective of this thesis is to systematically analyze and improve the whole maintenance process of the machine workshop at the construction site in Tau. To reach this objective, the first stage is to get an exact overview about the existing processes at the machine workshop area and to build up workflows for continuing analysis. It is very important to get more transparency of the whole maintenance processes, so a clear chronicle of the actual state is the basis for further actions. Furthermore a better traceability of all kind of maintenance tasks should be accomplished.

It will be very helpful to work directly at the construction site and to be part of the workshop team to analyze and perform various service, repair and maintenance tasks directly at field work at different machines and vehicles. Together with the team members at the construction site all relevant factors for a more efficient maintenance will be figured out. Existing difficulties and challenges will be handled and analyzed, afterwards an optimal target state will be figured out. Therefore teamwork and extended interviews with all involved experts will be essential. The main task is to develop and evaluate several concepts for improvement by using a catalogue of requirements. After all relevant information is gathered and the whole surrounding field is monitored, a more efficient maintenance strategy will be established. During a final proof of concept phase different prototypes will be implemented and evaluated. The gained experiences and results should be usable for the commitment at other tunnel construction sites too. There are many different theories available which would be able to deal with this complex task. One tool is Systems Engineering which is used within this thesis.

Some fundamentals which are used in this work are process and system analysis, modelling of workflows (BPMN) and a proof of concept phase. The techniques of Systems Engineering will be used to achieve the best possible results for a more efficient maintenance at tunnel sites in general. Therefore the main focus of attention will be a proper course of action, according to SE.

1.6 Structure of the thesis

This master thesis is structured into a theoretical and a practical part with an additional case study which is performed directly at the tunnel site Solbakk. The theoretical part at chapter 2 is dealing with the topic of maintenance related to tunneling, the history of maintenance, some important definitions and strategies, objectives and reliability of maintenance systems. Chapter 3 is dealing with the topic of Systems Engineering and systems in general, some important definitions and the SE philosophy according to Hall-BWI which is further used at the case study in chapter 4. The practical part with the case study at chapter 4 describes the development and evaluation of different variants for improvement of the maintenance process itself. This section is structured into a preliminary study, a main study and three detail studies. After the evaluation process of the main study the three most successful variants will be analyzed further in own detail studies. Finally prototypes for all variants are elaborated and implemented at the construction site Solbakk.

The main objective of this work is to establish, evaluate and implement three different prototypes for a quality intensification of the machine maintenance process at the construction site Solbakk. The diverse fields of these prototypes are organizational-, technical- and process oriented. The design and evaluation of these prototypes is figured out through the usage of the SE concept. According to the concept of Systems Engineering the first important step analyses the different systems at the construction site regarding to different filters. These filters can be distinguished according to e.g. labor view, areal view, vehicle view, tool view, etc. Through the use of these different filters or rather views it is possible to get a much better overview of each individual filtered system and consequently about the whole maintenance process itself. The various connections between the different systems can be visualized and existing problems may be figured out. Process analysis by the use of BPMN can also contribute to a better overview of existing processes. The main case study establishes the best variants for an improvement of the maintenance process. The three variants which seem to be the most successful will be selected and prototypes are developed and implemented directly at the site afterwards. Different problem solving cycles help to determine the most effective measurements for a better machine maintenance.

In the end a conclusion is provided in chapter 5. A summary and a critical statement about the usability of the chosen and implemented prototypes according to the SE concepts is made. Also the experiences which were made during the case study by the application of the SE concept are mentioned. Further a short outlook will be given according to the gained experience and evaluated results out of the case study and about the usability of the developed prototypes.

2 Maintenance

The globalization of the markets and the increasing competition is still advancing nowadays. Rising costs and pressure to perform are the resulting consequences and challenges for companies in this day and age. The main objective is to produce high quality products or services at low costs. Therefore economization and innovation are absolute necessary. A high degree of automation and increasing complexity of machines and equipment is the result[1].

For the maintenance process of tunneling vehicles this can be seen in a similar way. The machines and the equipment are always getting more complex and automated. Service and repair tasks are depending on this trend. To deal with this responsible task it is essential to have high qualified and well experienced mechanics available at the machine workshops. A proper management of maintenance is also unavoidable.

The term maintenance is often designated as non-productive, what is actually not true. As a result of this point of view the maintenance process has to deal with many questions regarding functionality and efficiency[2].

At a drill and blast excavation process the miners are operating the different tunneling vehicles with the objective to excavate as much material as possible out of the tunnel. So this work can be seen directly linked to the process of the tunnel construction. To keep all of these machines running the mechanics of the workshop are performing different service and repair tasks in the background. This maintenance work is not visible for some miners because they are always operating the well prepared machines and equipment. But the importance of the service and repair tasks can be seen at any machine breakdown. Then it is obvious for every miner that the whole tunnel excavation is partly not possible or even impossible to be executed when different machines are not able to be used. Long waiting times and even stoppage of the excavation process can cause huge problems and costs for the company. It is obvious that the maintenance process should be seen as very productive.

In the 1950´s mostly high qualified employees were used to work at the production machines. These workers performed the operation of these machines as well as the maintenance and care measurements. So they developed a kind of connectivity to “their” machine. But this kind of operation and maintenance tasks, which were done more or less by the same person, changed drastically in the 1960´s when there was the economically boom. The introduction of multi-shift operation and automation guided to the employment of partly low educated employees. An estrangement of the operators to the machines was the consequential result. The operators were mainly responsible to operate the machines and special qualified mechanics and electricians performed the maintenance processes itself[3].

[1] (Pawellek 2013) p. 1
[2] (Reichel et al. 2009) p. 13
[3] (Reichel et al. 2009) p. 13f

This multi-shift operation can be seen equal at a shift model of a tunneling construction site. To finish a tunnel project as fast as possible it is usual to operate day and night. There is no machine or device referred to only one operator. All workers have to use and to be able to operate multiple machines in different sequences. Because of this multiple operations of the machines the awareness of the workers for a careful use of the machines is obvious lower.
Often it is even not possible to track which operators caused some damages at the vehicles if they are not honest and don’t inform the workshop manager or even the foreman.

At the tunnel site Solbakk an introduction of special operator manuals for each machine therefore was done. Before a worker starts the tunneling vehicle he has to write down his name, the machine hours at the beginning and at the end of the work and if necessary special incidents. This measurement will be controlled frequently and should lead to a better and more careful use of the machines and to fewer machine damages.

2.1 Terms of maintenance

Maintenance / machine care (DIN 31051)
These are all measures to keep the nominal condition or to decelerate the dismantling of an existing reserve of wear-out of considered units. An example therefore would be greasing.

Inspection (DIN 31051)
These are all measures to determine and evaluate the actual condition of a considered unit including the determination of causative reasons of wear and the deduction of necessary consequences for a future utilization. An example therefore would be the measuring of a brake disk.

Maintenance / corrective maintenance (DIN 31051)
These are all measures for a recirculation of a considered unit to the operative condition to the same level like before the breakdown without improvements. An example therefore would be the exchange of a component against an equivalent spare-part.

Improvement (DIN 31051)
An improvement involves all technical and administrational measures as well as measures of the management to increase the functional reliability of a considered unit without changing the required function of the unit. An example would be the clearance of a weak spot through constructive modification of components.

Wear (DIN 31051)
Wear is the dismantling of a machines reserve of wear-out caused by chemical and / or physical processes.

Remark: such processes are generated by different loads e.g. friction, corrosion, aging, fatigue, breakage etc. Wear is unavoidable!

Reserve of wear-out (DIN 31051)
Reserve of wear-out is the stock of possible functional compliances among defined terms concerning manufacturing, maintenance or improvement of considered units.

Wear limit (DIN 31051)

The wear limit is the arranged or defined minimum value of the reserve of wear-out. This wear limit is shown within the graph of the dismantling curve of the reserve of wear-out. This can be seen in figure 4 and is only an example for a possible trend.

The basic tasks of the maintenance can be derived from the trend of the dismantling curve. The target of maintenance is to achieve a flat course of the dismantling curve at the area of the primary period of operation. To achieve that state it is very important to use effective lubrication systems. The function of the lubrication systems have to be controlled and maintained regularly. Also the lubricants have to be cleanded and changed from time to time. A good planning and organization of the maintenance process is essential[4].

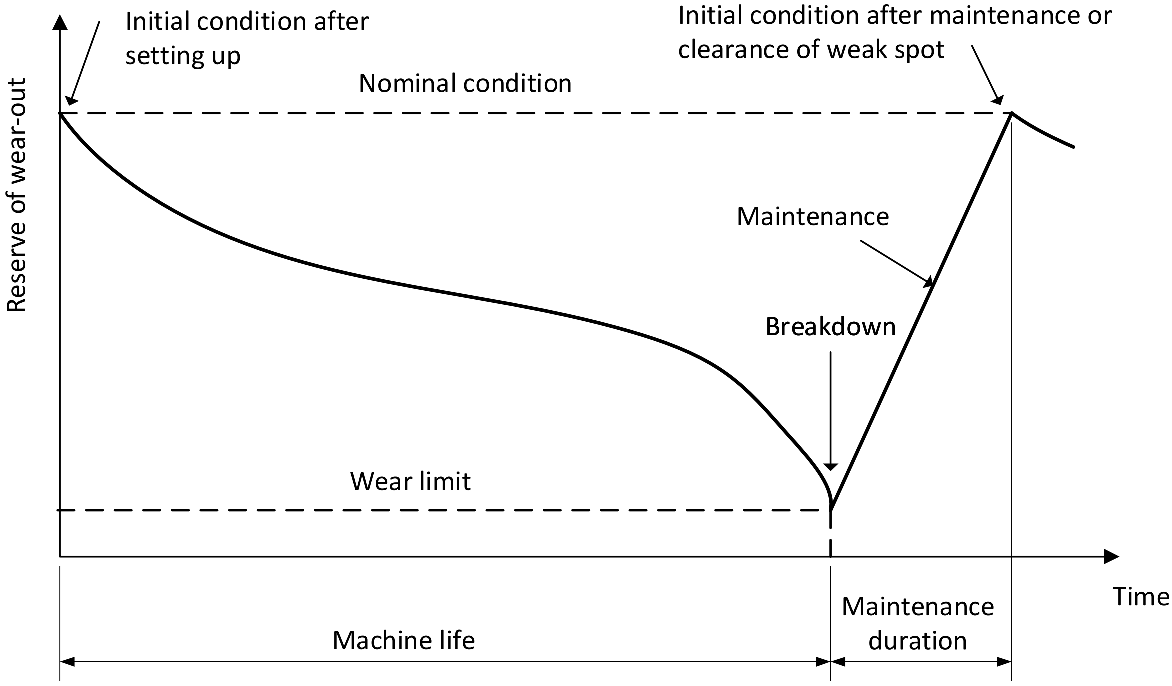

Figure 4: Trend of the dismantling curve according to Strunz[5]

[4] (Strunz 2012) p. 41
[5] (Strunz 2012) p. 42

Clearance of weak spots (DIN 31051)

These are measurements for improvement of a considered unit that the achievement of a defined wear limit is accessible with a probability which is within required availability.

Different tasks of maintenance (DIN 31051)

There are various tasks of maintenance defined. Some of these tasks are (DIN EN 13306):

- Inspection
- Monitoring
- Functional check
- Compliance test
- Improvement
- Revision
- Routine maintenance
- Trouble check
- Defect location
- Modification

An appropriate planning and execution of the maintenance process is the basis. A systematical proceeding is required and important input information must be accessible. The chosen strategy for maintenance is determining the configuration of the executed tasks and processes[6].

The different strategies for maintenance will be explained in detail in chapter 2.4. Also the link to the maintenance strategy of a tunneling workshop will be explained more properly.

[6] (Schenk 2010) p. 26

2.2 History

In the early times of the upcoming economy growth repair tasks were performed by machine operators and craftsmen together. If reparation is necessary was decided by the production unit itself. In the course of time the complexity of the machines and equipment was increasing and therefore workshops were built up as own foremen´s area. This foremen´s area had to follow the rising requirements of technological developments[7].

2.2.1 First maintenance generation (1940 – 1960)

The first generation of maintenance was of course not like the maintenance of nowadays. The mechanization and complexity of the machines was not very sophisticated and most machinery was oversized. Maintenance was just done unscheduled at a breakdown of a machine. Otherwise machines were just cleaned, visual inspected and greased[7].

2.2.2 Second maintenance generation (1960 – 1980)

The demand of goods was growing quite fast. This fact influenced the production and the degree of capacity utilization of the production machines was rapidly increasing too. Simultaneously there were drastically changes for all kind of production machines because of rising mechanization and complexity. To avoid downtimes of machines and thus of the production was very important. Planned maintenance was established and that was the starting point of preventive maintenance. Also the view of costs got more importance. When the transistor came to the market, a new era of maintenance began. With a transistor it was possible to perform functional switching's in fractional amounts of seconds. A huge boom of the electronic industry was the result. That meant for the maintenance process that existing contactor elements got replaced by the use of electronic circuits. In the 1970´s the first stored program controllers came on the market and the complexity of the machines got new dimensions. With computer programs it was possible to control and steer the planning of the maintenance[8].

2.2.3 Third maintenance generation (1980 – today)

Because of increasing complexity of the machines the susceptibility to trouble was increasing too. Especially for the electronic equipment it was a huge problem because of the relatively new technologies. The high amount of new parts and functions was very accident-sensitive. With the progress of mechanization additionally the requirements of the operator personal ran through a big change and they had to be much higher qualified. Gauges and instruments were replaced by display screens and whole processes were able to be visualized by the use of computers. Fast computers and software systems were steering the production processes. Again a rapid customization of the maintenance was needed. A need of specialists was

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[7] (Reichel et al. 2009) p. 52
[8] (Reichel et al. 2009) p. 52f

created e.g. specialists for hydraulic, pneumatic, automation etc. Weak points of the machinery were analyzed and improved. Also a change in the organization took place – central and decentralized maintenance units were created to increase the effectiveness of the whole maintenance process. It became necessary to debate about internal labor and external labor due to the high amount of working tasks and the increased reaction requirements. Therefore outsourcing for maintenance was unavoidable. A closer collaboration of the maintenance units and the production was tried to be achieved by Kaizen, Total Productive Maintenance (TPM) and continuous improvement processes[9].

In future the realization of legal restraints in the areas of operational safety, environment protection, acceptable costs and optimization of machinery will be very important. Without the basic knowledge about business economics it will be impossible to deal with that complex topic in future[9]. Also for a tunneling maintenance department it is very important to fulfill all required legal restraints and to ensure an efficient and safe working environment.

[9] (Reichel et al. 2009) p. 54

2.3 Kaizen / Total Productive Maintenance (TPM)

The preventive maintenance (PM) was developed by the General Electric Corporation in the 1950´s and was then introduced in Japan. The Japanese adopted that system and developed an improved program for a more efficient production. To maximize the efficiency of operational facilities the PM includes every single worker – therefore total productive maintenance (TPM) is the more appropriate definition. The basis of TPM is to include the machine operator to routine maintenance tasks. It has to be mentioned that many Japanese, especially at the management level, work for more than 10 hours daily. They perform voluntary overtime hours just to learn the rules of TPM. A company should possess perfect machines to produce a perfect product. But even the newest and best machines can become bad conditions quite fast if an appropriate maintenance is not performed continuously[10].

Also for the excavation processes of a tunnel construction site these rules can be a factor for success. If the miners would be integrated to the maintenance task itself they could control their machines more conscious and perform e.g. optical checks of the greasing conditions, fuel levels, function of lights etc. This takes not much time but can prevent serious prospective damages. If some inconsistencies are detected the foremen should be informed by the miners to initiate further actions for preventive maintenance. The miners must be aware of the huge advantages by active participating at the maintenance process. To raise this awareness of all employees is a huge challenge for the management of each construction site.

For a long time only the manufacturing costs were taken into considerations for cost reductions. But the maintenance costs are compared to the manufacturing costs relatively high - normally they represent about 5 – 15 % of the manufacturing costs. The type of the company is determining this value. The heavy industry will have a higher percentage rate, industry sectors with a lot of manual work and fewer machines will have a lower percentage rate[11]. Due to the use of many different heavy vehicles at a tunnel excavation process the maintenance costs for these machines are relative high compared to the acquisition costs itself. As a result of high wear and many damages the costs for service and repair tasks at a tunneling workshop are tremendous.

With the introduction of Kaizen the Importance of the maintenance changed drastically in 1993. In Japanese companies leading members of the production and the maintenance were combined to Kaizen teams and got a special management education about the Kaizen techniques. It was crucial to detect the productivity-deficiencies and to minimize the waste. In the Japanese language this waste is also called “Muda”. The waste at the maintenance process will be explained more in detail a little bit later. To perform this task the members had to perform the “5S-campagne”. It is called “5S-campagne” because this method is referred to 5 Japanese words which all have an initial letter with “S”. This “5S-campagne” can

[10] (Hartmann 2013) p. 1ff
[11] (Hartmann 2013) p. 7

be seen in figure 5. The maintenance team had now additional the responsibility to educate the production teams and was emancipated to improve to the company´s success[12].

Seiri => establish order (remove all unnecessary things)

Seiton => store every item on the appropriate place

Seiso => increase tidiness at the place of work

Seiketsu => personal sense of order

Shitsuke => discipline (keep rules and standards)

Figure 5: The “5S-campagne” according to Reichel[12]

For the maintenance team of a tunneling workshop the conscious use of this “5S-campagne” can lead to a much more efficient maintenance task itself. Because of lack of time many service processes are performed as fast as possible. This leads to a disorder at different working places in the workshop in the sense of widespread tools and equipment. Sometimes it can also happen that the mechanics lose tools during the repair tasks in the tunnel area. Due to this fact long searching times and high tool costs are the result and an efficient maintenance is not always possible. **Seiri** – establish order – is obvious very important. This means that currently unused tools and equipment should always be removed from the working area for a better overview and order. Simultaneously **Seiton** – store every item on an appropriate place and **Seiso** – increase tidiness at the whole working area. This is of course not always possible especially when the mechanics are performing repair tasks at the machines in the tunnel area. The dark and dirty circumstances complicate an efficient and clean performed maintenance process. Also water ingress and the high noise level are bad influence factors. Those are reasons why maintenance tasks at tunnel construction sites have to be considered as more difficult compared to maintenance tasks at “common” working areas. But it shows that it is even much more important to work in a systematic and tidy way because a lack of tools or expendable materials can cause fatal problems and interruptions at the machine maintenance process.

It is necessary for all mechanics to follow those principles as good as possible even when the working environment is not optimal for the repair and service tasks. Therefore – **Seiketsu** – the personal sense of order – is very important. To build standardized working areas would be helpful for all employees to keep a better order at the working places. It is important to increase the awareness of all involved workers for a more efficient way of working. Relatively short perseverative cleaning and sorting tasks can prevent long searching or waiting times

[12] (Reichel et al. 2009) p. 17

and consequently drastically reduce machine downtimes. The last keyword – **Shitsuke** – describes the needed discipline which the workers have to develop and to keep in mind all the time to perform all working tasks in an efficient way and therefore to improve the whole maintenance process continuously.

The improvement process should be continuously and comprehensive at every division of a company. This is of course a long-lasting process until it becomes as a matter of course. Consequent planning and power of endurance are essential factors. Each worker should be motivated to improve his own work continuously. The management has the responsibility to establish an environment so that a continuously transformation process is enabled[13].

This continuous process of improvement is partly done at some tunnel construction sites. The miners and mechanics are rewarded with bonus-payments if they cause no damages at the machines and equipment. This system leads to higher motivated employees who are working more careful with all vehicles and devices. The rate of damages can be drastically reduced with this measure because every worker is motivated to work more cautious. This can be seen as an improvement of the working style.

Waste in the maintenance process

It is obvious that waste should be avoided – even at a maintenance process. There are different types of waste which can be distinguished e.g. overproduction, waiting times, waste at transport processes, waste at the product processing itself, waste on stock, waste due to needless movements and defect products. By the meaning of waste concerning maintenance in general the main important types are waiting times, waste at transport processes, waste on stock and waste due to useless movements. When workers have to wait for a necessary reparation or maintenance of a machine, waiting times can be caused and these workers are unproductive in the meantime. Especially at reactive maintenance unproductive waiting times are unavoidable. Reactive maintenance means that the maintenance task is performed not before a failure of a machine or a machine breakdown occurs. The preventive maintenance is performed in periodic time intervals or after a defined usage of the machine. The preventive maintenance should be always preferred[14].

The different types or even strategies of maintenance are explained more in detail at chapter 2.4. To figure out the right maintenance strategy is a big challenge for every tunneling workshop unit because it is not always possible to perform the preventive maintenance due to lack of time and urgent need of diverse machines. Of course missed maintenance intervals can cause many problems and high additional costs. Because of the rough environment of the heavy machines the reactive maintenance has to be performed quite often. Then the mechanics just get a call from the tunnel foreman and then they have to drive

[13] (Brunner 2014) p. 6
[14] (Reichel et al. 2009) p. 39f

immediately to the damaged machine. The problem must be analyzed local and following the mechanics have to perform the repair tasks as fast as possible. A proper communication at a breakdown of a machine is a very important factor. The practical part of this thesis is dealing with this important topic of emergency communication at a maintenance process.

Waste due to transport reasons can be caused due to wrong arrangement of the workshop-layout or the position of the spare-part magazine to the production facility. So the responsible guy for the maintenance has to cover a distance maybe multiple times. Employees have to be educated to recognize the obvious waste and to avoid that waste in future[15].

This is a special problem for every tunnel construction site because of the increasing length of the tunnel. A machine breakdown in the tunnel is getting always more difficult because of the increasing distance of the defect machine to the workshop, which is mostly positioned outside of the tunnel. This is a problem for the moving as well as for the stationary machinery in the tunnel area. To transport a damaged vehicle out of the tunnel to the workshop can be very time intensive if the vehicle is not able to be driven by its own. Also for the stationary machinery in the tunnel (e.g. stone crusher, stations of conveyor belt system,…) it can be necessary to cover a distance multiple times to bring and transport the appropriate tools and spare-parts to the defect machines. This is often very difficult because for many different repair and service tasks there are always different tools used e.g. different wrench sizes, different coupling connections and special needed tools. Also to find the appropriate spare-parts is often difficult or even impossible for the mechanics. A well organized and good structured tool and spare-part magazine should be the basis for every tunneling workshop. The practical part of this thesis deals with that problem and shows how to overcome it.

[15] (Reichel et al. 2009) p. 40

2.4 Strategies of maintenance

A strategy of maintenance is the method of maintenance which is used to achieve specific objective of maintenance. [DIN EN 13306]

Various aspects have to be considered when choosing a strategy for maintenance. These aspects can be regarding legitimate-, technical-, safety-technical-, production relevant-, and economical determinations. A further distinction can be made according to the point in time into systematical and unsystematical maintenance. If maintenance is performed at a machine breakdown or at an appearance of a demand, it is called an unsystematical approach. If measures are performed in periodically time and utilization intervals or in dependence of a condition of a considered unit regarding defined edge conditions a systematically approach is existing. The chosen strategy of maintenance is determining the reliability of technical equipment[16].

In figure 6 the differentiation of the strategies of maintenance according to Matyas K. can be seen. Two main strategies of maintenance can be distinguished – the reactive maintenance and the preventive maintenance. There is an additional classification of the preventive maintenance into periodically preventive-, condition-based- and predictive maintenance[17]. These different strategies of maintenance will be explained in more detail.

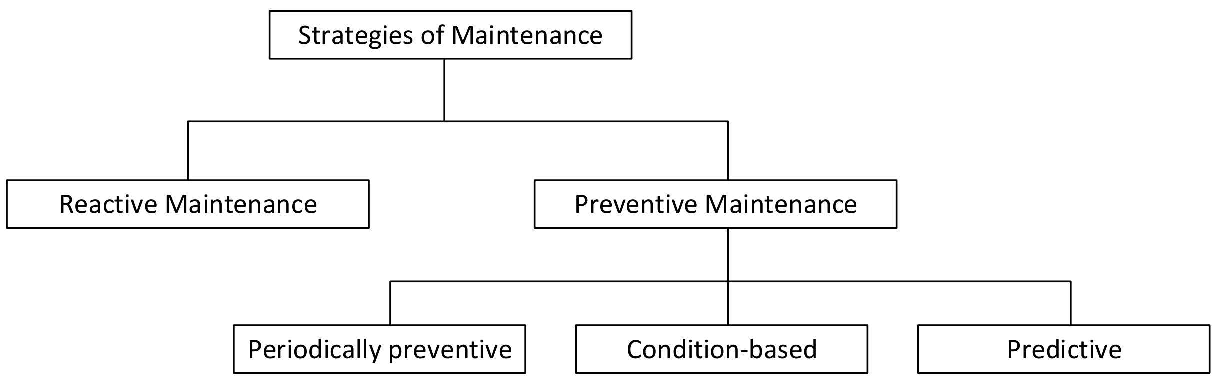

Figure 6: Strategies of maintenance according to Matyas[17]

2.4.1 Reactive maintenance

The breakdown of a component or the exceeding of a level of damage initiates the reactive maintenance. Sometimes the reactive maintenance is even called disturbance based maintenance or firefighters strategy. A strategy is always long-term planned to reach a certain objective. Reactive maintenance therefore is not a real strategy in that sense because maintenance tasks have to be performed spontaneous and quick in case of a machine breakdown. If the limit of damage of a certain part or component is exceeded, very high loads to other affected components or parts can occur and further secondary damages

[16] (Schenk 2010) p. 26
[17] (Matyas 2002) p. 13ff

can happen. High time pressure and the need of many resources e.g. labor, tools, spare-parts, auxiliary material, etc. are leading to the longest machine downtimes and the highest breakdown consequential costs, because of lack of planning and arrangements. Much technical equipment has additional a high potential of danger and the risk of accidents is drastically high when reactive maintenance has to be performed spontaneously. There are of course no costs for planning this kind of maintenance, only defect parts and components have to be changed. That seems to be very economic only at a first rough view but this is not true[18].

To find out the right maintenance strategy for a tunnel construction site is a very difficult task. Because of many unpredictable damages of tunneling vehicles at the underground working area a reactive maintenance has to be performed quite often. To perform only preventive maintenance is still not possible. The workers can only try to reduce vehicle damages and to work with more caution. Of course the preventive maintenance is very important and should be always preferred compared to the reactive maintenance. It is a big challenge for the workshop management of this tunnel site to plan the maintenance for all machines in advance. Many additional and unpredictable machine breakdowns complicate this task enormous.

2.4.2 Periodically preventive maintenance

Defined intervals of utilization are initiating the periodically preventive maintenance. Components and parts get replaced and changed after a certain time regardless of their condition. The intervals can be classified according to calendar time, operating hours, pieces, driven kilometers, take off and landings etc[19].

An example for a periodically preventive maintenance interval can be seen in figure 7. Most significant is the point of exchange of affected parts and components. Therefore the time is the control variable. It can be seen that the component is changed long time before the limit of the functional compliance is reached.

[18] (Schenk 2010) p. 27f
[19] (Schenk 2010) p. 28

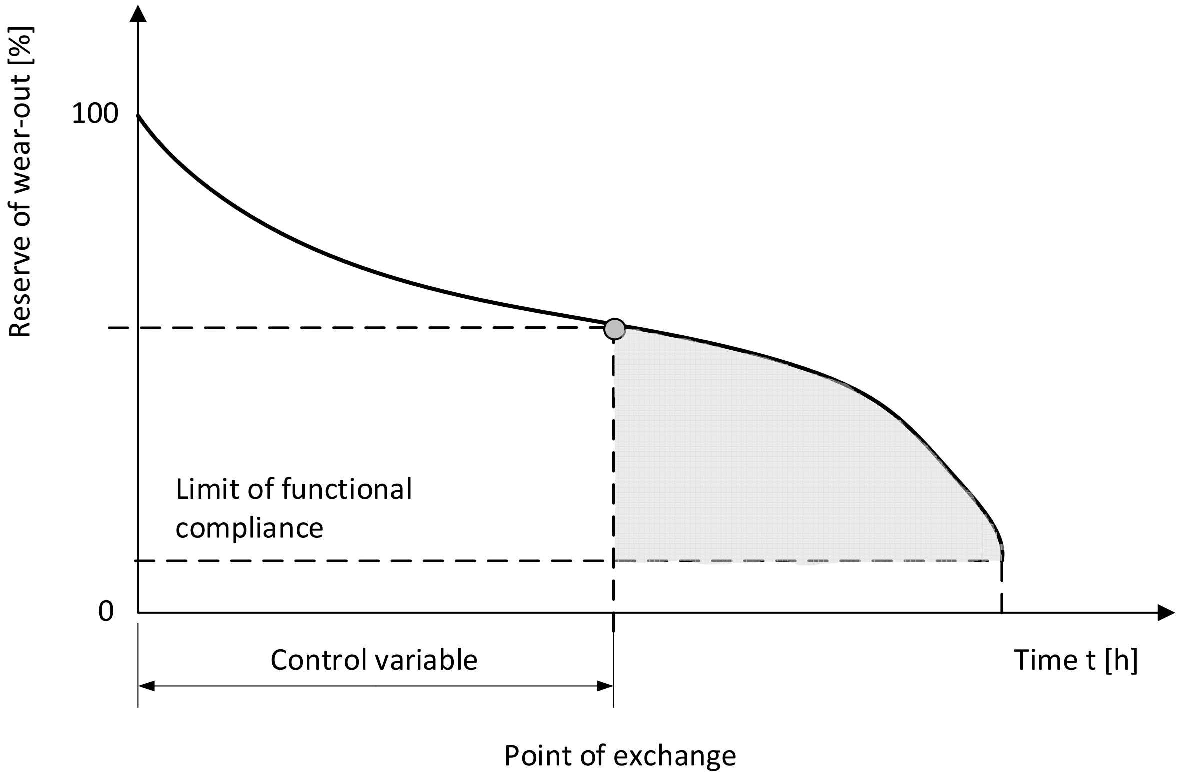

Figure 7: Control variable time at the periodically preventive maintenance[20]

The parts and components are changed before the reserve of wear-out is consumed. This fact leads to higher consumption of spare-parts and consumable materials. It is obvious that the costs for prevention are increasing but on the other hand the costs for breakdowns are decreasing enormous. Even if there should be a breakdown at the periodically preventive maintenance due to the exceeding of the limit of functional compliances of components the downtimes are normally lower. The problem is that all components have a different durability what causes the need of different maintenance intervals. To figure out the appropriate intervals is a big challenge but in general it can be said that it is valuable. Damages out of the past can be very useful for analysis and future planning of the intervals and therefore a good documentation is requisite. If the expected lifetime of diverse components and parts is well known the periodically preventive maintenance should be used. There is a much lower risk of breakdown for the equipment because of a good planning and preparation of all resources for the maintenance process in advance, compared to the reactive maintenance. The maintenance should be performed at a production stop. Through high repetition and planning of maintenance cycles the execution times of maintenance are optimized and lead to low machine downtimes[21].

At tunnel sites the periodically preventive maintenance is performed regularly. These performed standard service tasks at each machine are executed after exceeding of a certain time of engine hours or others e.g. hydraulic hours, shotcrete hours, kilometers etc. The

[20] (Schenk 2010) p. 29
[21] (Schenk 2010) p. 29f

exceeding of these defined hours is the starting point for the execution of a planned service. Such a service contains usually the change of the air and fuel filters, the change of hydraulic and motor oils and diverse repair works. It is important that there are responsible employees which track the machine hours all the time and to initiate actions at exceeded service intervals. The practical part of this thesis deals also with the topic of a better service preparation before the limit of the next service is reached in order to guarantee a higher efficiency of maintenance in future. An accurate monitoring and administration of all machine hours is the basis for an efficient maintenance process. A structured organization of needed spare-parts and tools is also essential.

2.4.3 Preventive condition-based maintenance

This type of maintenance is also called the strategy of inspection. The objective is to have a maximum utilization of the reserve of wear-out of the different components as well as low downtimes. For activating a maintenance process the control factor is changing. Therefore the condition of the components is the main control factor and the control variable is the reserve of wear-out. The graph of the preventive condition-based maintenance can be seen in figure 8. The control variable is not – like for the periodically preventive maintenance – the factor time. The maintenance is performed when the reserve of wear-out is exhausted. The information about the condition of equipment is needed to recognize abnormal behavior. Due to the fact that the reserve of wear-out is changing the intervals for maintenance get adjusted and regularly supervision of the whole system is necessary. So it is possible to detect breakdowns in time before they occur by inspections. The change of the reserve of wear-out must be measurable – this is a precondition for the application of the condition-based maintenance. A measurement of condition-based parameters must be technical practicable and economic. Actions for keeping the condition of the equipment fully operational can reduce breakdowns of machines and increase their reliability[22].

[22] (Schenk 2010) p. 30f

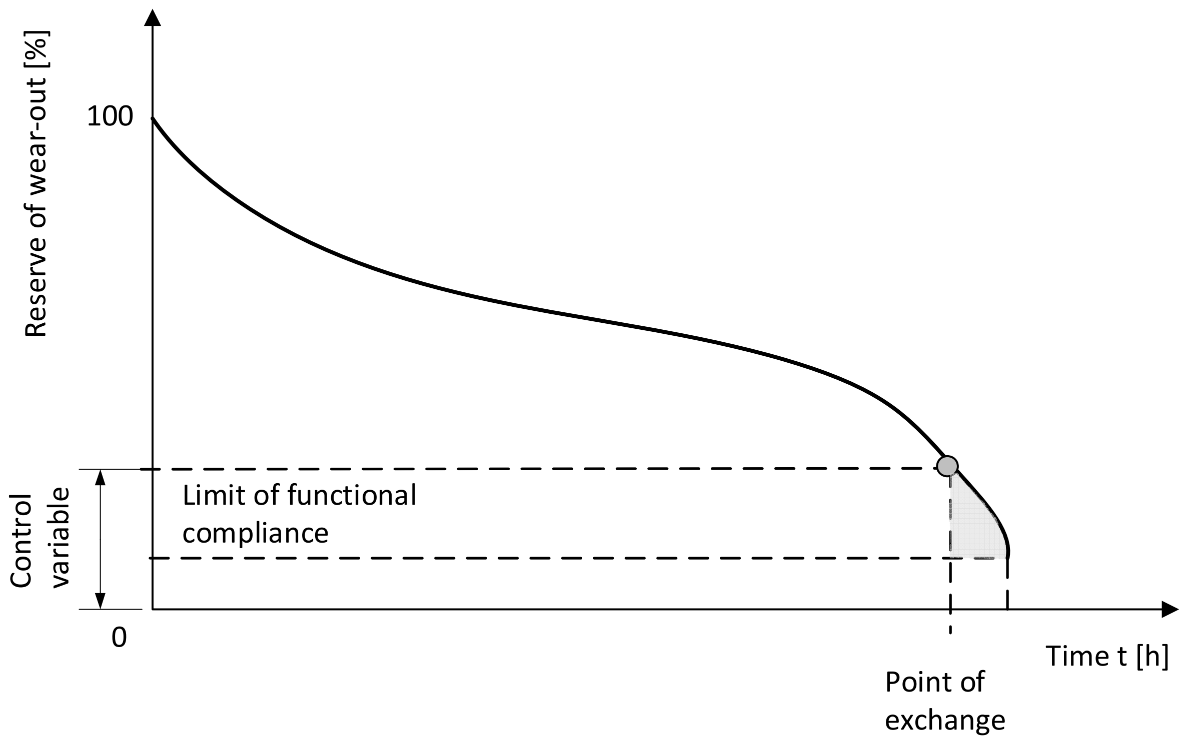

Figure 8: Control variable reserve of wear-out at the condition-based maintenance[23]

At the tunnel construction sites the condition-based maintenance has to be performed when machines show exceeded wear at certain components. The mechanics or even miners can help to improve the overall condition of all machines when they are performing some visible inspections at all machines regularly. An exceeded wear could be at e.g. worn out tires, defect lights, bad conditioned wear parts (wear plates), low greasing or oil levels, small or major damages in general etc. Therefore a good cooperation between the excavation team and the workshop team must be aspired to achieve a more efficient maintenance.

2.4.4 Predictive maintenance

The predictive maintenance is a consequent advancement of the condition based maintenance. The advancement of this strategy should prevent potential (blind) breakdowns. Basis of the application of this strategy is the definition of functions and possible disorders of functions. These functions can be classified into 3 categories – primary functions, secondary functions and needless functions. Another important point of view is the disorders of functions[24].

[23] (Schenk 2010) p. 30
[24] (Schenk 2010) p. 31ff

2.4.4.1 Primary functions

The main reasons for the investment of equipment are derived from the primary functions of that equipment. Examples are the speed of a conveyor belt system [m/s], capacity of a tank [m^3], flow rate [m^3/h] etc. Criteria's of quality have to be considered too e.g. a conveyor belt system has to guarantee additional to handle a defined amount of material [t]. Machines and equipment can have more functions and the task of the maintenance is to ensure the defined output for each function[25].

2.4.4.2 Secondary functions

The secondary functions have to be fulfilled as well as the primary functions. A breakdown of a secondary function can cause a high risk for operating safety and efficiency of equipment – the maintenance has to ensure a correct operation. Secondary functions are classified into following categories[25]:

- Operating safety (protective devices for health and safety)
- Environment protection
- Storage, transport, decking of a defined amount of material
- Suggestibility (possibility to regulate the performance)
- Appearance
- Operating efficiency

2.4.4.3 Needless functions

These are components, parts and functions of machines and equipment which are not really relevant for the desired functional compliance. But also these functions have to be maintained and cause costs[25].

2.4.4.4 Disorder of functions

Damages of equipment are focused and analyzed according to different failure modes. The influence factors for possible failures are analyzed and evaluated. Different failure modes are concerning e.g. safety, environment, operational relevant aspects and operational not relevant aspects. Breakouts have to be prevented at the predictive maintenance according to different functions. The most important point is to recognize potential for breakouts in early phases[25].

The predictive maintenance should prevent future breakdowns of machines and equipment through regularly analysis and evaluation. For the maintenance of a tunnel construction site this type of maintenance could avoid many disturbance breakdowns. Also the differentiation according to the different categories of functions would be very useful to set the right

[25] (Schenk 2010) p. 31ff

priorities of maintenance tasks to the different units of the vehicles. The practical part of this thesis will cover some aspects to reach a predictive maintenance as good as possible.

The challenge for each construction site is to find out the proper strategy or even strategies of machine maintenance in order to maintain the machines as efficient as possible.

Figure 9 shows a matrix for the classification of the different strategies for maintenance according to Rasch[26].

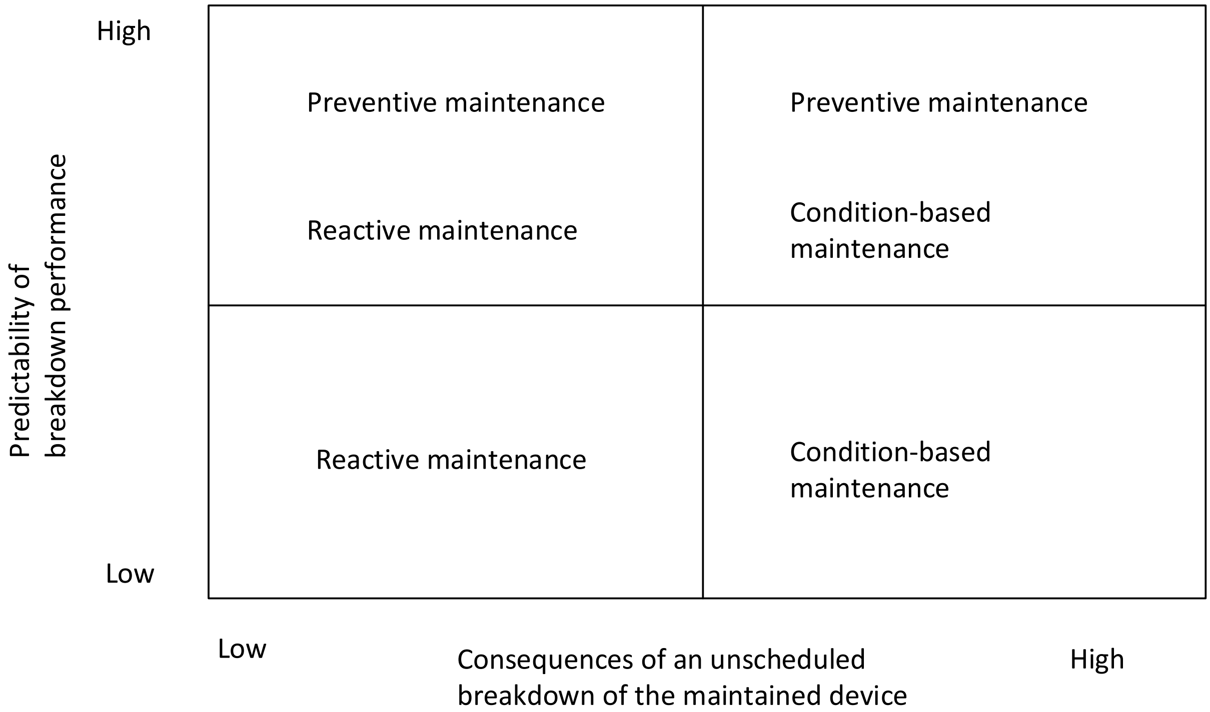

Figure 9: Matrix of classification for strategies of maintenance according to Rasch[26]

[26] (Rasch 2000) p. 95

2.5 Objectives of maintenance

To reduce breakdowns of machines and equipment it is necessary to perform the maintenance tasks in a **high quality standard**. The probability of breakdowns is decreasing if the inspection and maintenance tasks are performed more accurate. This leads to a higher availability of the machines. If the duration of maintenance is decreasing and the operations are performed in time before breakdown the availability of machines and equipment can be increased too. The proper maintenance **in time** can also reduce costs for maintenance due to low duration of maintenance time and less needed staff because of a better organization. It is important to reduce waste of resources and to **minimize the costs** for maintenance. At the direct maintenance this consideration affects the personal as well as material costs, at the indirect maintenance mainly the costs for equipment breakdown are affected [27].

This classification of maintenance costs into direct and indirect maintenance costs can be seen in figure 10. All kind of planned activities for maintenance belong to the direct maintenance costs. If worn out parts are not changed in time indirect maintenance costs occur because of e.g. breakdowns of machines. If there is a low effort to prevent breakdowns of equipment the direct costs of maintenance are low too. But then the risk of machine breakdowns is higher and this can lead to very high indirect maintenance costs[28].

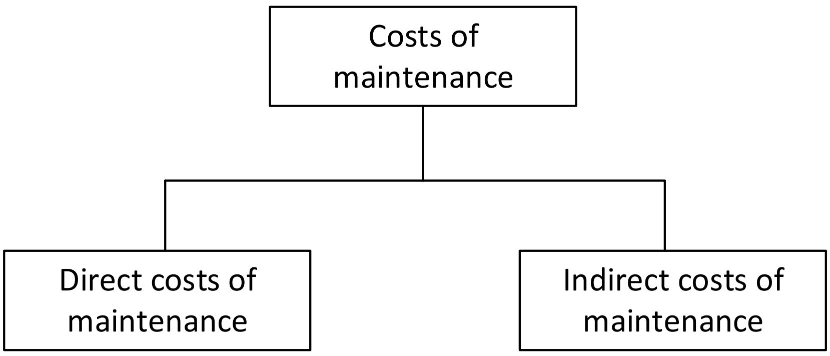

Figure 10: Classification of maintenance costs[28]

Also for a tunneling workshop unit it is important to find a good balance of the invested money for preventing machine breakdowns in the future. To reach a good degree of capacity utilization of maintenance and appropriate direct costs for maintenance is a very complex topic and needs a lot of experience from the responsible maintenance manager. The experience out of similar projects or similar used machines at the site is very helpful for better estimation of needed employees, used material / spare-parts and durations of service intervals.

[27] (Rasch 2000) p. 83f
[28] (Adam 1989) p. 101

High awareness is needed to figure out the appropriate level of inserted costs, time and quality for maintenance[29].

The objectives of maintenance are also shown in figure 11. It can be seen that all factors are influencing each other.

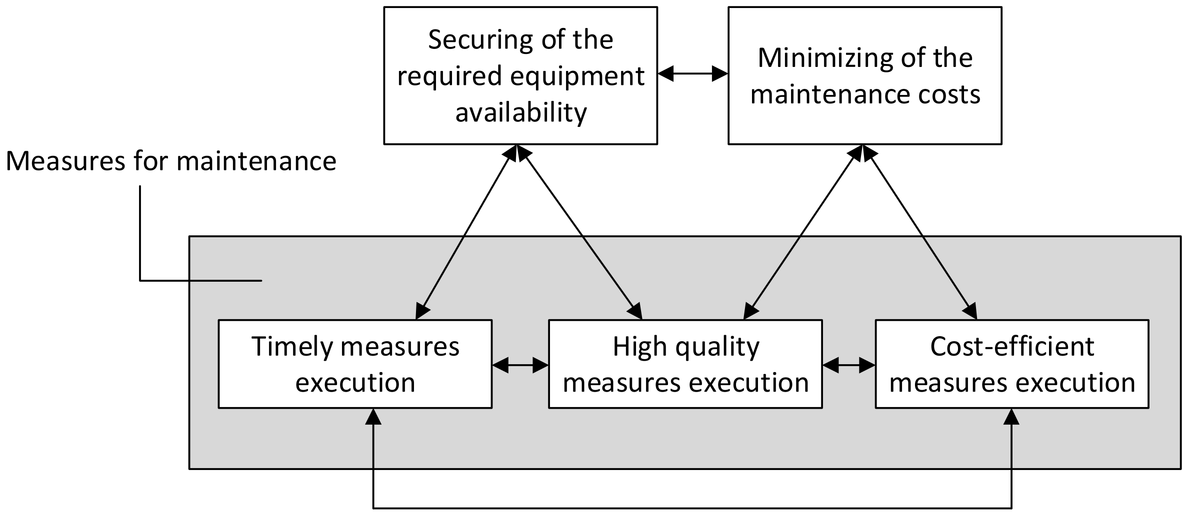

Figure 11: Objectives of maintenance[29]

According to Strunz the objectives of maintenance are mainly focusing on costs, production and safety. For the cost objectives it is important to optimize the expenditures for maintenance and to reduce the costs at machine breakdowns. The objectives of the production are to ensure the required availability of equipment and to guarantee independency through a good balance between intern and extern maintenance. The safety objectives have to prevent trapping hazards and health damages. The work has to be humanized and safety at work has to be ensured. The objectives of costs and production are superficial[30].

