DEGREE PROJECT FOR MASTER OF SCIENCE IN ENGINEERING
MECHANICAL ENGINEERING WITH EMPHASIS ON INNOVATIVE AND SUSTAINABLE PRODUCT DEVELOPMENT

Electric-driven Compaction Equipment Assessment: A Sustainable Lifecycle Approach

Emil Pettersson | Simon Hellgren

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In cooperation with Dynapac Compaction Equipment AB

Supervisor: Massimo Panarotto, Department of Mechanical Engineering, BTH
Abstract
Global warming, sustainability and human health are matters of rapidly increasing impact. Industries in mall markets are adopting the triple bottom line mindset, breaking the traditional focus on financial drivers by also including environmental and social value, leading to great progress with renewable energy and sustainable solutions. Despite these growing trends there are some industries falling behind, one being the Construction Industry, or more specifically, the Asphalt Compaction Industry. It is to a large degree left in the traditional ways and aside from a few examples, efforts to break these trends are rarely seen. Dynapac Construction Equipment AB attempted to do so in 2011, when they developed a concept roller powered by electricity. The concept was terminated early on and therefore never advanced from a concept stage. With the steadily increasing focus on renewable power and great advances in the electric drive technology new attention has been brought to the matter. This thesis study aspires to elaborate the value of electric compaction vehicles by assessing it against a diesel equivalent while including environmental and social factors in a Total Cost of Ownership calculation. The evaluation is done against four generalised, diverging markets, Sweden, South Europe, North America and Australia.

The evaluation is initiated by a qualitative approach to identify important customer value drivers. A transition is made from a qualitative to quantitative state by composing a functional model where functions and components are connected to associated value. Most the models are constructed in Excel™ and crossed with alterable input data promoting experimentation and simulation of different potential scenarios. Both for diverging markets and future projections. To further the study a concept development phase was added where attention is brought to the potential of utilizing a TCO for improvement purposes. Areas of big impact in the evaluation can be identified and targeted for optimisation. Three concepts are proposed and included to be assessed through second iteration of the TCO. Finally, the most promising concept, a Software based solution is defined further and presented in a bill of materials. Results and input data were validated against people possessing expertise within the asphalt compaction industry.

The evaluation shows that the electric roller, despite its initial investment price surpassing its diesel equivalent by 20 000 Euro, is cheaper in a TCO perspective in all markets. The experimentation phase yielded a set of particularly favourable scenarios and showed that the electrical roller is not beneficial when used in operations exceeding its estimated battery life.

Despite the general model used for the study being tailored for asphalt compaction vehicles it is applicable on other research fields, both as an argument towards the increase of renewable solutions and as the methodology which can be applied in assessments in other markets and industries, taking intangible factors into consideration.

Keywords: Total Cost of Ownership, Electric Vehicles, Construction industry, Asphalt Compaction, Sustainability, The triple bottom line.
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Preface
This thesis has been conducted in association with the Department of mechanical engineering, at Blekinge Institute of Technology, as the last examination for the Master of Science degree in Mechanical Engineering with emphasis on Innovative and Sustainable Product Development. The study was carried out in the spring of 2017 in cooperation with Dynapac Compaction Equipment AB.

We would like to state our sincerest gratitude to the individuals acting as advisor and co advisor throughout the study.

First and foremost, we would like to thank our advisor at Blekinge Institute of Technology; Post-Doctoral Research Fellow Massimo Panarotto, for his effortless commitment and guidance throughout the duration of the study. Our many intriguing discussions have provided us with a far greater understanding of the concept of value driven design and of the research process in general.

Secondly to Fredrik Åkesson, Manager of RCE Technology and Application Center within Dynapac Compaction Equipment AB, who has shown great interest in our work and has provided great accessibility in terms of supplying all the necessary information. He has also given invaluable feedback by sacrificing his time for continuous meetings.