29 (Rasch 2000) p. 84
30 (Strunz 2012) p. 19f

2.6 Reliability and availability of maintained systems

Systems which have to be maintained in order to be fully functional and available for operating have to be reliable. All parts and units of a machine show a certain course of failures – this well-known behavior is also called the “bathtub curve”.

This bathtub curve according to Geiger & Kotte[31] can be seen in figure 12. The curve is valid for all parts of a machine which are exposed to direct wear[32]. The X-axis is illustrating the time and the Y-axis is illustrating the failure rate designated with α(t). Mostly a big collectivity of identical units will be observed with this bathtub curve to figure out the failure behavior of units. The curve can be classified into 3 different segments into early failure, random failure and wear out failure. In many books of literature the curve is illustrated with a smooth line but this will happen seldom in practice[31].

According to Czichos & Habig the three different segments of early-, random- and wear out-failure rate are also called declining-, constant- and progressive- failure rate[33].

2.6.1 Early failures

The early failures are occurring relatively short after the initial operation of the units and they can be seen like children diseases of units[34]. This type of failures can also occur due to construction mistakes or fabrication / assembling mistakes of machines caused by the manufacturer. The failures occur at the initial phase of utilization and with the time they get quite rare[35].

For the operation of tunneling vehicles the distribution of failures or breakdowns can be seen in an equivalent way. The phase of early failures can be quite high at the initial operations of machines due to technical breakdown of new (untested) machines. Therefore early failures are often not avoidable, according to the workshop manager of the tunnel site Solbakk. Influence factors which are contributing to early failures can also be new (unknown) equipment or new hired employees, which are not able to operate the machines properly.

31 (Geiger & Kotte 2008) p. 323f
32 (Matyas 2013) p. 35
33 (Czichos & Habig 2010) p. 156
34 (Geiger & Kotte 2008) p. 323
35 (Matyas 2013) p. 36

2.6.2 Random failures

The failure rate of early failures is reducing asymptotic and leads to a constant failure rate and therefore to a constant lifetime of units[36]. The appearance of these failures cannot be predicted because they are independent of the age of the parts. This is caused by the coaction of disadvantageous circumstances[37].

Like at a tunnel construction site the machines can achieve quite a long durability if all maintenance tasks are performed in a proper way and with the appropriate frequency. Also the overall conditions of the underground vehicles can be suitable for quite a long time. The probability of random failures at right performed operations and maintenance at the machines is relatively low at this point of time.

2.6.3 Wear out failures

At the end of the quite stable random failure rate the curve is starting to increase again at the phase of wear out failure caused by aging and wear of units over the time. Also the death rate of humans can be seen in the way of the bathtub curve[36].

Even well operated and well maintained underground vehicles will show a certain wear of units over the time due to the high workload and the rough working environment. Wear out failures cannot be avoided 100% even with a very intense maintenance. It is obvious that there will appear more and more wear out failures over the time and this will end in a high failure rate of machine units.

At the section of the wear out failures preventive maintenance is very important because of known failure causes. It is essential to guarantee a high availability of equipment[37].

[36] (Geiger & Kotte 2008) p. 323
[37] (Matyas 2013) p. 36

2.6.4 Summary

Due to the fact that different failure behaviors of units are existing it is difficult to figure out which parts and units have the same wear or failure behavior. Therefore it is difficult for the spare-part logistic to accumulate the appropriate parts on stock[38].

This is also a big challenge for the responsible workshop manager of a tunnel construction site and therefore longtime experience and a good knowledge about the used machinery and equipment is absolutely necessary.

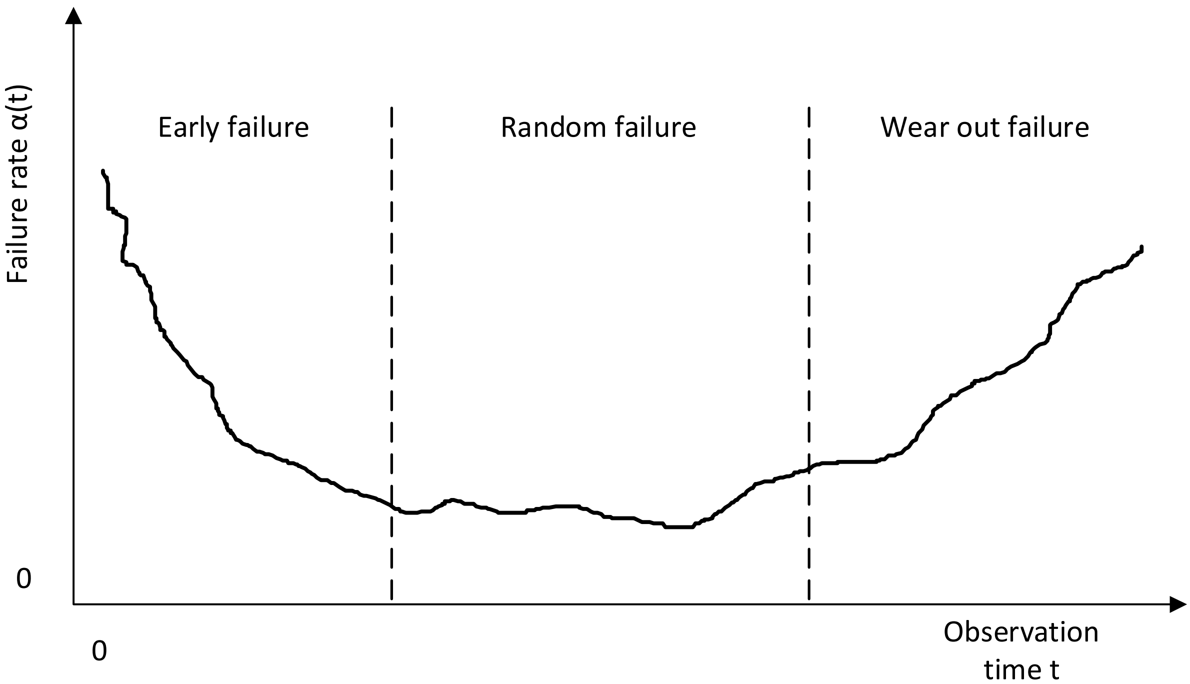

Figure 12: Failure rate α(t) depending on the observation time – bathtub curve[39]

[38] (Schuh 2013) p. 174
[39] (Geiger & Kotte 2008) p. 323

3 Systems Engineering

There are various different ways to describe Systems Engineering. But before the theory will be explained in more detail it is important to analyze some basics about the system theory itself. The term of a system is widely spread in many different disciplines especially related to engineering science. This chapter analyzes first the term of a system and tries to answer questions like:

- What is a system and which types can be classified?
- Which elements are included?
- How can systems be illustrated?

In the following subchapter the theory of the interdisciplinary science Systems Engineering according to the concept of HALL-BWI will be explained and following questions will be clarified:

- What is Systems Engineering?
- How does the structured proceeding of the SE concept of Hall-BWI look like?
- Which tools and methods are used?

Finally, the most important elements out of this concept will be explained more in detail. This elaborated knowledge out of the theory of Systems Engineering will be further used during the case study in chapter 4. Therefore, additional tools and methods will be explained. This tools and methods are used in the practical part.

3.1 Systems

In general, various different systems can be distinguished e.g. solar systems, light rail systems, ecological systems, social systems etc. Due to this fact only a general definition of the term system makes it possible to compare the characteristics of the different systems[40]. An example for such a general system notation can be seen in figure 13.

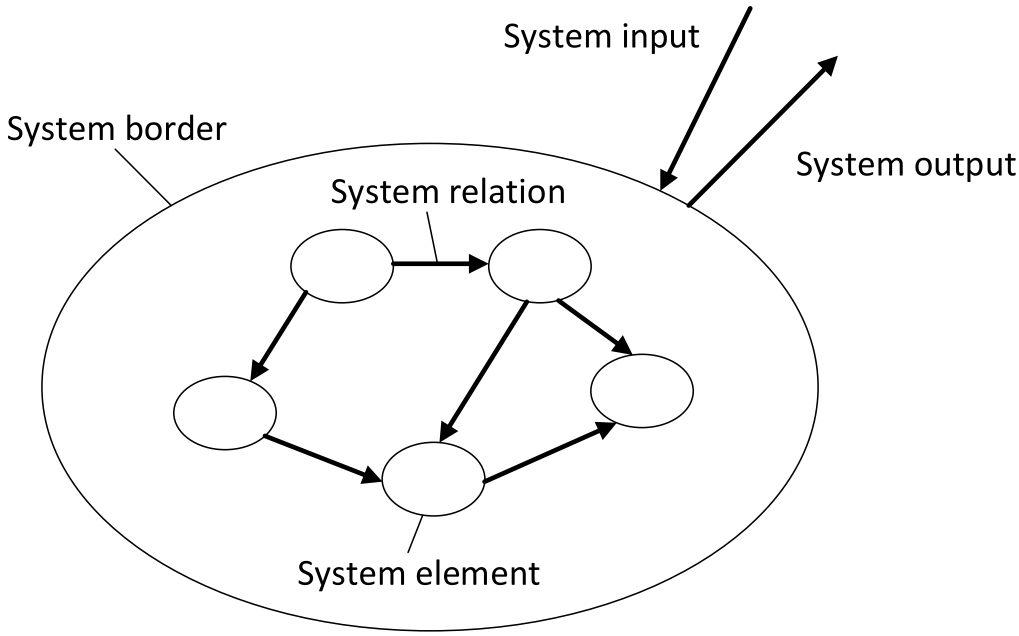

Figure 13: Principle of a general system[40]

The system in figure 13 consists of a system border and interacts with the environment through a defined system input and a defined system output. This system border is including the entire system and therefore it is well defined compared to the environment. The influence of the system to the environment is defined as the system output. The input of a system is defined as the influence of the environment to the system itself. Within every system several system elements are located which are connected to each other via characteristic relationships[41].

Such an element of a system could be for example one or more persons or even a department. The tasks of such system elements should be equally distributed in that way that the workload of each employee is equitable. The amount of interfaces should be reduced as good as possible[42].

[40] (Krallmann et al. 2002) p. 23
[41] (Krallmann et al. 2002) p. 24
[42] (Grünwald 2013) p. 118

System elements have functions and properties and these elements can be seen also as own systems, so-called sub systems. But it is also possible to combine some systems to one extensive system which is called main system[43].

The system border of a tunnel construction site could be the construction site itself and the different system elements could be diverse departments, employees, machines etc. It is very important to figure out the most important relationships within such a system to understand the overall function of it. Input and output factors of a construction site could be for example consumable materials, water, mucking material etc.

It can be said that every description of a system is made by individual persons and therefore the aspects of the whole system are individual as well. Due to this fact it is still not possible to generate a general valid system out of a concrete system[44].

3.1.1 Classification of systems

It is difficult to transfer the gathered knowledge from one system to another – this can only be done on a very abstract level. With a determined system definition the universal validity of the statements of a system can be qualified. Therefore, a classification of systems is needed to compare the different characteristics of systems to each other. Table 1 shows some possible criteria for the classification of systems[45].

Table 1: Criteria for classification of systems[46]

Property	**Characteristics**	
Level of existence	Real	Ideally
Type of development	Natural	Artificial
Relation to environment	Closed	Open
Dependency on parameters of properties	Static	Dynamic
Determinability of characteristics	Deterministic	Stochastic
Degree of comprehension of human elements	Mechanistic	Non-mechanistic

[43] (Haberfellner et al. 2012) p. 34ff
[44] (Krallmann et al. 2002) p. 24
[45] (Krallmann et al. 2002) p. 26f
[46] (Krallmann et al. 2002) p. 26

Following important system aspects related to Systems Engineering are explained in more detail:

Relation to the environment:
An open system has relationships to the environment. On the other side a system which is totally isolated from the environment and has therefore no relationships to the surrounding environment is called a closed system[47].

Most of the real systems can be classified as open systems and therefore a system of a tunnel construction site can also be seen as an open system due to the fact of many interactions with the environment.

Type of development:
Systems which are created without the influence of humans are natural systems e.g. the planetary system or the cardiovascular system of a mammal. Artificial systems are created by the influence of the human e.g. computer systems or social systems[47].

As a result every construction site can be seen as an artificial system.

Dependency on parameters of properties:
Static and dynamic systems can be classified according to the time dependency. When properties of relations and elements are not changing over time, the system can be seen as static. If the properties of relations and / or elements are changing over time, the system is dynamic and therefore the behavior and the structure of that system is flexible, like for example a company or even a human[47].

As a result every maintenance unit of a construction site can be described as a high dynamic system.

[47] (Krallmann et al. 2002) p. 27

3.2 SE concept of HALL-BWI

In the last few years the competitive pressure on many companies and almost every industry sector increased dramatically. The communication nowadays is done via e-mails and the companies are spread thousands of kilometers all over the world. Systems Engineering therefore is managing and establishing appropriate solutions to existing difficulties and problems and it can be seen as a creative activity[48].

There are various factors which contribute to the high competitive pressure according to Stevens – some of the most important aspects are e.g. [48]:

- Establishing of new technologies
- Higher complexity of various products
- Shorter cycles for product development
- Reduction of trade barriers
- Cooperation of worldwide teams
- Software as main force of changes

“Systems engineering is the key technology to manage this complexity.”[49]

It can be seen that the whole industrial environment is changing very fast and various difficulties have to be overcome by each company in order to be competitive and therefore successful in the future. To develop new products and processes the concept of Systems Engineering is an essential factor for success.

There are different concepts of Systems Engineering available but within this thesis the SE concept of HALL-BWI will be focused and also used during the case study in chapter 4.

3.2.1 Terms and definitions

There are various diverse definitions of Systems Engineering available on the market. Reasons therefore are individual opinions of different institutions which advanced the development of Systems Engineering in the past. Some descriptions are listed as followed:

[48] (Stevens et al. 1998) p. 2f
[49] (Stevens et al. 1998) p. 2

"Here is a short list of disciplines that systems engineering is not: applied mathematics, applied probability and statistics, economics, operations research, computer science, numerical analysis, simulation, system theory, system science, human factors engineering, software engineering, agricultural engineering, civil engineering, electrical engineering, industrial engineering, manufacturing engineering, mechanical engineering. It has even been said that systems engineering is just good "blank" engineering, where the "blank" can be filled by any engineering descriptor whatever". [50]

"Systems engineering is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system. […] In summary, the systems engineer is skilled in the art and science of balancing organizational and technical interactions in complex systems". [51]

"The function of systems engineering is to guide the engineering of complex systems". [52]

"Systems engineering is the management technology that controls a total system life-cycle process, which involves and which results in the definition, development and deployment of a system that is of high quality, trustworthy, and cost effective in meeting user needs". [53]

According to Sage & Rouse Systems Engineering can be seen as a management technology which is interacting with fields like science, organization and environment. The information flow between all elements is of high interest[53]. Figure 14 illustrates Systems Engineering as a management technology.

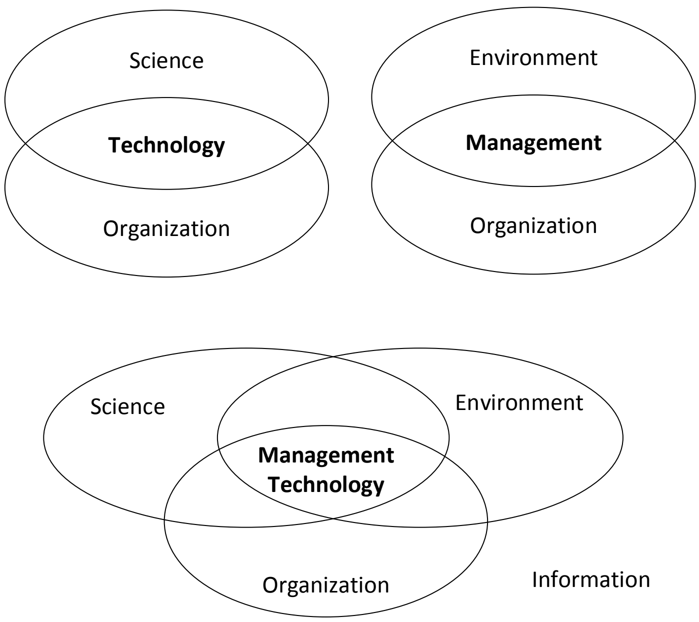

Figure 14: Systems Engineering as a management technology[53]

[50] (Wymore 1993) p. 1
[51] (Kapurch 2007) p. 3f
[52] (Kossiakoff et al. 2011) p. 3
[53] (Sage & Rouse 2009) p. 3

As a summary of all different definitions it can be said that the task of Systems Engineering is to solve different problems as efficient as possible by a methodical proceeding and it can be seen as a multidisciplinary management discipline. To have a better overview it is necessary to reduce the complexity of systems by the use of different principles and models. Requirements should be fulfilled as good as possible with high quality at the process of problem solving or product development.

Systems Engineering differs from other engineering disciplines because it focuses on the whole system from the outside with interactions to the environment, as well as on the inside. Complex systems nowadays consist of various different elements and therefore it is necessary to involve all kind of different engineering disciplines for a proper design and development[54].

3.2.2 Philosophy

For solving very complex problems Systems Engineering is a structured model for thinking as well as for the proceeding of actions with an objective to solve a problem in the most efficient way. Figure 15 shows the Systems Engineering concept according to Hall-BWI which consists out of different components[55].

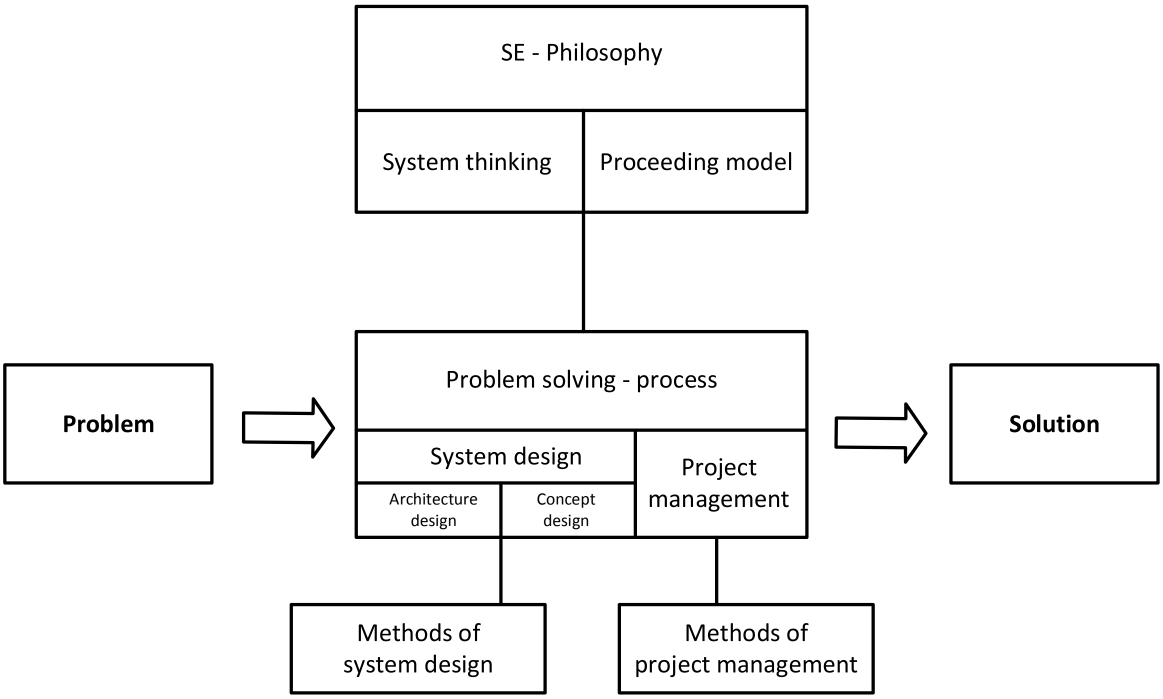

Figure 15: Components of the Systems Engineering concept according to Hall-BWI[56]

[54] (Kossiakoff et al. 2011) p. 4f
[55] (Haberfellner et al. 2012) p. 33ff
[56] (Haberfellner et al. 2012) p. 33

Within the next chapters the most important components of this concept will be explained in more detail.

3.2.3 System thinking

The system thinking as well as the proceeding model can be seen as a guideline for the analysis of a system and are therefore fundamental parts in Systems Engineering. The components of system design and project management are building the problem solving process[57]. The system thinking is a very important aspect out of the Systems Engineering philosophy from the concept of Hall-BWI – see figure 15.

For a better understanding of complex systems it is important to use a certain way of thinking and a famous one is called system thinking. This concept allows the modeller to explain the system on an appropriate level. It is very important to think always about the system as a whole and to observe the environment in which the system is located[58].

As already explained in chapter 3.1 a system consists of elements and relationships.

By the usage of different “filters” it is possible to emphasize various characteristics of elements and their relationships. These kinds of system views are called aspects of a system. The system view on individual aspects reduces the complexity for the observed sub system and improves the entire overview. Furthermore it is possible to distinguish different types of flows among these system elements e.g. flow of material, flow of information and flow of energy[59].

The whole system overview gets more structured by building different sub systems on an appropriate level. It is necessary to concentrate on a limited amount of systems and elements to understand the most important interactions among them. Therefore the challenge is to figure out the proper level of profoundness.

[57] (Baumann 1991) p. 69
[58] (Haberfellner et al. 2012) p. 33ff
[59] (Haberfellner et al. 2012) p. 39ff

3.2.4 Proceeding model

The proceeding model is the second element out of the Systems Engineering philosophy – the location within the Systems Engineering concept of Hall-BWI can be seen in figure 15.

There are four basic ideas which should be added to the proceeding model of Systems Engineering. These ideas are[60]:

1. Usage of the top-down approach
2. Principle of building different variants
3. Structuring of system development and realization according to time aspects (phase sequence)
4. Usage of problem solving cycle (formal proceeding guideline)

These four elements or even ideas should be combined with each other. Therefore it is important to understand every single idea. Following these ideas will be explained a little bit in more detail.

3.2.4.1 Top-down approach

Before the term of the top-down approach will be explained it is necessary to define some various terms of observation to deal with different levels of complexity. These types of observation are black box-, grey box- and white box observation and they will be described according to Haberfellner[61].

Black box observation
To reduce complexity of a system the black box observation is very helpful. At this type of observation only the function and the existing or desired inputs and outputs of a system are relevant. The internal structure is not relevant or even not known.

White box observation
If the relationship between input and output of a system is very important or the internal relations should be observed in detail, then this procedure is called a white box observation.

Grey box observation
A grey box can be structured partly or even rough. If it is structured very rough then the level of detail will be low. On the other hand it can be said that partly structured means that the level of detail can differ very much from detailed to low or even unstructured areas.

It is very important that the field of consideration is first focused quite broad and then it has to be narrowed step by step. This has to be done for the area of the problem as well as for the

[60] (Haberfellner et al. 2012) p. 57ff
[61] (Haberfellner et al. 2012) p. 38ff

area of solutions. It is not allowed to start with detailed analysis at the area of the problem due to the fact that first a rough structure has to be established and various aspects have to be considered and later on the area of the objectives has to be established also quite rough to figure out as many aspects as possible. The necessary level of deepness will be figured out during the phase of the system analysis. It has to be mentioned that parts of systems can be illustrated with a different level of degree. As a rule it can be said that the planning task should be done with the top-down approach and the bottom-up approach is normally used for realization[62].

This top-down approach with the restriction of the field of observation according to Haberfellner can be seen in figure 16. It can be seen that the whole complexity of the system is distributed to three different levels from level A to level C[63].

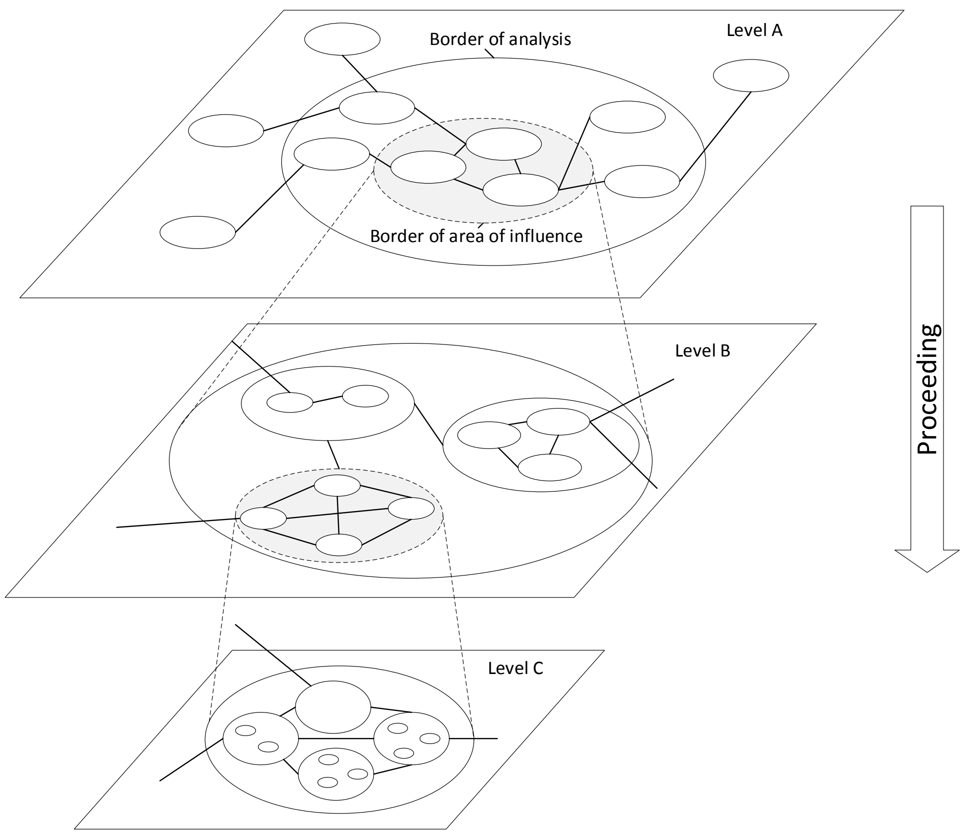

Figure 16: Top-down approach with the restriction of the field of observation[63]

3.2.4.2 Building different variants

It is necessary to have a broad overview of different variants of solutions for an existing problem. The first created solution should not be chosen because various other solutions are imaginable. Different variants of possible solutions must be established and evaluated to sort out the variants which seem to be not very successful. If a principle of a solution is figured

[62] (Haberfellner et al. 2012) p. 38ff
[63] (Haberfellner et al. 2012) p. 60

out to be successful then variants of total concepts have to be developed according to the chosen principle of solutions at a lower level. Again it is needed to evaluate and choose the best variant and then the detail variants have to be established and elaborated as well[64].

The principle of the incremental building of variants and the evaluation or even elimination combined with the top-down approach according to Haberfellner can be seen in figure 17.

It can be seen that at the beginning there is a problem or even a defined task and therefore some variants of solutions have to be build. After the evaluation of the best possible solution diverse variants of total concepts have to be established and evaluated. After the successful selection of the best variant of total concepts the building of variants for detail concepts has to be done[64].

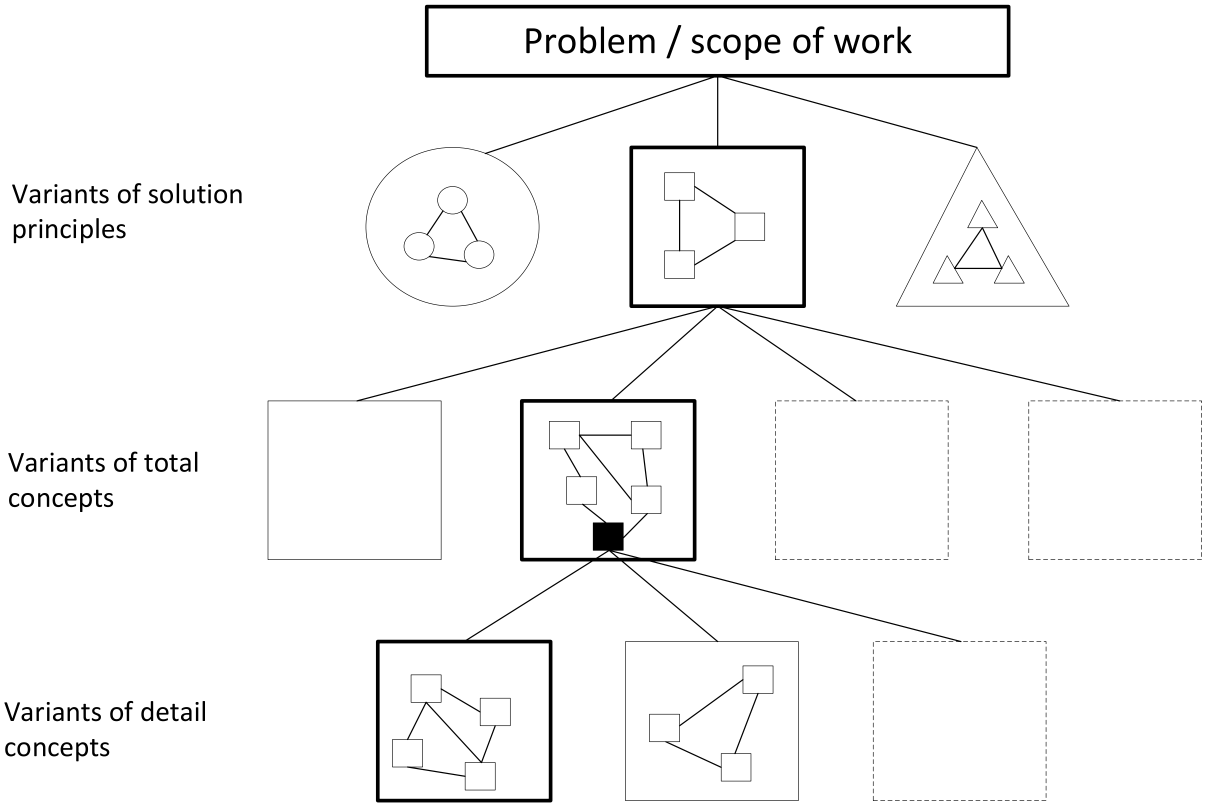

Figure 17: Incremental building of variants and elimination[65]

To think in alternatives, like at the principle of building variants, is essential for a good planning. If they are not taken into consideration, the risk of figuring out other possible principles of solutions only at a later point of time will be increased. Hence, the planning effort will be much higher and as a result the process of building different variants is

[64] Haberfellner et al. 2012) p. 61ff
[65] (Haberfellner et al. 2012) p. 62

essential, especially at the early phases of a project. With the progress of the project the importance of the “thinking in variants” will be reduced[66].

3.2.4.3 Project phases

A further proceeding to the top-down approach and the building of variants is the development and the realization of a project into structured phases which are separated by logical- and time aspects. These phases can be also seen as macro logic and are a theoretical pattern for a gradually planning process, evaluation process and realization process of projects and used to structure projects into manageable partitions. The possibility of correction and even termination of project decisions is very important especially at early phases[67].

The basic version of the concept of phases according to Haberfellner can be seen at figure 18. It has to be distinguished between the phases of life of the system or solution and the different phases of the project. Both types of illustration start with an impulse. At the phases of life the system is increasing in terms of development and detailing and will be established and used. The project phases which run parallel are the pre study, the main study, various detail studies, the phase of system building, introduction / implementation and the completion of the project. Simultaneously various achievements are created like for instance problems and ideas, principles of solutions, the master plan and detailed plans, the system which is ready for introduction and the implemented system. Additional it can be seen that there is the possibility of abandonment for the first phases of the project[67].

[66] (Haberfellner et al. 2012) p. 61ff
[67] (Haberfellner et al. 2012) p. 65ff

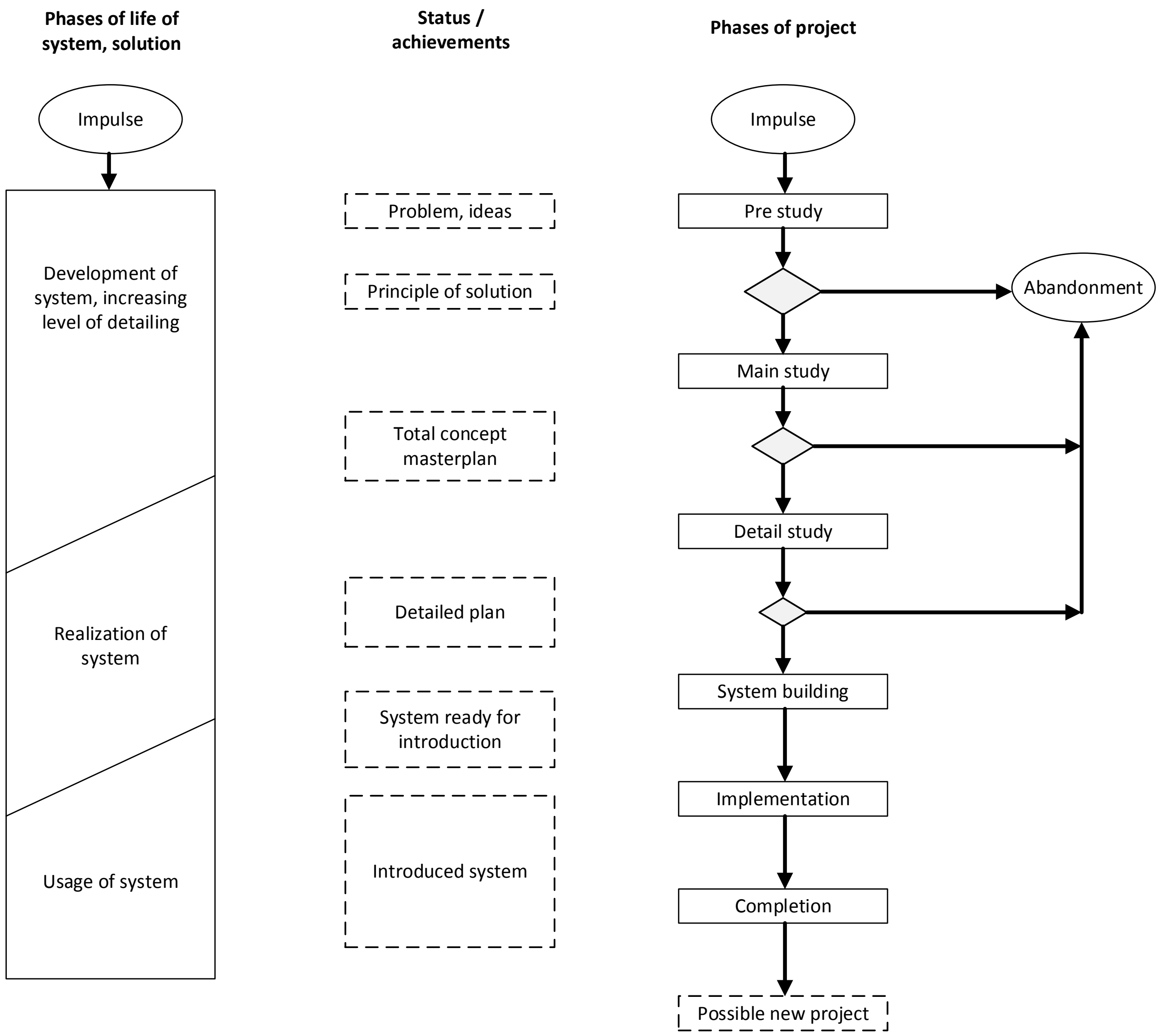

Figure 18: Basic version of the concept of phases according to Haberfellner[68]

Following the individual phases of a project will be explained in more detail according to the description of Haberfellner[69].

Impulse:

The phase of the impulse is the start phase and therefore the awareness of the problem will be developed as well as the readiness to act. This process is mostly not very structured. The objective is to determine if it is meaningful to start the phase of the pre study. It is not mandatory to discuss about the introduction of certain solutions for the problem at this point of time.

Pre study:

Within the phase of the pre study it has to be clarified if the way of solving the problem is appropriate and where chances and problems are located. Especially important is to figure out the proper limit for the border of analysis. It has to be checked if new or modified

[68] (Haberfellner et al. 2012) p. 65
[69] (Haberfellner et al. 2012) p. 66ff

solutions have to be established and which requirements they should fulfill. According to some aspects like economic view, technical view, political view, social view etc. it has to be figured out which principles of solutions are promising. Finally the solution which seems to be the most successful will be focused further.

Main study:
After the pre study it is essential to develop several variants of total concepts according to the chosen solution principle. Therefore it is necessary to compare various aspects of different variants like cost effectiveness and functionality and to set priorities. A total concept should be the result out of the main study and this concept must be focused further.

Detail study:
At the phase of the detail study the view of observation will be narrowed. This phase is usually done after the main study but there is also the possibility to clarify the detail study simultaneous to the main study. It will be focused to develop concepts for solutions which are quite detailed so that they can be further built up and introduced. Due to the fact of continuously additional gained information it is maybe necessary to modify the total concept during the phase of the detail study.

System building:
The phase of system building can be seen as the phase of building the solutions. That could be for example the manufacturing of products or the establishing of software. Even the development of documentations, operator manuals, organization of maintenance etc. can be referred to the phase of system building. It is maybe necessary to perform special tests of objects before they get introduced.

Implementation:
At the phase of the implementation of the system it is tried to perform the initial operation. This could be for example concerning the usage of different devices and therefore it is mandatory to instruct the operators before starting the operations and to transfer the know-how which is needed. After the successful handover the regularly initial operation can be done.

Completion:
The completion phase can be seen as a basis for further projects. But this phase can also contain aspects like touching up.

3.2.4.4 Problem solving cycle

The last basic idea of the proceeding model according to Haberfellner is the problem solving cycle. The Dewey´sche logic of problem solving is the basis for the problem solving cycle which can be used at every phase of the project and therefore it is also called micro logic.

The sub steps of this micro logic are referred to the searching of the objectives, the searching of the solutions and their selection[70].

The basic version of this problem solving cycle according to Haberfellner can be seen at figure 19.

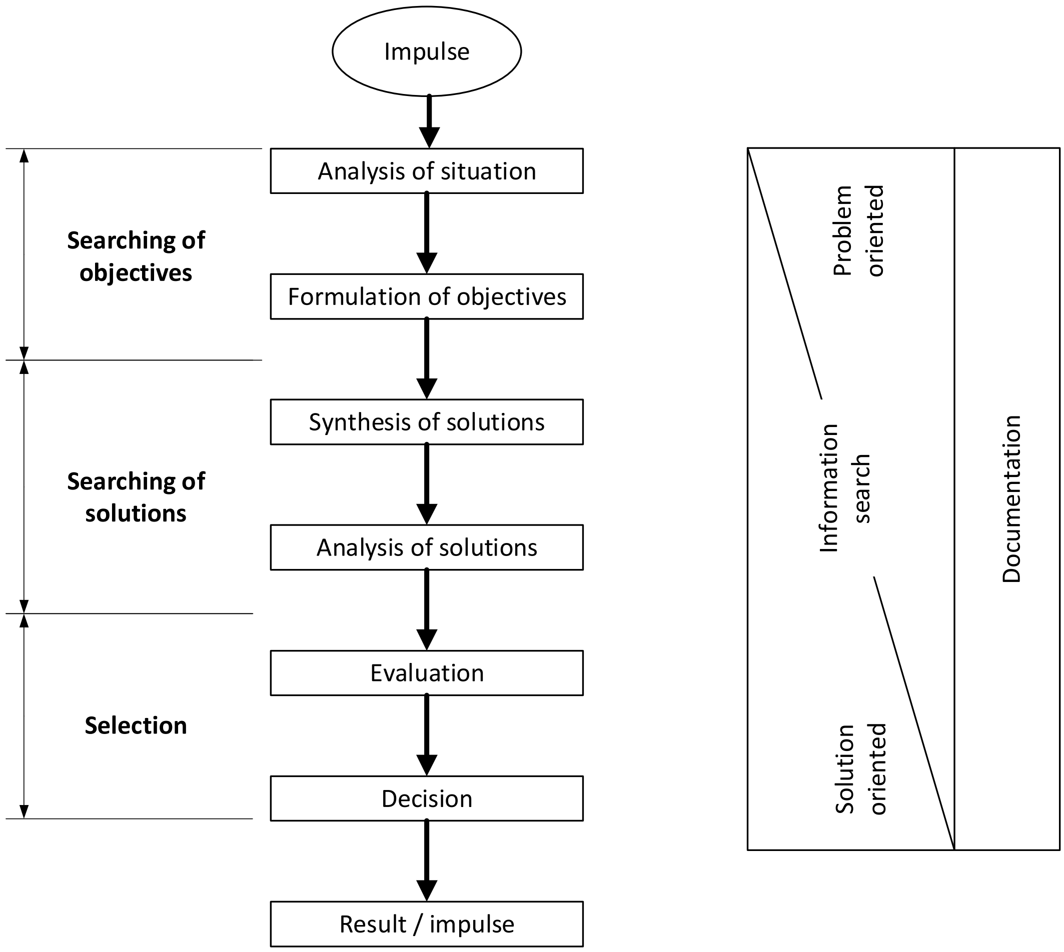

Figure 19: Basic version of the problem solving cycle[71]

At the problem solving cycle of figure 19 it can be seen that documentation as well as the searching of information (solution and problem oriented) has to be done simultaneously to the individual steps of the problem solving cycle. The individual steps will be explained a little bit in more detail according to Haberfellner[72].

Impulse:

The impulse for the start of the problem solving cycle within a certain phase of a project can be the developed results out of a previous phase and therefore it can be seen as a trigger for initiating the work-logic.

[70] (Haberfellner et al. 2012) p. 73ff
[71] (Haberfellner et al. 2012) p. 74
[72] (Haberfellner et al. 2012) p. 74ff

Analysis of situation:

This step has the task to get a better understanding of the initial situation and therefore a better understanding of the problem itself should be achieved. To get familiar with the job definition it is necessary to get a good overview of the actual situation and to define certain objectives.

Formulation of objectives:

Purpose of this step is to figure out various relevant objectives. There is a different degree of objectives at hand like e.g. “must-objectives”, which have to be reached. “Wish-objectives” would be nice to have but they have not a very high importance and between these two types of objectives are so-called “should-objectives” located. All kind of objectives should be defined completely and with a neutral result. The acceptance of objectives is the result out of this step.

Synthesis of solutions:

At this step different possible variants of solutions will be developed and therefore this step can be seen as a creative and constructive process. The whole information out of the previous steps has to be considered at this point. These different established variants should be comparable to each other in an objective way and therefore the application of various creativity techniques is unavoidable.

Analysis of solutions:

This step can be seen as a critical and mainly analytical process whereby the different variants of solutions are checked according to their efficiency. Weak points of concepts must be figured out and it has to be checked if the solutions fulfill all necessary requirements. The behavior of the individual solutions referred to the integration into the main system must be considered and analyzed. All aspects like for instance safety, operability etc. have to be considered and analyzed as well at this step of the problem solving cycle.

Evaluation:

Suitable variants of solutions are systematically compared and the most successful variant will be figured out. Due to the fact that different solutions have different characteristics it can be quite difficult to make them really comparable. There are some methods and techniques which can be used for the evaluation process e.g. a balance of arguments or a value benefit analysis.

Decision:

As a result out of the evaluation process a variant of solution has to be chosen and further developed. This must not necessarily be the best variant according to the evaluation part. Sometimes it can happen that problems or even objectives will be re-engineered.

Result:
The result out of the whole procedure can be an appropriate solution which is able to get realized or even acts as a further impulse for initiating the next phase of the project like the main or even a detail study.

The supply of information is essential at every step of the problem solving cycle. At the phase of searching objectives the gained information is mainly concerning about the problems and at the phase of searching solutions the gained information is more solution oriented. Techniques for information search could be for example interviews, questionnaires, brainstorming, checklists, etc. It is very important that all steps and results are documented in a traceable way. The method of the problem solving cycle can be used for simple as well as for high complex assignments of tasks. As a summarization of the problem solving cycle three statements or even questions according to Haberfellner can be made[73]:

- The first phase of searching of objectives tries to answer what do we want and why
- The second phase of searching of solutions tries to figure out which possibilities are available to reach the objectives
- The last phase of the selection tries to answer which variant is the best of all

3.2.5 Problem solving process

This process out of the SE concept of Hall-BWI is supported by the process of system thinking and the proceeding model which were already explained in the earlier chapters. Questions about the problem and possible solutions are answered by the phase of the system design. Measures like planning, supervision, control and steering tasks are part of the project management phase. The focus in this section is concerning contents, time and cost aspects. Additionally the fact that all kind of available resources are limited must be always kept in mind[74].

Very important steps during the problem solving process are the repetition cycles which have to be done frequently. Sometimes it is also necessary to go back to an earlier step and to modify results in order to achieve an improvement of the overall situation. It can be distinguished between rough cycles, which are exceeding the sections like searching of objectives, searching of solutions and selection and between fine cycles, which are performed within these three main sections[75]. The illustration of these repetition cycles at the problem solving cycle according to Haberfellner can be seen at figure 20.

[73] (Haberfellner et al. 2012) p. 74ff
[74] (Haberfellner et al. 2012) p. 131f
[75] (Haberfellner et al. 2012) p. 155ff

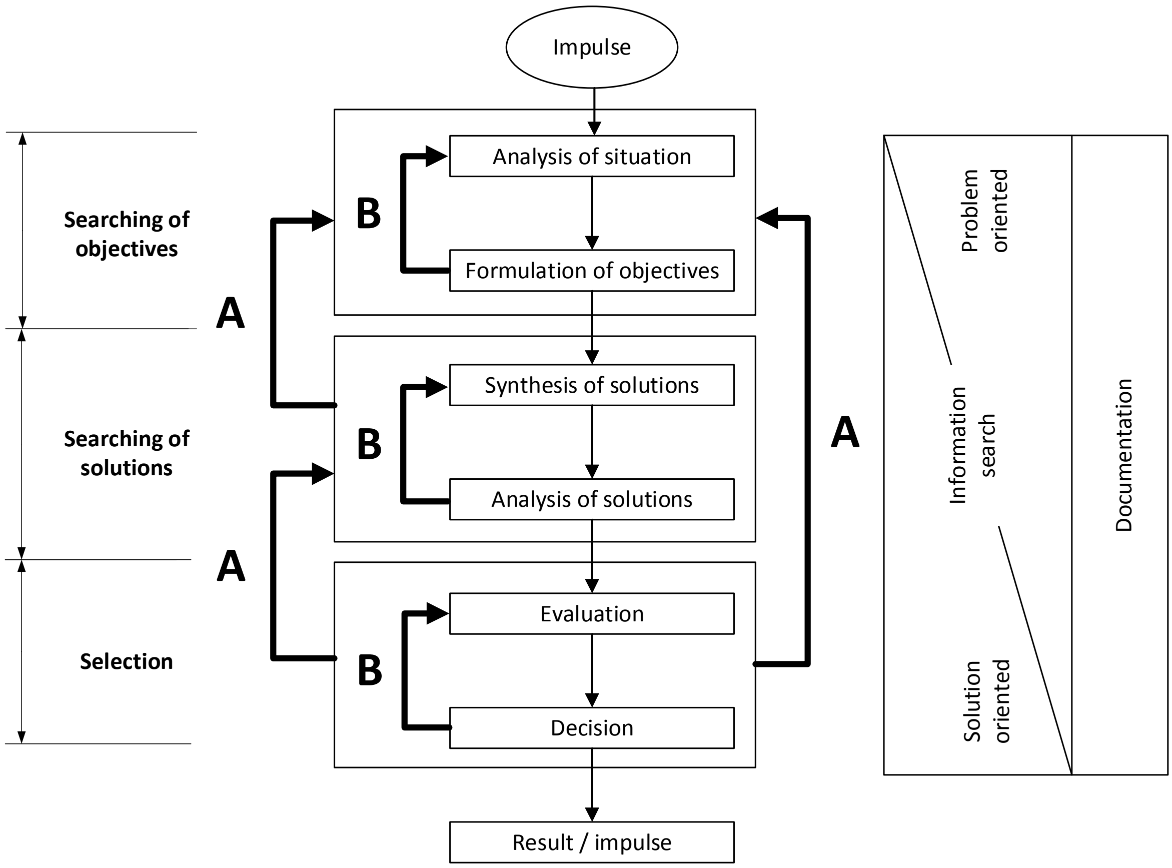

Figure 20: Repetition cycles at the problem solving cycle according to Haberfellner[76]

In figure 20 it can be seen that rough cycles are performed between the different main phases (labeled with the letter A) and fine cycles are performed within the main phases themselves (labeled with the letter B). With the new gained information it can be necessary to go one (or even more) steps backwards within the problem solving cycle.

It has to be mentioned that at the process of a problem solving cycle it is also necessary to make anticipations in advance as well as fallbacks like the repetition cycles. Quite often many repetitions can be necessary. Various methods, techniques and tools are building the basis of the problem solving process of Systems Engineering. These tools and methods should help to reduce the risk of making wrong or improper decisions. They are very helpful to figure out the best solutions[77].

[76] (Haberfellner et al. 2012) p. 157
[77] (Haberfellner et al. 2012) p. 155ff

3.2.5.1 System design

The phase of system design is part of the Systems Engineering concept of Hall-BWI – as already seen in figure 15. The two main parts of system design are the architecture design and the concept design and they will be described according to Haberfellner[78]:

Architecture design:
First the design of the basic architecture of the system will be elaborated. The term of architecture design describes the correlation of functions to various elements of a structure. If the architecture of a product is customizable, expandable and robust it can be seen as a suitable solution. The architecture design has to be established before details are developed.

Concept design:
The chosen system-architecture will be elaborated in more detail at this point of the problem solving process.

3.2.5.2 Project management

The phase of project management is also a part of the Systems Engineering concept of Hall-BWI – see figure 15. It is important to take the customer and all limited resources – like for example financial sources and material, manpower etc. – into consideration. All organizational and anticipated measures are referred to the project management for planning, supervision, conducting and steering of a project. The "iron triangle" is one basic concept of project management and it indicates which terms of a project have to be fulfilled in general. These terms are costs, appointments and requirements like for example quality and aspects of functionality. But it is obvious that these three aspects are competing to each other[79].

The "iron triangle" of project management according to Haberfellner can be seen in figure 21.

[78] (Haberfellner et al. 2012) p. 183ff
[79] (Haberfellner et al. 2012) p. 165ff

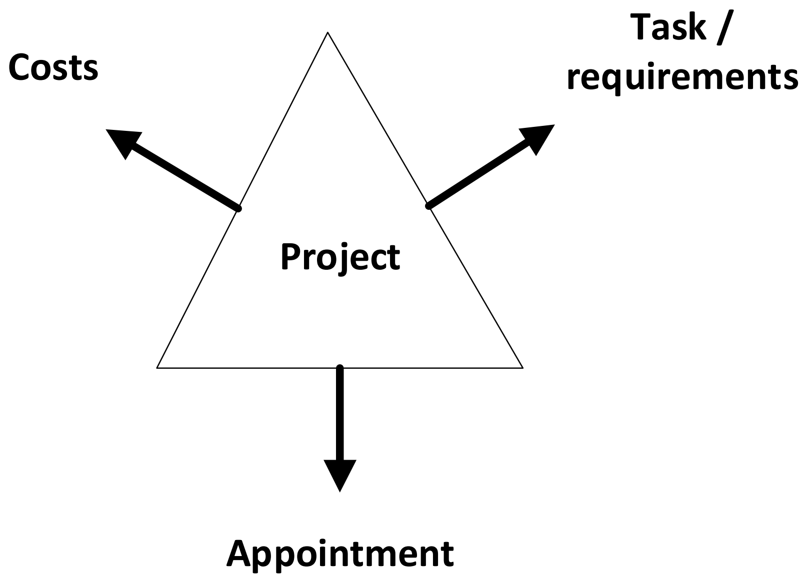

Figure 21: "Iron triangle" of project management[80]

3.2.5.3 Support tools

Some tools for supporting the Systems Engineering process which were used at the practical part of this thesis will be explained in more detail.

Catalogue of objectives:

Before the catalogue of objectives will be explained it is necessary to clarify exactly the definition of an objective. Führer & Züger[81] defined some criteria of a "real" objective:

- In the future
- Imaginable
- Realistic
- Action is needed to achieve that objective
- Aspired conscious
- Wants to be achieved
- Should be verbalized with a neutral result

Normally there are more requirements for an objective at hand and therefore various sub-objectives have to be established. This configuration is called a catalogue of objectives and can contain a main category of objectives, objective properties or even benchmark, degree of objectives / restrictions and the priorities of the objectives. These priorities like must-, should- and wish objectives were already explained in the previous chapter.

[80] (Haberfellner et al. 2012) p. 168
[81] (Führer & Züger 2010) p. 37f

Morphological scheme:

The morphological scheme or morphological box is a widely used creativity technique for creating ideas and finding solutions. First a problem gets split into its components and for every component different characteristics are searched. The whole problem will be solved by the combination of specific variants of solutions. The possibilities to figure out and create new solutions as well as the logical combinations of solutions are very helpful[82].

The objective of the morphological scheme is to figure out a high amount of possible solutions with a systematically proceeding and was developed by F. Zwicky. First it is necessary to define the problem and afterwards different parameters have to be established. For every parameter it is necessary to establish all possible characteristics and then various combinations of each parameter with the other parameters will be made. It is necessary to build up only meaningful combinations which can be realized afterwards. Finally there will be an evaluation and selection of created combinations[83].

Balance of arguments:

With a balance of arguments the positive and negative aspects of various different variants are numerated. But at this point no weighting or calculation is done and therefore this balance of arguments should only make the decision process more transparent[84].

Value benefit analysis:

A translation of different variants into a comparable scale is done with the value benefit analysis. The basis of this analysis is that all aspects of every variant should be transformed into a similar scale. Then it is possible that the individual efficiencies of the variants can be compared against each other. At the beginning all relevant criteria for the analysis have to be figured out and weighted that the sum of all criteria equals 100%. Then it is possible to find out the relative importance of each variant according to the achievement of objectives and therefore each criterion of the variants gets valued with a certain amount of points according to this achievement. These points are then multiplied with the weights of the individual criteria and afterwards they are summed up. The total amount of points can be seen as the total advantage of the individual variant[85].

Scaling matrix:

A scale which is used for the determination of the basic requirements of parameters is called a scaling matrix if the parameter values are within a fixed range and reach from e.g. very good to very bad. The transformation of all parameters to a common scale has to be done to compare the variants. Then the individual characteristics are identified and the absolute position of each variant will be determined at the scale[86].

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[82] (Schawel & Billing 2014) p. 171
[83] (Haberfellner et al. 2012) p. 388
[84] (Taschner 2013) p. 157f
[85] (Taschner 2013) p. 158ff
[86] (Gundlach 2006) p. 108ff

The scaling matrix can be used to support the value benefit analysis by determining the degree of achievement of the individual objectives for each criterion of each variant in a transparent way.

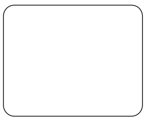
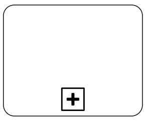
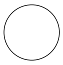
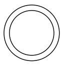
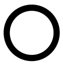
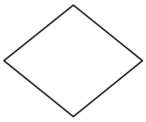
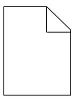
Business Process Model and Notation (BPMN)

To illustrate a flow of information between participants of a system the tool of BPMN is widely used. This notation consists of gateways, activities and events. Coordinated activities are the basis for every business process. It can be said that every business process has a defined start and endpoint, needs time, uses resources, cause costs and there is the possibility to plan and steer such a process. BPMN therefore can be seen as a standardized language which uses certain symbols and elements to illustrate and analyze various processes. Positive aspects are a clear definition and a structured documentation of processes and through the standardization of this language it is possible that all involved participants have a similar interpretation to existing processes. Furthermore it is possible to optimize processes by accurate planning and illustration with BPMN[87].

Table 2 shows the most important elements out of the BPMN tool in accordance to Gadatsch[88]. A description of the different elements can be seen at this table as well.

[87] (Göpfert & Lindenbach 2013) p. 1ff
[88] (Gadatsch 2008) p. 88

Table 2: BPMN notation according to Gadatsch[89]

Symbol	Name	Description
	Activity	A procedure is described by an activity. This can be a single activity or a complex activity (subprocess – indicated with a plus).
	Activity with subprocess	
	Start event	
	Intermediate event	During processes events are occuring. They can be the result of an activity or a trigger itself. The three basic types of events are start events, intermediate events and end events. Additonal exceptions are possible.
	End event	
	Gateway	The course of the process is decided by gateways. Different types of gateways can be distinguished e.g. XOR, AND, OR and event-based types.
	Sequence flow	The chronological sequence of the activities out of the process is described by the sequence flow.
	Message flow	The exchange of messanges between the different objects is illustrated by the message flow.
	Data object	If information or data is needed at the input or it is the output of an activity is indicated by the data object.

Special organizational units are responsible for the execution of activities within a BPMN. They are called “swim-lanes”. A “pool” is the fusion of one or many swim-lanes. An example of such a pool and a swim-lane according to Becker[90] can be seen at table 3.

[89] (Gadatsch 2008) p. 88
[90] (Becker et al. 2012) p. 73

Table 3: Pools and swim-lanes of BPMN according to Becker[91]

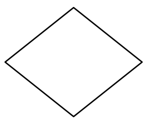
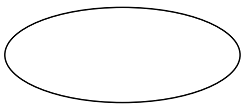
Element	Symbol
Swimlane	
Pool	

Entity relationship model (ERM)

The entity relationship model is used to illustrate databases and it is a common method when modeling them. The ERM consists of entities, attributes and relationships. An entity can be seen as an object and can have various attributes. One or even more attributes create a primary key for each entity. This primary key for each entity is necessary to uniquely identify the different entities within a database. There are different types of cardinalities possible e.g. one-to-one, one-to-many and many-to-many[92].

Basis of a database should be always an entity relationship model. A model is created with all information of the database and it should allow unexperienced people to understand the systematic of the database. It is important to create an accurate model of the reality with the most important aspects. The three basic elements of an ERM can be seen in table 4. Entities are shown as rectangles, relationships as rhombi and attributes as ellipses[93].

Table 4: Basic elements of ERM according to Wieken[94]

Element	Symbol
Entity	
Relationship	
Attribute	

[91] (Becker et al. 2012) p. 73
[92] (McKeown 1992) p. 92f
[93] (Wieken 2009) p. 224ff
[94] (Wieken 2009) p. 226

4 Case study

This part of the thesis tries to implement the concept of Systems Engineering to the process of the machine maintenance of the machine workshop at the construction site of the Solbakk tunnel in Tau / Norway. Due to the fact that this is a very complex task the methods of Systems Engineering are used to determine the most efficient fields for improvement of the maintenance process in a systematically proceeding. Together with the workshop manager and the mechanics at the site existing difficulties and therefore an optimal target state of the maintenance process will be figured out and afterwards it will be tried to implement some improvement concepts step by step. Active participation at various maintenance processes is the fundamental basis for understanding the whole system of the machine maintenance at the site. This chapter will be structured into the following subchapters:

1. Initial situation
2. Preliminary study
3. Main study
4. Detail studies
5. Prototypes, implementation and results

At the first section of this chapter a rough overview of existing problems which induced to this thesis will be explained and then in a preliminary study directly at the construction site Solbakk in Tau / Norway a precise determination of the current state will be established. By the usage of many different filters various systems of the whole construction site will be developed for further analysis. Afterwards the most important relations between the different system elements will be figured out. Additionally many interviews will be made to figure out as much problems as possible. Furthermore an illustration of many different maintenance processes will be made by the usage of BPMN (Business Process Model and Notation) to illustrate all processes graphical and therefore to figure out additional weak points at the execution or preparation of the maintenance processes. The analysis of various maintenance processes by the use of different BPMN will help to figure out some important variants for improvement of the existing maintenance process.

At the phase of the main study many fields for improvement are already known out of the preliminary study but they are not evaluated yet. Therefore a catalogue of requirements will be established together with the workshop manager from this site. A classification of the different objectives will be made according to their importance. Then various variants for improvement have to be established by the usage of the morphological scheme and afterwards a balance of arguments has to be created to rethink all different variants according to their advantages and disadvantages. When the balances of arguments are finished and all relevant factors are considered a scaling matrix and a value benefit analysis will be developed. Therefore it is necessary to make an appropriate numerical rating of the different objectives – this is done with a special weighting of objectives together with the responsible employees at the site. Finally a graphical interpretation of the gained results will be developed for a better understanding. The most effective variants for an improvement of the maintenance process will be obvious.

In three different detail studies the fields for improvement out of the main study with the best ranking or degree of improvement will be covered. The different fields will be located in three different segments: organizational, technical and process-oriented. Additionally problem solving cycles have to be developed and analyzed to build up several different variants for improvement for each of these three segments later on.

An evaluation of each variant will be made and finally a prototype for the best variant of each segment will be established and implemented directly at the construction site Solbakk.

4.1 Initial situation

The excavation process at the Solbakk tunnel was already ongoing for about half a year at the beginning of this thesis and the length of the excavated tunnel at the beginning of the field study was at about 700m. Main objective of the thesis should be a more efficient machine maintenance process according to the workshop manager at the site. To achieve a better overview of all performed machine maintenance tasks and to keep track of the working tasks of all mechanics as well as to increase the cost transparency for all service and repair tasks is an essential concern.

A big problem is the unawareness of the mechanics concerning their working reports of performed machine maintenances. They perform the routine maintenance tasks but sometimes they are not writing the special designated working reports or write them just insufficient. The same problem exists for the writing of material or spare-part reports, because the workers are not aware of the high importance of detailed documentation. In general the overview of available spare-parts and working tools at the workshop is not appropriate organized and this causes high searching times and therefore longer downtimes of the machines. Of course a machine breakdown cannot be predicted sufficiently therefore it is much more important to perform all service and repair tasks on schedule to prevent future downtimes as good as possible. It is important to keep the machine manufactures guarantee upright. Additionally many machine damages can be referred to wrong operating tasks of the miners and therefore the miners have also to be taken into consideration to achieve a more efficient machine maintenance process at the workshop in Solbakk.

4.2 Preliminary study

The following preliminary study was done directly at the construction site in Tau / Norway and started in February 2014. The participation at various different service and repair tasks in cooperation with the workshop members is the base for further analysis. The gained knowledge and working experience out of past construction sites are important influence factors as well. At the beginning it is crucial to abstract the whole construction site into appropriate systems with all important elements. Using different filters will lead to different views of the main system and therefore various aspects will be considered more accurate. Also the understanding of the complex system will increase due to this broad consideration and observation. Furthermore many different BPMN are build up in order to find out existing problems at various processes and therefore to develop different fields for improvement.

4.2.1 Machine workshop

The first step will be a closer look to the machine workshop of the construction site Solbakk where almost all service and repair tasks of the tunneling vehicles are performed. This workshop area is the center point of the whole maintenance process. The configuration of this machine workshop of February 2014 can be seen in figure 22.

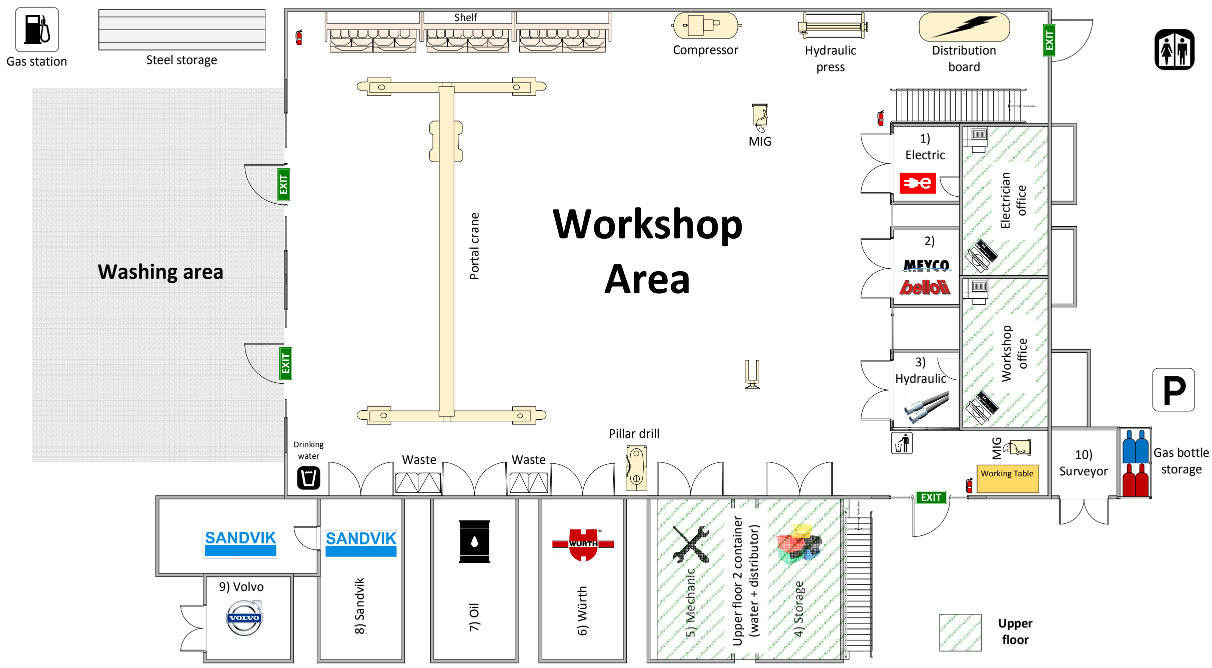


Figure 22: Machine workshop Solbakk

The machine workshop consists of various containers for electric parts, diverse spare-parts of machines, hydraulic equipment, mechanic parts and tools, oils and storage of equipment. A huge portal crane is used for lifting heavy parts and units of the machines. A working table in the corner and some welding devices and other tools for maintenance are located within the workshop hall as well as some heavy weight shelves for the storage of diverse spare parts and materials. On the upper floor are the electrician and workshop offices located and outside are the water and air junctions for the tunnel stored. The gas bottle storage, the steel storage, the washing place and the gas station for the cars and for the heavy vehicles are located outside of the workshop. The whole area of the workshop will be additionally analyzed in more detail to figure out some fields for improvement according to e.g. arrangement, used equipment, layout etc.

4.2.2 Building of system divisions

Due to the active participation at all areas of the construction site by performing different maintenance tasks it is possible to illustrate various systems of the construction site graphical. All important elements and relationships are figured out and evaluated. In the end only the most important factors are left and will be considered further. To get an exact overview different views or even filters will be used at the overall system. According to the use of these filters different aspects are focused and finally three levels of system division will be established. The main systems are referring to a labor view, an areal view and a view for the vehicles. The areal system consists of a further sub system of tools and equipment for the maintenance process itself. This sub system is important because it shows all the basic tools and equipment which are available at the workshop in Solbakk to perform all service and repair tasks. The system overview can be seen in figure 23. Only the most significant fields for improvement will be figured out and treated within this thesis. At the different developed systems some fields for improvement are already mentioned (red colored) at the legend. Some of these fields for improvement are overlapping to more systems and therefore these fields are labeled from V1 to V10. The letter V is the abbreviation for “variant” and the 10 best variants for improvement of the maintenance process will be figured out and explained at the main study.

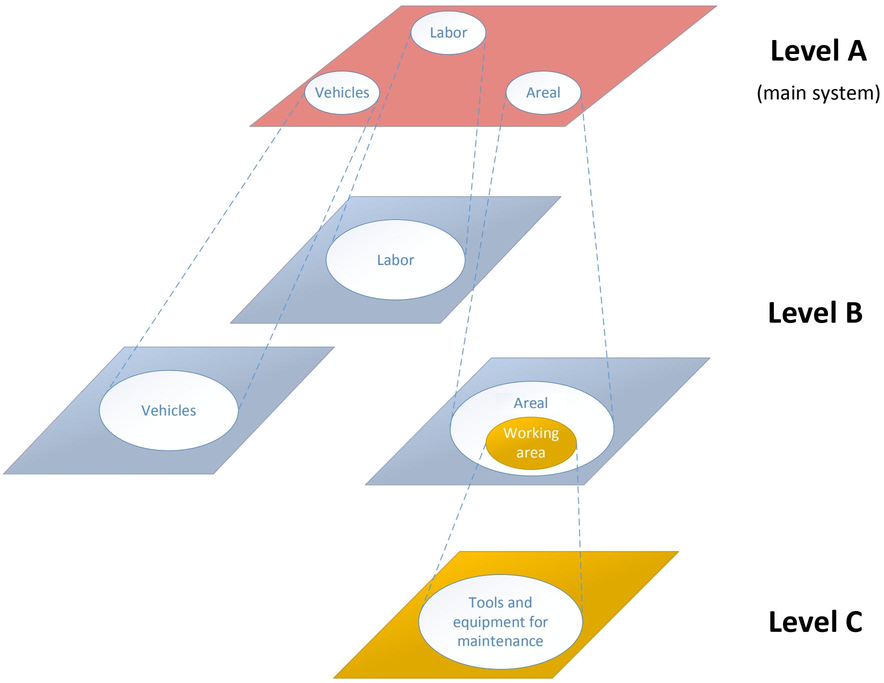


Figure 23: Overview of system division

4.2.2.1 Labor system Solbakk (Level B)

A very important aspect concerning system thinking is the labor system with all involved employees at the site. It is possible to figure out where the most problems between employees or even departments are located. Just a rough overview of the labor system can be seen in figure 24. The arrows indicate the information flow between the elements. The system is structured into the employees at the management level, the manual workers at the workshop and the manual workers at the drill and blast excavation team (miners). Furthermore the extern workers for the conveyor belt system are illustrated within the borders of the labor system Solbakk. Additionally the extern suppliers and the building owner are taken into consideration.

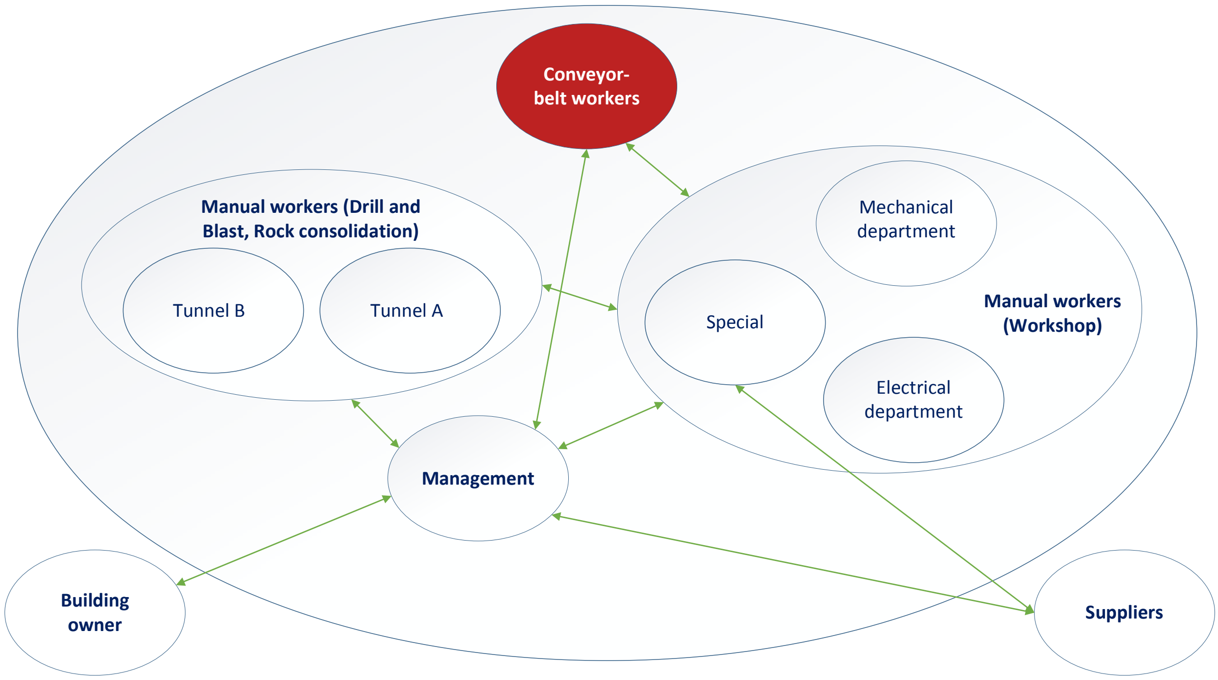


Figure 24: Rough overview of the labor system Solbakk

The complete system of the staff can be seen at figure 25 and is much more detailed because it is observing all involved employees at the site and additional persons outside of the boundaries which are interacting with the system. Main focus is of course at the intern system communication structure concerning all workers and departments. The arrows between the system elements show a different format due to the different frequency of information exchange. If the arrows are drawn more continuous instead of being dotted this is an indicator for a higher frequency of information exchange.

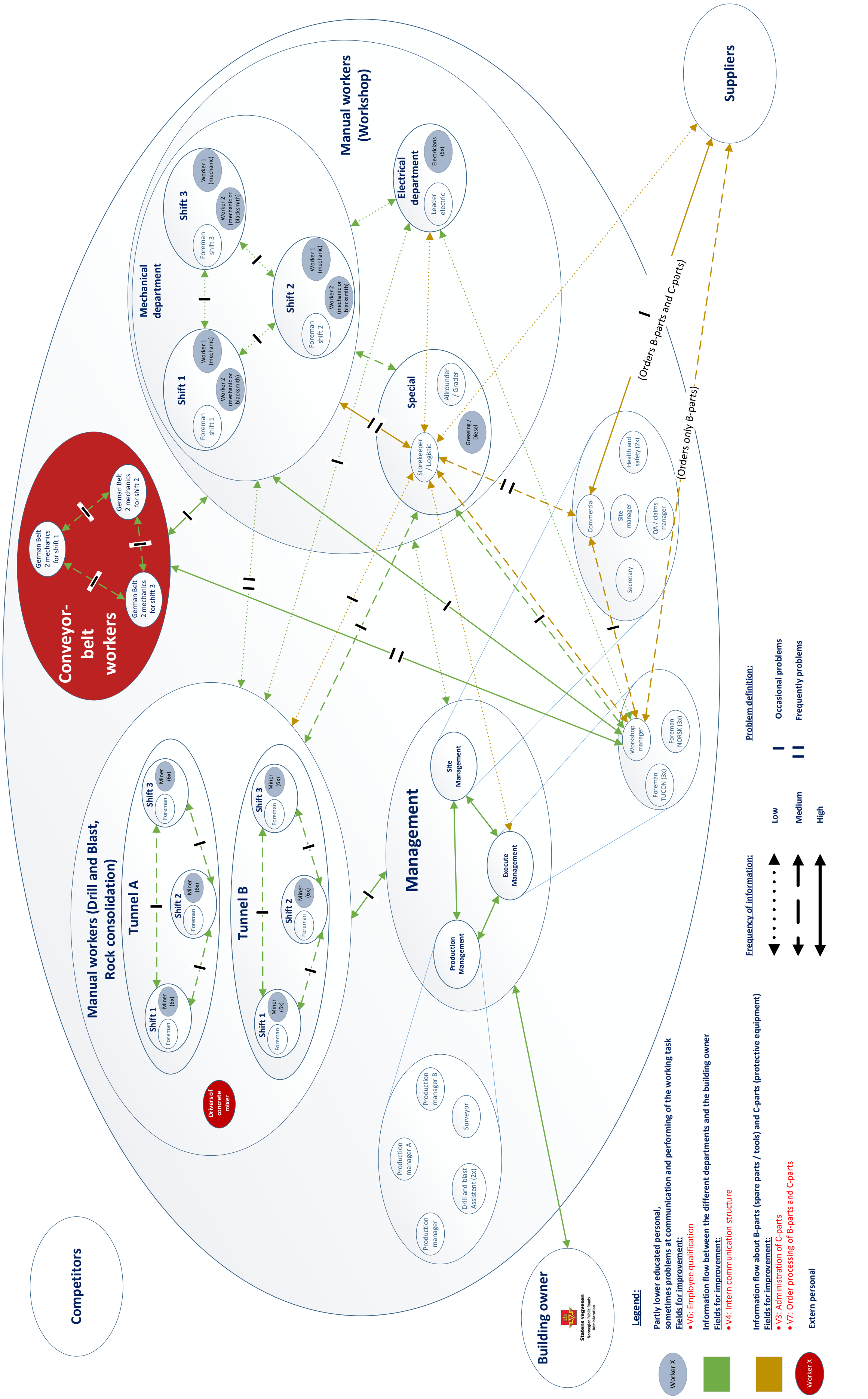


Figure 25: Labor system – relevant flow of information (Level B)

A further distinction at this system is the problem definition into occasional problems and frequent problems during communication. At the legend of the complete labor system in figure 25 it can be seen that occurring problems are labeled in a different way – according to their frequency. Occasional problems are labeled with one stroke, frequent problems are labeled with two strokes.

The different colors of the arrows are explained in the legend. Most communication is done between the different departments and employees (green arrows). A separate view is made for the information flow of spare-parts, tools and protective equipment (brown arrows). This view is highlighted due to many existing problems at this area of order and release of these mentioned items. The extern workers are highlighted with red color and employees with occasional communication problems are highlighted with blue color. Resulting from the analysis and determination of the different problems various fields for improvement were detected and they will be covered within the main study. Some of these variants for improvement are already written down to the legend of the labor system Solbakk at figure 25. They are written in red letter.

4.2.2.2 System – focused on vehicles of the drill and blast process (Level B)

The main focus of the maintenance process is of course at the machinery on site. Therefore it is very important to have an exact overview about all machines and equipment. An overview of all heavy machines at the site classified by functions can be seen in figure 3. It is also essential for the responsible workshop manager to know about the sequence of usage of the machines in order to plan and determine the service intervals.

Machines and equipment should be maintained when they are not needed for the excavation process. Figure 26 shows a rough overview of the machinery at the site according to the sequence of the drill and blast process. This sequence can deviate a little bit e.g. tasks can be performed in parallel or in a slightly different order. Additional to these machines the personal cars have to be considered too – this can be seen at the complete system which is focusing the vehicles of the drill and blast process in figure 28.

Because at the tunnel construction site Solbakk there are two tunnels build in parallel the drill and blast process has to be performed at each tunnel in a similar way. The green arrows at the vehicle systems at figure 26 and figure 28 show the sequence of the machine usage at the drill and blast excavation process. The brown arrows show the path of the excavated material which has to be mucked out of the tunnel.

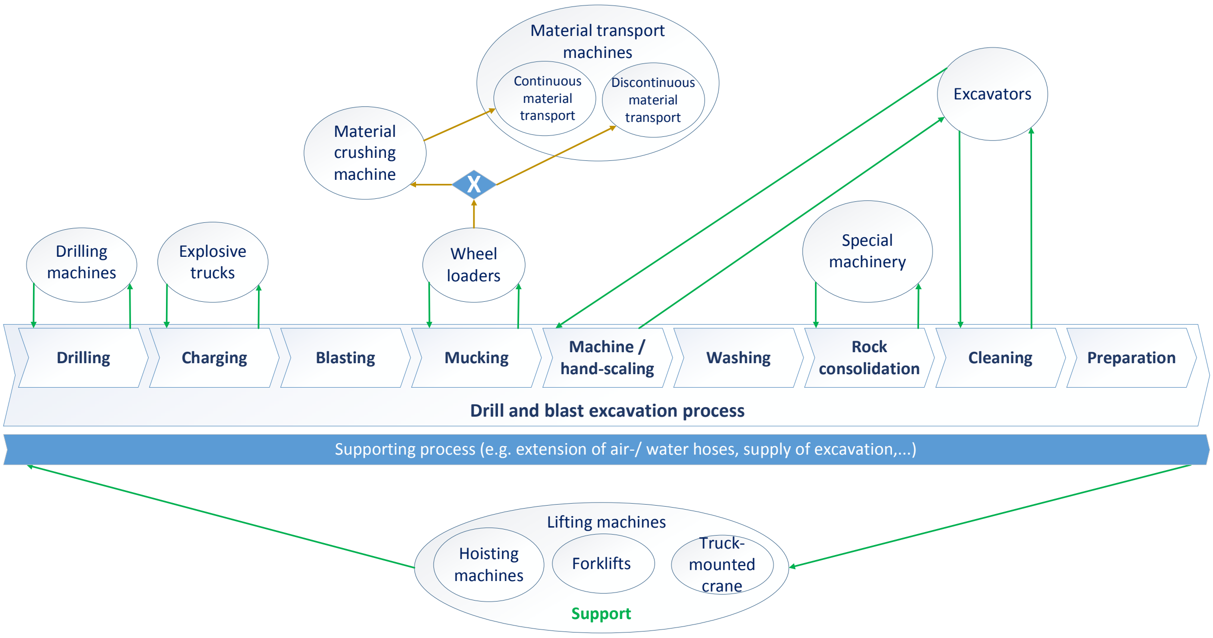


Figure 26: System – focused on vehicles of the drill and blast process (rough overview)

The drill and blast process starts with the drilling at the face with a drilling jumbo. Various holes with different diameters have to be drilled. At the center of the face the drilled diameter is about 102mm by the usage of special reaming bits and all other holes have a diameter of about 48mm. The drilling depth at the face is about 5,2m per hole. Depending on the rock classification different anchors of about 3 to 4 meters can be used. The holes therefore have to be drilled 20cm deeper into the rock. Figure 27 shows an ongoing drilling process at the face by the usage of a Sandvik drilling jumbo.

Figure 27: Ongoing drilling process at the face with a Sandvik drilling jumbo

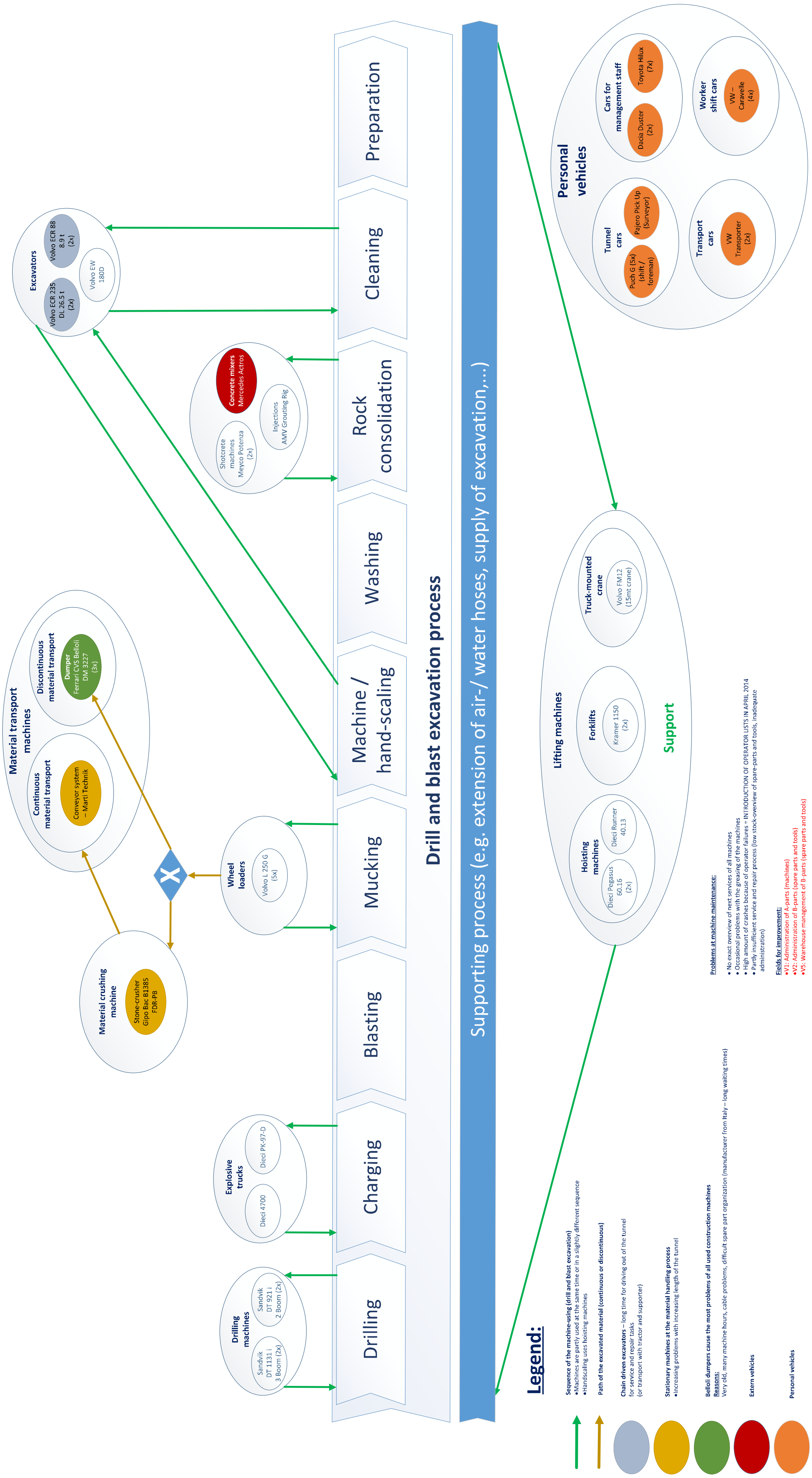


Figure 28: System – focused on vehicles of the drill and blast process (Level B)

Afterwards the face is charged with the 2 component reaction explosive agent by the usage of the explosive trucks and then the blasting process is ignited. When the blast process is finished the wheel loaders start to muck the released material out of the face area. At regular operation they muck the rocks into the stone crusher where the rocks get crushed into smaller pieces and then they are transported out of the tunnel by a conveyor belt system. If there should be e.g. maintenance at the crusher or at the conveyor belt system the wheel loaders muck the material into the dumpers which bring the material out of the tunnel. This discontinuous material transport is of course not as effective as the continuous material transport with the conveyor belt system. The mucking process with a wheel loader into the stone crusher can be seen at figure 29.

Figure 29: Mucking process at the stone crusher

Afterwards the machine scaling is done with excavators followed by the process of the hand scaling and the washing process. Hoisting machines are supporting the hand scaling process. The following rock consolidation is performed with special machines according to the illustration in figure 28 like the shotcrete machines, the trucks for injections and the external concrete mixers. Then the face has to be cleaned and prepared for a new start of the drilling process. For the supporting processes like e.g. extension of the water hoses and the air tube or the general supply of the excavation process various hoisting machines are used.

Furthermore the personal vehicles have to be considered too because they have to be maintained and administrated as well. These vehicles are highlighted orange at the vehicle system in figure 28. They are separated into tunnel cars, cars for the management staff, transport cars and worker shift cars. The tunnel cars are mainly used to drive at the construction site and in the tunnel. The transport cars are used to deliver various stuff and equipment from different suppliers to the magazine and to the workshop.

In figure 28 a good overview of all used machines and equipment of the construction site Solbakk is generated. Therefore it is possible to figure out existing difficulties or problems. It is important to have much information about the used machines on hand. Due to the cooperation at various maintenance processes and as a result out of many interviews it is possible to make a classification of these machines regarding to their maintenance problems. The blue highlighted machines are the chain driven excavators at the site. Due to the slow movement of these machines the service and repair tasks will become much more difficult with increasing length of the tunnel. The same problem is valid for the yellow highlighted stationary machines at the material handling process. Especially the conveyor belt system is growing quite fast and therefore much more effort for maintenance must be considered in future. The green highlighted machines are the quite old Belloli dumpers. According to the mechanic foreman of the workshop they cause the highest costs for maintenance due to their high age and many machine hours. Further problems of these dumpers are the long delivery times for spare-parts. Additionally cable-problems at these dumpers make the maintenance task more complicated.

A huge problem at the site is that there is no exact overview about the machine services available and sometimes the service intervals can be exceeded. Additionally frequent problems with the greasing of these machines can occur. Due to the fact of many machine damages and breakdowns because of operator failures special machine operator lists were already introduced in April 2014. Furthermore problems which have to be considered are a bad overview of the stock for spare-parts and tools and an insufficient administration of them. Many fields for improvement were detected during the analysis of the vehicle system and they will be covered at the main study. Some of these variants for improvement are already written down (red lettering) in the legend of the vehicle system at figure 28.

4.2.2.3 System – focused on the area of the construction site (Level B)

By using other filters concerning the flow of material a new system is generated. This developed areal system is including some major elements regarding to their location and a rough illustration of this system can be seen in figure 30. The complete areal system can be seen at figure 32 and is much more detailed. For a better understanding the system will be explained according to the complete demonstration at figure 32.

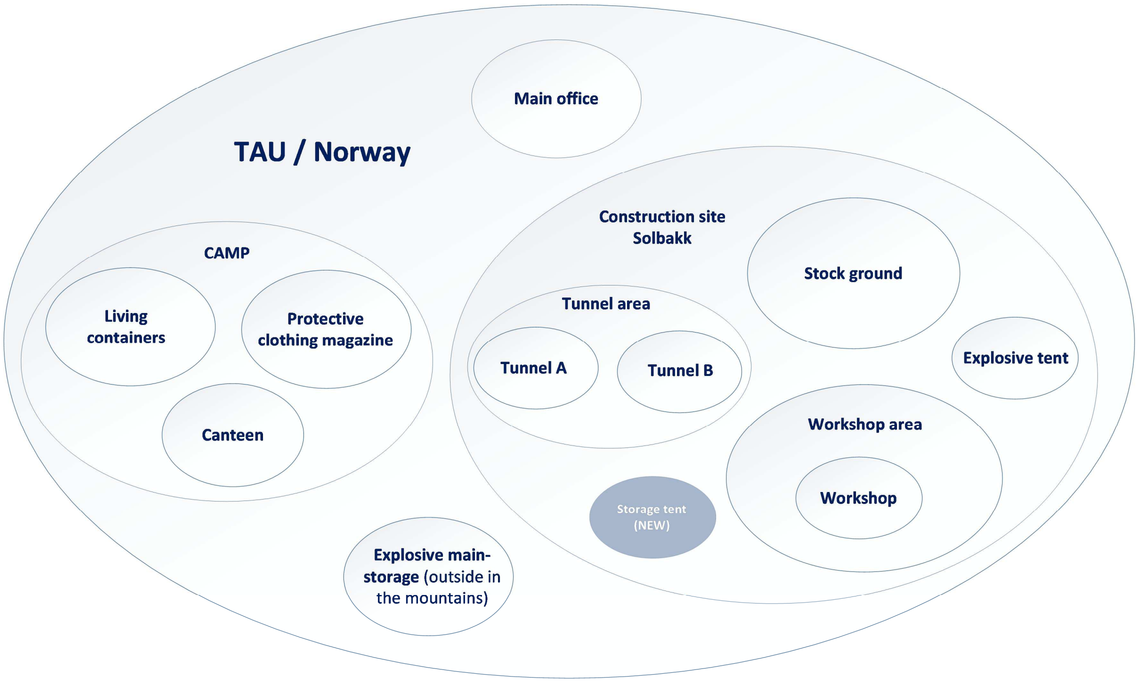


Figure 30: System – focused on the area of the construction site (rough overview)

A very important element is the construction site itself with the tunnel area (Tunnel A, Tunnel B and the portal area) and the stock ground for storage of all important materials e.g. anchors, steel mats, water pipes, material for the conveyor belt extension etc. Also the water preparation and the waste containers are located there. The explosive tent is including the tanks for the emulsion of the two component reaction explosive agent and is located next to the workshop area. Figure 31 shows an overview of the construction site.