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Karlskrona June 2017,

Emil Pettersson
Simon Hellgren
Acronyms
EOL - End of life
ToW - Tank to wheel
WoW - Well to wheel
C2C - Cradle to cradle
TCO - Total cost of ownership
LCC - Life cycle costing
EC - Engineering characteristics
CBC - Customer buying criteria
CBA - Cost Benefit Analysis
TBL - Triple Bottom Line
EVOKE - Early Value-Oriented design with KnowlEdge maturity
CODA - Context-oriented domain analysis
FAST - Function Analysis System Technique
AHP - Analytic Hierarchy Process
IPA - Interpretative phenomenological analysis
TOPSIS - Technique for Order of Preference by Similarity to Ideal Solution
VD - Value Driver
EC - Engineering Characteristic
VDD - Value Driven Design
TBO - Total Benefits of Ownership
CBA - Cost-Benefit Analysis
MADM - multi-variable attribute decision making
1 INTRODUCTION

In the society in which we live today, sustainability has become a common insight. This has made global warming and human prosperity cared for issues. The relevance of these matters has grown rapidly over the years and does not seem to stop. These new trends and advancing research in the electric drive field have made it impossible to focus solely on financial aspects. If you want to succeed as a company social and environmental aspects need to be prioritized.

Literature stresses the importance for businesses to focus on sustainability during the development of new products and services. Triple Bottom Line [1] for example, is a development framework that strives to solve social and environmental problems while adding value to the company and the customers. The original developer of TBL, John Elkington, describes its agenda as:

“... focuses corporations not just on the economic value that they add, but also on the environmental and social value that they add – or destroy.” [1]

In the book “The Triple Bottom Line: Does it all add up?” [2] the current and future in society is further described as:

“... current patterns of wealth creation will generate worsening environmental and social problems, pressures will continuously build on both corporations and governments to make a transition to sustainable development.” [2]

This affects industries of all sectors to lean towards sustainable sources and solutions, something that can be seen in the automotive industry, for example by Tesla [3], one of the companies in the forefront of their field. Replacing fossil power sources is one of the means which sustainability can be achieved. In the research field of electric drive the automotive industry is still considered highly progressive and mature.

The construction equipment industry has not yet shown the same general progress in terms of use of renewable resources for vehicle propulsion. The industry is characterized by big and heavy machines, which makes the reduction of fuel consumption of great significance to promote sustainability while reducing total costs and increasing attractiveness for customers. Furthermore, noise levels can be drastically reduced by electric drive, thus providing health benefits workers and other humans in close contact with the machines. To some degree, e.g. the recent advances of Volvo Construction Equipment, with their electric load carrier concept [4], represents one of a few breakthroughs in this industry. The concept replaces the conventional load carriers with autonomous machines powered by electricity. However, electrical drive has the potential to further contribute to sustainability by a larger scale than load carriers.

The construction equipment industry is probably one of the sectors that has not yet fully explored the potential of vehicle propulsion and transmission by electricity. This is mainly because this industry is and driven by short-term financial decisions. Companies within the construction industry are therefore focused on revenue in the present rather than in the future. This makes development of “radical” technologies difficult. [5] For example in 2011 Dynapac Construction Equipment AB developed an electric concept roller, (a) in figure 1, next to its diesel equivalent, (b). A concept which generated interest among affected stakeholders on an initial stage but was however never introduced to the market. The solution was presented with
the statement to reduce operational costs but was halted due to the high investment cost and limited technology. New attention has been geared by the new developments in the electric drive technology and the potential of increased regulations in terms of sustainability. When competitors and similar markets are advancing, all companies need to follow.

![Figure 1. Dynapac CC900E (a) & CC900 (b).](image)

Literature [6] stress the importance of displaying potential financial improvements to drive innovation in companies focusing on financial growth, such as the compaction industry. In a sustainability context, it is necessary to quantify the financial benefit of more sustainable product concepts. The electric driven concept for example was never introduced to the market, because it was difficult to argue for its financial improvements in terms of environmental and social aspects. No studies on the application of this type of technology has been performed in the asphalt compaction equipment sector. However, many studies have been done, including Total Cost of Ownership (TCO) lifecycle calculations comparing conventional cars and school buses with electrically driven alternatives [7], [8]. A variety of these TCO studies are also available on various other markets, including aero-engines [9]. Nonetheless, these are of specific examples that in many cases merely analyse cost. Hence, decision makers at Dynapac Compaction AB lack a sound information basis to develop and introduce the electricity-driven roller. The thesis will aspire to compare the mentioned electric roller concept with its diesel equal. Even though this study will describe an example of implementation on compaction equipment the intention is for the result to be intangible on different industry and organisation sectors, this with the focus on renewable sources with electric drive.

### 1.1 Objective

The purpose of the study is to compare the value and cost provided by a conceptual electric asphalt compaction roller against a diesel driven alternative. The study has the objective to measure financial, environmental and social benefits in a Total Cost of Ownership [10], covering four main generalized markets, all with different conditions and preferences. By targeting differentiating segments a projection of how the benefits affect diverging markets can be generated.