Figure 31: Overview of the construction site Solbakk / Tau

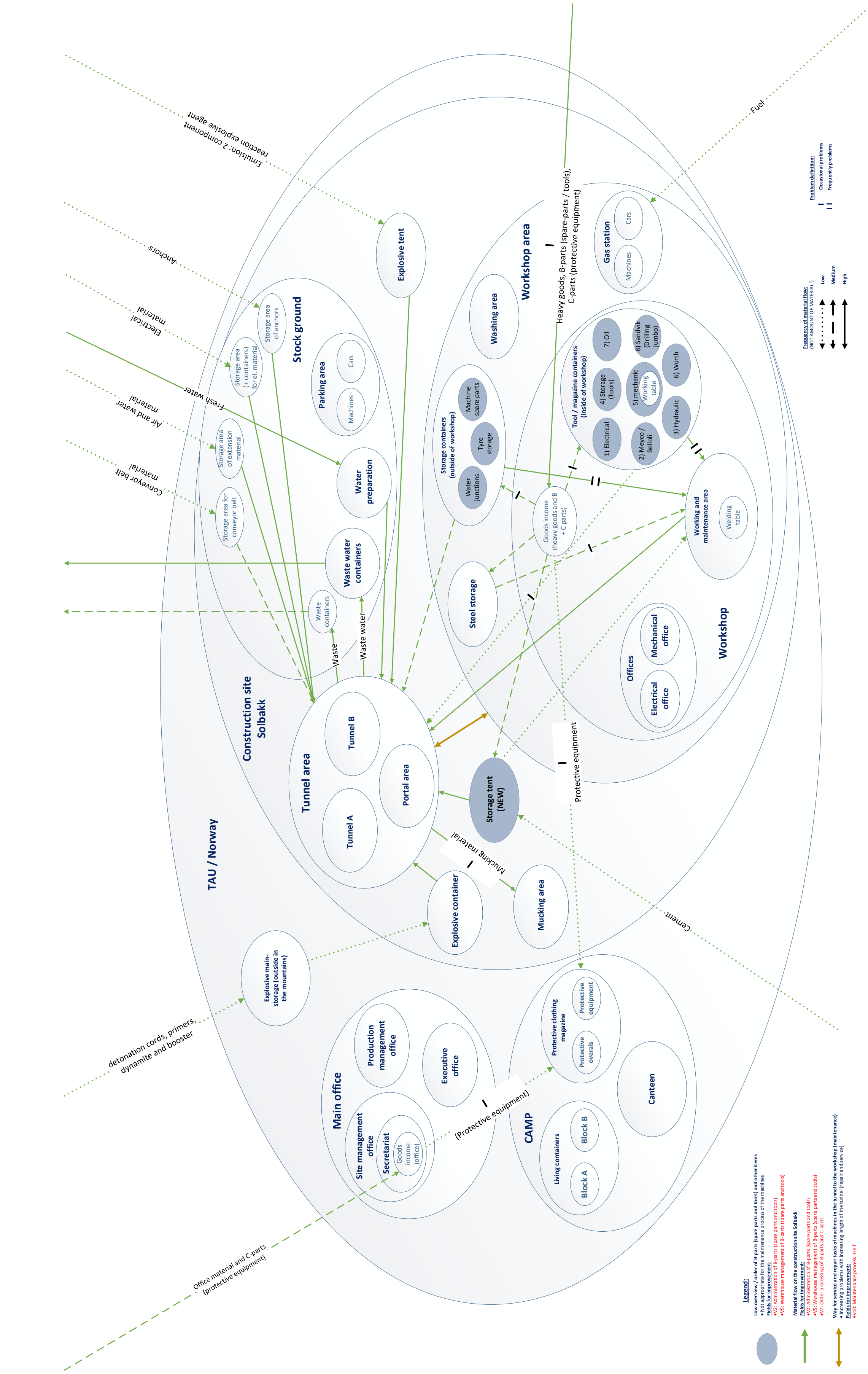


Figure 32: System – focused on the area of the construction site (Level B)

The big grey tent in the background at figure 31 is the machine workshop and the smaller tent in front is for the explosive emulsion tanks. The blue containers at the right side of the picture are for the treatment of the waste water out of the tunnel, the green containers at the left side are for the fresh water supply. It can be seen that the blue conveyor belt is underrunning the street to a transfer station and is than continuing to the last cross-transfer station where the excavation material is finally mucked directly into the sea.

At the workshop area at figure 32 there is the working area, the tool and spare-part containers, the offices, the gas station, the washing area and the steel storage. A new storage tent and the explosive container are additionally located at the construction site. For safety reasons the main storage of the explosives e.g. detonation cords, primers, dynamite and booster is located outside in the mountains. The camp and the canteen are located about four kilometers away from the construction site. The magazine for the protective equipment is also located at the camp area. An improvement of the whole magazine administration process will be covered through this thesis in a later chapter. The main office is located directly at the construction site itself, only a public street is crossing this area.

The frequency of material transfer is shown at this system (according to figure 32) with green arrows. This flow of material is concerning the flow of e.g. water, waste, protective equipment, heavy goods, spare-parts, tools, detonation cords, explosives, fuel and also the flow of the mucked material out of the tunnel. Also at this system there is a distinction of the frequency of material transfer into low, medium and high. It has to be mentioned that the frequency of the material transfer is considered and not the amount of material. If the arrows are drawn more continuous instead of being dotted this is an indicator of a high frequency of the material transfer.

An additional distinction at the areal system is the problem definition into occasional problems and frequent problems among the different flows of material. In the legend of the complete areal system at figure 32 it can be seen that occurring problems are labeled in a different way – according to the frequency of occurring. Occasional problems are labeled with one stroke, frequent problems are labeled with two strokes like at the previous labor system.

The different colors of the arrows are explained in the legend but most of the arrows are indicating the material flow at the construction site Solbakk. There is only one brown arrow which is indicating the way for service and repair tasks of the machines and equipment from the tunnel to the workshop. This point of view is highlighted separate because of increasing problems of the maintenance with increasing length of the tunnel. Some containers for tools and spare-parts as well as the new storage tent are highlighted with blue color. This highlighting is emphasizing existing problems of the organization of spare-parts, tools and other items due to a bad overview. Out of this analysis of the whole area different problems can be detected and various fields for improvement were developed. Also these fields for improvement will be covered at the main study, like the fields for improvement of the labor and the vehicle system. Some variants for improvement are also already written down red lettered to the legend of the areal system in Solbakk at figure 32.

4.2.2.4 System of tools and equipment for maintenance (Level C)

The system of tools and equipment for maintenance is a sub system of the areal system from chapter 4.2.2.3. Different filters are bordering this system according of the most important tools and equipment for the machine maintenance regarding to their function. Figure 33 shows a rough overview of the maintenance equipment according to its functions.

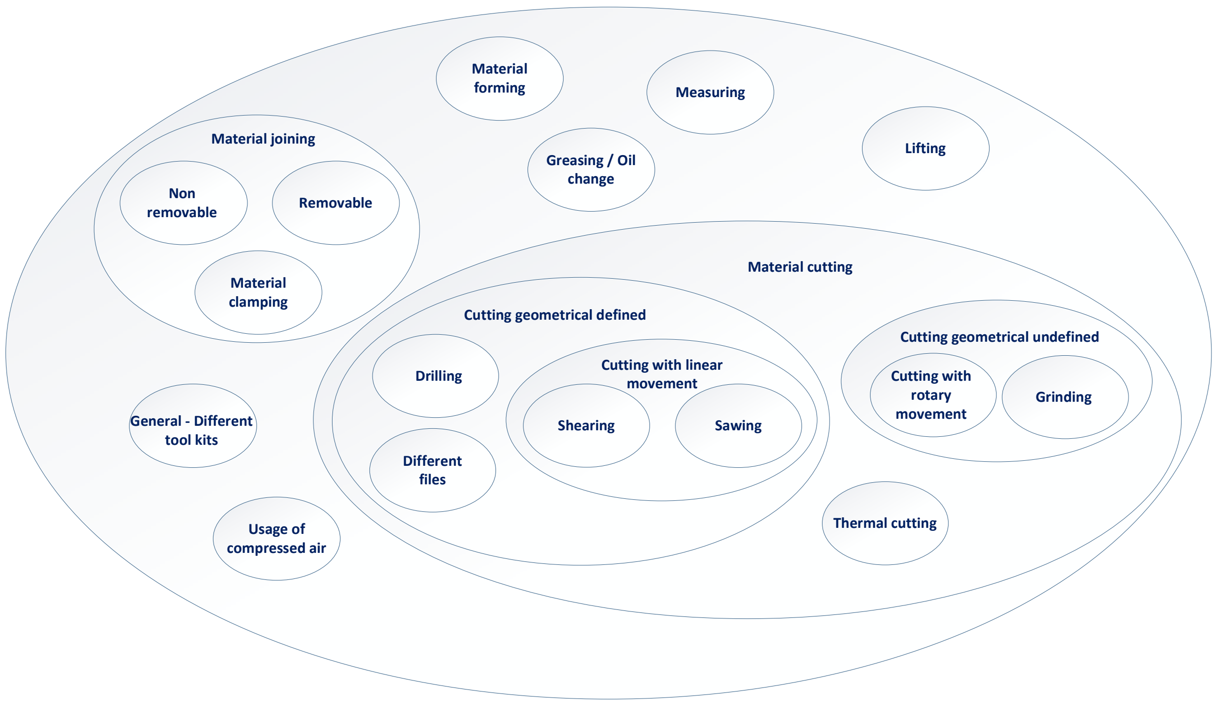


Figure 33: Rough overview of the tools and equipment for maintenance

The exact system of the tools and equipment for maintenance can be seen at figure 34. The major tasks of a mechanical workshop are of course the material joining and cutting tasks. For the joining of material it can be distinguished between removable and non-removable connections. Also the devices for clamping the material and hold it in a fixed position are important for the whole maintenance processes. The material cutting process can be classified into geometrical defined cutting e.g. drilling, shearing, sawing and into geometrical undefined cutting e.g. cutting with rotary movement and grinding. Also the thermal cutting is a very important process which is performed many times a day at a tunneling workshop department. Further important devices for the maintenance process are material forming devices (e.g. hydraulic presses), measuring devices (e.g. measuring tape, barometer etc.), lifting devices (e.g. portal crane, chain pulls, hydraulic jacks, etc.), devices for greasing and oil changes (e.g. grease presses, hand pumps etc.), devices for the usage of compressed air (e.g. diverse compressors) and in general different tool kits for reparation of all kind of machine breakdowns and damages.

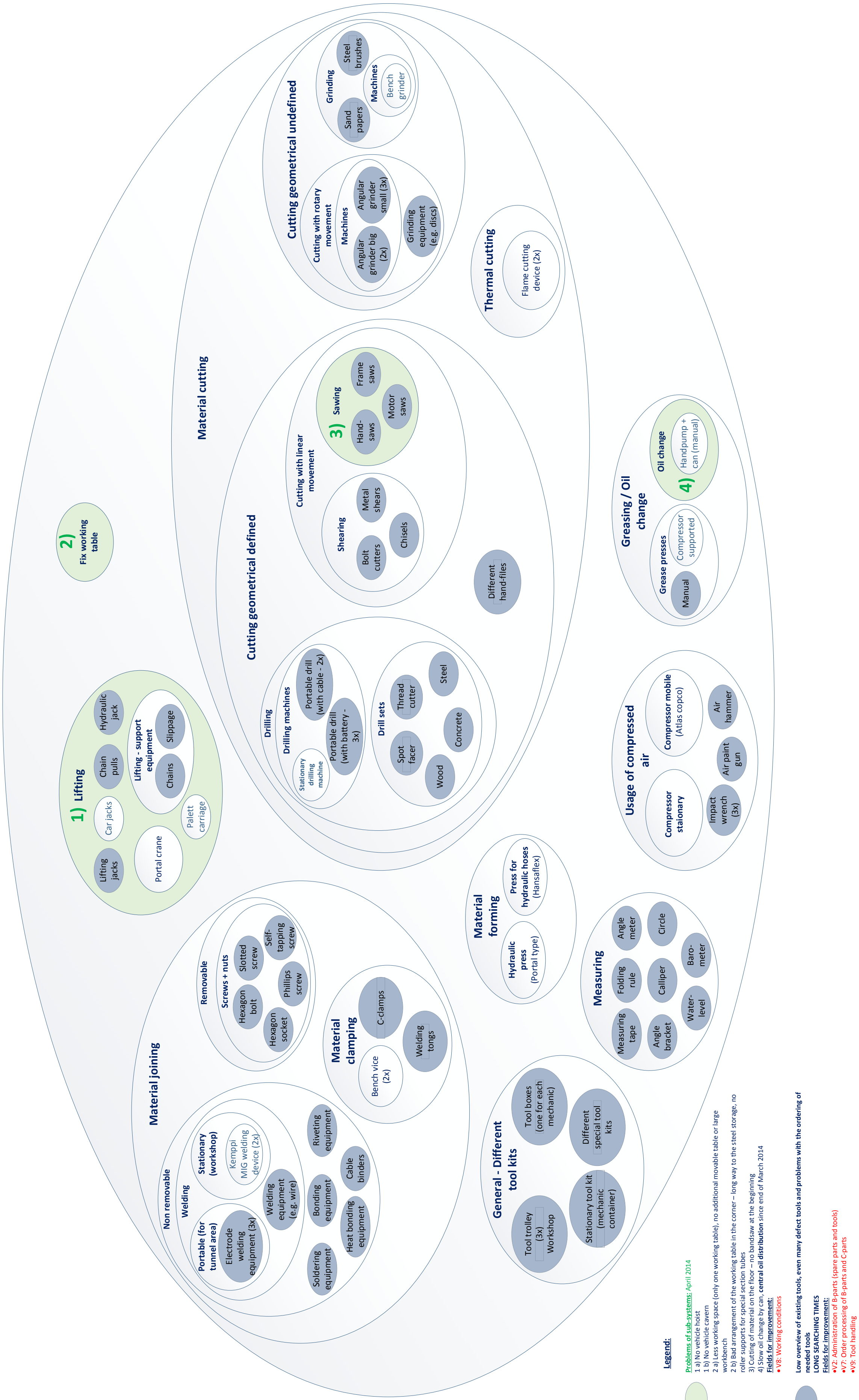


Figure 34: Tools and equipment for maintenance (Level C)

In general it can be said that in almost every tunneling workshop there is always a problem with the tidiness and the order of all kind of tools and equipment. This is caused due to the fact that the mechanics have to drive quite often into the tunnel to repair the machines and to perform all kind of service and repair tasks also at the stationary machinery. Due to this high driving effort and the changing of the area of work it is not always possible to keep all needed tools and equipment together. Quite often it happens that tools get lost during the working tasks. There is also an existing problem concerning the small electrical tools for maintenance because many different persons and employees (even extern workers) have access to these tools and they don't bring them always back after use. This causes high searching times as well as high tool costs in case of disappearing of tools.

At the system of tools and equipment in figure 34 there some elements are highlighted blue. This should indicate that at these elements or even tools is a bad overview caused due to the fact of disorganization which was explained earlier. The consequences of the bad overview are long searching times for tools and equipment and therefore high downtimes of damaged machines. Figure 35 shows a shelf for tools at the workshop Solbakk.

Figure 35: Low overview of tools at the workshop

A picture of the only working table at the workshop can be seen in figure 36. This mess will lead to a very inefficient way of performing the maintenance tasks. The responsible workshop personal has to be educated about the consequences of such a way of working. It is very important that the awareness of the workers increases – therefore the theory of Kaizen which was already explained at chapter 2.3 would be a great opportunity to raise this awareness and therefore to increase the efficiency of the maintenance process.

Figure 36: The working table at the workshop

As a result of this working style long searching times for tools are the logical result. Sometimes there are also problems with tools which are available at the workshop but which are not working appropriate or which are even defect. Especially the electrical tools are sometimes defect and the mechanics recognize that just at the moment when they need the tools e.g. in the tunnel area. Additional distances to the workshop and back to the tunnel area as well as additional searching times are the consequences. The process of ordering and distribution of tools has high potential for improvements. The green highlighted elements in figure 34 are difficulties which were detected at the workshop area in April 2014. They are also labeled with numbers and explained within the legend at this system of tools and equipment for maintenance.

Some major problems are for example a missing vehicle hoist or even a vehicle cavern in the workshop. Especially for the personal cars this would really simplify the working and maintenance tasks which have to be performed at the bottom side of the cars. A further problem is that there is only one working table in the corner of the workshop. Even the arrangement of the table is not optimal due to the location in the corner – the steel storage for example is quite far away and long distances have to be covered when a steel profile is needed. This can be seen also in figure 22 which shows the former workshop layout of February 2014. A missing band saw makes the cutting tasks of the mechanics more difficult because they have to use angular grinders or even flame cutting devices to cut the needed profiles etc. on the floor. At the beginning of this thesis there was a very slow process of the oil change at the machines due to the fact that that the oil had to be changed by the usage of ordinary oil cans. As a result of this a central oil distribution was installed in March 2014 to achieve much faster oil changes. Also the spillage of oil should be reduced through this measure. The old situation with the oil cans can be seen at figure 37.

Figure 37: Old situation at the oil container of the workshop

Figure 38 shows the mounted central oil distribution at the workshop in Solbakk.

Figure 38: Central oil distribution at the machine workshop

Out of the analysis of the system for tools and equipment for maintenance some problems could be detected and also some fields for improvement were developed. These fields for improvement of the system for tools and equipment will be covered within the main study, like the fields for improvement of the other systems. Some variants for improvement are already written down red lettered in the legend of the system for tools and equipment for maintenance at figure 34.

4.2.3 Interviews for further problem identification

Together with the workshop manager many interviews were made according to the existing problems and difficulties of the maintenance process. Due to the field work directly at the service and repair tasks of the machinery additional useful information is gathered. Also some mechanical foremen and mechanics of the workshop are asked about their experiences and ideas to overcome existing obstacles. Some of the considered problems which are mentioned by the majority are:

- Inefficient maintenance (searching times, exceeded service intervals…)
- Coordination problems
- High machine downtimes
- Partly low qualified personal
- Low overview of available spare-parts and tools
- Problems at the order and release process of diverse items
- Communication problems
- Low transparency of maintenance tasks
- Problems at shift change
- Many operator mistakes

This are only some of all mentioned and observed problems which are existing at this site. All of these factors contribute to an inefficient maintenance process, cause high costs and must be reduced! Out of these points it can be seen that also the miners have to be taken into consideration because they operate all the heavy underground vehicles. To achieve an efficient maintenance process it is important to involve all employees at the site – like it is already mentioned within the theory of total productive maintenance (TPM) at chapter 2.3. It is not enough to take only the responsible mechanics into consideration.

Because of the multinational team at the site in Solbakk there are many language barriers and communication problems. This is a very important aspect which has to be considered especially at emergency maintenance when the involved workers are exposed to a very high stress level and mistakes at work can cause dangerous situations. Also the level of qualification of all available workers has to be mentioned because of different abilities to perform various repair and service tasks or even operations at the machines. Communication problems at shift changes have to be avoided in future due to a better arranged communication. The bad overview of available spare-parts and tools leads to very high searching times and causes long downtimes of defect machines. Furthermore it has to be mentioned that also the extern workers (e.g. workers from the conveyor belt system or from some leasing companies) have free access to the machine workshop and therefore to the tools and equipment. There is no full-time storekeeper to control and administrate the use and removal of working equipment and spare-parts.

4.2.4 Process modeling with BPMN

Due to the active participation at service and repair tasks in the workshop and in the tunnel at the moving and stationary machinery it is possible to observe various inconsistencies. To improve existing working processes it is essential to analyze the actual situation of the processes very accurate. Afterwards existing problems and difficulties can be analyzed and thoughts about an improved situation can be made. For analyzing the actual processes the use of BPMN (Business Process Model and Notation) is a very helpful tool and widely used. At the construction site Solbakk many processes were illustrated with BPMN to figure out existing problems and obstacles. Some of these BPMN were made referring to e.g.

- Diverse machine maintenance processes
- Order + release processes of spare-parts / tools as well as for protective equipment
- Usage of tools
- Obtaining of machine hours and working hours of the mechanics
- The changing process of defect hydraulic hoses etc.

Due to the analysis of all mentioned processes with the illustration of BPMN it was possible to figure out various variants for improvement of the maintenance processes. To show all of these BPMN would be too much detailed for this thesis and is not relevant and necessary. They were just established during field work at the site to analyze all kind of performed maintenance processes as accurate as possible. The different results or even established variants for improvement out of the actual situations and the target situations will be covered within the main study – it can be said that the development of various BPMN contributed to many fields for improvement of the maintenance process.

4.2.4.1 Rough overview of the maintenance processes at the site

Figure 39 shows a rough BPMN of the whole maintenance tasks at the construction site Solbakk. The two major maintenance tasks at the construction site are the repair process (mostly unplanned) and the service process (mostly planned). The exact single lanes of the maintenance processes will be explained in more detail with separate illustrations within the following chapters. It can be seen that the construction site itself has the function of the BPMN pool. The different swim-lanes are the tunneling unit, the shift mechanic unit (located in the tunnel or at the workshop because this unit is always in movement) and the workshop unit. Usually the repair task is initiated when there is a machine breakdown in the tunnel. The shift mechanics are called and if repair at field work in the tunnel is not possible the machine has to be brought to the workshop where the repair process (by incident) is performed. The second major maintenance task is the (mostly planned) service process of the machines. If the engine hours of a tunneling vehicle are exceeded this process must be started and the necessary service process at the affected vehicle must be carried out.

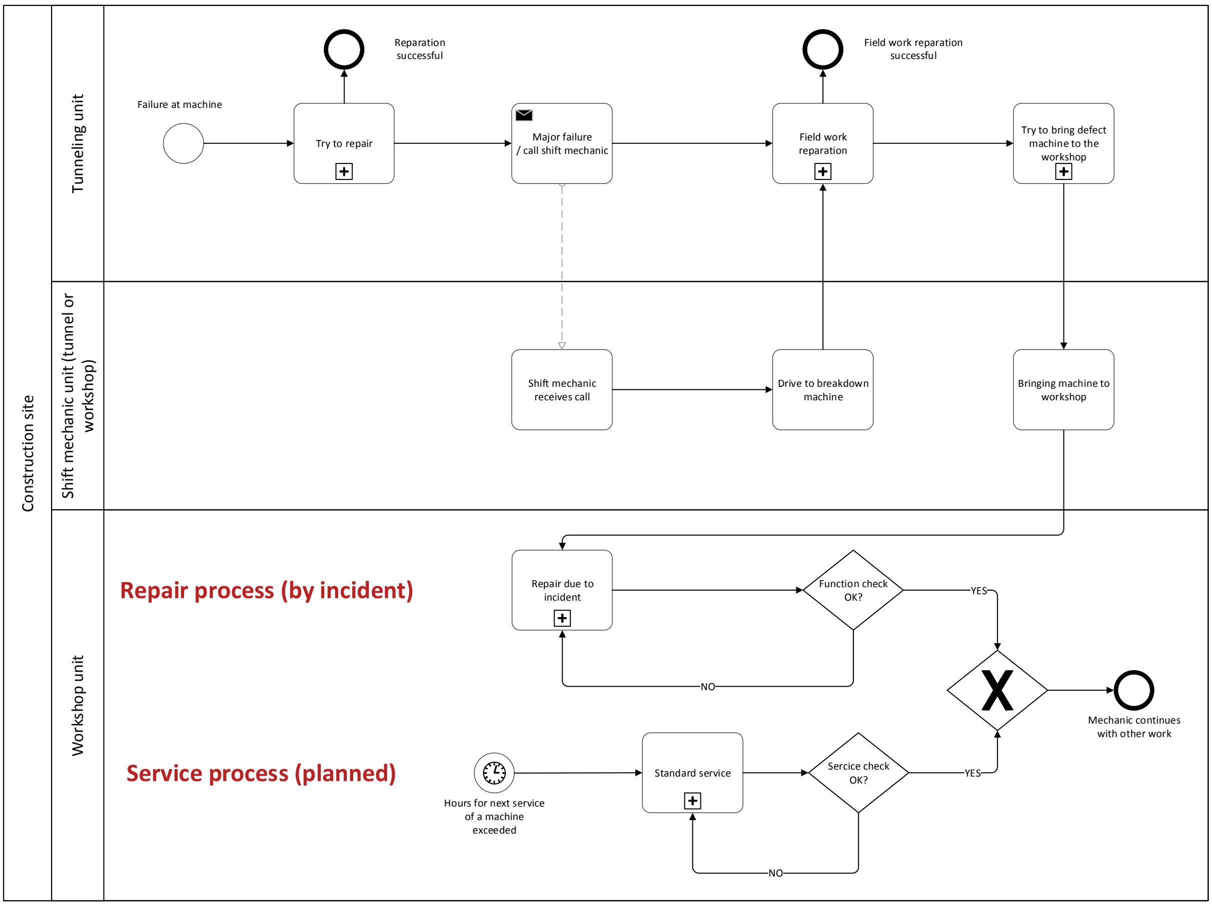


Figure 39: BPMN of the major maintenance tasks at the site - overview

At the illustration of the BPMN in figure 39 additional sub processes can be seen which are indicated with a plus. This is for reasons of reducing complexity due to the use of more sub systems and therefore it increases the understanding of the whole system. The observation of the whole maintenance process is also an initial point to figure out existing problems and to develop further variants / fields for improvement. A closer view to the separate swim-lanes will be given in the next chapters.

4.2.4.2 Tunneling unit

The first complete swim-lane of the tunneling unit can be seen in figure 40. Usually the repair process of the machines is initiated by a failure at a machine during operation in the tunnel. This failure can also occur when the machine is working outside of the tunnel.

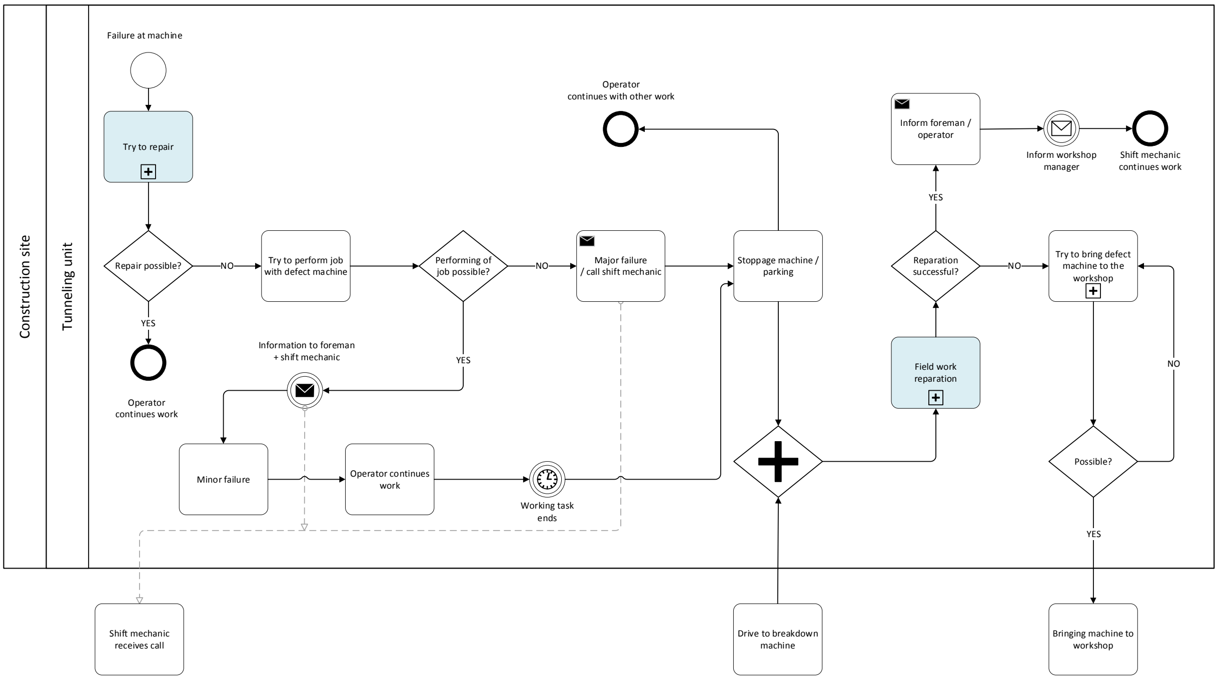


Figure 40: BPMN tunneling unit

Two processes in the swim-lane of the tunneling unit are labeled with blue color because these sub processes will be observed a little bit in more detail later on. The explanation of these sub processes should also show how a detailed BPMN has to look like with an appropriate level of detail of the sub processes to keep the overview as good as possible. This swim-lane of the tunneling unit is only responsible to initiate the repair process of machines because a service task will normally not be performed in the tunnel area due to shortage of space and not appropriate available tools and equipment. The service process therefore will be explained at the swim-lane of the workshop.

As explained before the repair process is started by the breakdown or at a failure at a machine. This can also be a minor failure but operating of the vehicle is still not acceptable. Then the operator of the machine will try to repair the machine by his own by e.g. checking the main switch, looking at activated emergency stop buttons or control the fuel level etc. This sub process is called “try to repair” and will is illustrated at figure 41.

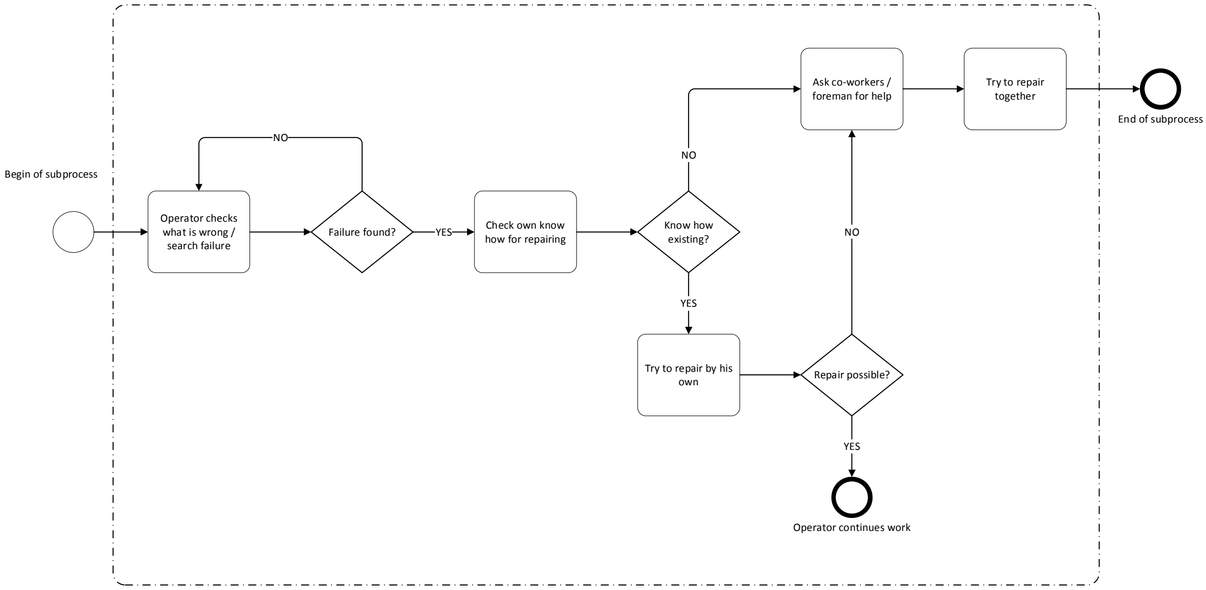


Figure 41: BPMN sub process “Try to repair”

At the beginning of the sub process “try to repair” the miner checks if he is able to figure out the failure or the function of the machine which is not working appropriate. If it is possible for him to repair the failure he will continue the work immediately. If he has not the necessary knowledge to perform the repair task and he is not able to repair the machine alone, the co-workers or the foreman will be asked for help. Together all involved workers are trying to solve the existing functional disorder. A field for improvement of the maintenance process at this point is a better flow of communication at incidents and a higher basic technical knowledge of the operators to repair minor failures on their own and therefore to save a lot of time.

If the rough reparation together with the other miners and the foreman is possible the operator will continue his work even if there should be a minor failure left at the machine. When the working task with the affected machine is finished the machine will be parked at the side and the shift mechanic will be informed about the incident for a further necessary control. But if performing of a job is not possible a major failure is on hand and the shift mechanic will get a call immediately, the miner has to continue with another work until the machine is repaired. This sub process of “field work reparation” can be seen in figure 42.

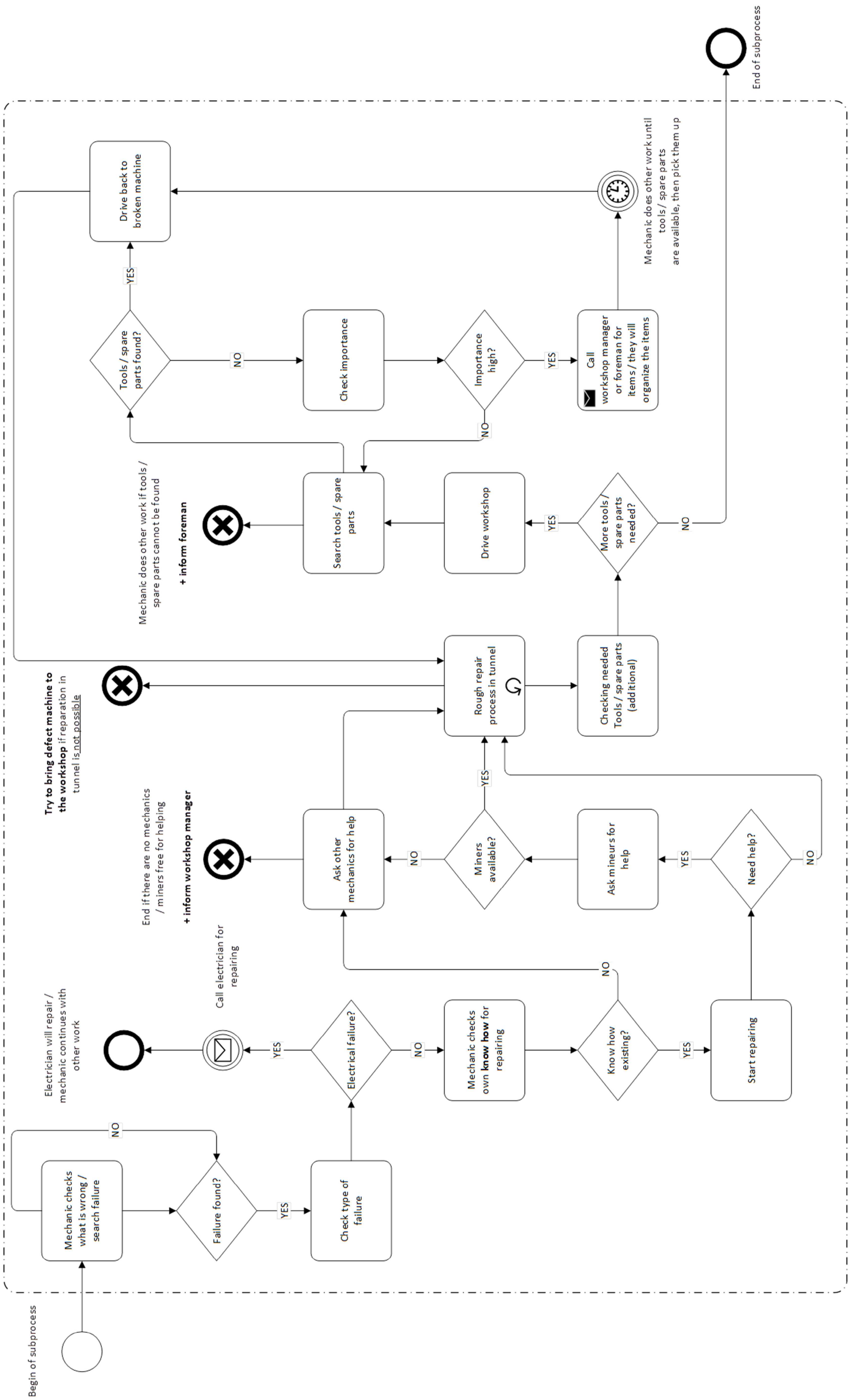


Figure 42: BPMN sub process “Field work reparation”

When the mechanic arrives at the broken machine he has to find out the type of the failure. If there is an electrical failure present he will call the responsible shift electrician which has then to perform the repair task and the mechanic will continue with his daily work. If the failure is not electrical based the mechanic has to start with the repair task direct in the tunnel at the machine. If he needs help he will ask the miners for support. If the failure is complex he will call another mechanic co-worker which is perhaps able to correct the failure. In case of special used machines or high complex failures it can be also required to call the support mechanics of the machine manufacturer for obtaining further maintenance instructions. Alone or if necessary in team work the repair process is carried out. When additional spare-parts or tools are needed for repair they have to be brought from the workshop or from the storage tent. If the needed equipment cannot be found the foreman or the workshop manager has to be informed in case of high urgency. They will organize the missing items, meanwhile the mechanic continues with other work until the stuff is available. Sometimes the distance from the breakdown machine to the workshop area has to be covered multiple times. This is of course a long lasting process and leads to a very inefficient maintenance process – this must be avoided in future as good as possible.

Some fields for improvement are also a better communication, better organized repair tasks, a higher overview of spare-parts and tools at the workshop, better qualified maintenance personal or even special education of the personal, a better organized tool handling system in general etc. Many of these variants for improvement can be figured out of the observed problems out of the various developed BPMN. This is a very efficient way of analyzing existing processes and it is a fundamental basis for developing various variants for improvement.

If the repair task is successful the machine operator and the responsible foreman will be informed. Furthermore the workshop manager has to be informed by the mechanic who executed the repair task – this is necessary for the documentation of the machine breakdown as well as for tracking the performed working tasks of the mechanic and to administrate the used spare-parts and tools. At this point of machine and spare-part / tools administration a very high potential for improvement exists! Additionally the process of ordering tools and spare-parts is improvable. If the broken machine cannot be repaired in the tunnel it has to be brought to the workshop. This is of course a special sub process with various points which have to be considered but this will not be covered within this thesis. This leads to the next swim-lane of the shift mechanic unit which can be seen in figure 43.

4.2.4.3 Shift mechanic unit

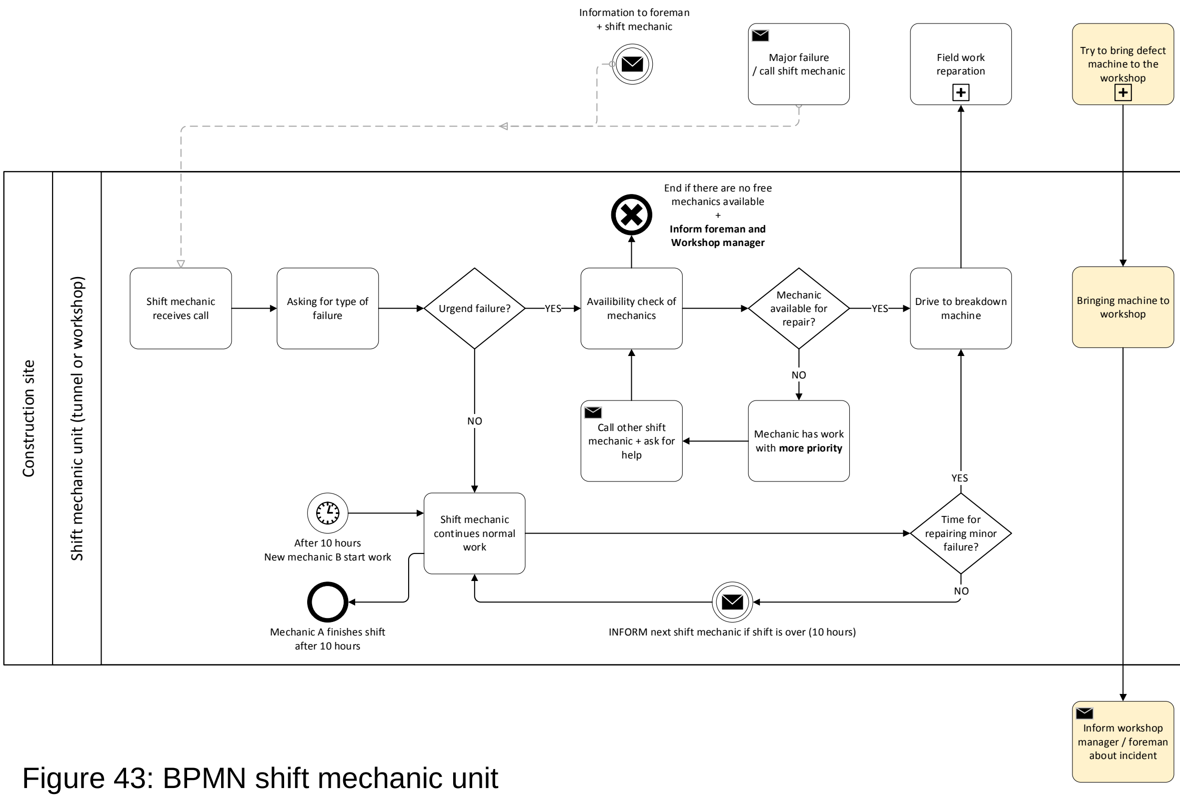


Figure 43: BPMN shift mechanic unit

In figure 43 it can be seen that the shift mechanic gets a call because of the broken machine in the tunnel. The mechanic has to check the urgency for repair of the damaged machine – even if the repair task of the broken machine is very important it can happen that he and the co-workers have still no time for it. This is of course bad but such circumstances occur quite often. Otherwise he will drive to the broken machine immediately. If the failure has not to be repaired urgently the shift mechanic continues with his ordinary work until the next shift change. If he or the next shift mechanic has free capacity they will drive to the broken machine to repair it. The three yellow highlighted elements or even activities at the right side of the BPMN in figure 43 are just for the flow of the damaged machine from the tunnel to the workshop. These steps initiate now the repair process (by incident) at the workshop. The following swim-lane of the workshop unit is illustrated in figure 44.

It can be seen that for the shift mechanic unit fields for improvement are existing regarding the emergency communication at a machine breakdown and at the communication process at every shift change. It is not always easy for the mechanics to set the right priorities of the working tasks – therefore a proper and frequent communication with the foremen and the workshop manager has to be arranged.

4.2.4.4 Workshop unit

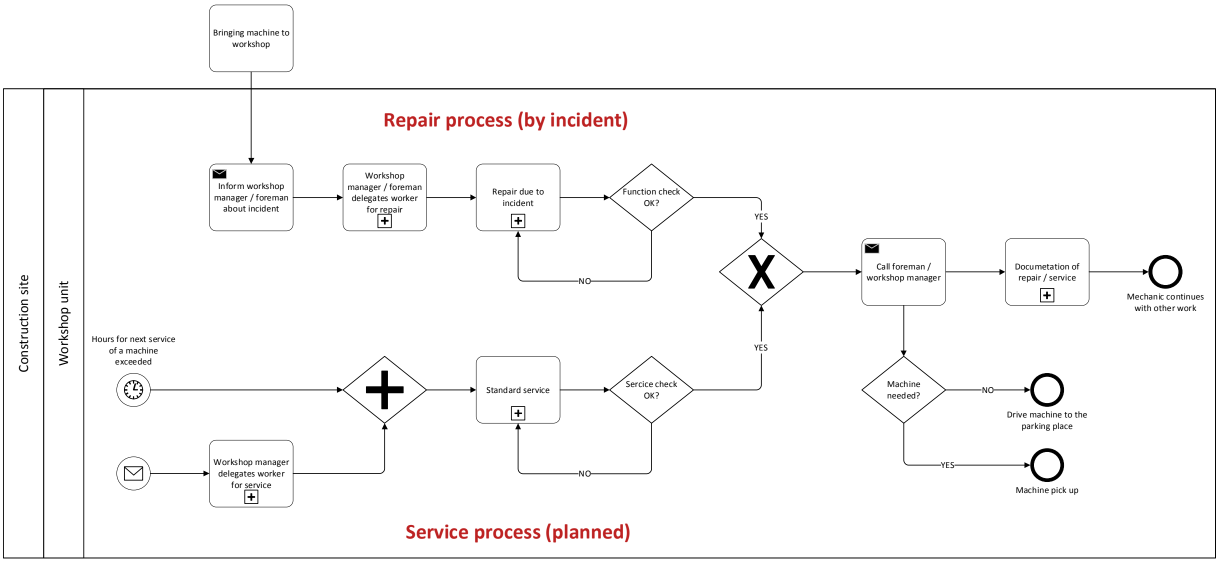


Figure 44: BPMN workshop unit

The defect machine is brought to the workshop and the foreman or the workshop manager have to be informed about this incident – this can be seen in figure 44. According to the urgency of the machine the workshop manager or the foreman delegates one or more workers to the repair task. This is of course a more or less complex process – it depends very much on the actual overall workload and the free capacities of the mechanics. If there is available personal at the workshop the repair process (due to incident) starts. Because of the fact that this repair process can have various diversities it will not be explained in more detail. Some different BPMN for diverse repair tasks were already established at the site during cooperation at field work maintenance and the results out of their analysis will be covered within the main study.

After every performed repair process the function of the repaired unit or machine has to be controlled. If the function is working appropriate the repair process is finished. Then the responsible workshop manager has to be informed and an accurate documentation of the whole procedure should be made – including the name of the mechanic, needed working hours, the used spare-parts and a description of the performed working tasks which were executed. Meantime the repaired machine is brought out of the workshop to a parking place or – if needed – directly brought back to the tunnel area. That process requires of course a high qualified and motivated workshop team and additional all mechanics must contribute with their hand written documentation sheets to a well administrated machine maintenance. When the sheets of documentation are finished the mechanics continue with other work. There are sometimes huge problems with these maintenance reports – they are sometimes written insufficient, without needed times, with no clear description of the executed tasks or they are even not filled out. This is a very important field for improvement and will be covered later on.

The second major task of the maintenance process at a tunneling workshop is the performing of the (most times planned) service tasks at the machines. Just before the engine or hydraulic (etc.) hours of a machine at the site are exceeding the hours of the next mandatory service this process has to be started. Therefore it is very important to keep track of all needed hours of all machines which are used at the site. These hours must be controlled and checked at least once a week because exceeded service intervals can cause high costs. To perform the task of reading the machine hours and administrate them will be considered and analyzed at the main study. For the service process of a machine the workshop manager has to delegate a free worker to perform that task.

During standard service tasks various actions have to be done e.g. changing of oil-/, fuel- and air filters, check of main functions and lights, checking of the greasing level / the level of the coolant etc. When all these actions are performed and all checks are completed the same process like at the repair process will be done – inform the workshop manager, write the documentation for the service, the machine will be picked up and the mechanics continue with their routine work. The whole maintenance process with all swim-lanes can be seen at figure 45.

The handwritten sheets of the mechanics have now to be administrated further by the workshop manager. He should feed an appropriate Microsoft Excel-file or even a specialized database with all necessary information about the executed service and repair tasks. This is very important for further planning and organization of future maintenance processes. To create a well-organized system for the machine administration of the maintenance process is essential for every tunneling workshop unit.

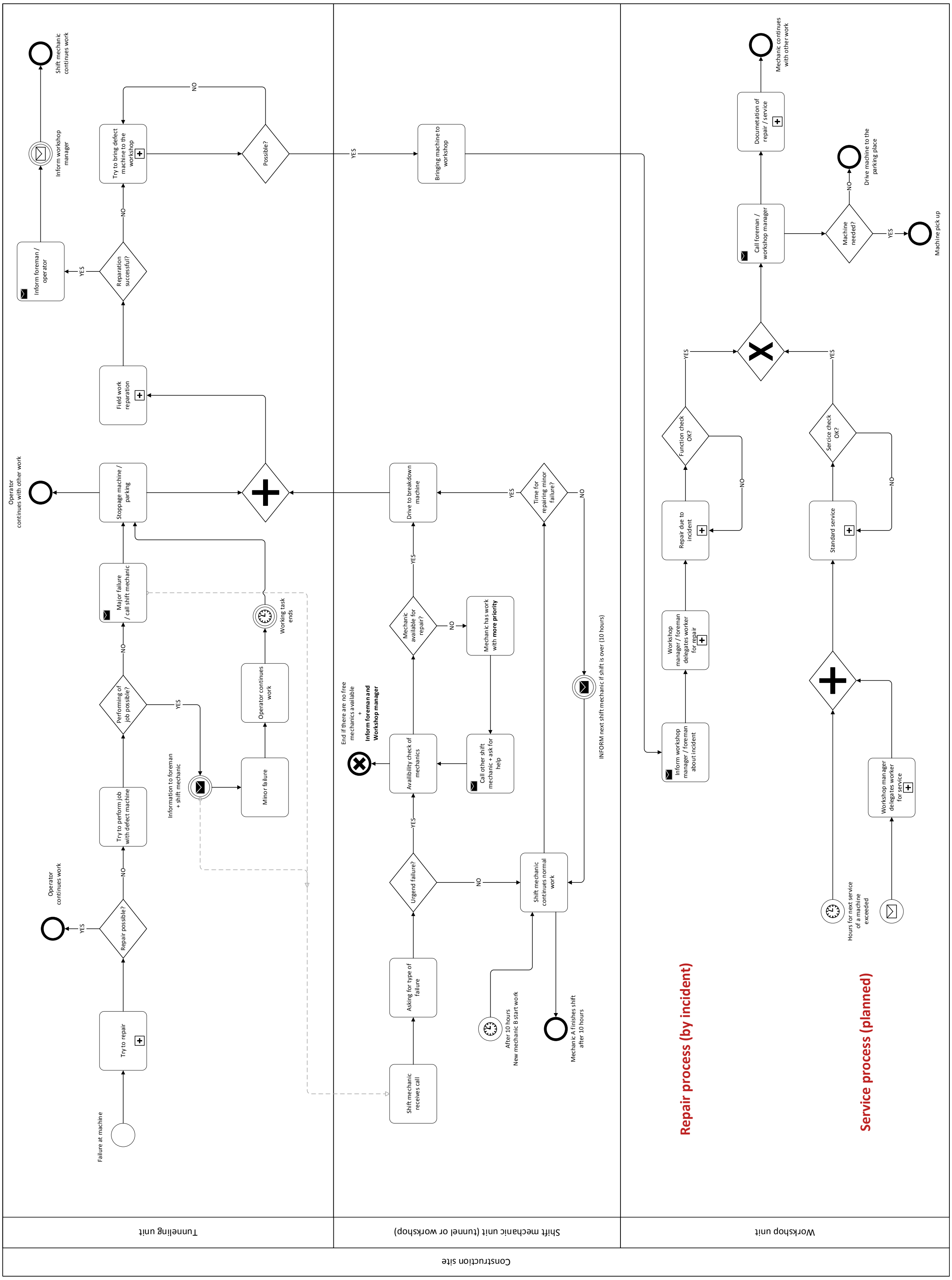


Figure 45: BPMN of the repair and service process

4.3 Main study

Out of the various results from the preliminary study it is important to figure out which variants or even fields for improvement are the most effective ones to support and improve the maintenance process of the workshop unit at the construction site Solbakk. A lot of existing problems and difficulties were already detected, but now they must be classified and evaluated to figure out the best variants of solutions. This is done within the main study. For the process of building different variants the top down approach has to be used. Different prototypes have to be developed later on and will be implemented at the construction site Solbakk – see chapter 4.5.

4.3.1 Catalogue of requirements

To figure out the best solutions for an improvement of the maintenance process it is essential to define all necessary objectives – therefore a catalogue of requirements has to be established. This is done together with the workshop manager and the commercial manager at the site. Also the experience which was gained at field work maintenance contributes to some important aspects. Table 5 shows the most significant objectives of maintenance according to their importance (e.g. must-, should- and wish objectives). The objectives are classified according to financial, functional, social and future objectives.

Table 5: Catalogue of requirements

Objective category:	Objective properties	Degree of objective	Priority
Financial objectives			
Costs	Investment costs (machines, tools etc.)	Minimum	M
	Monthly additional expenses	Minimum	S
	Costs of purchase (spare parts + raw material)	Reduce up to 40 %	W
	Monthly costs for workers (salary)	Minimum	S
	Additional costs for further education of workers	Minimum	S
	Overtime hours of all workers (workshop)	Minimum	M
	Process optimization (cost factor - maintenance)	-	S
Functional objectives			
Efficiency of repairing (unplanned)	More efficient repair process of machines in the tunnel	Minimize time	M
	More efficient repair process of stationary machinery	Minimize time	S
Effort	Effort to establish prototypes	Minimum	S
Safety	Machine operator skills	As high as possible	S
	Safety awareness of all workers in the workshop	As high as possible	S
Accidents	Amount of working accidents	Minimum	S
Damages	Amount of machine damages	Minimum	S
Documentation / administration	Documentation / administration of machine services	Increase	M
Efficiency of machine service (planned)	Efficiency of service tasks	Increase	S
Efficiency of workshop	Workflow	Increase	S
Transparency	Overview of machine / service costs	Increase	M
	Better traceability of worker tasks / hours	Daily	S
Balance of stock	Overview (spare-parts, raw material, tools, protective clothing...)	Increase	S
Sustainability / reusability	Sustainability of prototypes	As high as possible	S
Quality of maintenance	Quality of maintenance	Increase	S
Social objectives			
Workers	Keep all workers at the site	-	W
Waste treatment	Produced waste	minimum	W
	Waste treatment in general (e.g. sorting of trash,..)	As good as possible	S
Future objectives (next construction site)			
Maintenance process	Industry advance	Increase	S
Workshop	Independence of local suppliers at the beginning of project	> 2-3 months	W
	Organize workshop in advance (together with future WS manager)	-	W
Machines	Organize machines in advance (together with future WS manager)	< time + costs (well known machines)	W
Magazine	Have the right stock of protective clothings	< stock as possible	W

The costs for maintenance should be always as low as possible and therefore cost reductions are always preferred. Further it has to be mentioned that overtime hours of the workers should be reduced to a minimum. For the functional objectives it can be said that a higher efficiency should be achieved by shorter times for maintenance, higher transparency of available and used spare-parts and tools, a better documentation of the maintenance process, higher awareness of all employees etc. The social objectives are not really relevant for the maintenance process itself but they are concerning the waste treatment and the possibility to keep all workers at the site. The future objectives are more important concerning an industry advance for the maintenance process (e.g. better machine administration etc.). A better organized workshop unit due to organization in advance (before the excavation starts at early job site installations) and the selection of appropriate machinery and stock of the magazine would be very efficient points. But normally there is not so much time available and therefore this are only wish objectives.

Out of the developed objectives it is now necessary to build up several variants for improvement. Therefore the method of the “morphological scheme” is used.

4.3.2 Morphological scheme

The established morphological scheme can be seen in figure 46. There are 17 parameters defined which are individual for each variant of improvement. The parameters for these variants are highlighted with a dark and a bright background color. This is for the distinction of the area in which the different variants are resident. The parameters which are highlighted with bright background color are referred to improvements which are directly affecting cost savings at the construction site Solbakk [e.g. investment costs relative (A), effort to establish (B), monthly additional expenses (C), efficiency / cost savings of repair (E), reduction of damages / accidents (G), efficiency / cost savings of service (I), overview of stock (L), flexibility for the maintenance process (N) and motivation of workers to execute new variants (Q)] and the parameters which are highlighted with dark background color are referred to improvements for the whole tunneling industry sector [e.g. process optimization (D), safety (F), documentation / administration of maintenance (H), efficiency of workshop (J), transparency of maintenance (K), sustainability / reusability (M), quality of maintenance (O) and industry advance (P)].

Each parameter has a different degree of characteristic. The different variants for improvement are labeled with different colorful lines and have an own path through the morphological scheme – according to the individual characteristics at each parameter field. In total there are 10 variants for improvement of the maintenance process developed and each variant can be seen within the morphological scheme in figure 46.

Out of this morphological scheme the 10 variants for improvement of the machine maintenance which seemed to be the most successful are:

- V1: Administration of A-parts (machines)
- V2: Administration of B-parts (spare-parts and tools)
- V3: Administration of C-parts (protective equipment)
- V4: Intern communication structure
- V5: Warehouse management of B-parts (spare parts and tools)
- V6: Employee qualification
- V7: Order processing of B-parts and C-parts (spare-parts, tools and protective equ.)
- V8: Working conditions
- V9: Tool handling
- V10: Maintenance process itself

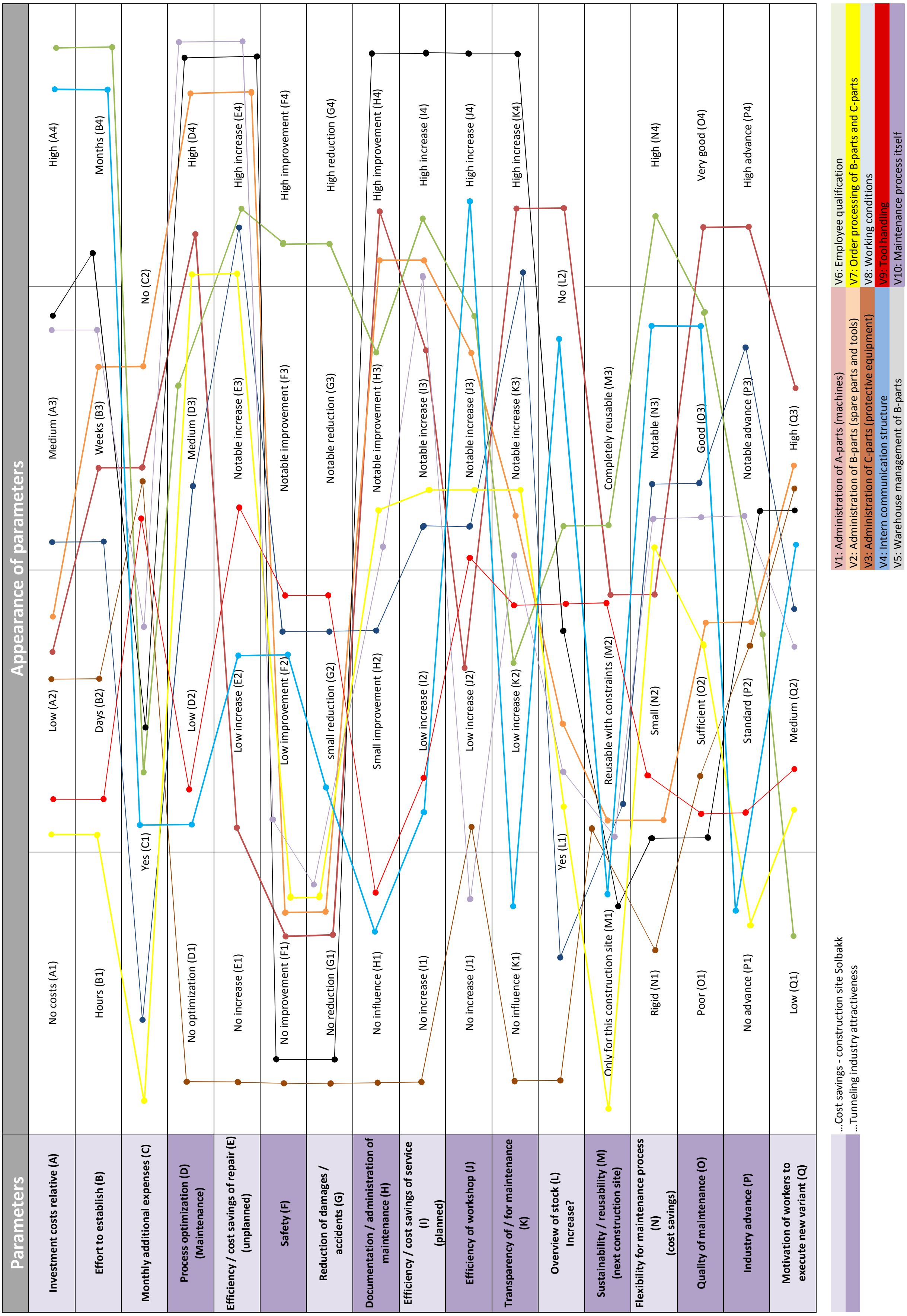


Figure 46: Improvement of maintenance – Morphological scheme

In the following chapters of the practical part the terms A-, B- and C-parts will be used sometimes and therefore a short description is necessary for a better understanding. A-parts are all machines and equipment at the construction site which have a motor and therefore they have the highest value of all parts. All of these A-parts have to be maintained and administrated. B-parts are all spare-parts of the machines and therefore they are used for the maintenance processes of the A-parts. Also the tools which are needed to perform the maintenance tasks are classified to B-parts. It is obvious that the value of B-parts is lower. Finally, C-parts are all clothes and protective equipment (e.g. helmets, safety boots + shoes, headlights, first aid systems etc.). They are not directly supporting the maintenance process itself but they are also needed at the construction site for performing the service and repair tasks. C-parts are the cheapest and have the lowest value.

The variants of figure 46 are classified into different categories. The variants V1 – V3 are considering technical aspects, the variants V4 – V7 are considering organizational aspects and the variants V8 – V10 are considering process aspects itself. For each of these categories the best variant has to be figured out and a prototype should be implemented directly the construction site Sobakk.

Example out of the morphological scheme:

To understand the morphological scheme of figure 46 and to get a feeling for the chosen parameters an example out of these 10 variants will be explained. The variant of the administration of A-parts (machines) will be chosen and explained in more detail (variant number one which is labeled with light red color).

The investment costs (A2) for an improved machine administration are low compared to the investment costs of other variants (e.g. no need of additional computers, seminars, equipment, instructors etc.). The effort to establish (B3) this variant will take weeks and lasts therefore quite long. But if a proper machine administration is established no additional costs (C2) will accumulate. This variant has a positive influence for the optimization of the maintenance process (D4) due to the fact that a proper documentation and administration lead to a better planning of all repair and service tasks. The cost savings and the efficiency of repair (E2) will not increase very much because the tasks of repair occur normally incident based. Also an improvement according to the safety aspect (F1) cannot be achieved. The same is true for the reduction of damages and accidents at the tunneling vehicles (G1). But for the documentation and administration of the maintenance process a high degree of improvement can be achieved (H4). Also the cost savings and the efficiency for performed services (I3) can be increased due to the fact that service tasks can be planned and administrated in advance. For the efficiency of the workshop (J2) only a low increase can be expected – this would need some additional measures and organization. On the other hand the transparency for maintenance (K4) will increase very much due to the use of an improved machine administration – this is a very important aspect and will make this variant very valuable. To reach a better overview of stock (L2) is unfortunately not possible because this variant focuses mainly on the machines and on the maintenance of them. To reach a better overview of all available spare-parts, tools and protective equipment the variants V2 (administration of B-parts [spare-parts and tools]) and V3 (administration of C-parts [protective equipment]) are brought into consideration. The sustainability and the reusability of the variant of administration of A-parts (M2) will be notable for the use at new construction sites. But there are also some constraints concerning different equipment at each construction site. For the flexibility of the maintenance process (N2) only small advantages will be achieved. The stored information of all kind of service and repair processes can be used for further planning of future maintenance activities. A very positive aspect is that the quality of maintenance (O4) will increase drastically due the possibility to store and organize various data of all machines and services of them. Furthermore the aspect of the industry advance (P4) will be very good compared to old / existing tools for machine administration. Finally the motivation of workers (Q3) will be very high to use a new administration tool for maintenance. There is the possibility to develop a system which can be learned easily by the workers.

For all other variants the proceeding is similar like for variant number one of the improved machine administration which was shown just before. With the morphological scheme it is possible to figure out the differences between the different variants for improvement.

For each variant it is important to figure out as much positive as well as negative aspects. To get a better overview of all variants a balance of arguments will be made.

4.3.3 Balance of arguments

The balance of arguments for the maintenance can be seen in table 6. The comparison of all positive and negative aspects will lead to a better overview of all variants. Furthermore every variant can have different setups. The best configuration of each variant must be developed later on with own problem solving cycles. It is now essential to figure out the most important objectives and parameters for all variants which are able to be compared with each other.

Table 6: Balance of arguments – maintenance variants

Variant:	Advantages	Disadvantages	Examples for variant:
V1: Administration of A-parts	Transparency of costs / working hourss etc.	Needs long time to be established	Machine administration program - database
Technical	Better control / overview of next servie	Worker must be able to handle the program	Machine administration program - excel based
	Good documentation	Difficult to find the right "depth" of the program	
	Overview of all tasks (repair + service)		
	Comparison of machines (maintenance works / costs etc.)		
	Overview of used spare-parts		
	Very high industry attractiveness		
	Can be re-used on other construction sites		
	High increase of the maintenance administration-quality		
	Possible to store the documents		
V2: Administration of B-parts	Structured system	Higher effort to work with the system	Administration program - database
Technical	Easy finding of needed items (spare parts / tools)	Worker must be able to handle the program	Administration program - excel based
	Good overview about stock	Needs long time to be established	
	Overview about needed items for ordering		
	Reduce searching time		
	No downtime of machine service because of lack of spare parts / tools		
	Balanced stock		
	Efficiency of maintenance can be increased drastically		
	Possible to order items earlier		
	High cost saving potential		
V3: Administration of C-parts	Needs not so much time to be established	No influence on the maintenance process itself	Administration program - database
Technical	Easier program	No high value of protective equipment	Administration program - excel based
	Better overview about protective- equipment stock	Worker must be able to handle the program	
	Easy to figure out needed items for ordering		
	More structured system compared to now		
V4: Intern communication structure	Better timing for maintenance / service / repair	Sometimes language / technical problems	New job descriptions (foreman tunnel / workshop)
Organization	Reduce amount of drives between workshop and broken machines (tunnel)	Takes more time at the beginning (introduction)	Improve "first communication"
	Better workload of workers	Not all workers are interested to improve the communication	Organize daily shift-commissioning
	No multiple made service processes (e.g. oil changes 2x,...)		
	Better control of whole maintenance process		
	Higher efficiency of maintenance		
V5: Warehouse management of B-parts	Better overview about stock	Storekeeper needed to maintain the orders / stock	Re-arrange the storage tent + workshop (spare parts)
Organization	Reduce searching time	Additionall administration program for tools / spare parts needed	Sorting / spatial separation of different items
	Possible to order items in advance (overview)	Storekeeper must be able to handle the necessary program	Labelling of the shelfs / items
	Even unskilled / new people can find needed things	New labelling system necessary	Link with administration program
	No interrupted services because of lack of spare parts		
	Higher efficiency of the workshop		
V6: Employee qualification	High increase in the flexibility	Need a lot of time to educate workers	Instruction manuals
Organization	Even unskilled workers can learn fast	Sometimes expensive courses	Tool lists
	High increase in technical knowledge	Long lasting	Language lessons
	Higher qualified workers = more efficient	No gurarantee for success	Professional training (intern)
	Increase the quality of the work	Some workers will not welcome this process	Professional training (extern)
	Increase safety awareness		Presentations
	Reduce accidents / damages		Education technical / safety
	Instruction material is always reusable at other construction sites		Machine operating courses
			Cleaning instructions for machines
V7: Order processing of B- and C-parts	Achieve appropriate stock	Need of responsible person	Introduce storekeeper
Organization	No downtime of machine maintenance due to lack of spare parts / tools	Maybe need of second responsible person (if person A is at home)	Using of an admin. program for spare parts / tools
	Good overview	Higher effort	Comparison of different suppliers (better prices)
	Low costs / effort to establish	Maybe need of an administration program for overview	
	Better purchase prices can be achieved (through comparison of suppliers)		
V8: Working conditions	Workers are more motivated	Expensive	New workshop layout
Process	Better for health of workers	Not directly yield for the maintenance process	New arrangement of working-machines in the WS
	Easier working positions possible	Effort for restructuring	Improve working positions
	Better workflow in the workshop		Introduce movable tables in the workshop
	More efficient working possible		Build a new big workbench
	Higher output possible		Build material stands
	Higher flexibility of working process possible		Private container for workers of workshop
			Give better working instructions
			Praise for good work
V9: Tool handling	More structure in the tool system of the workshop	Maybe not all workers will contribute to a better tool handling	Tool boxes for defect tools (repair at low workload)
Process	No danger of taking defect tools multiple times	Easier to put defect items back on their initial place	Tool boxes for electrical / mechanical faults
	Defect tools are sorted out (repaired / replaced)	Often high workload with more priorities - lack of time	
	More safety for workers		
	Even unskilled / new people can improve that process		
	No downtime of machine maintenance due to defect tools (esp. tunnel)		
V10: Maintenance process itself	Reduce accidents due to high stress of worker to finisch maintenance	Never 100% clear which processes should be done in advance	Standardization of service
Process	Save a lot of time when performing tasks in advance	Sometimes overproducing	(e.g. filter / oil - lists)
	Reduce breakdown-time of machines	Workers must be instructed before to perform that task	Maintenance in advance (e.g. jacking hydr. hoses)
	Easier repair process	Sometimes no time to do works in advance	Preparation of maintenance before accident
	Reduce driving times to measure e.g. hydraulic hoses (tunnel - workshop)	Need of good personal + organization	
	Perform e.g. jacking of hydraulic hoses at low workload	Need of good communication	
	High efficiency increase of the machine maintenance		

4.3.4 Weighting of objectives

The process of weighting the different objectives is very important for classifying the degree of improvement of each variant for the maintenance process. The rating of all objectives is done together with the responsible workshop manager at the site – also the ideas and opinions of some co-workers are taken into consideration. The result of the weighting of objectives for maintenance can be seen in table 7.

Table 7: Weighting of objectives for maintenance

Group of criteria	Criteria	Weight (rounded)		Rating of importance 10% - 100%														
		Group	Single	1	2	3	4	5	6	7	8	9	10	Rating group	% group exact	Rating single	% single exact	Points single
Construction site Solbakk		50											x	10	50,00			
Solbakk	Investment costs relative		8									x				9	15,52	7,76
	Effort to establish		6							x						7	12,07	6,03
	Monthly additional expenses		5						x							6	10,34	5,17
objectives	Efficiency / cost savings of repair (unplanned)		8									x				9	15,52	7,76
	Reduction of damages / accidents		9										x			10	17,24	8,62
	Efficiency / cost savings of service (planned)		5						x							6	10,34	5,17
	Overview of stock - Increase?		3				x									4	6,90	3,45
	Flexibility for mainatenance process		4					x								5	8,62	4,31
	Motivation of workers to execute variant		2		x											2	3,45	1,72
Subtotal competitive strength																58	100,00	50,00
Tunneling industry		50											x	10	50,00			
attractiveness	Process optimization		5						x							6	10,34	5,17
	Safety		6							x						7	12,07	6,03
	Documentation / administration		5						x							6	10,34	5,17
objectives	Efficiency of workshop		5						x							6	10,34	5,17
	Transparency of maintenance		8									x				9	15,52	7,76
	Sustainability / reusability		8									x				9	15,52	7,76
	Quality of maintenance		8									x				9	15,52	7,76
	Industry advance		5						x							6	10,34	5,17
Subtotal industry attractiveness																58	100,00	50,00
		100	100										Summe:	20	100,00			

In table 7 it can be seen that the chosen criteria are separated into a group of the objectives for the construction site Solbakk (bright highlighted) and into a group of tunneling industry attractiveness (dark highlighted). These two main groups were already explained in more detail in chapter 4.3.2 within the description of the morphological scheme.

The criteria of the objectives for cost savings at the construction site Solbakk are the relative investment costs, the effort to establish each variant (needed time until implementation), the monthly additional expenses (caused by each variant), the increase of efficiency / cost savings of unplanned reparation tasks, the reduction of damages and accidents (directly on the site), the increase of efficiency / cost savings of planned service tasks, a higher overview of the stock, the flexibility for the maintenance process and the motivation of all workers to perform and execute the new variant.

The criteria out of the objectives for the tunneling industry attractiveness are general process optimizations, an increase of the safety aspect (education and preventive tasks), an improved documentation and administration for each maintenance task (traceability), a higher efficiency of the machine workshop, an increased transparency of maintenance, high sustainability and reusability of each variant at following construction sites in future, improved quality of all maintenance tasks as well as a high industry advance compared to other competitors.

In total 100 points can be split to the different criteria of both main groups. A rating of importance can be seen at table 7 – with columns from 1 to 10. This numbers from 1 to 10 are representing the importance of the variants from 10% to 100%. This means that a cross at the column number 4 indicates a importance of 40% regarding the affected criterion.

The responsible employees were asked separately to value the importance of each variant from 1 to 10. Afterwards an average value was taken. It can be seen that the two main groups are both rated with a 10 – so both main fields have the same importance according to the rating and each main group receives 50 points. Then every single criterion is ranked from 1 to 10 (indicated with green crosses). Out of the single rating of each criterion the percentage is calculated and then the exact points for the affected criterion are figured out. These exact points get then rounded and finally the points can be used at the following value benefit analysis.

Example out of the weighting of objectives:

Following an example out of the rating will be shown for the criterion of process optimization which is located within the second main group of the tunneling industry attractiveness. This criterion is rated with 60% importance (green cross at column number 6). These chosen 6 points can be seen also in the column “rating single”. The exact percentage of these 6 points compared to the total points of this second main group (58 points) is about 10,34%. In total there are 50 points left for all 8 criteria of the main group for the tunneling industry attractiveness. So the 10,34% of total importance for the criterion of process optimization lead to 5,17 calculated points. The rounded value therefore will be 5. That means that the criterion of the process optimization will get 5 points for the following value benefit analysis. For all other criteria the proceeding is still the same as for this example for the process optimization.

The different objectives respectively criteria of objectives are now classified and rated and can be used for the following value benefit analysis. But before the value benefit analysis can be established it is necessary to evaluate an appropriate matrix for scaling of each criterion for every variant according to the achievement of the individual objectives. This scaling matrix will be explained in more detail in the next chapter.

4.3.5 Scaling matrix

The scaling matrix is used to figure out the influence of each variant to each parameter or even criterion and therefore to make the different variants comparable concerning to their contribution to an improvement of the maintenance process. This matrix contains of course the same criteria like the table of the weighting of objectives and the following value benefit analysis which will be explained in the following chapter. An extraction of the scaling matrix of the main study can be seen in table 8.

Table 8: Extraction of the scaling matrix of the main study

Group of criteria	Criteria	Notes						Unit	Variants					
									V1: Administration of A-parts (machines)		V2: Administration of B-parts (spare parts and tools)		V3: Administration of C-parts (protective equipment)	
		0 - BAD	1	2	3	4	5 - GOOD		V1		V2		V3	
Construction site														
Solbakk	Investment costs relative	High		Medium		Low	No costs			4		4		4
	Effort to establish	> 50	< 50	< 30	< 14	< 7	< 1	Days	45	1	40	1	10	3
objectives	Monthly additional expenses	High		Medium		Low				4		4		4
	Efficiency / cost savings of repair (unplanned)	Low increase		Notable increase		High increase				1		4		0
	Reduction of damages / accidents	Low reduction		Notable reduction		High reduction				0		0		0
	Efficiency / cost savings of service (planned)	Low increase		Notable increase		High increase				3		5		0
	Overview of stock - Increase?	Low increase		Notable increase		High increase				0		5		4
	Flexibility for mainatenance process	Small		Notable		High				1		1		0
	Motivation of workers to execute variant	Low		Medium		High				5		5		4
Tunneling industry														
attractiveness	Process optimization	Low		Medium		High				5		5		0
	Safety	Low improvement		Notable		High improvement				0		0		0
objectives	Documentation / administration	Low improvement		Notable		High improvement				5		5		0
	Efficiency of workshop	Low improvement		Notable		High improvement				1		3		1
	Transparency of maintenance	Low increase		Notable increase		High increase				5		2		0
	Sustainability / reusability	Low reusability		Reusable with		High reusable				4		4		4
	Quality of maintenance	Low		Medium		High				5		2		1
	Industry advance	Small		Notable		High				5		2		2

Each criterion has a different characteristic for each variant. Table 8 shows only a small extraction of the scaling matrix with three variants – the complete scaling matrix for the whole maintenance process of the main study can be seen at table 9. At the field of notes there are six columns from 0 to 5 whereby 0 is representing a very bad influence of the variant concerning an improvement and 5 is representing a very good influence of the variant concerning an improvement of the maintenance process.

The unit column is used to define special parameters for the evaluation – in this case there is only one row dealing with the unit of days and therefore also the left column at each variant is used only once. The left column of each variant is only for indicating the amount of days which are necessary for establishing the affected variant. The right column of each variant is for determining the influence of the affected variant concerning the diverse objectives. As a rule it can be said: “Higher numbers in the right column of each variant (compared to other variants) are representing a better variant for improvement.”

Example out of the scaling matrix:

The proceeding to develop a scaling matrix will be shown according to the scaling matrix in table 8 with three variants. First, the criteria for the objectives of the construction site Solbakk will be covered (bright highlighted group). The relative investment costs for each of these three variants are quite low due to the fact that no additional equipment (e.g. additional computers) must be bought. The costs therefore are considered as low and every variant gets four points for this criterion. The effort to establish is varying quite much between these three variants from 45 days for variant number one to 10 days for variant number three. Therefore the variants number one and two get only one point and the variant number three gets three points because of a shorter time for establishing. It is obvious that a shorter time for introduction of a variant is better and therefore more points are the result.

The administration of machines (A-parts), spare-parts and tools (B-parts) needs of course much more effort than the administration of protective equipment (C-parts) due to a higher level of complexity. When a new variant for administration is implemented, the monthly additional costs for all three variants should be quite low and therefore each variant gets four points for this criterion. The efficiency of unplanned repair tasks will only increase in case of a better organization of B-parts (spare-parts and tools) due to the fact of drastically reduced searching and waiting times. Therefore variant number two gets four points due to a systematically improvement of the whole administration of the stock. The administration of A-parts and C-parts at this point will not be very helpful for this criterion and therefore gets only one or even zero points. No reduction of damages can be achieved with all three variants and therefore no variant gets a point.

The efficiency of planned services will increase very much with the variant of administration of B-parts (spare-parts and tools) and therefore this variant receives five points. Also the administration of A-parts can contribute to a notable improvement of the maintenance process due to the possibility of the storage of information about all performed services – this stored information can be used as a basis for further planning of maintenance in the future. Therefore variant number one gets three points. The administration of protective equipment has no influence according to the planned machine service and therefore no points are the result.

To achieve a better overview of stock the machine administration will not be very helpful and therefore deserves no points. The administration of B-parts will be very effective and five points for variant number two are the result. Also the overview of stock for the protective equipment will increase drastically with a proper administration and a better overview about all items of C-parts will be the result – four points for variant number three. The flexibility for the maintenance process will be affected only a little bit due to appropriate planning and order – but not remarkable – one point for the variants number one and two. The administration of the protective equipment (variant number three) will not contribute to an improvement and therefore receives no point for this criterion.

The last criterion of motivating the workers to work with the chosen variant is for the first two variants of the machine and the spar-part/ and tool administration very high and therefore each variant receives five points. Reason therefore is a user-friendly program for each variant which can be developed. This is also true for variant number three for the administration of the protective equipment. But for this variant the time for introduction will be shorter and therefore the usability of the administration will not be as much developed – so four points are given to that variant.

This was the rating of the criteria from the objectives for the construction site Solbakk for the first three variants. This process has to be done similar for all criteria of the objectives of the tunneling industry attractiveness as well as for all remaining variants. The scaling matrix in table 8 shows that the variants number one and two have much more points compared to variant number three. It can be estimated that these variants will be much more efficient concerning an improvement of the maintenance process. But to get an exactly calculated result a value benefit analysis must be established – this will be covered within the next chapter.

Table 9: Complete scaling matrix of the main study

Group of criteria	Criteria	Notes 0 - BAD	1	2	3	4	5 - GOOD	Unit	V1: Administration of A-parts (machines) V1		V2: Administration of B-parts (spare parts and tools) V2		V3: Administration of C-parts (protective equipment) V3		V4: Intern communication structure V4		V5: Warehouse management of B-parts (spare parts and tools) V5	
Construction site																		
Solbakk	Investment costs relative	High		Medium		Low	No costs			4		4		4		3		2
	Effort to establish	> 50	< 50	< 30	< 14	< 7	< 1	Days	45	1	40	1	10	3	45	1	60	0
objectives	Monthly additional expenses	High		Medium		Low				4		4		4		2		1
	Efficiency / cost savings of repair (unplanned)	Low increase		Notable increase		High increase				1		4		0		5		5
	Reduction of damages / accidents	Low reduction		Notable reduction		High reduction				0		0		0		1		0
	Efficiency / cost savings of service (planned)	Low increase		Notable increase		High increase				3		5		0		3		5
	Overview of stock - Increase?	Low increase		Notable increase		High increase				0		5		4		3		4
	Flexibility for mainatenance process	Small		Notable		High				1		1		0		2		1
	Motivation of workers to execute variant	Low		Medium		High				5		5		4		3		4
Tunneling industry																		
attractiveness	Process optimization	Low		Medium		High				5		5		0		2		5
	Safety	Low improvement		Notable		High improvement				0		0		0		1		0
objectives	Documentation / administration	Low improvement		Notable		High improvement				5		5		0		1		4
	Efficiency of workshop	Low improvement		Notable		High improvement				1		3		1		3		5
	Transparency of maintenance	Low increase		Notable increase		High increase				5		2		0		4		4
	Sustainability / reusability	Low reusability		Reusable with		High reusable				4		4		4		2		1
	Quality of maintenance	Low		Medium		High				5		2		1		3		2
	Industry advance	Small		Notable		High				5		2		2		3		2

Group of criteria	Criteria	Notes 0 - BAD	1	2	3	4	5 - GOOD	Unit	V6: Employee qualification V6		V7: Order processing of B-parts and C-parts V7		V8: Working conditions V8		V9: Tool handling V9		V10: Maintenance process itself V10	
Construction site																		
Solbakk	Investment costs relative	High		Medium		Low	No costs			1		4		1		4		2
	Effort to establish	> 50	< 50	< 30	< 14	< 7	< 1	Days	100 +	0	10	3	60	0	5	4	21	2
objectives	Monthly additional expenses	High		Medium		Low				1		2		3		3		2
	Efficiency / cost savings of repair (unplanned)	Low increase		Notable increase		High increase				4		4		1		2		4
	Reduction of damages / accidents	Low reduction		Notable reduction		High reduction				5		0		1		1		0
	Efficiency / cost savings of service (planned)	Low increase		Notable increase		High increase				5		3		1		1		5
	Overview of stock - Increase?	Low increase		Notable increase		High increase				1		4		0		2		3
	Flexibility for mainatenance process	Small		Notable		High				5		2		3		1		2
	Motivation of workers to execute variant	Low		Medium		High				1		3		5		2		2
Tunneling industry																		
attractiveness	Process optimization	Low		Medium		High				3		4		1		1		5
	Safety	Low improvement		Notable		High improvement				5		0		1		1		1
objectives	Documentation / administration	Low improvement		Notable		High improvement				3		2		0		0		3
	Efficiency of workshop	Low improvement		Notable		High improvement				3		3		4		2		0
	Transparency of maintenance	Low increase		Notable increase		High increase				1		3		0		1		3
	Sustainability / reusability	Low reusability		Reusable with		High reusable				5		1		0		3		4
	Quality of maintenance	Low		Medium		High				4		1		4		1		4
	Industry advance	Small		Notable		High				2		0		0		1		4

4.3.6 Value benefit analysis

The value benefit analysis is determining the best variants for the improvement of the maintenance process. The basis for this analysis is the scaling matrix and the table of weighting of objectives. These values have to be combined respectively multiplied with each other within the value benefit analysis. An extraction of value benefit analysis of the maintenance process for the first three variants can be seen in table 10.

Table 10: Extraction of the value benefit analysis of the main study

Group of criteria	Criteria	Weight		Variants					
				V1: Administration of A-parts (machines)		V2: Administration of B-parts (spare parts and tools)		V3: Administration of C-parts (protective equipment)	
				V1		V2		V3	
		Group	Single [g]	n	n*g	n	n*g	n	n*g
Construction site Solbakk objectives		50							
	Investment costs relative		8	4	32	4	32	4	32
	Effort to establish		6	1	6	1	6	3	18
	Monthly additional expenses		5	4	20	4	20	4	20
	Efficiency / cost savings of repair		8	1	8	4	32	0	0
	Reduction of damages / accidents		9	0	0	0	0	0	0
	Efficiency / cost savings of service (planned)		5	3	15	5	25	0	0
	Overview of stock - Increase?		3	0	0	5	15	4	12
	Flexibility for mainatenance process		4	1	4	1	4	0	0
	Motivation of workers to execute variant		2	5	10	5	10	4	8
			Subtotal competitive strength		95		144		90
Tunneling industry attractiveness objectives		50							
	Process optimization		5	5	25	5	25	0	0
	Safety		6	0	0	0	0	0	0
	Documentation / administration		5	5	25	5	25	0	0
	Efficiency of workshop		5	1	5	3	15	1	5
	Transparency of maintenance		8	5	40	2	16	0	0
	Sustainability / reusability		8	4	32	4	32	4	32
	Quality of maintenance		8	5	40	2	16	1	8
	Industry advance		5	5	25	2	10	2	10
			Subtotal industry attractiveness		192		139		55
n... number out of the scaling matrix		100	100						
			Total		287		283		145

It can be seen that the criteria of the two major groups are identical like the criteria before. The column weight has 50 points for each main field and is split into the single points of every criterion – these numbers (orange written) were figured out at the process of weighting of objectives in chapter 4.3.4. The number “n” which is located at the left column of every variant is received out of the scaling matrix from chapter 4.3.5. Now these numbers of the weighting of the objectives of every single criterion [g] are multiplied with the numbers out of the scaling matrix of each criterion [n]. A higher result indicates a more efficient variant for improvement. Afterwards the multiplied values are summed up to subtotal values. The results are subtotal values for the competitive strength (out of the objectives for the construction site Solbakk) and subtotal values for the industry attractiveness (out of the objectives for the tunneling industry attractiveness). The overall efficiency of each variant can be seen in the last row which is indicated with “total”. This is the final result – the highest number indicates the best variant for improvement. Therefore the three variants with the highest numbers should be chosen and elaborated at individual detail studies within the next chapters. For analyzing the best variants a view to the complete value benefit analysis is necessary – the entire value benefit analysis can be seen at table 11.

Table 11: Value benefit analysis of the main study

Group of criteria	Criteria	Weight		Variants																			
				V1: Administration of A-parts (machines)		V2: Administration of B-parts (spare parts and tools)		V3: Administration of C-parts (protective equipment)		V4: Intern communication structure		V5: Warehouse management of B-parts (spare parts and tools)		V6: Employee qualification		V7: Order processing of B-parts and C-parts		V8: Working conditions		V9: Tool handling		V10: Maintenance process itself	
				V1		V2		V3		V4		V5		V6		V7		V8		V9		V10	
		Group	Single [g]	n	n*g	n	n*g	n	n*g	n	n*g	n	n*g	n	n*g	n	n*g	n	n*g	n	n*g	n	n*g
Construction site		50																					
Solbakk	Investment costs relative		8	4	32	4	32	4	32	3	24	2	16	1	8	4	32	1	8	4	32	2	16
	Effort to establish		6	1	6	1	6	3	18	1	6	0	0	0	0	3	18	0	0	4	24	2	12
objectives	Monthly additional expenses		5	4	20	4	20	4	20	2	10	1	5	1	5	2	10	3	15	3	15	2	10
	Efficiency / cost savings of repair		8	1	8	4	32	0	0	5	40	5	40	4	32	4	32	1	8	2	16	4	32
	Reduction of damages / accidents		9	0	0	0	0	0	0	1	9	0	0	5	45	0	0	1	9	1	9	0	0
	Efficiency / cost savings of service (planned)		5	3	15	5	25	0	0	3	15	5	25	5	25	3	15	1	5	1	5	5	25
	Overview of stock - Increase?		3	0	0	5	15	4	12	3	9	4	12	1	3	4	12	0	0	2	6	3	9
	Flexibility for mainatenance process		4	1	4	1	4	0	0	2	8	1	4	5	20	2	8	3	12	1	4	2	8
	Motivation of workers to execute variant		2	5	10	5	10	4	8	3	6	4	8	1	2	3	6	5	10	2	4	2	4
Subtotal competitive strength					95		144		90		127		110		140		133		67		115		116
Tunneling industry		50																					
attractiveness	Process optimization		5	5	25	5	25	0	0	2	10	5	25	3	15	4	20	1	5	1	5	5	25
	Safety		6	0	0	0	0	0	0	1	6	0	0	5	30	0	0	1	6	1	6	1	6
objectives	Documentation / administration		5	5	25	5	25	0	0	1	5	4	20	3	15	2	10	0	0	0	0	3	15
	Efficiency of workshop		5	1	5	3	15	1	5	3	15	5	25	3	15	3	15	4	20	2	10	0	0
	Transparency of maintenance		8	5	40	2	16	0	0	4	32	4	32	1	8	3	24	0	0	1	8	3	24
	Sustainability / reusability		8	4	32	4	32	4	32	2	16	1	8	5	40	1	8	0	0	3	24	4	32
	Quality of maintenance		8	5	40	2	16	1	8	3	24	2	16	4	32	1	8	4	32	1	8	4	32
	Industry advance		5	5	25	2	10	2	10	3	15	2	10	2	10	0	0	0	0	1	5	4	20
Subtotal industry attractiveness					192		139		55		123		136		165		85		63		66		154
n... number out of the scaling matrix		100	100																				
			Total		287		283		145		250		246		305		218		130		181		270

At the value benefit analysis of table 11 it can be seen that the best variant for improvement of the maintenance process is variant number six – the employee qualification – with a total amount of 305 points. The second best variant with a total amount of 287 points is variant number one – administration of A-parts (machines). Variant number two – the administration of B-parts (spare-parts and tools) – is the third best variant with 283 points. It can be said that improvements of the maintenance process itself and of the intern communication structure are also very valuable. A better performed warehouse management of B-parts and in general a better processing of the ordering process of B-parts and C-parts are ranked next. The variant for a better tool handling has not a big influence to the improvement of the maintenance process itself and this is the reason why it is ranked quite low. The variant of the administration of C-parts as well as the variant for the improvement of the working conditions for the workers are the worst ones due to the fact that these improvements do not really contribute to a higher efficiency of the machine maintenance in the workshop. An overview of the ranking of all variants with their total points can be seen in table 12.

Table 12: Ranking of all variants for improvement

Variant:	**Points**	**Ranking**
V6: Employee qualification	305	1
V1: Administration of A-parts (machines)	287	2
V2: Administration of B-parts (spare parts and tools)	283	3
V10: Maintenance process itself	270	4
V4: Intern communication structure	250	5
V5: Warehouse management of B-parts (spare parts and tools)	246	6
V7: Order processing of B-parts and C-parts	218	7
V9: Tool handling	181	8
V3: Administration of C-parts (protective equipment)	145	9
V8: Working conditions	130	10

There is the question about the influence of each variant according to the competitive strength of the company compared to the tunneling industry attractiveness in general. Therefore all different subtotals of the competitive strength and of the industry attractiveness of the value benefit analysis can be compared to each other.

But this is a very exhausting process to keep all different numbers and rankings in mind because of the complexity. As a result of this problem a graphical analysis will be established and delivers the whole information at a glance.

4.3.7 Graphical interpretation of the evaluation of the main study

Out of the value benefit analysis the different strengths and weaknesses of each variant for improvement can be seen. But an interesting view of this analysis is the distribution of all criteria according to the two main fields of objectives. This view is indicating the influence of the variants which are increasing the competitive strength of the company compared to the variants which are increasing the industry attractiveness of the maintenance process. Therefore the results out of the value benefit analysis are the basis for the development of the graphical interpretation from the main study - this can be seen in figure 47.

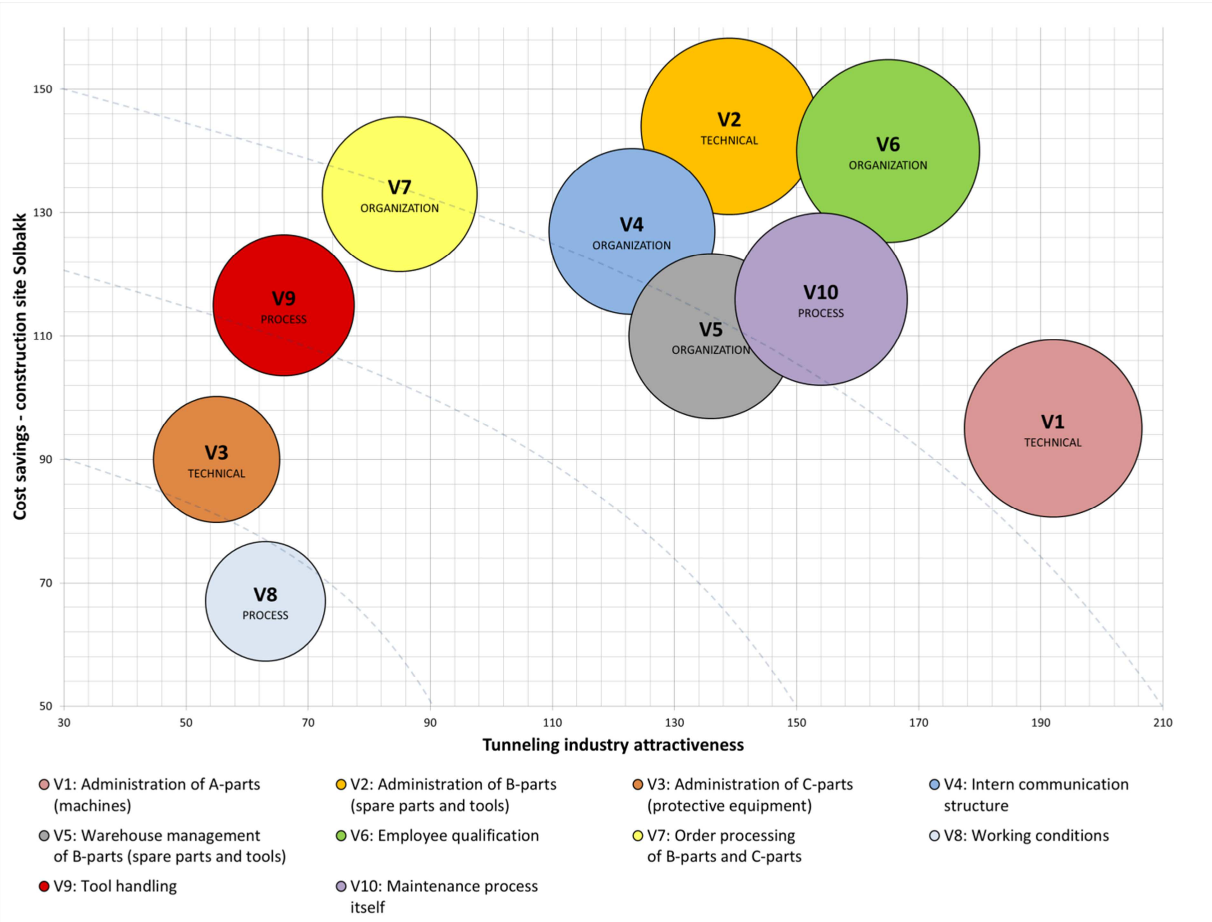


Figure 47: Maintenance overview – graphical interpretation of the different variants

The X-axis of this graphical interpretation is indicating the tunneling industry attractiveness of the variants and the Y-axis is indicating the improvements / cost savings which can be achieved with these variants directly at the construction site Solbakk. The axes are split according to the different objectives of the two main fields for improvement of the maintenance process like at the classification out of the table for weighting of objectives, the scaling matrix and the value benefit analysis. The ten spheres are indicating the ten variants for improvement. When a sphere is located more to the right side of the diagram it can be said that this variant contributes to a higher value for an improvement of the tunneling industry attractiveness in general. When a sphere is located more to the top of the diagram it is obvious that this variant contributes to a higher improvement of the competitive strength of the company. This can be related directly to cost savings of the machine maintenance at the construction site Solbakk. The best position for a variant would be in the right top corner of the diagram, the worst position would be in the left corner at the bottom.