The next step of this study, is to focus on further improving the value provided by the CC900 and CC900E. This part of the study focused on the development of novel services that can be combined with the rollers. These product/service combinations have the purpose to increase the value of the rollers for customers and society at large.
The overall objective of this work can be summarized as the following aim:

“To further elaborate the value of electric asphalt compaction vehicles compared to conventional gasoline based alternatives.”

1.2 Research Questions
The main purpose of the study is to find and quantify parameters which represent the cost of financial, environmental and social aspects differentiating diesel and electric driven asphalt compactors. To satisfy this aim the following question was composed:

“What environmental, economic and social factors are affected, and how, when replacing a diesel-powered asphalt compactor with an electrical alternative?”

To further the study, and show how the assessment can be utilized for new optimization opportunities, the project was expanded. The TCO was used to identify potential obstacles, preventing adoption of the new concept. An additional research question was therefore composed as a complement:

“Furthermore, how would an integrated service concept promote the value provided by the compaction vehicles?”

This research question allows for exploration of service alternatives which can improve the result of the study and provide additional research value.

1.3 Expected Outcomes
A successful study would present an equal comparison between electrical and diesel alternatives in the compaction equipment industry. The assessment would prove whether the drawbacks of diesel powered vehicles or equipment in comparison adds up to an indisputable argument for a change to be made.

The study means not only receiving results which are knowledge-based, but using tools to develop a general method which can be implemented on similar problems. The study should display results mirroring reality in terms of practice. The output of the study will be a foundation on which decision-making regarding rollers of different power sources can be argued for and developed by.

Society as whole will be able to benefit from the research. This from high quality infrastructure to the least possible impact on the environment. Electrical compaction equipment may not only benefit the environment, but potentially additional sustainable aspects all resulting to promote financial factors. For Dynapac, successful research in the field would build a foundation for further development. Economic and environmental benefits would act as arguments and contribute to a strong development in the field.

As students, we see this as an opportunity to learn. The project will cover our area of expertise and give us the opportunity to use this expertise and develop it for our future work. Electric vehicles in general will probably be a big part of the future, which makes being a part of the development of them exciting.
2 RESEARCH METHODOLOGY

The following section of the report will represent an overview of the methodology utilized in the study. Hence, focus on the “how’s” rather than the “what’s”.

Figure 2. Overview of the Design Research Methodology [9, p.15].

Figure 2 above illustrate the general process which the study is conducted with. The bald arrows represent the main process, the light represents iterations in the process [11, p.14]. The description and picture does not consider the fact that many iterations and some stages are worked on in parallel [11, p.17].

2.1 Research Clarification

This stage is the part of the study were grounds for assumptions are sought for. This is mainly searched for in previous research; books, journals, articles, etc. From this result boundaries are identified for which the upcoming parts of the study is conducted. This makes for a picture of the problem, thus transforms assumption made decisions into fact based one's. [11, p.15]

Literature Analysis

From the problem described verbally by company contact, the process of identifying existing research of interest was directed. The process involves clarifying problems solved and unsolved in the matter [11, p.44]. An understanding of the explored and unexplored space of the topic was needed to ensure that the study is relevant. This information sets the foundation of which the boundaries for the study is established. These boundaries in turn direct the literature review and the other way around [11, p.52].

The following steps are suggested in the book; “DRM, A Design Research Methodology” [11] to quickly determine validity of a paper:

- Read the abstract.
- If the abstract is interesting, then read the introduction and the conclusions.
- If these are interesting and relevant, then read the results.
- If these are relevant read the background, objectives and setup.
These steps have been applied to cover large quantities of research at a fast phase. In the study, approximately 60 research papers, articles and theses was used.

The literature study was conducted from a critical perspective. It is important the information’s gathered are based on facts and not assumptions [11, p.52-53]. When looking at literature information that had clear grounds was prioritized, it was also important that the information is not influenced by external factors [11, p.52].

2.2 Descriptive study I
The main goal of this part of the study is to clarify which aspects of the study that is crucial for its success. The study now needs empirical data to validate the research that was done in the previous parts. This generates a further precise problem formulation. [11, p.16]

Input data
The input for the study was composed after research where the road construction industry was considered in several countries which were later clustered and assigned into groups depicting generalised markets. In addition, the information gathered was validated and further developed by conducting interviews with Dynapac representatives, with market expertise offering insight into potential customer value drivers and construction expertise to help shape valid hardware characteristics. The initial information was gained through individual interviews with the representatives, while the later validation steps consisted of 20-30 interviews each.

Initially all interview subjects were targeted within the Dynapac organisation to secure the scope and goal of the study. People with areas of expertise in areas such as market research and construction were chosen to provide the information necessary in respective part of the study.

As the work progressed more tiers were targeted and in addition to the experts already involved several “customers” were included. These customers were actors within the road compaction industry.

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Number of interviews</th>
<th>Organisations</th>
<th>Occupations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial information</td>
<td>20-30</td>
<td>Dynapac Asphaltsbolaget</td>
<td>CEO</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Site manager</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Roller operator</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Construction engineer</td>
</tr>
</tbody>
</table>

2.3 Prescriptive study
In the prescriptive study, adequate information to reformulate the problem formulation is acquired. The formulations now include a prediction of the sought result. In this stage, it is possible to choose which design aspects of which to focus on to develop a conceptual design. This design support is evaluated against the assumptions made in the earlier stages. However, this is not enough to prove its success as the information needs to be evaluated. [11, p.16]
Evaluation methods
To comprehend lack of information in the beginning of the study, it will begin with qualitative methods and transition into quantitative progressively. Steps of both the qualitative and quantitative approach are iterated multiple times. The upcoming paragraphs will explain the approach in the matter.

Qualitative approach
The first stage of the prescriptive study is reserved for a qualitative assessment. This is done with the aid of evaluation methods, promoting the handling of subjective value. The goal of the stage is to achieve an estimation of CBC, Customer Buying Criteria and achieve an approximation of which rollers that suits respective market. Furthermore, what criteria is important to examine in upcoming evaluation.

Quantitative approach
The task of this stage is what one can refer to as a multi-variable attribute decision making. When such decision-making is done, a qualitative approach cannot be considered as the only approach used in the process. The qualitative approach is rather a guiding step towards the correct decision. [12] Thus, a quantitative approach was added. The intention of this stage is to use the information gathered in the qualitative stage and quantify the parameters generated, soft and subjective ones so that they can be measured to depict reality in a common denominator.

Develop and improve
To utilize the new knowledge gained from the assessments and add another dimension to the study new service concepts are created to add value to the current products. Here the TCO model is probed and results pointing to be significant in the total cost targeted. The weak links are used as a foundation in initial brainstorming sessions [13-14] where ideas to eliminate wastes and provide additional value are generated. To find the solution providing most radical improvements the ideas are evaluated with early stage methods before being implemented in the large simulation models. Criteria and their impact are connected to the results gained from the TCO to identify the optimal concept. To further realise the concepts and identify the most promising solution a simplified technology roadmap [15] was created, followed by the composing of a bill of materials [16]. These explain which of the concepts that are closest in time to realise, respectively components that are needed and the cost of these.

2.4 Descriptive study II
The descriptive study II, like the first one aspires to evaluate with data. In this one empirical data is sought to assess the applied solution. The conceptual design needs to be evaluated based on empirical studies. The practitioners ensure that the problem formulation is fulfilled by the design and that it solves this problem. [11, p.16-17]
Quality and validity

The validation/evaluation and quality insurance of this assessment was done using triangulation. This method embodies the use of multiple ways of approaching validation. It uses a combination of qualitative and quantitative methods to achieve a superior result. [17, p.602]

One of the advantages of applying triangulations is its multi-purpose. You can use it generally to ensure your confidence of result [17, p.608]. In this assessment, it was used multiple ways; e.g. input-, output- and concept-validation. What one want to achieve is validation from these sources pointing in the same direction.

More accurately three different evaluation approaches were used in this assessment:

- Dynapac expert opinions are used as a qualitative validation method.
- Customers comparing our new concepts with the assessed rollers.
- External experts evaluate the TCO calculation the input data.

Table 2. Clarification of validation substance.