Furthermore the size of the colored spheres is indicating the importance of the variants – if a sphere has a larger diameter, the overall importance of that variant can be seen as higher. The sizes of these spheres as well as the allocation of each sphere according to the axes of the diagram are directly connected to the results out of the value benefit analysis. The different colors of these spheres are linked to the different variants for improvement and therefore an explanation can be seen in the legend of figure 47. A short abbreviation of the variants from V1 to V10 can be seen directly within these spheres as well as the indication of the belonging of each variant to the different groups of improvement. These groups are classified according to the technical-, organizational- and to process improvements itself. The task of this thesis is to develop and implement one prototype for each of these three groups. Only the three most promising variants will be focused further at different detail studies.

4.3.7.1 Organizational aspect – V6: Employee qualification

For the field of organization it is quite easy to see that variant number six – improvement of the employee qualification – seems to be the most successful. This is also the variant with the most total points of all. Furthermore the distribution of this variant seems to be quite equal at both axes at the diagram of figure 47. This variant seems to be good balanced between the two main fields of improvement like for the competitive strength and the industry advance.

The key for success is a high qualified and educated staff at the site – concerning mechanics, miners and managerial staff. Every employee has to be involved to the improvement process. It is essential to work together as a team for reaching the best results – this was already mentioned at the theory of the Total Productive Maintenance (TPM) at chapter 2.3. The process of developing a solution for the organizational aspect will be covered in the following detail study. Afterwards an appropriate prototype will be figured out, developed and implemented at the construction site Solbakk.

4.3.7.2 Technical aspect – V1: Administration of A-parts (machines)

The technical field for improvement will be covered with variant number one – administration of A-parts (machines). This variant is located at the right side near the bottom of the diagram. Therefore this variant will have a very positive influence to the tunneling industry attractiveness – it is the best variant at this main field. The second main field of the competitive strength is not covered as much as the industry attractiveness by this variant.

But according to the sum of the total points this is the second best variant of all. A better administration and documentation of the whole maintenance process will be developed – due to the fact that there is no standard program for the administration of the whole machine service and repair tasks used this will be a quite interesting point also for future construction sites. The best solution for implementing a prototype of this variant will be also figured out in the following detail study.

4.3.7.3 Process aspect – V10: Maintenance process itself

According to the ranking of table 12 variant number ten for improvement of the maintenance process itself is only ranked at the fourth place. Variant number two for the administration of the B-parts (spare-parts and tools) has slightly more points than the mentioned variant number ten.

But variant number two is located at the field of technical improvement. For this main field a technical solution will be already created (variant number one for administration of A-parts). To develop additionally a variant at the field of process optimization will lead to a much wider range of analysis. It is positive that this process optimization can be aligned and integrated to the other two variants of the organizational and technical field for improvement.

Due to this fact it is possible to achieve the best total package of improvement out of all variants for the machine maintenance at the construction site Solbakk. To figure out which process is supporting the variants for improvement of the technical and organizational area as good as possible will be elaborated within the affected detail study.

4.4 Detail study

Within the main study it was possible to figure out the most important variants for improvement of the maintenance process. Now it is essential to figure out the best possible solutions of improvement for each of these three variants as well as to implement three individual prototypes at the construction site Solbakk later on. Because of various possible solutions for each variant and a high degree of complexity a structured proceeding is unavoidable.

4.4.1 Detail study organization: Variant 6 – Employee qualification

This detail study deals with the organizational aspect of the three main fields for improvement of the maintenance process. A high knowledge and qualification of the employees at the machine workshop of a tunneling construction site is a prerequisite for an efficient maintenance process. To figure out a proper solution for a better employee education one or even more problem solving cycle(s) must be established and the results must be analyzed.

4.4.1.1 Employee qualification

The chosen variant of the employee qualification seems to be most successful variant of all according to the ranking of the main study – this can be seen in table 12. To increase the level of knowledge or even qualification of all involved employees it is first necessary to know which kind of employees are available for working at a machine workshop.

Catalogue of requirements:

First it is necessary to define a catalogue of requirements together with the workshop manager and the involved workers at the site. Table 13 shows the most significant objectives for the employee qualification.

Table 13: Catalogue of requirements – employee qualification

Objective category:	Objective properties	Degree of objective	Priority
Financial objectives			
	Monthly costs per worker (salary)	Minimum	M
	Costs for further education	Minimum	M
	Time for disemployment at wrong behavior	As short as possible	S
Personal objectives	Communication	As good as possible (German, English)	S
	Team spirit	Increase	W
	Flexibility of workers	Increase	S
	Willingness of workers to stay at the site (traveling costs etc.)	At least 4 weeks	M
Qualification of workers	Technical knowledge	As high as possible	S
	Experience in the workshop / tunneling sector	Min. 2 years	S
Motivation	Motivation of workers	Increase	S
	Responsibility of workers	Increase	W
	Willingness of workers to learn	Increase	W

The salary of the workers as well as the costs for further education must be as low as possible in order to keep the running costs low. At wrong or obvious dangerous behavior of a worker the time for termination of existing working contracts should be as short as possible. The main language at the construction site Solbakk is English and therefore good language skills of all employees are urgently needed and must be improved to avoid misunderstandings. Furthermore teamwork and the flexibility of workers should be increased through appropriate management and education. Most of the workers must stay at the site for four weeks in a row – a longer time at the construction site leads to less travelling and administration efforts and costs. But this is not always preferred by the workers because they have families at home. The technical knowledge as well as the gained experience from former tunnel construction sites are very valuable points. Finally, the motivation and the responsibility of all employees by performing their working tasks should be as high as possible. Therefore the willingness of workers to learn and improve their knowledge are essential factors for obtaining a better qualified staff – but this task cannot be steered from the upper management and belongs to the own character and motivation of each employee.

Out of the developed objectives it is now possible to build up several variants of available employees. Therefore the method of the “morphological scheme” is used.

Morphological Scheme:

The morphological scheme for the analysis of available workers can be seen in figure 48. In total there are 11 different parameters classified in order to distinguish and compare all developed variants to each other. To figure out the best type of education for the workers at the site it is first necessary to classify the available sources of workers for performing the maintenance tasks.

Finally, five variants of available employees for the maintenance team at a tunneling construction site are defined, according to their level of education:

- V1: Un-/ semi-skilled worker
- V2: Low-skilled worker
- V3: Skilled worker
- V4: High-qualified skilled worker
- V5: Foreman (all-round)

It can be said that the level of education respectively the qualification of the workers is increasing from variant number one of the un- or semiskilled worker, up to the variant number five, which is the foreman. This should be the best educated staff because of high technical knowledge and a lot of experience at the maintenance sector in tunneling.

It is essential to figure out the most appropriate employees for the maintenance team of the tunneling workshop – the different established variants can be seen within the morphological scheme in figure 48.

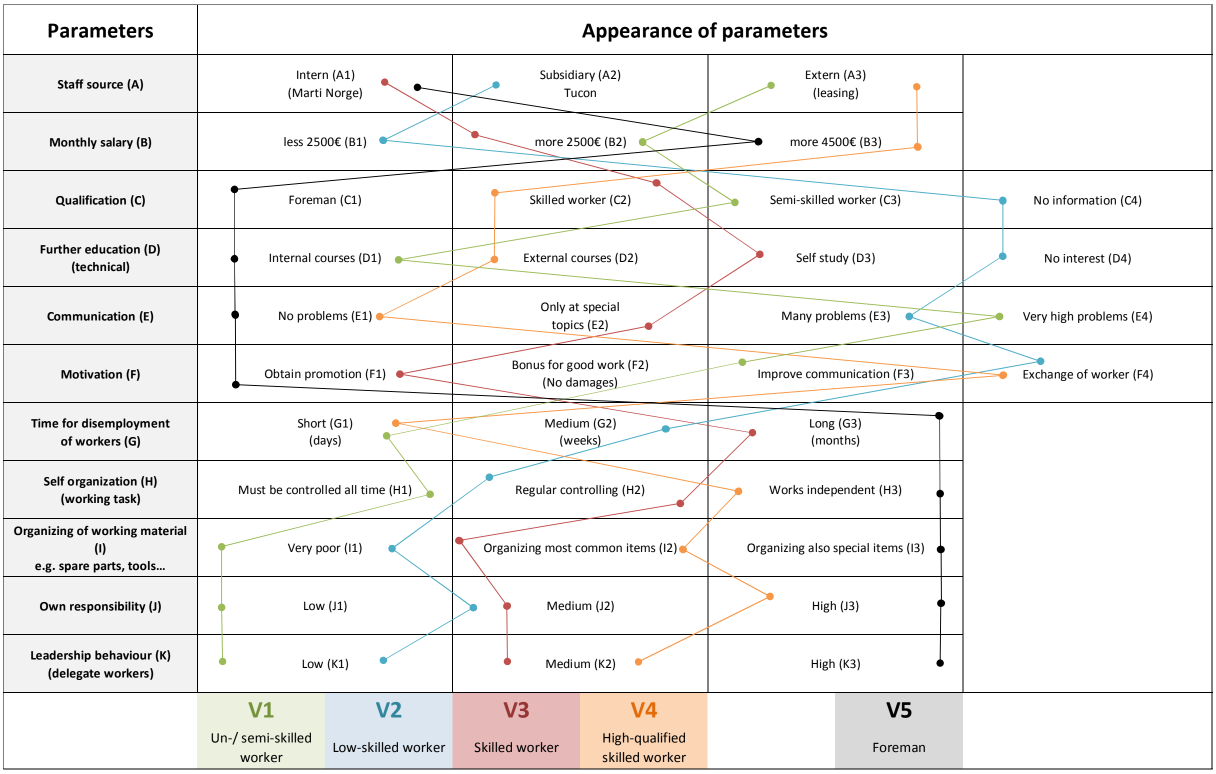


Figure 48: Morphological scheme of available workers for maintenance

Example out of the morphological scheme:

For a better understanding of the morphological scheme in figure 48 an example out of these five available variants of employees will be explained. Variant number two of the low skilled workers will be chosen and explained in more detail (variant number two is labeled with blue color).

The staff source for such employees at the construction site Solbakk could be the workers from the Marti subsidiary Tucon (A2). These workers have a relatively low monthly salary compared to other workers (B1). But their level of qualification is often not exactly known and sometimes it can happen that profession certificates are missing (C4). This is of course a critical point, especially when new workers are arriving at the site. Unfortunately the willingness of these workers to develop themselves further (e.g. at the area of technical knowledge) is usually not very high (D4) – maybe existing language problems contribute to this negative aspect and as a result many communication problems can occur (E3). The motivation of low skilled workers is sometimes done with the threat of exchanging them (F4). This fact leads to some stress situations if working tasks cannot be performed fast and effective – the motivation of employees (e.g. for the foremen) could be also done with bonus payments. The time for termination of existing working contracts is quite low for low skilled workers (G2). These workers are regularly controlled by the management to check if they perform the given tasks well (H2). The organization of working material e.g. spare-parts and tools is quite poor (I1) due to many misunderstandings because of communication problems. But the own responsibility of these workers is alright due to the fact that these workers have normally a lot of experience at this sector and they know what is to do (J2). The leadership behavior of low skilled workers is very low – they are normally not willing to delegate working tasks to other workers (K1).

For each variant of available employees it is important to figure out the most important positive as well as negative aspects. This is done with a balance of arguments.

Balance of arguments:

The balance of arguments for the different available employees at the site can be seen at table 14. The comparison of all positive and negative aspects will lead to a better overview of all existing variants.

Table 14: Balance of arguments – Employee qualification

Variant:	Advantages	Disadvantages
V1: Un-/ semi-skilled worker	Does every kind of work	Bad educated
	Easy replacement	Lack of experience in the working field
	Can be educated by courses	Sometimes huge communication problems
	Can learn simple tasks fast	Needs to be controlled all the time
		Bad self organization
		Low responsibility
		Cannot delegate tasks to other workers
		Often not able to operate the construction vehicles
		Only for unskilled labour
V2: Low-skilled worker	Low costs	Often no information about education
	Medium time for exchange with other workers	Sometimes communication problems
	Does every kind of work	Motivation problems
	Can work alone at routine tasks	Sometimes unexperienced
	Can be replaced easy	Sometimes not qualified for operating many machines
		Low interest in further education
V3: Skilled worker	Good educated	Long time for disemployment (replacement is difficult)
	Good technical background	Low interest in work of others
	Experience with most machines	Earns more than average
	Responsibility higher than average	Not responsible for delegating people
	High motivated through promotion or even bonus	No type for leadership
	Interested in his working field / self studying	Needs sometimes to be controlled / delegated
	Good self-organization (work + material)	
	Only few communication problems	
V4: High-qualified skilled worker	Experts of their field	Very high costs
	Short time for disemployment (if hired as contract worker)	Does even not always have a good solution
	High knowledge	Cannot be replaced very easy (very high knowledge)
	A lot of experience	Long use of this personal is very expensive
	Works independent	Dependency on the knowledge of the worker
	Good self-organization (work + material)	
	Nearly no communication problems	
	Is normally extern educated / instructed	
	Can delegate tasks to other workers	
V5: Foreman (all-round)	Very good educated (all-round)	Very high costs
	Very good technical background	Eventually problems when he leaves the construction site
	High responsibility	Long time for disemployment
	Good at delegating tasks to other workers	Sometimes overcharged with delegating tasks
	Good leadership behaviour	Cannot be replaced very easy (very high knowledge)
	Nearly no communication problems	
	Very good organization (work + material)	
	Normally no need of further education	

Weighting of objectives:

In table 15 it can be seen that the chosen criteria are separated into groups of the financial objectives, personal objectives, qualification objectives and objectives of motivation.

Table 15: Weighting of objectives – Employee qualification

Group of criteria	Criteria	Weight (rounded)		Rating of importance 10% - 100%														
		Group	Single	1	2	3	4	5	6	7	8	9	10	Rating group	% group exact	Rating single	% single exact	Points single
Financial objectives		45											x	10	43,48			
	Monthly costs per worker (salary)		30										x			10	66,67	30,00
	Costs for further education		9			x										3	20,00	9,00
	Time for disemployment		6		x											2	13,33	6,00
			Subtotal financial													15	100,00	45,00
Personal objectives		20						x						5	21,74			
	Communication		6									x				9	30,00	6,00
	Team spirit		3				x									4	13,33	2,67
	Self organization		5								x					8	26,67	5,33
	Willingness to stay at the site		6									x				9	30,00	6,00
			Subtotal personal													30	100,00	20,00
Qualification of workers		25							x					6	26,09			
	Technical knowledge		13									x				9	52,94	13,24
	Experience workshop / tunneling		12								x					8	47,06	11,76
			Subtotal qualification													17	100,00	25,00
Motivation and responsibility		10	10		x									2	8,70		100,00	10,00
			Subtotal motivation														100,00	10,00
		100	100										Sum:	23	100,00			

First it is important to evaluate the groups. The 100 available points get separated into the different groups and afterwards they get separated further to the single criteria. These groups are highlighted with yellow background color – like the crosses for the rating of these groups and the calculated values and points. The fields for the single criteria are highlighted with green background color as well as their crosses at the process of the rating of importance.

The rating of importance for all criteria was figured out by teamwork – the responsible employees were asked separately to evaluate the importance of each criterion. Afterwards an average value was taken. The proceeding of evaluating the points for each single criterion will not be explained in more detail at this point because this can be seen at the example in chapter 4.3.4.

Scaling matrix:

The scaling matrix contains the same groups and criteria like the table of weighting of objectives in table 15. The scaling matrix for the employee qualification can be seen in table 16.

Table 16: Scaling matrix – Employee qualification

Group of criteria	Criteria	Notes						Unit	Variants									
									Un-/ semi-skilled worker		Low-skilled worker		Skilled worker		High-qualified skilled worker		Foreman (all-round)	
		0 - BAD	1	2	3	4	5 - GOOD		V1		V2		V3		V4		V5	
Financial objectives																		
	Monthly costs per worker (salary)	> 6000	< 6000	< 4500	< 3500	< 3000	< 2400	€/month	2600	4	2300	5	4000	2	6200	0	4800	1
	Costs for further education	High - urgent needed		Medium - pos. effects		Low - not needed				1		1		3		4		4
	Time for disemployment	Months		Weeks		Days				5		3		1		4		0
Personal objectives																		
	Communication	High problems		Sometimes problems		No problems				1		3		3		4		4
	Team spirit	No team-player		On average		Good teamplayer				1		4		3		2		2
	Self organization	Bad		On average		Good				1		2		4		5		5
	Willingness to stay at the site	< 1	< 2	< 3	< 4	< 6	> 6	Weeks	3	3	4	4	4	4	2	2	4	4
Qualification of workers																		
	Technical knowledge	Bad		On average		Good				1		2		3		5		5
	Experience workshop / tunneling	< 0.5	0.5 - 1	1 - 2	2 - 4	4 - 6	> 6	Years	< 0.5	0	5	4	5	4	> 6	5	> 6	5
Motivation and responsibility		Low		Medium		High				1		2		3		4		4

At the scaling matrix of the employee qualification in table 16 it can be seen that the low-skilled worker is the cheapest. The high qualified worker is the most expensive – these workers are mostly rented at the site. The low educated employee has a high need of further education compared to the higher qualified staff. The time for termination of existing working contract is the shortest for the unskilled employees and for the high qualified skilled workers, because this staff is mostly rented externally. The exchange of a foreman is not easy due to the high knowledge and experience. It can be said that the lower educated staff has more communication problems at the site. The team spirit among the ordinary workers is the best because they are often changing the construction sites together as a team. The self-organization of the higher qualified employees is very high due to the fact that they have to delegate working tasks to other workers or they work independent as specialists – therefore a good organization is unavoidable. The willingness of workers to stay at the site is still balanced for all variants. The high qualified workers have the best technical knowledge. The experience at the field of tunneling and in the workshop area is quite high for all kind of employees, except for the unskilled workers – they are mostly just hired for small tasks to perform unskilled labor and therefore they don't know the business from former construction sites.

Value benefit analysis:

The values out of the table of weighting of objectives as well as the values out of the scaling matrix have to be multiplied with each other within the value benefit analysis. This value benefit analysis of the employee qualification can be seen in table 17.

Table 17: Value benefit analysis – Employee qualification

Group of criteria	Criteria	Weight		Variants									
				Un-/ semi-skilled worker		Low-skilled worker		Skilled worker		High-qualified skilled worker		Foreman (all-round)	
				V1		V2		V3		V4		V5	
		Group	Single [g]	n	n*g	n	n*g	n	n*g	n	n*g	n	n*g
Financial objectives		45											
	Monthly costs per worker (salary)		30	4	120	5	150	2	60	0	0	1	30
	Costs for further education		9	1	9	1	9	3	27	4	36	4	36
	Time for disemployment		6	5	30	3	18	1	6	4	24	0	0
			Subtotal financial		159		177		93		60		66
Personal objectives		20											
	Communication		6	1	6	3	18	3	18	4	24	4	24
	Team spirit		3	1	3	4	12	3	9	2	6	2	6
	Self organization		5	1	5	2	10	4	20	5	25	5	25
	Willingness stay at the site		6	3	18	4	24	4	24	2	12	4	24
			Subtotal personal		32		64		71		67		79
Qualification of workers		25											
	Technical knowledge		13	1	13	2	26	3	39	5	65	5	65
	Experience workshop / tunneling		12	0	0	4	48	4	48	5	60	5	60
			Subtotal qualification		13		74		87		125		125
Motivation and responsibility		10	10	1	10	2	20	3	30	4	40	4	40
			Subtotal motivation		10		20		30		40		40
n...number out of the scaling matrix		100	100										
			Total		214		335		281		292		310

It can be seen that the best variant for an improvement of the maintenance process is variant number two – the low skilled workers. Reasons therefore are the positive financial aspects (e.g. lower salary) and suitable personal objectives. Fields for improvement of these workers are a higher qualification which leads to a higher knowledge and more motivation to perform the working tasks.

Figure 49 shows a graphical distribution of the various aspects of the employee qualification. The most important objectives are the financial objectives and the qualification objectives. The motivational objectives have the lowest influence.

It is essential that the low skilled workers get educated at the fields of qualification and motivation in order to receive more efficient employees for the machine maintenance process.

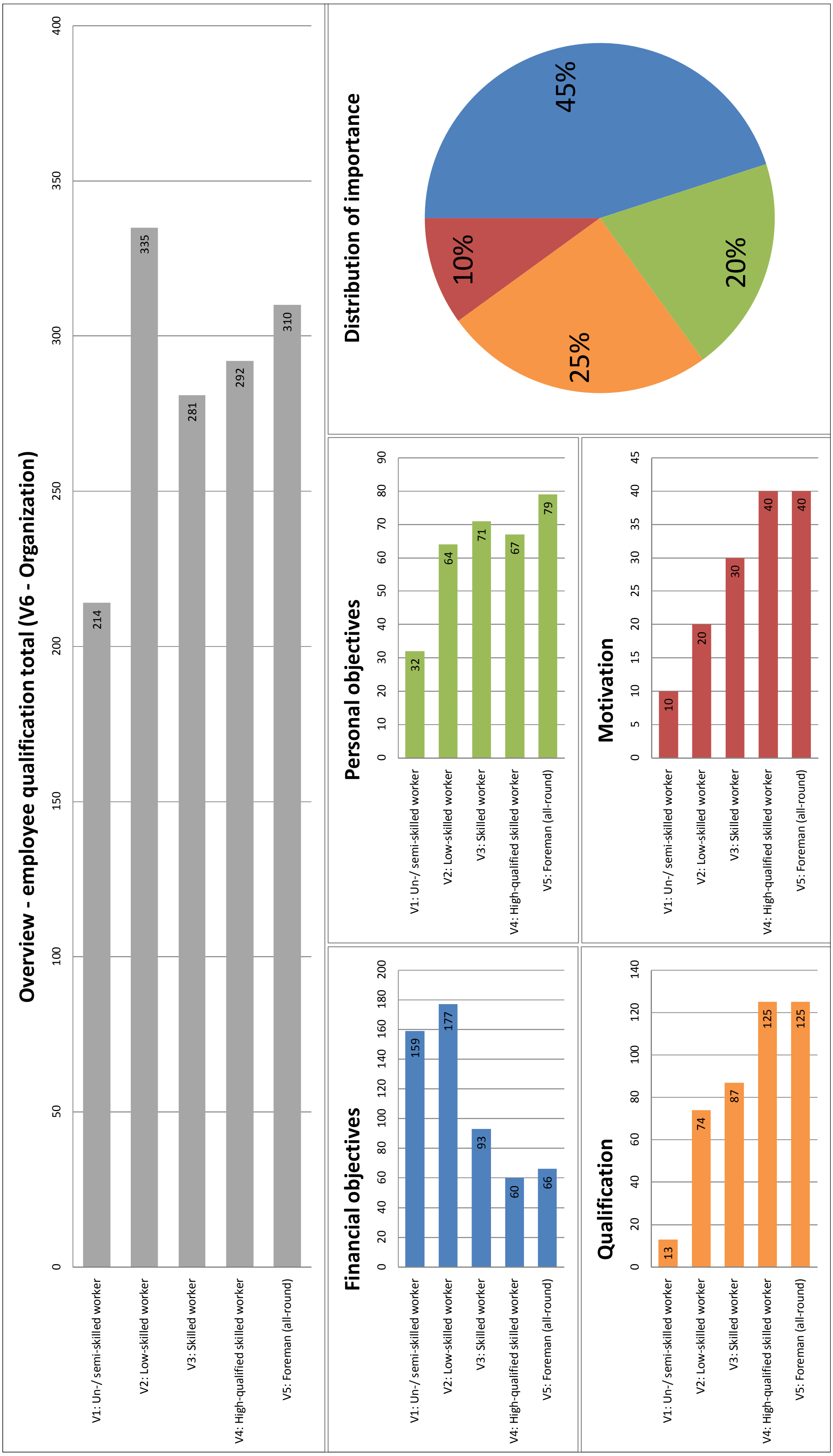


Figure 49: Graphical interpretation of the different employee sources

The main task is now to figure out which kind of education the low-skilled workers should receive in order to perform future maintenance tasks more efficient. This task has to be done with an own problem solving cycle within the next chapter.

4.4.1.2 Education of workers

To figure out the best variant for the education of the workers at the construction site Solbakk the following problem solving cycle has to be performed and the results have to be analyzed. It is essential to increase the knowledge of all involved employees at the site as well as to increase the motivation of all team members to perform their working tasks.

Catalogue of requirements:

The catalogue of requirements for the education of workers at the construction site Solbakk can be seen in table 18. This catalogue was developed together with the workshop team.

Table 18: Catalogue of requirements – Education of workers

Objective category:	Objective properties	Degree of objective	Priority
Financial objectives			
Costs	Costs for education	Minimum	M
	Monthly additional expenses	Minimum	S
Needed material	Additional needed material (e.g. computers)	Minimum	S
Functional objectives			
Effort	Effort to establish	Minimum	S
Sustainability of education	Sustainability of education	As good as possible	S
Reusability	Reusability of education materials	As good as possible	M
Learning method	Learnability of workers	As easy as possible	W
Quality	Quality of learning material	High	M
Safety awareness	Safety awareness of workers	Increase	S
Knowledge	Knowledge of workers about specific topics (after education)	High increase	S
Motivation	Motivation of workers to perform the education	As high as possible	S
Time	Needed time to perform works more efficient	Minimum	S
Previous knowledge	Needed previous knowledge of workers	Minimum	S
Proceeding objectives			
Celebration	Amount of needed education units	As many as needed	S
Amount of participants	Amount of participants (which are interested)	As many as possible	W
Social objectives			
Attendance	All workers are participating voluntary		W
Teamwork	Workers work together and help each other by learning the content		W
Future objectives			
Specialize content	Possibility of educating special (needed) content	As high as possible	M

The objectives for the education of the workers at the site are classified into financial objectives, functional objectives, proceeding objectives, social objectives and future objectives. Very important are low costs and a high reusability of the education materials. Also the quality and the possibility of educating special needed content should be as high as possible.

Morphological scheme:

Figure 50 shows the morphological scheme with the different possible variants for education of workers at the site. In total 10 different parameters are classified which make it possible to compare all variants to each other.

Finally, three variants for the education of the maintenance team of a tunneling construction site are developed – these variants are:

- V1: Language education
- V2: Technical education
- V3: Safety education

Parameters	Appearance of parameters			
Investment costs (A) - relative	Low (A1)	Medium (A2)	High (A3)	
Monthly additional expenses (B)	Yes (B1)		No (B2)	
Evaluating and grading of participants (C)	High (C1)	Medium (C2)	Low (C3)	
Effort to establish the education program (D)	Days (D1)	Weeks (D2)	Months (D3)	
Sustainability (E)	Good (E1)	Good - if participant reviews a lot by himself (E2)	On average (E3)	Bad (E4)
Quality of material (F)	Very good (F1)	Good (F2)	On average (F3)	Bad (F4)
Needed time to improve the performing of the task (G)	Immediately (G1)	After a few lessons / hours (G2)	After many lessons / hours (G3)	
Amount of needed education units (H)	More than 1x per week (H1)	1x per week (H2)	2x per month (H3)	Only one time per section (H4)
Change of education content (I)	Low (I1)	Medium (I2)	High (I3)	
Reusability for other workers (J)	Low (J1)	Medium (J2)	High (J3)	
	V1 Language education		V3 Safety education / V2 Technical education	

Figure 50: Morphological scheme – Education of workers

Example out of the morphological scheme:

The example will be demonstrated at variant number two – the technical education (labeled with blue color). The relative investment costs are high compared to other variants (A3) but there are normally no additional monthly expenses (B2). The grading of all participants is achievable because of the possibility to make examinations after the education units (C1). The effort to establish a technical education takes very much time due to the high complexity of all relevant fields for education (D3). The sustainability is quite high with appropriate materials for education, especially when all participants are interested in the technical topics (E1) and if the materials have a good quality (F1). To perform diverse maintenance tasks more efficient needs some education lessons and hours (G2), but usually there are not many units of education needed (H3). Additionally there is the possibility of changing the content of education if the materials are developed internally (I3). Finally, the reusability for other workers as well as for other construction sites is very high (J3).

Balance of arguments:

The balance of arguments for the education of the workers at the construction site Solbakk can be seen at table 19.

Table 19: Balance of arguments – Education of workers

Variant:	Advantages	Disadvantages
V1: Language education	Better communication possible	Need of many courses
	Not so much misunderstandings	Only working if the participants learn even at home
	Can be learned additional at home (vocabularies)	Expensive (professional trainers)
	Good course materials available	Many workers are not motivated to learn languages
	Possible to learn from professional teachers	Some workers are not able to get educated in German or English
	Workers can use foreign languages also in their private life	High effort to learn a foreign language
	Knowledge can also be used on every other construction site	No directly yield
	Possible to evaluate and grade the participants	Monthly additional costs (continuing course necessary)
	Comparison of the language level of the workers	
V2: Technical education	Very helpful at the performing of the daily jobs	Courses need long time to be developed + expensive (if performed intern)
	Maintenance tasks can be performed more efficient	High costs for extern courses
	Not a very high pre-knowledge necessary	Not all workers like to attend to such courses
	Possible to educate in a theoretical and practical way	Many educating hours needed
	High learning success if combining theoretical and practical education	Courses take a long time (workers cannot be at ordinary work)
	Increase of the technical knowldedge of the workers	Extern courses are maybe blocked (some days in a row)
	Better understanding of the matter	
	Avoiding of working mistakes and higher working-safety possible	
V3: Safety education	Increase the safety awareness of the workers	Many different safety topics
	Possible to educate safety for machine operating and maintenance tasks	High time consuming to be developed (intern)
	Higher safety-awareness reduces accidents and damages	No directly yield
	High sustainability with appropriate learning materials	Need of special instructors
	Possible to evaluate and grade the participants	
	Can be performed by intern or extern personal (teaching)	

Weighting of objectives:

The rating of objectives for the education of workers can be seen in table 20. It is essential to figure out and evaluate the most important criteria for the education of the workers.

Table 20: Weighting of objectives – Education of workers

Group of criteria	Criteria	Weight (rounded)		Rating of importance 10% - 100%														
		Group	Single	1	2	3	4	5	6	7	8	9	10	Rating group	% group exact	Rating single	% single exact	Points single
Financial objectives		35									x			8	33,33			
	Costs for education		21										x			10	58,82	20,59
	Monthly additional expenses		10					x								5	29,41	10,29
	Additional needed material (e.g. computers)		4		x											2	11,76	4,12
	Subtotal financial															17	100,00	35,00
Functional objectives		40											x	10	41,67			
	Effort to establish		6								x					8	14,55	5,82
	Sustainability of education		5							x						7	12,73	5,09
	Reusability of education materials		7										x			10	18,18	7,27
	Learnability for workers		2			x										3	5,45	2,18
	Quality of learning material		4						x							6	10,91	4,36
	Safety awareness of workers		3				x									4	7,27	2,91
	Knowledge of workers about specific topics (afterwards)		4						x							6	10,91	4,36
	Motivation of workers to perform the education		1	x												1	1,82	0,73
	Needed time of workers to perform work better		4					x								5	9,09	3,64
	Needed previous knowledge of workers		4					x								5	9,09	3,64
	Subtotal functional															55	100,00	40,00
Proceeding objectives		15					x							4	16,67			
	Amount of needed education units		9							x						7	58,33	8,75
	Amount of participants (which are interested)		6					x								5	41,67	6,25
	Subtotal proceeding															12	100,00	15,00
Future objectives		10			x									2	8,33			
	Possibility of educating special (needed) content		10														100,00	10,00
	Subtotal future																	
		100	100										Sum:	24	100,00			

All criteria are classified into groups according to financial objectives, functional objectives, proceeding objectives and future objectives. First the group weighting has to be done and afterwards the rating of the individual criteria will be made. This rating process was already explained in a previous chapter. It can be seen that the financial objectives and the functional objectives are much more important compared to the proceeding objectives and the future objectives.

Scaling matrix:

The scaling matrix for the education of workers can be seen at table 21.

Table 21: Scaling matrix – Education of workers

Group of criteria	Criteria	Notes						Unit	Variants					
									Language education		Technical education		Safety education	
		0 - BAD	1	2	3	4	5 - GOOD		V1		V2		V3	
Financial objectives														
	Costs for education	High		Medium		Low				0		1		2
	Monthly additional expenses	High		Medium		Low				1		5		4
	Additional needed material (e.g. computers)	High		Medium		Low				2		3		4
Functional objectives														
	Effort to establish	Months		Weeks		Days				4		1		2
	Sustainability of education	Bad		On average		Good				3		5		2
	Reusability of education materials	Low		Medium		High				1		5		4
	Learnability for workers	Hard		Medium		Easy				1		3		2
	Quality of learning material	Bad		On average		Good				5		4		5
	Safety awareness of workers	No influence		On average		High				0		3		5
	Knowledge of workers about specific topics (afterwards)	Bad		On average		Good				2		5		3
	Motivation of workers to perform the education	Low		Medium		High				2		4		1
	Needed time of workers to perform work better	Weeks / Months		Days		Hours				1		3		4
	Needed previous knowledge of workers	High		Medium		Low				4		4		2
Proceeding objectives														
	Amount of needed education units	> 8	< 8	< 6	< 4	2	1	days/month	7	1	2	4	1	5
	Amount of participants (which are interested)	Few		Some		Many				1		4		1
Future objectives														
	Possibility of educating special (needed) content	Low		Medium		High				1		5		2

It can be seen that the costs for education are the highest for the language education due to the fact that that this education is mostly performed with external teachers. This language education is also the only education which has additional monthly expenses due to the fact of many needed courses. Furthermore a lot of additional material (e.g. books, more computers etc.) is needed. The technical education has the highest effort to be established because of various complex topics. But if these technical materials are developed, the sustainability and reusability are very high. Learning languages is a very exhausting process, only a few workers are willing to learn a foreign language. A proper safety education has the best influence to a higher safety awareness of the workers at the site. The motivation of workers to participate in different education units is very high for the technical education, compared to the other variants. To achieve an improvement in learning a language many lessons are needed. The amount of participants is mostly limited. Only smaller groups can be taught by the teachers. The possibility to educate special content is the best for the technical education, if the learning materials are developed internally. For language education it is usually not possible to educate special content at the beginning, because basics and vocabularies have to be learned within the first lessons.

Value benefit analysis:

The values out of the table of weighting of objectives and the values out of the scaling matrix for the education of workers have to be multiplied with each other within the value benefit analysis. This value benefit analysis of the education of workers can be seen in table 22.

Table 22: Value benefit analysis – Education of workers

Group of criteria	Criteria	Weight		Variants					
				Language education V1		Technical education V2		Safety education V3	
		Group	Single [g]	n	n*g	n	n*g	n	n*g
Financial objectives		35							
	Costs for education		21	0	0	1	21	2	42
	Monthly additional expenses		10	1	10	5	50	4	40
	Additional needed material (e.g. computers)		4	2	8	3	12	4	16
		Subtotal financial			18		83		98
Functional objectives		40							
	Effort to establish		6	4	24	1	6	2	12
	Sustainability of education		5	3	15	5	25	2	10
	Reusability of education materials		7	1	7	5	35	4	28
	Learnability for workers		2	1	2	3	6	2	4
	Quality of learning material		4	5	20	4	16	5	20
	Safety awareness of workers		3	0	0	3	9	5	15
	Knowledge of workers about specific topics (afterwards)		4	2	8	5	20	3	12
	Motivation of workers to perform the education		1	2	2	4	4	1	1
	Needed time of workers to perform work better		4	1	4	3	12	4	16
	Needed previous knowledge of workers		4	4	16	4	16	2	8
		Subtotal functional			98		149		126
Proceeding objectives		15							
	Amount of needed education units		9	1	9	4	36	5	45
	Amount of participants (which are interested)		6	1	6	4	24	1	6
		Subtotal proceeding			15		60		51
Future objectives		10							
	Possibility of educating special (needed) content		10	1	10	5	50	2	20
		Subtotal future			10		50		20
n...number out of the scaling matrix		100	100						
			Total		141		342		295

The best variant for education of the workers at the construction site is the technical education. The financial objectives are quite good for this type of education. But this variant has the best functional properties. Additionally the proceeding properties are the best due to the fact of only few needed education units and many possible participants. Finally, the future objectives are also the best for this variant due to the possibility of educating special content for diverse service and repair tasks.

A graphical distribution of the evaluated results from the education of workers can be seen at figure 51. The high importance of the functional objectives and the financial objectives leads to the fact that the technical education should be focused further.

There is the question about "how" this technical education should be performed at the construction site Solbakk. To answer this question, an own problem solving cycle has to be made within the next chapter. It should be possible to figure out a variant of education which can be used for many workers. Finally, better qualified and educated employees should increase the efficiency of the machine maintenance process at the site.

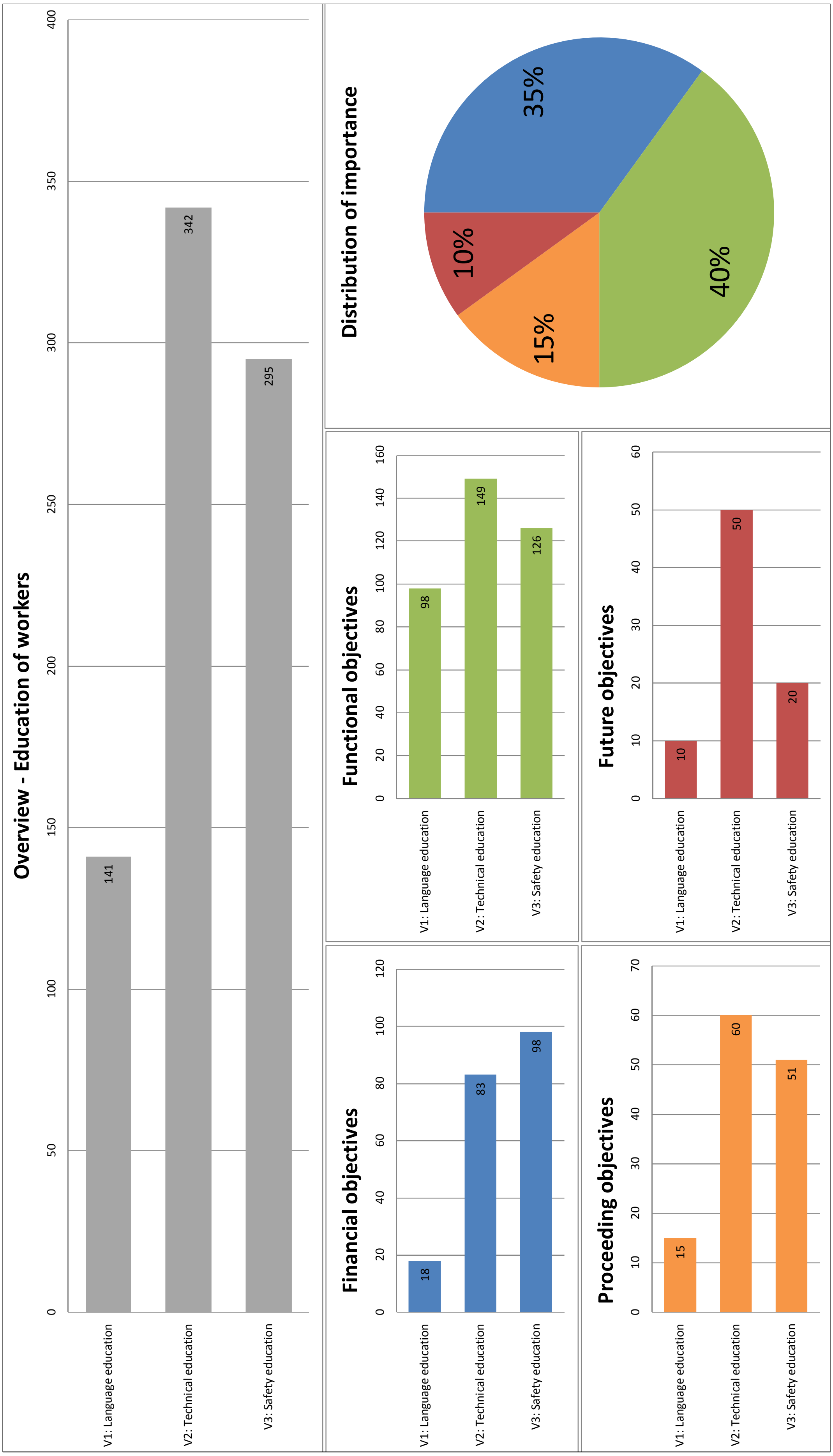


Figure 51: Graphical interpretation of the different education sources

4.4.1.3 Types of education

To figure out the best method or even type of education for the workers an own problem solving cycle has to be developed. It would be good if many employees could be educated at the same time to increase the total knowledge and skills of the whole workshop team. The education should be as easy as possible for the workers, so that every worker has the ability to participate at the education units and to learn a lot. Existing language problems must be considered because of the multinational team at the construction site Solbakk.

Catalogue of requirements:

To figure out the best type of education a catalogue of requirements must be established. But the objectives for figuring out different types of education are quite the same like at the catalogue of requirements in table 18 for the education of workers.

Morphological scheme:

The morphological scheme for the different types of education can be seen in figure 52. In order to compare all variants 10 different parameters are classified within that morphological scheme.

In total four variants for the type of education are established at this point – these variants are:

- V1: Theoretical training
- V2: Practical training
- V3: Theoretical and practical training
- V4: Introduction of instruction materials

At the theoretical training there will be courses and seminars established for the workers and different lecturers will teach them technical basics by the use of presentations. At the practical training different practical exercises of maintenance processes will be given to the workers. This could be done at the workshop area. The combination of these two types builds variant number three. This variant is very effective but also much more expensive and time consuming compared to the other variants.

The introduction of special instruction materials is a new aspect of education for the workers at the construction site. These manuals could be developed and introduced directly at the construction site Solbakk. They could show all needed steps of the different service and repair tasks by the use of pictures. Therefore they can be seen as guided manuals for maintenance.

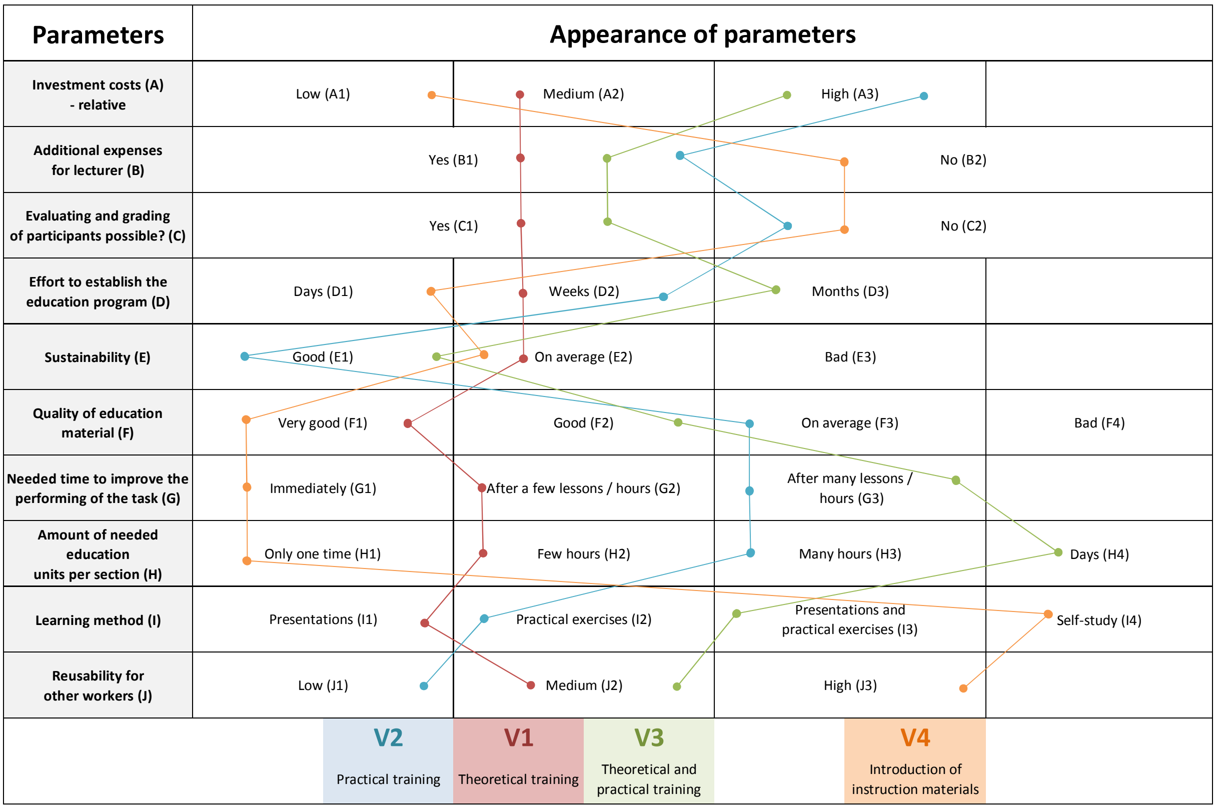


Figure 52: Morphological scheme – Types of education

<u>Example out of the morphological scheme:</u>

Variant number four – introduction of instruction materials – will be explained (labeled with orange color). The investment costs of self-developed instruction materials are low compared to other variants (A1). A huge advantage is that no additional lecturers are needed to hold courses or even seminars (B2). A grading of employees is of course not possible because the workers get only the manuals (C2). The effort for establishing special instruction materials is quite low compared to other variants (D1) and also the sustainability of this type of education is quite good (E2). The quality of this kind of education materials is very good (F1) due to the fact that the established documents can contain many pictures and instructions – they can be printed out or sent to another construction site per e-mail without problems. The workers can work more efficient (G1) because they have just to read the manuals step by step and therefore no additional education units are necessary to perform the daily jobs (H1). The education is just done by self-study (I4) according to the proceeding within these manuals. Finally, the reusability of these materials even for other construction sites is very high (J3).