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Number of interviews</th>
<th>Organisations</th>
<th>Occupations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st input validation</td>
<td>15-30</td>
<td>Dynapac</td>
<td>CEO</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PEAB</td>
<td>District Manager</td>
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<tr>
<td></td>
<td></td>
<td>Smaller contractors</td>
<td>Site manager</td>
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<td></td>
<td></td>
<td></td>
<td>Construction manager</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Product Marketing Manager</td>
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<td></td>
<td></td>
<td></td>
<td>TAC Manager</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Roller operator</td>
</tr>
<tr>
<td>2nd input validation</td>
<td>10-20</td>
<td>Dynapac</td>
<td>NCC</td>
</tr>
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<td>PEAB</td>
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<tr>
<td></td>
<td></td>
<td>Smaller contractors</td>
<td></td>
</tr>
<tr>
<td>Result Validation</td>
<td>10-20</td>
<td>Dynapac</td>
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<td>PEAB</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Smaller contractors</td>
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</tr>
</tbody>
</table>

To achieve the triangulation the applications mentioned above was conducted using both sent forms and in person interviews. Forms and interviews are designed to let the participants explain their related expertise in the matter, get a brief anonym description of the problem then answer a couple of short questions. All the participants in the studies exceeded five years of experience in their field of work. This was not a requirement for the study, but increases the validity of the result. The duration of the interviews varied from ten minutes to an hour, notes were taken and reviewed subsequently.

The assessment, primarily the TCO-model is also validated by sensitivity analysis through the Morris method [18]. This method aspires to evaluate input factors and the effects of their alteration; how sensitive they are to change. This is done using a one-factor-at-a-time approach. The result from this will be the importance of factors and if factors behave correctly within given model. [18] In this assessment the method of Morris was applied mainly to the functional
model within the TCO-model. The method made sure that calculations behaved the way they were supposed to at a variety of inputs.

3 KNOWLEDGE DOMAINS

3.1 Product development

When presenting product development, Ulrich and Eppinger describes it as “the set of activities beginning with the perception of a market opportunity and ending in the production, sale, delivery of a product”. In their book, they present the product development process in a generalized manner consisting of six phases; Planning, concept development, system-level design, detail design, testing and refinement and production ramp-up. They also refer to five important aspects defining successful product development. Product quality, product cost, development time and development cost are used to assess profit of the work. Ultimately the goal is to provide maximum value to the customers by identifying and meeting their needs in a time- and cost efficient manner. [19]

Collopy and Hollingsworth [20] describes value-driven design as “a framework against which methods, processes and tools can be assessed”. It is an approach used in design decision making to not only choose a solution that meets customer requirements but to choose the design that produces the highest monetary value throughout its entire lifetime. In other words, “The best design” [20]. By creating a “measurement” for the perceived value brought by different criteria from the customer’s perspective, solve trade-offs and explore several potential solutions, resulting in the optimal concept. [21] Further Collopy and Hollingsworth states that improving objective, monetary functions will result in the optimal design [20].

3.1.3 Concept development

The ideal way to go about the generation of ideas and concepts is to diverge - converge multiple times, which is illustrated in figure 3. Numerous cycles of this will generate many ideas at the developer’s disposal. The selection of ideas should be at low detail and preferably with illustrations displaying the thoughts surrounding them. When continuing with ideas to concept selection it is hard to grasp and consider a large quantity of ideas and concepts. Ideally five to twenty ideas are advanced to the next level of consideration. These are then elaborated in terms of detail to make a comparison dependant of certain criteria to sift the solutions. [22, p.346-347]

![Figure 3. The overall design process. [23, p.187]](image-url)
Developing solutions nowadays, does not mean only exploring physical ones. To further the functionality of a solution services are integrated to the physical product to create a combinational system; Product Service System. This kind of solution requires the developer to lean towards managing the usage of the product rather than just selling it. A PSS promotes the developer to immerse the value that the solution brings to offer the customer by an overall enforced system. [24]

3.1.4 Concept selection

In concept selection and the refinement of solutions, designs can be included, excluded or combined depending on requirements [22, p.349]. There are a big variety of methods to choose from (e.g. Decision matrices, external decisions, etc.). All practitioners have their own way of going about the process, whether this might be simply selecting the first concept thought of [19, p.145]. Structured methods for concept selection has many benefits. This is often done in two stages; concepts screening and scoring, both of which are done with decision matrixes based on weights and criteria [19 p.148-149].

When selecting concepts this can be done using intuition, experience or just doing an arbitrary choice. The requirements for this is often subjectively chosen which can result in promising ideas being sifted [22, p.349]. To make this more trustworthy the practitioner can use more rational methods. The selection of a concept can only be done when comparing its effects to the purpose of the sought design. It is important when evaluating concepts that differentiate to do so with criteria that embrace the positive and negative aspects of the concept. This makes a comparison possible on common grounds for its achievement of the overall objective. [23, p.139]

Apart from the more traditional values of measurements; “hard parameters” (e.g. costs, risk, performance, etc.) applied to criteria’s, nowadays you must consider “soft parameters” such as (e.g. knowledge, emotions, etc.). When considering design decisions, it’s harder to influence it with “soft parameters”; engineers are used to work with numbers in this forum. However, the problem can be solved by converting the “soft parameters” to a cost or income for the specific design. This can be done with the integration of quantitative value models (e.g. Total Cost of Ownership or Cost-benefit analysis.). [25]

3.2 Modelling & Simulations

In product development knowledge-based decisions are central. The knowledge regarding a problem is usually limited at the beginning of a project. As the work progresses more information regarding the problem is generated but as can be seen in figure 4, in the same process development cost is constantly rising and design freedom decreasing. [26]
To escalate the knowledge obtained in the early stages of product development modelling and simulation can be applied. This means product attributes are illustrated and evaluated through experimentation to assess and enhance these features from multiple standpoints in an early stage of the development process. Johan wall [26] builds his thesis on the definition by Sellgren [27] who describes simulation-driven design as “a design process where decisions related to the behaviour and the performance of the design in all major phases of the process are significantly supported by computer based product modelling and simulation” but further develops this statement to apply the same methodology on the optimisation of solutions in early design phases. [26] An illustration of the potential benefits of this approach can be seen in figure 5 below.
3.2.1 Virtual models
As physical experiments often require much time and monetary resources virtual simulations can be used to promote innovative outcomes rather than becoming halted by the obstinate, traditional designs that may originate from physical prototypes under limited resources. With the advanced technology of today models, simple or complex, can easily be built and simulated and analysed with multiple aspects using computer software. The virtual approach also promotes parallel experimentation, where multiple designs can be assessed iteratively while avoiding early commitment to specific concepts, which is illustrated in figure 6 below. The parallel approach also promotes the identification of potential failure, thus enabling enhanced knowledge and potential of improvements. [26]

![Figure 6. Parallel experimentation. [26, p 9]](image)

3.3 Methods for concept selection/assessment methods
Early in the process of product development, where there are still many assumptions at play, the qualitative methods are to prefer over quantitative ones. [28] The qualitative methods are better at generating early stage reference to compare designs. With qualitative methods handling “soft parameters” (i.e. ergonomy, safety and environmental aspects which can be hard to measure.), of a design and foreseeing their cost can be easy, this is proven difficult with the quantitative methods. [29, p.201] In the later stages of the design process when information increases both in quantity and quality; the quantitative methods are to prefer when conducting monetary assessments [25].

However, [28] argues for the need to use both qualitative and quantitative methods in decision making with an evaluation approach on more complex solutions. Qualitative methods used mainly assumptions to argue for the benefits of different aspects of the assessed solution and thus the weight of these different criteria can be obtained. This gained knowledge can then be used along with quantitative methods, where “soft parameters” are quantified into measurable units such as time or cost. [25]

3.3.1 Qualitative methods for concept selection
In product development, the most popular methods for concept selection is decision matrices. With adequate requirements to the design space the practitioner can select concepts efficiently with these. [30] The upcoming paragraphs with explain the decision matrices considered in the study and the arguments for including or excluding them in the process.
Pugh
The Pugh-Matrix is what is refer to as a decision matrix [29, p.148]. The matrix is a decision making tool which aims to benchmark and compare solution based on criteria’s, hence provide a qualitative ranking [31]. This is both the strength and the weakness of the Pugh; the method does not direct the practitioner to the solution that is optimal for the customer, rather the optimal one in this specific alternative that are benchmarked [25, p.44]. The Pugh-Matrix is also heavily dependent of the customer's preference [31].

IPA based method with TOPSIS
The method that is referred is tailored to fit early stage development of a PSS. The method consists of two phases; Pugh- and TOPSIS-matrix. [32] What differentiates the method from other alternatives is the criteria’s which are categorised in terms of customer and provider. The method aspires to aid the practitioners to make correct design choices early, thus not having to pay the penalty of changing design in the later stages of the process. [33]

AHP
AHP is a decision support tool that is referred to as a multi-criteria decision making approach. The tool can be applied in the product development process to solve complex decisions. AHP uses Pairwise analysis to create grounds