For each variant it is important to figure out the most important aspects to make them comparable to each other. This is done with the balance of arguments.

Balance of arguments:

The balance of arguments for the different types of education of the workers at the construction site Solbakk can be seen in table 23. To figure out the best variant of all, various aspects of all four variants have to be considered.

Table 23: Balance of arguments – Types of education

Variant:	Advantages	Disadvantages
V1: Theoretical training	Increase the knowledge of the workers	Documents need long time to be established
	Possible to educate many workers (e.g. presentations)	Responsible person for developing course material necessary
	Show examples of good performed work vs. bad performed work	Need of lecturer for the courses
	Illustrate risks of work	Not all workers can attend the course because of the necessity to work
	Show problems of wrong executed tasks	Difficult to find a time where most workers have time to attend the course
	Possible to evaluate and graduate the workers (examinations)	
	Comparison of the knowledge-level of the different workers	
	Possibility to ask specific questions during the course	
	Education materials can be resused	
V2: Practical training	High sustainability for the workers	Not possible to take a lot of participants to the course
	Performed works are easier to understand and learn	Sometimes lack of pre-knowledge of the workers
	Possibility to ask specific questions during the course	Difficult to compare the knowledge-level of the workers
	Performing of practical work-examples possible (maintenance tasks)	No high learning success if workers are only watching to the instructor tasks
	Visualize correct executed tasks	Need of own instructor for the course
	Possibility to integrate the workers to the course tasks	High costs for performing practical examples
		Course maybe blocked (huge content)
		Lessons take a lot of preparation time for the instructor
V3: Theoretical and practical training	Combining the theoretical and the practical learning method	Very long time to be established
	Very high sustainability for the workers	High costs for development
	Obtaining higher qualified personal	Responsible instructor needed (theoretical and practical training)
	Possibility to ask specific questions during the course	Person for developing course material (theoretical / practical) necessary
	Indistinctnesses can be clarified	Not possible to take a lot of participants to the practical training
	High learning success	Course maybe blocked (huge content)
	Education materials can be reused	
V4: Introduction of instruction materials	Instruction materials with pictures (step by step sequence)	Need of many different instruction manuals
	Easy traceability and performing of the working tasks	Difficult to perform the working tasks without the instruction manuals
	Even low-skilled workers can perform maintenance tasks with a manual	Low possibility to ask someone in case of misunderstanding
	Possibility to add tool-lists - NO waiting times due to missing tools	Need of original pictures from the maintenance tasks for each instruction
	Short time to establish documents	Manuals only usable for specific topics
	Self studying - no need of a course or presentation	High effort to establish a system with all needed instruction manuals
	High reusability of the materials for the whole company (other sites)	
	Possibility to translate the instructions in different languages	
	Insertion of pictures - language probems have no high influence	
	Relatively small documents - can be sent via e-mail	

Weighting of objectives:

The weighting of objectives for the different types of education is essential to figure out which criteria of the various types of education are the most important. The results can be seen in table 24.

Table 24: Weighting of objectives – Types of education

Group of criteria	Criteria	Weight (rounded)		Rating of importance 10% - 100%														
		Group	Single	1	2	3	4	5	6	7	8	9	10	Rating group	% group exact	Rating single	% single exact	Points single
Financial objectives		45											x	10	45,45			
	Costs for education		22										x			10	50,00	22,50
	Additional expenses for lecturer		18								x					8	40,00	18,00
	Costs for additional needed material		5		x											2	10,00	4,50
	Subtotal financial															20	100,00	45,00
Functional objectives		35									x			8	36,36			
	Effort to establish		6										x			10	16,39	5,74
	Sustainability of education		3						x							6	9,84	3,44
	Reusability of education materials		6										x			10	16,39	5,74
	Learnability for workers		2			x										3	4,92	1,72
	Quality of learning material		4							x						7	11,48	4,02
	Grading of participants		2				x									4	6,56	2,30
	Knowledge of workers about specific topics (afterwards)		5								x					8	13,11	4,59
	Motivation of workers to perform the education		1		x											2	3,28	1,15
	Needed time of workers to perform work better		4							x						7	11,48	4,02
	Needed previous knowledge of workers		2				x									4	6,56	2,30
	Subtotal functional															61	100,00	35,00
Proceeding objectives		5		x										1	4,55			
	Amount of needed education units		5															
	Subtotal proceeding																100,00	5,00
Future objectives		15				x								3	13,64			
	Possibility of educating special (needed) content		15														100,00	15,00
	Subtotal future																	
		100	100										Summe:	22	100,00			

The most important criteria belong to the financial objectives and to the functional objectives. The least interesting objectives are the proceeding objectives concerning the amount of needed education units. The future objectives with the possibility of educating special content are rated with 30% importance.

Scaling matrix:

The scaling matrix to figure out the individual ranking of each variant or even type of education can be seen in table 25.

Table 25: Scaling matrix – Type of education

Group of criteria	Criteria	Notes						Unit	Variants						
									Theoretical training		Practical training		Theoretical and practical training		Introduction of instruction materials	
		0 - BAD	1	2	3	4	5 - GOOD		V1		V2		V3		V4	
Financial objectives																
	Costs for education	High		Medium		Low				2		1		0		5
	Additional expenses for lecturer	High		Medium		Low				2		2		1		5
	Costs for additional needed material	High		Medium		Low				5		3		2		4
Functional objectives																
	Effort to establish	Months		Weeks		Days				3		3		1		4
	Sustainability of education	Bad		On average		Good				3		4		5		2
	Reusability of education materials	Low		Medium		High				3		1		3		4
	Learnability for workers	Hard		Medium		Easy				3		5		4		5
	Quality of learning material	Bad		On average		Good				5		3		4		5
	Grading of participants	No influence		On average		High				5		1		5		0
	Knowledge of workers about specific topics (afterwards)	Bad		On average		Good				3		4		5		2
	Motivation of workers to perform the education	Low		Medium		High				2		4		4		3
	Needed time of workers to perform work better	Weeks / Months		Days		Hours				4		3		2		4
	Needed previous knowledge of workers	High		Medium		Low				3		3		5		4
Proceeding objectives																
	Amount of needed education units	> 8	< 8	< 6	< 4	2	1	days/month	2	4	3	3	5	2	1	5
Future objectives																
	Possibility of educating special (needed) content	Low		Medium		High				4		2		3		4

In this scaling matrix it can be seen that the instruction materials have the best results according to the financial objectives due to the fact that they can be developed internally by the company. Also for the functional aspects the variant of the instruction materials seems to be the best compared to the other three variants. Additionally for the proceeding objectives and future objectives this variant is the best because there is a very high flexibility when manuals are established internally by the company.

Value benefit analysis:

The values out of the table of weighting of objectives and the values out of the scaling matrix for the type of education of workers are multiplied with each other within the value benefit analysis – this can be seen in table 26.

Table 26: Value benefit analysis – Type of education

Group of criteria	Criteria	Weight		Variants							
				Theoretical training V1		Practical training V2		Theoretical and practical training V3		V4: Introduction of instruction materials V4	
		Group	Single [g]	n	n*g	n	n*g	n	n*g	n	n*g
Financial objectives		45									
	Costs for education		22	2	44	1	22	0	0	5	110
	Additional expenses for lecturer		18	2	36	2	36	1	18	5	90
	Costs for additional needed material		5	5	25	3	15	2	10	4	20
			Subtotal financial		105		73		28		220
Functional objectives		35									
	Effort to establish		6	3	18	3	18	1	6	4	24
	Sustainability of education		3	3	9	4	12	5	15	2	6
	Reusability of education materials		6	3	18	1	6	3	18	4	24
	Learnability for workers		2	3	6	5	10	4	8	5	10
	Quality of learning material		4	5	20	3	12	4	16	5	20
	Grading of participants		2	5	10	1	2	5	10	0	0
	Knowledge of workers about specific topics (afterwards)		5	3	15	4	20	5	25	2	10
	Motivation of workers to perform the education		1	2	2	4	4	4	4	3	3
	Needed time of workers to perform work better		4	4	16	3	12	2	8	4	16
	Needed previous knowledge of workers		2	3	6	3	6	5	10	4	8
			Subtotal functional		120		102		120		121
Proceeding objectives		5									
	Amount of needed education units		5	4	20	3	15	2	10	5	25
			Subtotal proceeding		20		15		10		25
Future objectives		15									
	Possibility of educating special (needed) content		15	4	60	2	30	3	45	4	60
			Subtotal future		60		30		45		60
n...number out of the scaling matrix		100	100								
			Total		305		220		203		426

Variant number four – the introduction of instruction materials – is the best variant of all and has the most total points. There is a big gap to the second best variant of the theoretical training. The introduction of instruction materials has the best financial objectives, compared to all other variants. Furthermore the functional objectives are fulfilled quite well. A further positive aspect is the best ranking at the proceeding objectives, due to the fact that no education units are necessary as well as very good future objectives, due to the possibility of developing manuals with special content.

Figure 53 shows a graphical distribution of the evaluated results for the types of education for workers. It can be seen that the financial and the functional objectives are the most important aspects according to the evaluation.

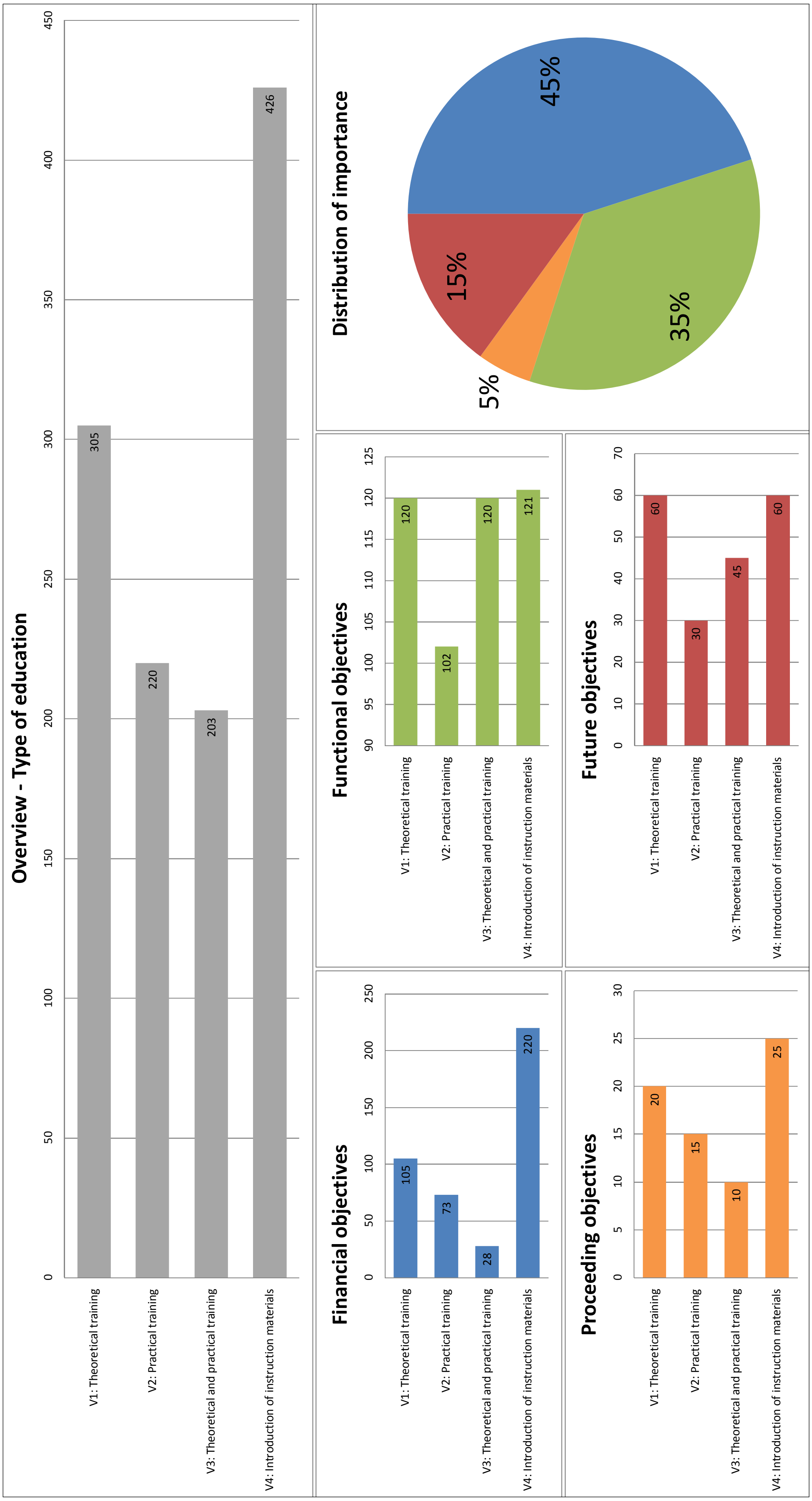


Figure 53: Graphical interpretation of the different possible types of education

4.4.1.4 Interpretation of the result

Because of the clear result in figure 53 it is not necessary to develop a further problem solving cycle at this point. The needed deepness for the level of analyzing is achieved and no further analysis must be done. The positive aspects of the introduction of instruction materials are predominant. The possibilities, to develop manuals which are exactly needed for special maintenance tasks, additionally to the possibility to translate them into different languages and the high degree of reusability are compelling. To implement this elaborated variant at the construction site Solbakk will contribute to a higher efficiency of the machine maintenance.

The task of introducing and implementing a prototype for the variant of introduction of instruction materials will be covered within chapter 4.5 – prototypes, implementation and results.

4.4.2 Detail study technical: Variant 1 – Administration of A-parts

This detail study deals with the technical aspect of the three main fields for improvement of the maintenance process. A proper performed administration of the machines (A-parts) concerning all needed service and repair tasks is prerequisite for an efficient maintenance process. To figure out which solution or even variant is the best for improving of this important area, one or even more problem solving cycle(s) must be established. The results must be analyzed in order to establish a prototype which has to be implemented directly at the construction site Solbakk.

4.4.2.1 Tools for administration of A-parts

It is essential to figure out which different tools or even possibilities are available to perform a machine administration. Various different aspects have to be considered. The whole workshop team like the mechanics, the foremen and the responsible workshop manager must cooperate as a team in order to achieve a better machine administration. Not all workers are able to use a computer - this has to be kept in mind! It is important to find out the best solution for all involved employees.

Catalogue or requirements:

The established catalogue of requirements for figuring out the most successful tool for the administration of A-parts can be seen at table 27.

Table 27: Catalogue of requirements – Tools for administration of A-parts

Objective category:	Objective properties	Degree of objective	Priority
Financial objectives			
Costs	Investment costs	Minimum	M
	Monthly additional expenses	Minimum	S
Needed material	Additional needed material (e.g. computers)	Minimum	S
Functional objectives			
Effort	Effort to establish the administration program	Minimum	S
Needed time	Time of workers to perform the administration task	Minimum	S
Reusability	Reusability of administration tool	As good as possible	M
Operability	Operability for all involved workers (Workshop)	As good as possible	S
Transparency	Overview of caused costs of service and repair tasks	As high as possible	M
	Overview of caused works (by workers)	As high as possible	S
	Overview of used spare parts for maintenance		W
Quality	Quality of administration	High	M
Previous knowledge	Needed previous knowledge of workers to perform the administration (e.g. computer skills)	Low	S
Reliability	Fail-safe program	As high as possible	M
Motivation	Motivation of workers to perform the administration	As high as possible	W
Proceeding objectives			
Celebration	Needed time for education of the administration task itself	Minimum	S
	Frequency of recording data	Record each service and repair task	M
Future objectives			
Specialize content	Possibility to adjust the machine administration tool	High	M
Cooperation	Cooperation between the workers in the workshop and the workshop manager	As good as possible	S

The objectives are classified according to financial aspects, functional aspects, proceeding aspects and future aspects. The most important objectives according to their priority are low investment costs for the administration tool, a high reusability, an increased overview of all caused costs of the maintenance processes and a high quality of the documentation. Every maintenance task must be recorded (the mechanics have to be involved to this process) and it must be possible for the responsible workshop manager to adjust the machine administration tool according to his needs.

Morphological scheme:

The morphological scheme of the different tools for administration of A-parts can be seen in figure 54. To compare all possible variants for a better administration of the maintenance process 10 different parameters are classified within that morphological scheme.

In total three variants of tools for administration of A-parts are established – these variants are:

- V1: Paper based administration
- V2: Computer based administration
- V3: Paper and computer based administration

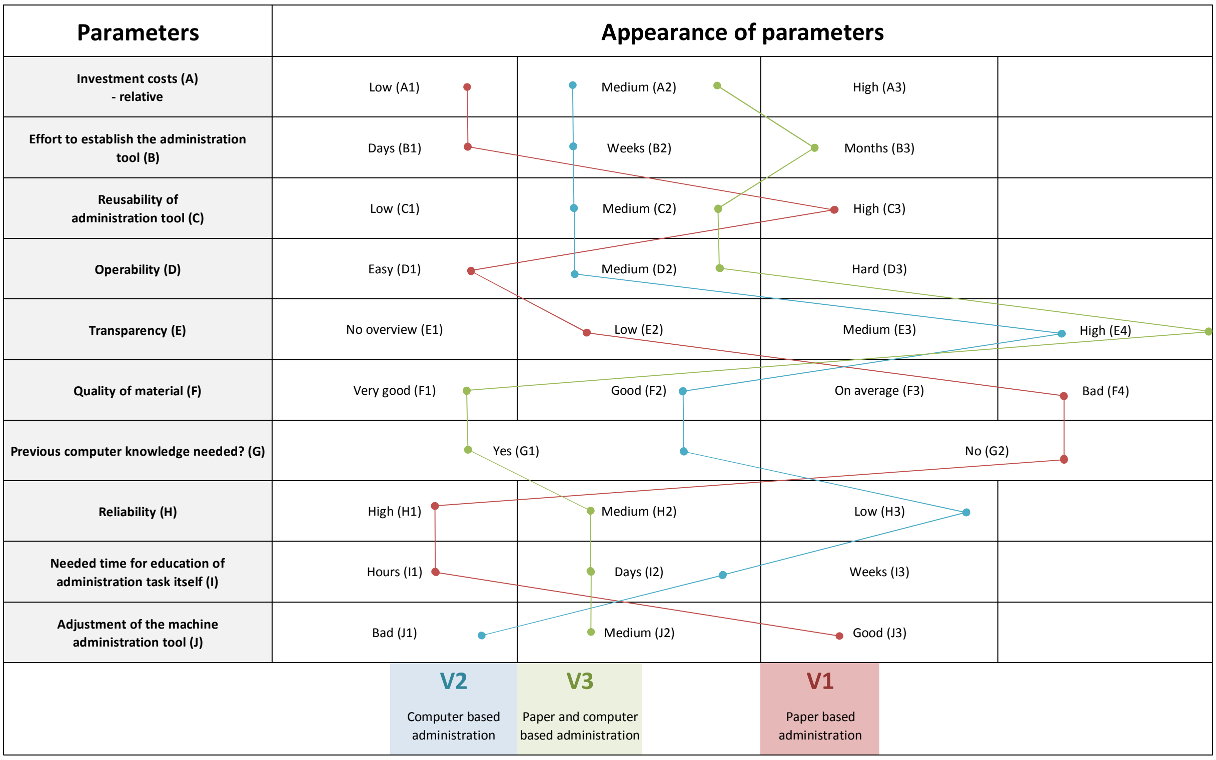


Figure 54: Morphological scheme – Tools for administration of A-parts

Example out of the morphological scheme:

The example will be demonstrated at variant number three – the paper and computer based administration (labeled with green color). The relative investment costs for this variant are on average (A2) and the effort to establish this kind of administration (B3) is the highest compared to the other variants. Special maintenance documents have to be developed and adjusted to a computer administration. The reusability of this combination is quite good (C2) but would be better for a pure paper based administration. With a good operability (D2) sufficient results can be achieved. This kind of administration has the advantage that only the responsible workshop manager has to be able to perform the computer administration. The workshop mechanics have just to fill out their maintenance sheets in a proper and correct way, so they don't have to be able to use a computer. The transparency is of course the best of all variants (E4) due to the fact that the whole information about the machine maintenance is administrated by a computer program and additional hand written maintenance reports are archived in folders. Therefore the quality of the maintenance materials is very good (F1).

As previously said, computer knowledge is only required for the responsible person (G1) who administrates the computer program. The majority of the workers has to write the service and repair reports by hand. At a pure computer based administration all employees should be able to use a computer for writing their working reports. The reliability of the paper and computer based administration is on average (H2) due to the fact that the hand written documents normally cannot get lost. But a computer program can shut down and important information therefore could get lost. The needed time for education of this variant (I2) as well as the adjustment of this machine administration tool (J2) are on average, compared to the other variants.

For each variant of the tools for administration of A-parts it is important to figure out all positive and negative aspects and compare them to each other. This is done with the balance of arguments.

Balance of arguments:

The balance of arguments for the tools for administration of A-parts at the construction site Solbakk can be seen in table 28. To figure out the best solution of all variants many aspects have to be considered.

Table 28: Balance of arguments – Tools for administration of A-parts

Variant:	Advantages	Disadvantages
V1: Paper based administration	Very easy to establish and introduce	Bad overview of work reports
	Easy to use for the workers at the workshop level	Nearly no overview about caused costs / hours of maintenance
	High reliability due to paper form	Insufficient documentation
	Very cheap variant	No overview about following services
	Can be adjusted very easy (printing out new formulars)	Bad overview about used spare parts
	Every worker should be able to use the sheets	Bad transparency
	No computer based knowledge necessary	Low quality of the administration material
V2: Computer based administration	Good transparency about the costs and working tasks	Difficult to adjust a fixed computer based administration tool
	Good quality of the maintenance material	Long time for education of the workers to use the tool
	Detailed documentation of the maintenance processes possible	No reliability in case of an harddisc failure
	Traceability of working hours per machine possible	Computer knowledge needed - not suitable for all workers
	Exact cost breakdown possible	More difficult operability for the workers
	Good overview aboout the whole maintenance	More expensive variant
		Need of higher educated personal
		Eventually additional computer needed at the workshop
		Longer time to establish
V3: Paper and computer based administration	Very good transparency about the costs and working tasks	High investment costs
	Very good quality of the material	Long time for establishing the administration tool
	Detailed documentation of the maintenance processes (paper form and digital)	Paper formulars must be filled out as a basis
	Traceability of working hours per machine possible	Computer knowledge needed - not suitable for all workers
	Exact cost breakdown possible	More administration work
	Written papers are the input for the computer based administration	
	Papers are the basis for the administration tool - higher reliability	
	Paper reports can be made in the workshop, administration in the office	

Weighting of objectives:

The weighting of objectives of the different tools for administration of A-parts is essential to figure out which criteria of the different variants are the most important to obtain an improved machine administration. The results can be seen in table 29.

Table 29: Weighting of objectives – Tools for administration of A-parts

Group of criteria	Criteria	Weight (rounded)		Rating of importance 10% - 100%														
		Group	Single	1	2	3	4	5	6	7	8	9	10	Rating group	% group exact	Rating single	% single exact	Points single
Financial objectives		20						x						5	21,74			
	Investment costs relative		15										x			10	83,33	16,67
	Additional needed devices (e.g. printer, scanner etc.)		5		x											2	16,67	3,33
			Subtotal financial													**12**	100,00	20,00
Functional objectives		45											x	10	43,48			
	Effort to establish the administration program		4					x								5	8,77	3,95
	Time of workers to perform the administration task		2			x										3	5,26	2,37
	Reusability of administration tool		6								x					8	14,04	6,32
	Operability		5						x							6	10,53	4,74
	Overview of caused costs		8										x			10	17,54	7,89
	Overview of caused works (by workers)		4					x								5	8,77	3,95
	Quality of administration		8										x			10	17,54	7,89
	Fail-safe - reliability of program		8										x			10	17,54	7,89
			Subtotal functional													**57**	100,00	45,00
Proceeding objectives		5		x										1	4,35			
	Needed time for education of the administration task itself		5															
			Subtotal proceeding														100,00	5,00
Future objectives		30								x				7	30,43			
	Overview of future services		20										x			10	71,43	21,43
	Possibility to adjust the machine administration tool		10				x									4	28,57	8,57
			Subtotal future													14	100,00	30,00
		100	**100**										**Sum:**	**23**	**100,00**			

The most important criteria of the tools for administration of A-parts are the functional objectives. Also the future objectives like the overview of future services and the possibility to adjust the administration tool are very important. The financial objectives are just on average and the least important objectives are the proceeding objectives, like the needed time for the education of the administration tool itself.

Scaling matrix:

The scaling matrix to figure out the individual ranking of each variant of tools for administration of A-parts can be seen in table 30.

Table 30: Scaling matrix – Tools for administration of A-parts

Group of criteria	Criteria	Notes: 0 - BAD	1	2	3	4	5 - GOOD	Unit	Variants: Paper based administration V1	Computer based administration V2	Paper and computer based administration V3
Financial objectives											
	Investment costs relative	High		Medium		Low			5	3	2
	Additional needed devices (e.g. printer, scanner etc.)	High		Medium		Low			5	5	3
Functional objectives											
	Effort to establish the administration program	Months		Weeks		Days			4	2	1
	Time of workers to perform the administration task	High		Medium		Low			4	2	2
	Reusability of administration tool	Low		Medium		High			5	3	3
	Operability	Hard		Medium		Easy			4	2	3
	Overview of caused costs	Low		Medium		High			0	5	5
	Overview of caused works (by workers)	Bad		On average		Good			1	3	5
	Quality of administration	Low		Medium		High			1	4	5
	Fail-safe - reliability of program	Low		Medium		High			5	1	3
Proceeding objectives											
	Needed time for education of the administration task itself	Weeks		Days		Hours			4	3	2
Future objectives											
	Overview of future services	Low		Medium		High			0	5	5
	Possibility to adjust the machine administration tool	Low		Medium		High			5	1	3

The paper based administration is the cheapest variant of all referred to the investment costs. The variant of the paper and computer based administration needs perhaps additional devices like printers and scanners and is the variant, which has the highest effort to be established. It can be seen that the paper and computer based administration has the best results according to the functional objectives.

The proceeding objectives can be achieved very well with the paper based administration due to the fact that not much time must be invested to educate the mechanics – the employees have just to fill out repair sheets by hand. The future objectives are fulfilled very well with the paper and computer based administration because of the very good overview of future services of all machines and equipment.

It is important that the computer administration at variant number two and even at variant number three is not too complicated to use for the responsible workshop manager – therefore the buzzword “usability” is very important at this point.

Value benefit analysis:

The values out of the table of weighting of objectives and the values out of the scaling matrix of the tools for administration of A-parts are multiplied with each other within the value benefit analysis and can be seen in table 31.

Table 31: Value benefit analysis – Tools for administration of A-parts

Group of criteria	Criteria	Weight		Variants					
				Paper based administration V1		Computer based administration V2		Paper and computer based administration V3	
		Group	Single [g]	n	n*g	n	n*g	n	n*g
Financial objectives		20							
	Investment costs relative		15	5	75	3	45	2	30
	Additional needed devices (e.g. printer, scanner etc.)		5	5	25	5	25	3	15
			Subtotal financial		100		70		45
Functional objectives		45							
	Effort to establish the administration program		4	4	16	2	8	1	4
	Time of workers to perform the administration task		2	4	8	2	4	2	4
	Reusability of administration tool		6	5	30	3	18	3	18
	Operability		5	4	20	2	10	3	15
	Overview of caused costs		8	0	0	5	40	5	40
	Overview of caused works (by workers)		4	1	4	3	12	5	20
	Quality of administration		8	1	8	4	32	5	40
	Fail-safe - reliability of program		8	5	40	1	8	3	24
			Subtotal functional		126		132		165
Proceeding objectives		5							
	Needed time for education of the administration task itself		5	4	20	3	15	2	10
			Subtotal proceeding		20		15		10
Future objectives		30							
	Overview of future services		20	0	0	5	100	5	100
	Possibility to adjust the machine administration tool		10	5	50	1	10	3	30
			Subtotal future		50		110		130
n...number out of the scaling matrix		100	100						
			Total		296		327		350

The paper based administration has the best financial- and proceeding objectives. But the paper and computer based administration is the best variant of all with the most total points due to the best results at the functional objectives and at the future objectives.

Figure 55 shows a graphical distribution of the evaluated results of the different tools for administration of A-parts.

It can be seen that variant number three – the paper and computer based administration – has the most total points due to the highest ranking within the functional- and future objectives, these are the most important fields according to the weighting of objectives. The financial objectives and the proceeding objectives are not as important compared to the other objectives. It is reasonable to perform the future machine administration with hand written papers at the workshop level and with computer administration at the management level.

Now it is essential to figure out the best software concerning the usability and needed complexity for the machine administration. This has to be done together with the responsible workshop manager at the site and an own problem solving cycle has to be established.

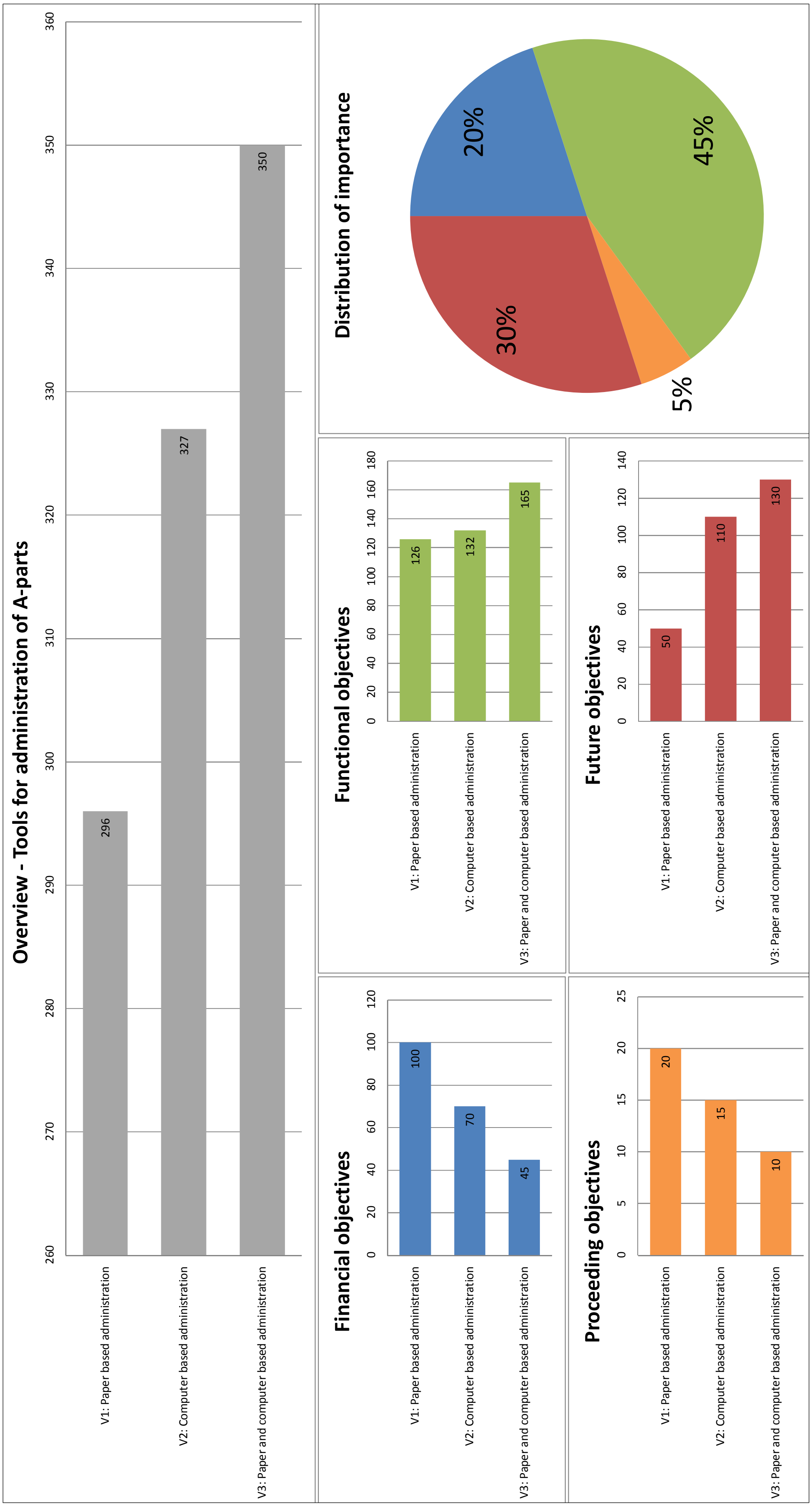


Figure 55: Graphical interpretation of the different tools for administration of A-parts

4.4.2.2 Software for administration of A-parts

There are just some programs for maintenance available on the market but they are partly very rigid organized or not sophisticated enough. Also the evaluation results out of some user forums for these partly unknown standardized programs are quite bad. Sometimes there is even the need of special instructors for educating the software, what can be very expensive. Even possibilities to buy customized software are given. To work with standard Microsoft Excel sheets is the most common way at the moment. Additionally it is possible to develop an own database program (like with e.g. Microsoft Access), a so-called home-made software solution. The following problem solving cycle should help to figure out the best solution out of some possible software variants for the implementation at the construction site Solbakk.

Catalogue of requirements:

The most important objectives according to the variants of software for administration of A-parts can be seen at the catalogue of requirements in table 32.

Table 32: Catalogue of requirements – Software for administration of A-parts

Objective category:	Objective properties	Degree of objective	Priority
Financial objectives			
Costs	Investment costs	Minimum	M
	Monthly additional expenses	Minimum	M
Needed instructor	Additional needed costs for instructor of the software	Minimum	M
Functional objectives			
Maintenance and service	Maintenance of software	Minimum	S
	Service of software	As good as possible	S
Quality & Stability	Quality and stability of software	As good as possible	S
Needed time	Time of workers to perform the administration task	Minimum	S
Reusability	Reusability of administration software	As good as possible	M
Operability	Operability for users	As easy as possible	S
Transparency	Overview of caused cost and hours	As high as possible	M
Documentation	Dokumentation of maintenance process	High	S
Reliability	Reliability of the software	As high as possible	M
Working load	Working load of the hardware	As low as possible	W
Proceeding objectives			
Celebration	Needed time to obtain and introduce a functional SW	Minimum	S
	Frequency of recording data	Record each service and repair task	M
Future objectives			
Specialize content	Possibility to adjust the machine administration tool	High	M

The objectives are classified into financial-, functional-, proceeding- and future objectives. The most important aspects are low investment costs as well as low monthly additional expenses and low costs for additionally needed instructors. The reusability and the transparency of all maintenance tasks should be as high as possible and the software should be reliable. It is essential to record each service and repair task and it must be possible for the responsible workshop manager to adjust the machine administration tool by himself.

Morphological scheme:

The morphological scheme for the different possible types of software for administration of A-parts can be seen in figure 56. To compare all variants for improvement 10 different parameters are classified within that morphological scheme.

In total four variants for the possible types of software for the administration of A-parts are analyzed – these variants are:

- V1: Standard software
- V2: Customized standard software
- V3: Individual software
- V4: Home-made software

The standard software is the most rigid of all variants. The customized standard software is a little bit more flexible due to customization but the costs are of course higher. The individual software is developed by external software companies and exactly fitted to the company needs – this is of course the most expensive variant of all. Finally, the home-made software is developed internally. This type is maybe not as professional as other variants but a very high usability can be achieved with an appropriate level of complexity. Furthermore this variant can be seen as a cheap solution.

Parameters	Appearance of parameters			
Investment costs (A) - relative	Low (A1)	Medium (A2)	High (A3)	
Costs for instructor of the software (B)	Low (B1)	Medium (B2)	High (B3)	
Maintenance and service supply (C)	Low (C1)	Medium (C2)	High (C3)	
Quality and stability (D)	Bad (D1)	On average (D2)	Good (D3)	
Operability for users (E)	Easy (E1)	Medium (E2)	Hard (E3)	
Ability of integration (F)	Bad (F1)	On average (F2)	Good (F3)	Very good (F4)
Working load of the hardware (G)	Low (G1)	Medium (G2)	High (G3)	
Needed time for education of the software to the users (H)	Low (H1)	Medium (H2)	High (H3)	
Needed time to introduce a functional software (I)	Low (I1)	Medium (I2)	High (I3)	
Possibility to adjust the main software - creation (J)	Low (J1)	Medium (J2)	High (J3)	
Possibility to change the software later on (K)	Low (K1)	Medium (K2)	High (K3)	
	V1 Standard software / V2 Customized standard software		V4 Home-made software / V3 Individual software	

Figure 56: Morphological scheme – Software for administration of A-parts

Example out of the morphological scheme:

The example will be demonstrated at variant number four – home-made software (labeled with orange color). This variant has the lowest investment costs (A1) due to the fact that it can be established within this thesis by the student and no additional extern solution must be bought. Therefore also no costs for an instructor have to be paid (B1). The maintenance and service supply is just on average (C2) due to the fact that future problems can only be answered and solved directly at the site with the responsible workshop manager and the student, who is creating the software. The quality of this software cannot be compared with high-priced solutions of other companies and is therefore on average (D2). But due to less complexity it is possible to achieve a very high operability (E1) and this is a very important aspect. Of course the ability of integration of this home-made software with other programs (F1) is bad compared to e.g. standard software, but the working load of the hardware (G1) and the needed time for the education of the software to the final users (H1) are very low. The time for introduction of this software is on average (I2) but the possibility to adjust it by the workshop manager is quite high (J3) as well as the possibility to change the software later on (K3).

For each variant of the different types of software for the administration of A-parts it is important to figure out all positive and negative aspects and to compare them to each other.

Balance of arguments:

The balance of arguments for the different types of software for the administration of A-parts at the construction site Solbakk can be seen in table 33. To figure out the best solution various aspects of all four variants have to be considered.

Table 33: Balance of arguments – Software for administration of A-parts

Variant:	Advantages	Disadvantages
V1: Standard software	Low costs	More difficult operability (fixed system)
	Many different solutions available	High working load of the hardware
	High service supply	Low possibilities to adjust the software
	High quality and stability	
	High ability of integration	
	Low time to introduce a functional software	
	Well known for many users	
V2: Customized standard software	Possibility to adjust the software	Relative high costs
	Service supply available	High costs for the instructor
	High quality	High working load of the hardware
	Easier operability compared to standard SW	Long time for education of the software to the users
	Integration possible (limited)	
	Tailor-made software for individual needs	
	More comfortable to work with the tailor-made software	
V3: Individual software	Easy operability for users	Long time for introduction of the software
	Low working load of the hardware	High investment costs
	Possibility to adjust the software	High costs for the instructor of the software
	Very complex software solutions possible	Bad ability of integration
	Tailor-made software for individual needs	
V4: Home-made software	Low costs for the instructor of the software	Not very complex software solutions possible
	Easy operability for users	Low ability of integration
	Low working load of the hardware	
	Short time for education of the software to the users	
	High possibility to adjust the software	

Weighting of objectives:

The weighting of objectives of the different types of software for the administration of A-parts is essential to figure out which aspects of the different variants are the most important in order to obtain an improved machine administration tool at the construction site Solbakk. The results can be seen in table 34.

Table 34: Weighting of objectives – Software for administration of A-parts

Group of criteria	Criteria	Weight (rounded)		Rating of importance 10% - 100%														
		Group	Single	1	2	3	4	5	6	7	8	9	10	Rating group	% group exact	Rating single	% single exact	Points single
Financial objectives		32									x			8	32,00			
	Investment costs		17										x			10	52,63	16,84
	Costs for instructor of the software		8					x								5	26,32	8,42
	Costs for later changes of the software		7				x									4	21,05	6,74
	Subtotal financial															19	100,00	32,00
Functional objectives		40											x	10	40,00			
	Needed time to introduce a functional software		10									x				9	24,32	9,73
	Quality and stability of software		6						x							6	16,22	6,49
	Operability for users		11										x			10	27,03	10,81
	Maintenance and service supply		3			x										3	8,11	3,24
	Working load of the hardware		1	x												1	2,70	1,08
	Overview for relevant data		9								x					8	21,62	8,65
	Subtotal functional															37	100,00	40,00
Proceeding objectives		16					x							4	16,00			
	Possibility to adjust the main software - creation		11									x				9	69,23	11,08
	Needed time for education of the software to the users		5				x									4	30,77	4,92
	Subtotal proceeding															13	100,00	16,00
Future objectives		12				x								3	12,00			
	Possibility to change the software later on		12															
	Subtotal future																100,00	12,00
		100	100										Sum:	25	100,00			

Most important groups of criteria are the financial objectives and the functional objectives. The proceeding objectives as well as the future objectives are less important.

Scaling matrix:

The scaling matrix to figure out the individual ranking of each variant of software for the administration of A-parts can be seen in table 35.

Table 35: Scaling matrix – Software for administration of A-parts

Group of criteria	Criteria	Notes						Unit	Variants			
									Standard software	Customized standard SW	Individual software	Home-made software
		0 - BAD	1	2	3	4	5 - GOOD		V1	V2	V3	V4
Financial objectives												
	Investment costs	High		Medium		Low			4	2	0	4
	Costs for instructor of the software	High		Medium		Low			2	1	1	5
	Costs for later changes of the software	High		Medium		Low			0	1	1	4
Functional objectives												
	Needed time to introduce a functional software	Months		Weeks		Days			4	3	1	2
	Quality and stability of software	Bad		On average		Good			4	3	3	2
	Operability for users	Hard		Medium		Easy			1	3	4	4
	Maintenance and service supply	Low		Medium		High			4	3	3	2
	Working load of the hardware	High		Medium		Low			4	4	1	1
	Overview for relevant data	Bad		On average		Good			2	4	5	4
Proceeding objectives												
	Possibility to adjust the main software - creation	Low		Medium		High			0	3	5	5
	Needed time for education of the software to the users	High		Medium		Low			1	1	3	4
Future objectives												
	Possibility to change the software later on	Low		Medium		High			1	3	5	5

The home-made software is the best variant at the financial objectives and the functional objectives are reached quite good compared to the other variants. The proceeding objectives as well as the future objectives of the home-made software are also ranked very high.

Value benefit analysis:

The values out of the table of weighting of objectives and the values out of the scaling matrix for the types of software for the administration of A-parts are multiplied with each other within the value benefit analysis and can be seen in table 36.

Table 36: Value benefit analysis – Software for administration of A-parts

Group of criteria	Criteria	Weight		Variants							
				Standard software V1		Customized standard software V2		Individual software V3		Home-made software V4	
		Group	Single	n	n*g	n	n*g	n	n*g	n	n*g
Financial objectives		32									
	Investment costs		17	4	68	2	34	0	0	4	68
	Costs for instructor of the software		8	2	16	1	8	1	8	5	40
	Costs for later changes of the software		7	0	0	1	7	1	7	4	28
		Subtotal financial			84		49		15		136
Functional objectives		40									
	Needed time to introduce a functional software		10	4	40	3	30	1	10	2	20
	Quality and stability of software		6	4	24	3	18	3	18	2	12
	Operability for users		11	1	11	3	33	4	44	4	44
	Maintenance and service supply		3	4	12	3	9	3	9	2	6
	Working load of the hardware		1	4	4	4	4	1	1	1	1
	Overview for relevant data		9	2	18	4	36	5	45	4	36
		Subtotal functional			109		130		127		119
Proceeding objectives		16									
	Possibility to adjust the main software - creation		11	0	0	3	33	5	55	5	55
	Needed time for education of the software to the users		5	1	5	1	5	3	15	4	20
		Subtotal proceeding			5		38		70		75
Future objectives		12									
	Possibility to change the software later on		12	1	12	3	36	5	60	5	60
		Subtotal future			12		36		60		60
n...number out of the scaling matrix		100	100								
		Total			210		253		272		390

The best variant of software for administration of A-parts is variant number four – the home-made software. This is a clear and obvious result out of the problem solving cycle. It can be seen that the home-made software has the best ranking at the financial- and proceeding objectives. The future objectives and the functional objectives are also covered quite well.

As a result variant number four – the home-made software will be focused further and a prototype has to be developed and implemented at the construction site Solbakk. Figure 57 shows a graphical distribution of the evaluated results for the different types of software for the administration of A-parts. It can be seen that the financial objectives and the functional objectives have the highest impact to this evaluation result.

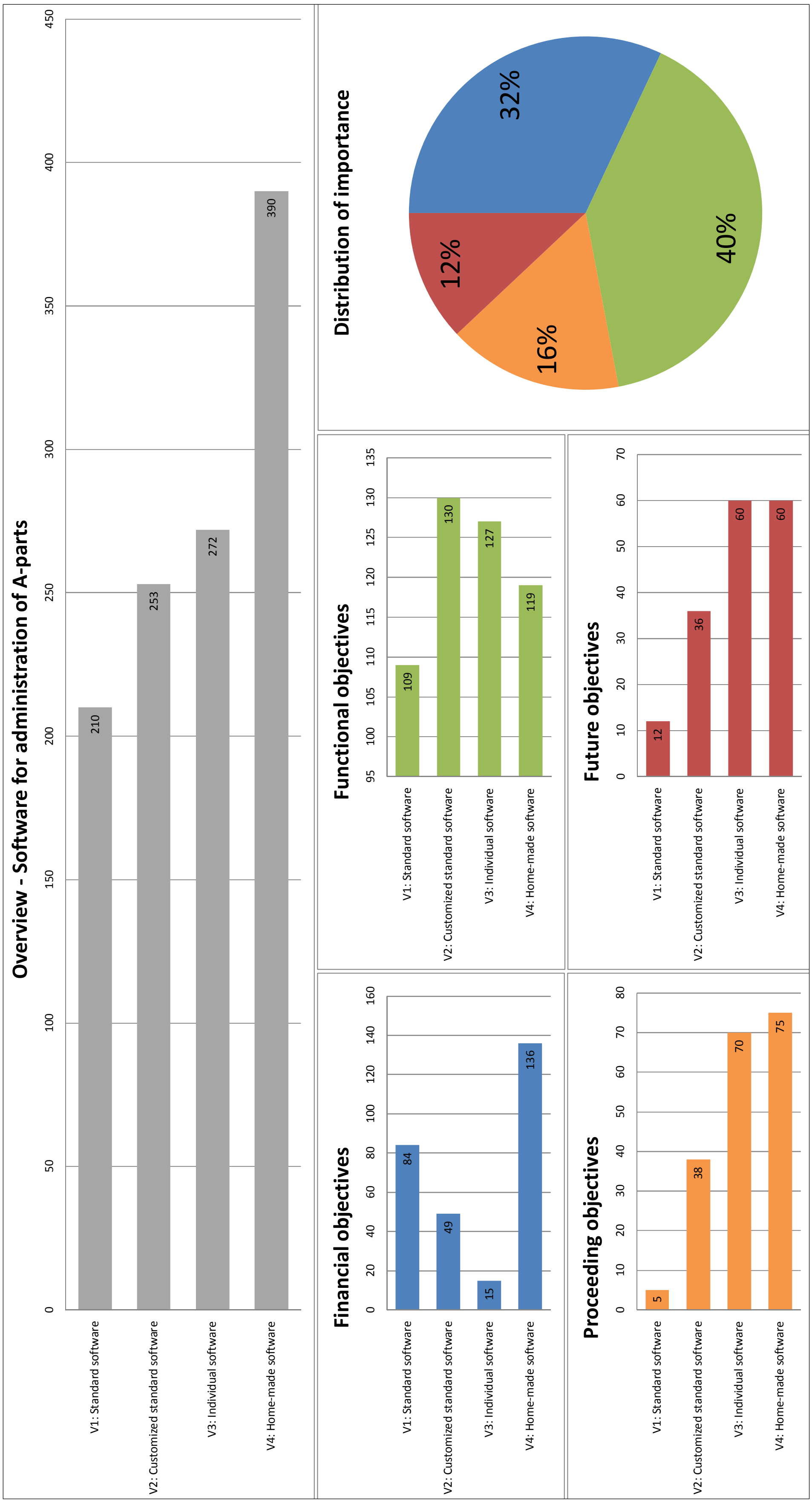


Figure 57: Graphical interpretation of the different types of software for administration of A-parts

4.4.2.3 Interpretation of the result

Due to the clear result in figure 57 a further problem solving cycle is not necessary. The positive aspects of the home-made software are predominant. The possibility to develop a software solution is a big challenge and has to be done together with the responsible workshop manager directly at the site, because he will administrate this software later on by his own. It is important to build up software with a high usability for the workshop manager.

The task of developing and implementing a software for administration of A-parts will contribute to a much higher efficiency of the machine maintenance and will be covered within the chapter 4.5 – prototypes, implementation and results.

4.4.3 Detail study process: Variant 10 – Improvement of maintenance process

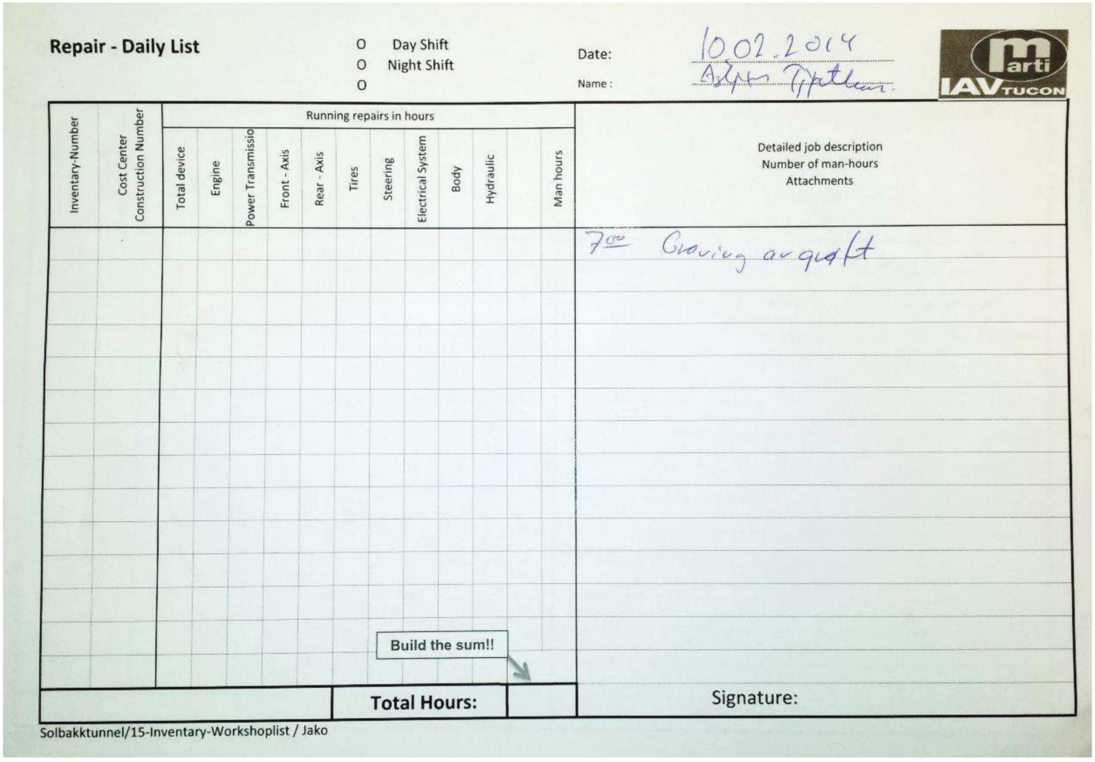
To achieve a good integration of all three variants together it is important to adjust them to each other. At the process optimization therefore an adjustment for the technical administration of A-parts will be done in order to achieve a higher efficiency of the whole maintenance process. To support this very important aspect of an improved machine administration tool as good as possible various aspects have to be considered.

Out of the preliminary study it is obvious that many service intervals are exceeded due to the fact of a bad documentation of the machine hours. This causes of course high costs and has a negative influence to the machine manufacturer's warranty. An improved process for the administration of the machine hours is an essential factor for the overall success of the whole machine maintenance. Further problems are the partly bad written working reports. Correct written maintenance reports are the basis for an efficient administration and documentation of the maintenance process.

These problems were already identified within the preliminary study and therefore it is not necessary to develop a further problem solving cycle at this point. It can be said that variant number ten – the improvement of the maintenance process – is a very important support process for the machine administration tool.

4.4.3.1 Improvement of working reports

The high importance of correct written working reports is not really known by some mechanics. They are maybe just not aware of the negative consequences. An example of such an insufficient written working report from a mechanic is shown in figure 58.


Repair - Daily List

O Day Shift
O Night Shift
O

Date: 10.02.2014
Name :

Inventary-Number	Cost Center Construction Number	Running repairs in hours: Total device	Engine	Power Transmissio	Front - Axis	Rear - Axis	Tires	Steering	Electrical System	Body	Hydraulic		Man hours	Detailed job description Number of man-hours Attachments

Build the sum!!

Total Hours:

Signature:

Solbakktunnel/15-Inventary-Workshoplist / Jako

Figure 58: Written working report

It can be seen that the mechanics maybe write the reports but the information of these reports is sometimes not sufficient. For a high quality administration of the machine maintenance the working reports must be filled out in an appropriate way. It is obvious that the hand written repair report of figure 58 is not usable for a proper documentation and administration of the machine maintenance process. The quality of these handwritten maintenance reports must be increased drastically!

4.4.3.2 Administration of the machine hours

At the beginning of this thesis the administration or even the reading process for the machine hours was not really defined or even delegated. Therefore a BPMN according to the old situation in March 2014 was established. This BPMN can be seen in figure 59 and will be explained only very rough:

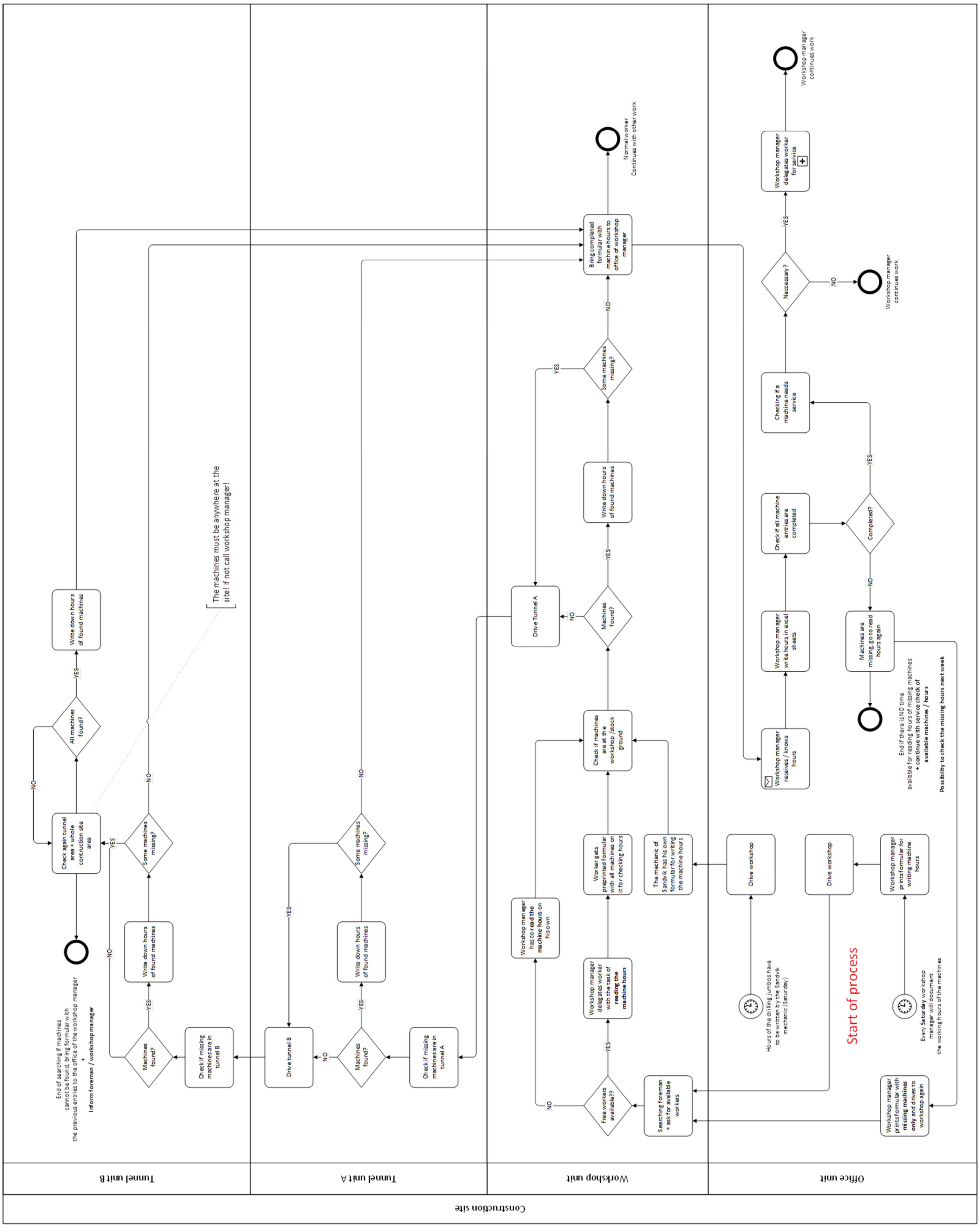


Figure 59: BPMN of the administration of the machine hours (March 2014)

<u>Situation of the administration of the machine hours in March 2014:</u>

Every Saturday the workshop manager is printing out the documents for writing the machine hours and drives to the workshop. He tries to delegate the task of reading the machine hours to an available worker. If no worker is available, the workshop manager has to read the machine hours of all machines on his own. Therefore he or if available the delegated worker has to search all the machines at the workshop area and in both tunnels in order to read and write down the machine hours. This is a very exhausting process and also very time intensive. Quite often some machines are not able to be found and their hours cannot be written.

If finally all machine hours are figured out and written down, the workshop manager has to write these hours into a conventional Excel sheet. Afterwards he checks if some machines must be prepared for future service tasks. Due to a bad overview within this Excel sheet it is possible, that sometimes service intervals of machines can be exceeded. This must be prevented in future!

4.4.3.3 Interpretation of results

At the last detail study of the process optimization it can be seen where some problems are located within the existing maintenance process. It is important to increase the quality of all written working reports as well as to figure out a better solution for the process of the administration of the machine hours. These processes have to be improved in order to achieve a more efficient maintenance process at the construction site Solbakk.

4.5 Prototypes, implementation and results

This chapter shows the developed prototypes for each of the three variants out of the three different detail studies as well as the experiences at the implementation and the use of them at the site. Out of the diverse problem solving cycles and the exact analysis of each variant at the detail studies it was possible to develop prototypes for an improvement of the machine maintenance process at the construction site Solbakk.

4.5.1 Organization – Employee qualification

The result out of the detail study for the employee qualification was the introduction of special developed instruction manuals. This kind of education seems to be very successful due to fast establishing, low costs, high reusability, possibility to educate specialized content etc. These developed instruction materials should help to reduce the needed time for machine maintenance tasks drastically and therefore the whole efficiency of the machine maintenance at the workshop should increase a lot.

4.5.1.1 Prototype

These instruction manuals must be established and introduced at the construction site Solbakk. They can be developed according to:

- Service tasks
- Repair tasks
- Cleaning instructions of machines

It should be possible for every employee to perform all delegated tasks by the use of these manuals. A detailed step by step scheme with many pictures is contributing to a high usability of these documents. But therefore it is necessary that once the service and repair tasks are recorded exactly and a lot of high quality pictures have to be taken for a later development of these materials. This takes of course quite a long time but it will be worth it.

Some fields which should be covered within each instruction manual for the machines are e.g.:

- Tool lists
- Statement of needed workers
- Short introduction of machine (e.g. build up)
- General safety instructions at the site
- Safety instructions for operating the machine
- Steps before start of work
- Detailed description of the service, repair or cleaning task etc.

A very important point is the introduction of generated tool lists within these instruction manuals. All needed tools and equipment must be recorded and documented in that way that future maintenance tasks can be prepared in advance. This is especially important for the service and repair tasks of the stationary machinery in the tunnel where the distance from the machines to the workshop and the spare-part magazine is continuously increasing with the proceeding of the tunnel excavation. Therefore a well preparation of all needed tools and spare parts is unavoidable! Because for special machines are often various tools and spare-parts needed which are not standard. An example for such a tool list out of an existing instruction manual can be seen at appendix 1. At appendix 1 also the required persons and their needed level of qualification can be seen. This is a further essential point because the workers should know how many people are needed to perform the diverse maintenance tasks.

Furthermore it must be clarified if special knowledge or education is needed for a certain maintenance task (e.g. crane driver license etc.). Then a short introduction of every machine as well as the most important safety instructions at the site and for operating the machine should be included within these manuals. Some important steps before starting the maintenance tasks must be also mentioned e.g. turn off the power supply, bring on safety labels, turn on warning lights etc. These are all necessary tasks to ensure a safe working environment for the executing mechanics and should be always kept in mind!

Finally, the detailed description of the maintenance task itself must be established. All steps respectively the pictures of the working tasks have to be listed in a chronological sequence to ensure an easy traceability. An example of a developed instruction manual can be seen at appendix 2.

4.5.1.2 Implementation and results

Various instruction manuals for all kind of service and repair tasks as well as many cleaning instructions were already established and successfully introduced at the construction site Solbakk. All workers appreciated the chronological buildup of these manuals and the exact defined tool lists. It was possible for the workers to prepare the service and repair tasks in advance – this is a very uncommon approach and therefore a lot of searching and measuring time (e.g. measuring of wrench sizes etc.) was reduced. Even quite untrained workers were able to perform special tasks like for example changing the crusher plates of the stone crusher. Without these manuals such a task would not be possible for unexperienced employees. It can be said that the implementation of these instruction manuals was very successful.

In future it would be also possible to establish some short presentations for diverse maintenance tasks. These presentations could be shown to the mechanics and existing problems or questions could be cleared as a team. The effort to establish these presentations is quite low because the instruction manuals would already exist. Also the possibility to translate all instruction manuals into different languages is a very positive aspect. The developed instruction manuals can be sent via e-mail to other construction sites and therefore an increased efficiency of the machine maintenance process for the company can be achieved.

4.5.2 Technical – Administration of A-parts

The result out of the detail study for the administration of the A-parts (machines) was to develop a home-made software tool. It was figured out that this system must be supported by the executing mechanics. They have to write their maintenance reports and the administration of these reports must be done by the responsible workshop manager at the site. The efficiency of the whole maintenance process should increase a lot by the use of this prototype.

4.5.2.1 Prototype

Together with the workshop manager of the construction site the most important parameters for an efficient machine maintenance tool were figured out. Following an appropriate entity relationship model was established. A rough overview of this entity relationship model without all attributes can be seen in figure 60.

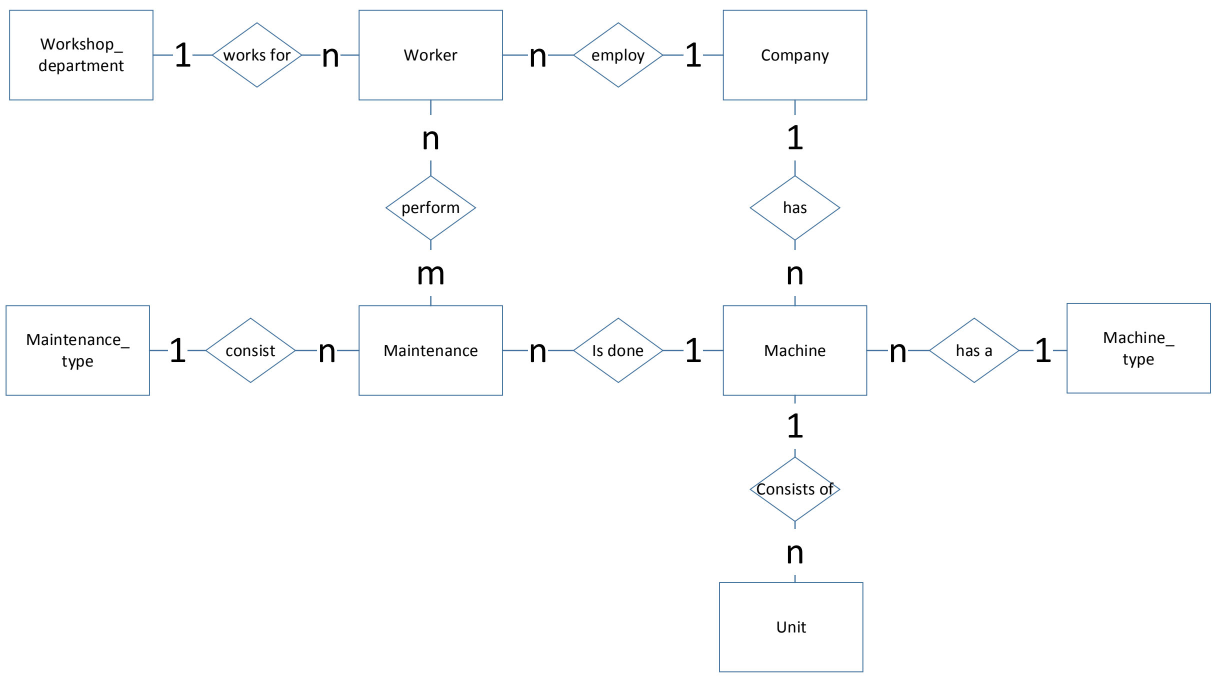


Figure 60: Rough overview of the entity relationship model

The most important elements are the workers and the departments, the machines with their different units and the classifications according to various machine types, the maintenance task itself with the different types of maintenance and the companies. Various different relationships between these elements have to be established to develop an improved administration tool for the machines. The exact entity relationship model of the machine administration with all important attributes can be seen in figure 61.

It can be said that each company can employ many workers which are working for different workshop departments at the site and perform the maintenance tasks at the tunneling machines. These machines belong partly to the same companies and are classified to certain defined machine types. Each machine consists of one or more units which have to be maintained. Every maintenance task belongs to a special type of maintenance e.g. repair tasks, service tasks, checks and damages.

First it was tried to implement an advanced Microsoft Excel sheet for a better machine administration due to the fact of the high operability and an easy handling. But the possibilities to establish a high quality maintenance tool according to the entity relationship model with Microsoft Excel are limited. Therefore a machine administration tool was developed with Microsoft Access, according to the entity relationship model in figure 61. A big advantage of such a database program is the possibility to create a many-to-many relationship – which is needed at the point of the machine maintenance, because more workers are able to perform various maintenance tasks – also together. Some further positive aspects of a Microsoft Access based database are:

- Systematically buildup of the database
- Possibility to create an user-friendly environment
- Graphical interpretation of maintenance possible
- Possibility of generating various high quality reports for maintenance
- Good traceability of all working tasks and used spare parts possible
- High overview of all machine hours can be developed
  (indication of future services) etc.

These are only some important aspects which can be achieved by the creation of a MS Access based database.

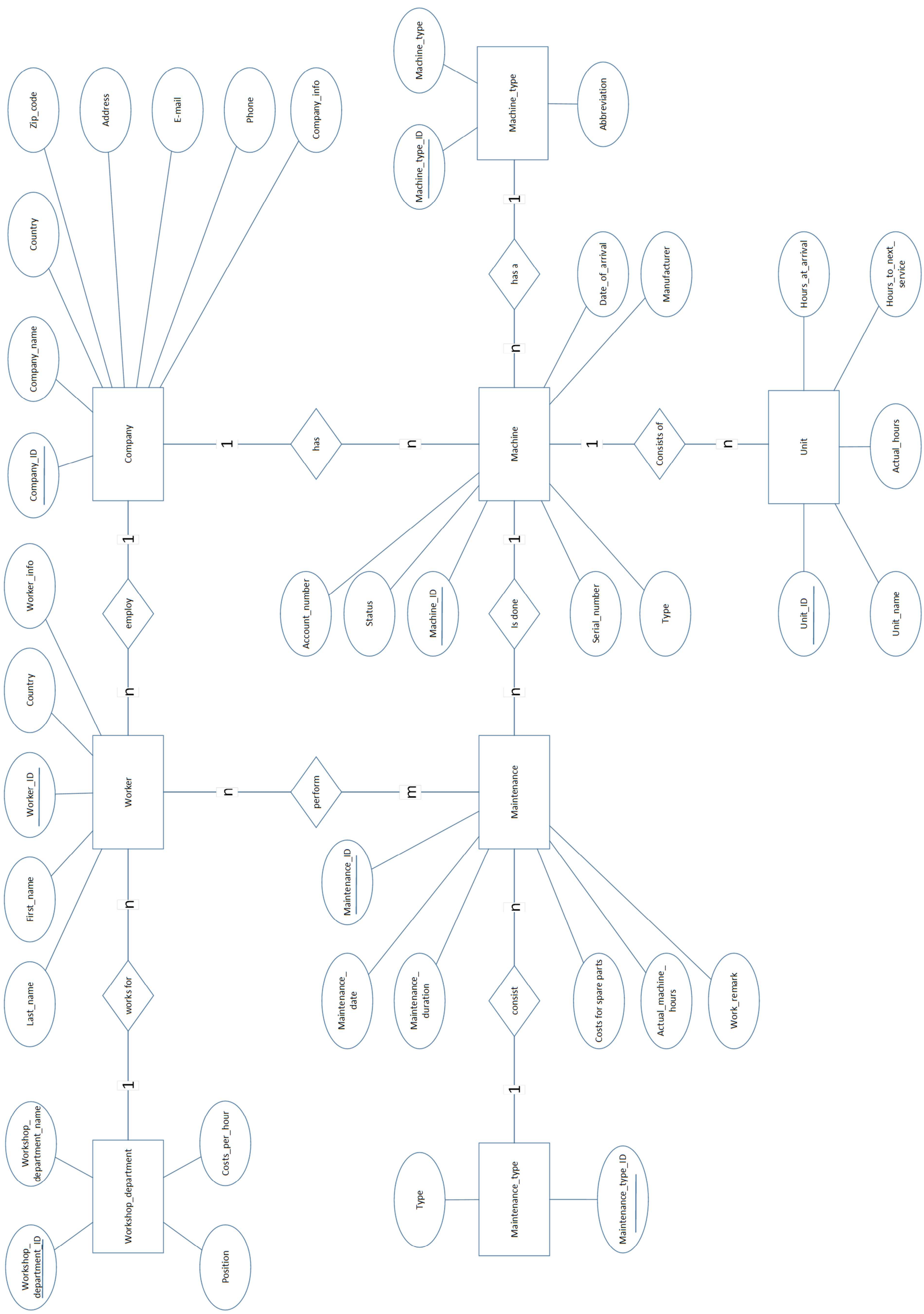


Figure 61: Complete entity relationship model for the administration of A-parts

4.5.2.2 Implementation and results

Together with the workshop manager many discussions were made according to an appropriate handling and design of this database tool. One of the most important aspects is the operability of this administration tool. Due to a lot of research it was possible to establish a database, which is fitting exactly to the needs of the machine maintenance administration at the construction site Solbakk. It is possible to use this database at other construction sites as well. A rough version of this prototype was already delivered to the responsible workshop manager and a short introduction was executed at the site.

This database could be improved further but this is not the objective of this thesis. The developed prototype is working well and this variant is also successfully implemented at the construction site Solbakk. Some screenshots of the developed database prototype can be seen at appendix 3.

For a better interpretation of the performed maintenance tasks various diagrams can be printed out with this prototype. A good overview of all caused costs is given. Also a very useful pivot table can be made just by clicking on the appropriate button. Various maintenance reports can be established and printed out as well. With this prototype it is possible to plan all maintenance tasks in advance. Required services will be indicated automatically and therefore no service tasks should be forgotten in the future. As a result, the efficiency of the whole machine maintenance process at the construction site Solbakk will increase a lot.

4.5.3 Process – Improvement of maintenance process

Out of the third detail study it is important that existing problems for the working reports and at the process of the administration of the machine hours must be reduced. These process improvements are supporting the administration process of the machines. Therefore the overall quality of the maintenance process will increase a lot through the integration of this variant.

4.5.3.1 Prototype

The prototype of process improvement was established and performed directly at the construction site Solbakk and can be seen as a continuous process of improvement. Various discussions and meetings were made together with the workshop manager and some of the employees of the workshop. In teamwork it was tried to figure out the most effective solution for a better machine maintenance process at the site.

4.5.3.2 Implementation and results – Working reports

The workers at the construction site Solbakk got informed about the high importance of proper written working reports. A closer view to all written maintenance reports was made. In case of insufficient written working reports the responsible mechanic was ordered to the office of the workshop manager in order to discuss the fields for improvement. It is now clearly defined which information has to be written onto the sheets e.g.

- Date
- Full name (block letters)
- Exact working hours per task
- Working hours total (sum)
- Shift (day or night)
- Exact description of the working tasks
- Time for lunch

The urgent need of proper handwritten maintenance reports is now explained to all mechanics at the site. A continuous control of these reports is done by the workshop manager to ensure a high quality documentation of all service and repair tasks. Through this precise analysis of all reports and the simultaneous administration with the database tool a high quality maintenance administration and documentation process is achieved.

4.5.3.3 Implementation and results – Administration of machine hours

For the administration of the machine hours various solutions were figured out to achieve a better process. Finally, it was decided to hire the worker for greasing and tanking of all underground vehicles, to perform this task. This worker is now going every Friday to the office of the workshop manager and picks up the machine-hour administration sheets. Then he is driving to the site and into the tunnel and performs his daily routine job. Simultaneously he is reading and writing down the actual machine hours of each machine. This is very efficient, because the time for tanking the vehicles can be quite long. It was evaluated that this variant is the most effective of all. When the worker has finished his job at the site, he is driving back to the office and delivers the actual machine hours to the workshop manager, who is now administrating these hours within his administration tool.

It can be said that the whole process of reading the machine hours was improved by 100% due to the fact that no separate workers or even the workshop manager himself have to perform this task in future, like it was done at the beginning of this thesis (compare figure 59).

5 Conclusion

At the end of this thesis it can be said that all prototypes out of the three different detail studies were successfully introduced directly at the construction site Solbakk in Tau / Norway. The high potential of the implemented prototypes was obvious for all involved employees at the site. It is now their task to improve and use these prototypes further.

The different prototypes were adjusted to each other during the field work of this thesis at the construction site in order to achieve the best possible increase of efficiency of the whole machine maintenance process. There is still the possibility to make further improvements, for example to develop a more advanced machine administration tool etc. But the main objective of this thesis was to highlight areas with existing difficulties and problems of the current maintenance process and to introduce different prototypes to overcome these problems as good as possible.

The workshop management will use and develop these prototypes further. It is essential to establish various instruction manuals for all kind of maintenance tasks. These manuals can be also translated into different languages and they are helpful for achieving better working results, even with lower qualified workers. Furthermore unexperienced workers are able to perform all kind of service and repair tasks by using these step-by-step instruction manuals. Especially the use of the developed tool lists is quite an uncommon but very effective approach for preparing different repair and service tasks in advance. Various transport ways and a lot of time for measuring and preparation will be reduced in future through the use of these well prepared documents. The systematical approach of SE therefore was essential to figure out the high importance of these manuals.

The workshop manager at the site is responsible to control all written service and repair reports more accurately in order to increase the quality of the documentation and administration of the machine maintenance at the site. Also workers are now aware of the high importance of their working reports in order to contribute to a total improvement of the maintenance process. The used machine administration tool will contribute to a much better overview of all performed service and repair tasks of the tunneling vehicles and equipment. It is now possible to have an exact overview about all maintenance tasks in a chronological sequence.

Furthermore the use of the database prototype leads to a higher transparency of all caused costs (labor costs / spare-part costs) for the different maintenance tasks. It is possible to plan and steer the service and repair tasks much more efficient. Through proper documentation it is also possible to develop a better order and release system for needed spare-parts of the machines. As a result exceeded service intervals of machines and supply shortages of spare-parts should be a thing of the past.

5.1 Summary

The SE concept of Hall-BWI was used within this thesis and guided systematically to the final results. The theory of maintenance helped to understand the importance of preventive and reactive maintenance. Furthermore it was very helpful to see the positive influence of Kaizen and Total Productive Maintenance (TPM) regarding existing maintenance processes. The theory of Systems Engineering on the other hand was essential to understand the different system elements and tools, which were used within this thesis, to elaborate this complex task.

The methodical process of system-thinking helped to increase the total overview of the entire maintenance process of the tunneling machines. Various problem solving cycles were made in order to improve the overall efficiency of the machine maintenance at the workshop of the tunneling construction site Solbakk. The top-down approach therefore was an essential tool to keep the needed overview at all performed steps within the different phases of the project. Furthermore, the structured building of variants was used to figure out many possible solutions or even variants for an improvement of the maintenance process. Especially the tool of the morphological scheme was very helpful at this point. Additionally the different balances of arguments were used to gain more information about the different variants and for the comparison of them.

Different tools like the scaling matrix or even the weighting of objectives were used. It was possible to figure out the most important aspects concerning an increase of efficiency for the maintenance process. The use of the value benefit analysis helped to compare all different variants with each other in a clear way due to the good traceability of the gained results. Additionally graphical interpretations were very helpful to illustrate the importance of each variant. Due to the structured proceeding it was possible, even for unexperienced employees, to understand the gradual development of the chosen variants and implemented prototypes.

The structuring of the project into different project-phases helped to deal with the overall complexity. At the preliminary study, the proceeding of the top-down approach and the method of system-thinking was used. As a result it was possible to keep the overview of the complex system. Additionally it was very valuable to develop various BPMN for different maintenance tasks. Through the analysis of these BPMN it was possible to figure out existing difficulties. In teamwork, various improvements for existing maintenance processes could be established.

Out of various detected difficulties and existing problems at the preliminary study different solutions or even variants for improvement for the maintenance process of the workshop unit could be developed. Ten variants, which seemed to be the most successful, were analyzed and a rated within the main study. Afterwards the three best variants were chosen and developed further in different detail studies. For each of these three variants a prototype was developed and introduced directly at the construction site Solbakk.

All three prototypes can be seen as successfully developed and introduced at the workshop unit of the construction site. Additionally they have a high potential for further improvements and can lead to notable cost savings of future maintenance processes. Even the possibilities to transfer these prototypes to other construction sites all over the world make these prototypes very valuable for the company.

5.2 Outlook

The implemented prototypes for a more efficient machine maintenance process at the tunnel construction site Solbakk will be used and developed further in the future. The high potential for improvement of various processes was shown within this thesis and the gained knowledge will lead to more economic and efficient machine maintenance processes. The elaborated prototypes will be used additionally at other construction sites in the future to achieve a higher efficiency of the maintenance process for the tunneling vehicles.

The topic of Systems Engineering will gain much more importance in the future due to the possibility to deal with high complex tasks and projects in a very structured and systematical way. The methods and tools of SE therefore are essential and very helpful to figure out many suitable variants or even solutions.

The administration and documentation process of the machine maintenance will be controlled by the responsible workshop manager. It is important to use the developed instruction manuals in order to deal with the multinational workshop members, who have different levels of experience and qualification. Also the strict control of the hand written working reports is essential to achieve a good traceability of all performed maintenance tasks. Furthermore, the task of the administration of the machine hours will be done by the responsible employee, who is greasing and tanking the machines at the site. The responsible workshop manager will use the prototype of the machine administration tool and therefore the total quality and efficiency of the maintenance process will increase a lot. It would be even possible to develop a more advanced database for the maintenance administration in the future. But this decision has to be made by the responsible workshop management.

There is even room for improvement for other variants of the machine maintenance process, which were developed within the main study, but not focused further within this thesis. To focus also on these variants for improvement by the development of further detail studies and problem solving cycles could additionally increase the overall efficiency of the maintenance process. There is still a lot of potential for improvements and the challenge is to develop the most successful variants, in order to achieve a more efficient maintenance process. Teamwork and Systems Engineering therefore will be the buzzwords for success.

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[DIN 31051] Grundlagen der Instandhaltung – DIN Deutsches Institut für Normung

List of illustrations

List of tables

Appendix

Appendix 1: Example of a tool list of an instruction manual

GIPO stone crusher - crusher plates changing manual

1) Tools needed

- Truck with crane (Volvo)
- Compressor (Atlas Copco)
- Enough air hose **(Check the compatibility of the connections: compressor / hose to hose / impact wrench)**
- Garden hose (for washing)
- Large air-hydraulic impact wrench
- Wrench (size 46)
- Nut (size 46) for the air-hydraulic impact wrench **(check the compatibility of the nut and the impact wrench)**
- Scraper (for removing dirt of the nuts)
- Slippage (to ensure working safety when climbing into the crusher)
- Lubrication spray
- Chain – double hanger with back-holding
- Crowbar
- Small shovel (for removing the dirt from the conveyor belt inside of the machine)
- Toolbox **(with large cable strap!)**
- Steel brush
- Wooden pallet

2) Persons needed

One authorized crane driver and two well-educated mechanic workers.

3) Short introduction of the machine

Identification: GIPOBAC
Type: B 1385 FDR-PB / Serial number: GB 731879
Year of manufacturing: 10 / 08

Figure 1: GIPO stone crusher

Appendix 2: Example of instruction manual

GIPO stone crusher - crusher plates changing manual

Figure 17: Removing of the nuts and washers

When all nuts, washers and conical plates are removed you have to uncase the conical cotters from the outside of the crusher. For that work you have to use a crowbar. This process can be seen in figure 18.

Figure 18: Removing of the cotters

When all cotters are removed you have to clean the whole area. Especially the area where the chain will be hanged in has to be very clean! Take the crowbar to remove the dirt.

Workshop Manager:
Jakobitsch Andreas

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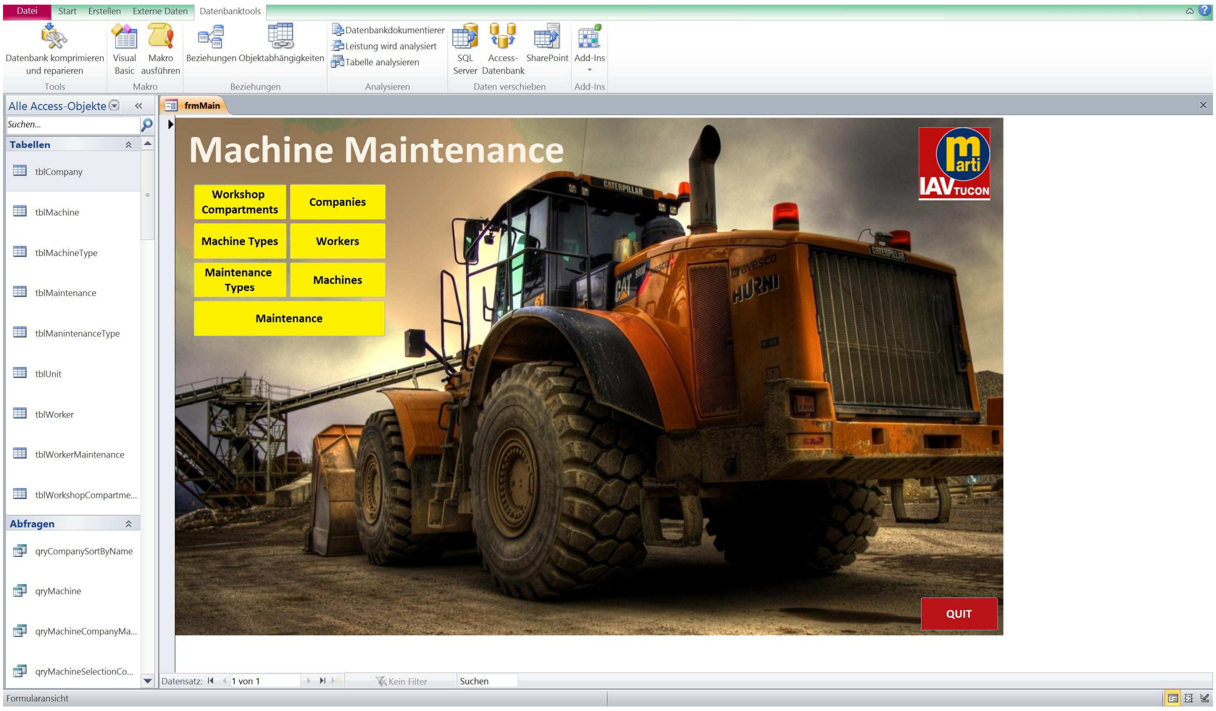
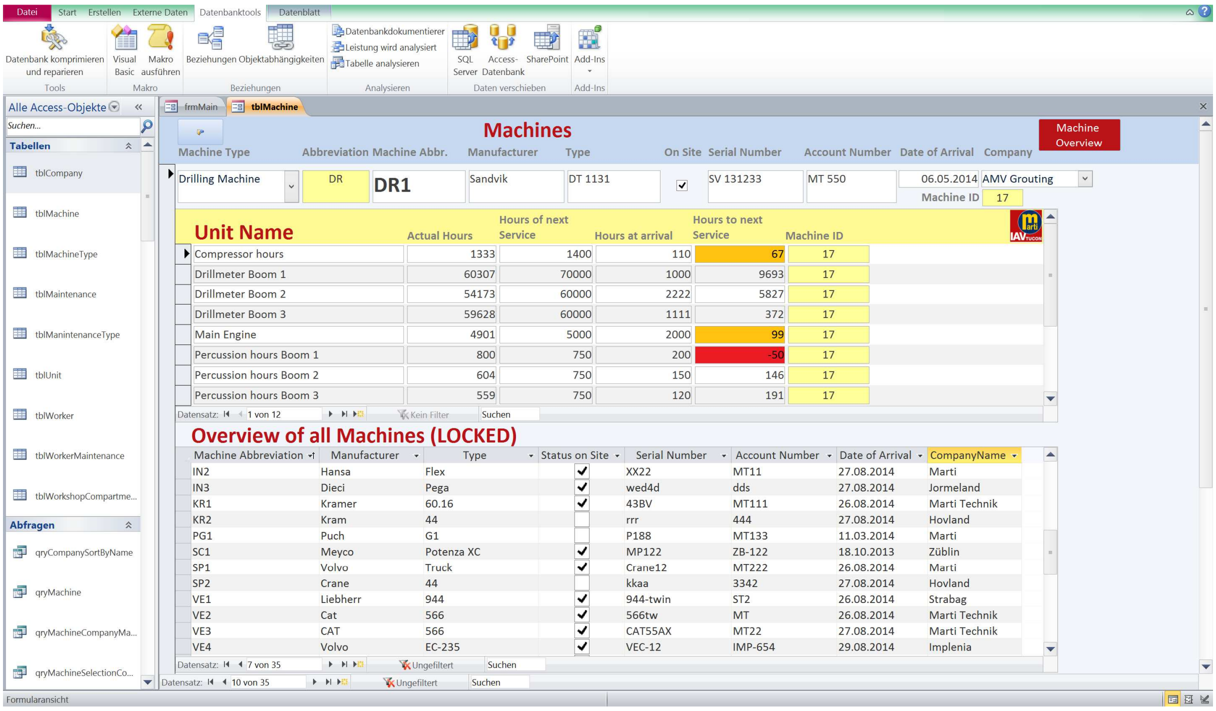
Appendix 3: Overview of the database prototype

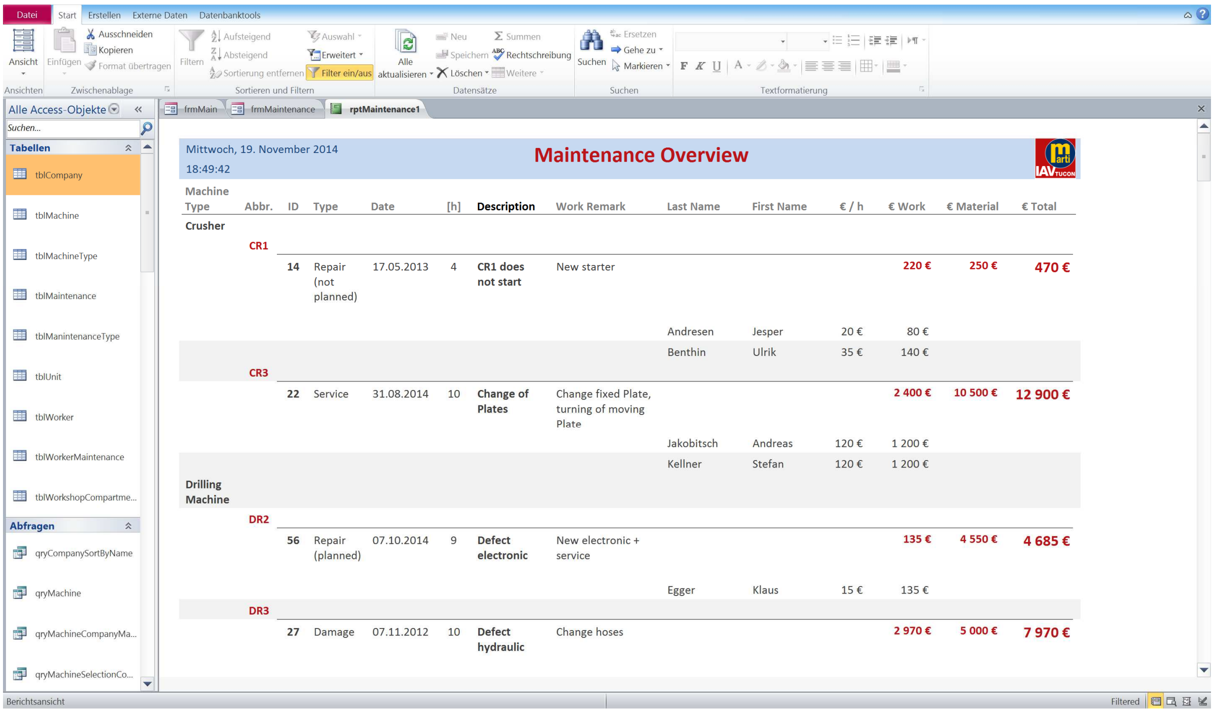
Main menu:



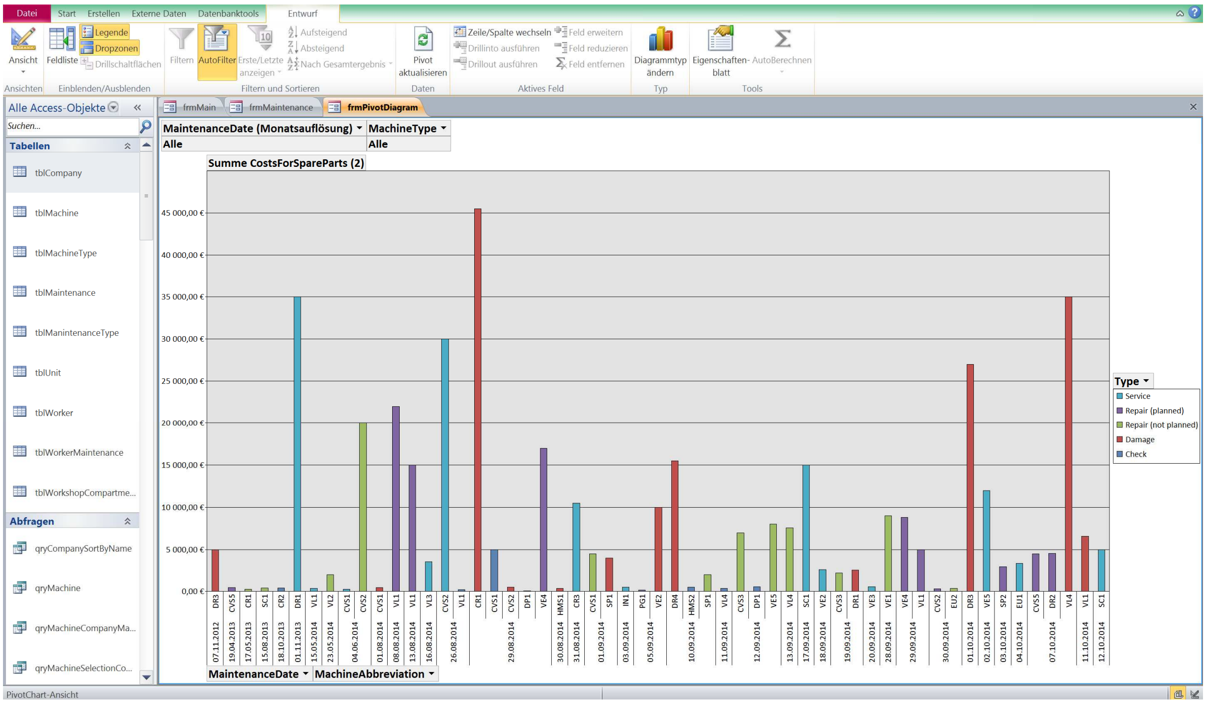
Machine menu:



Example of maintenance report:



Distribution of costs for maintenance:



General overview of maintenance: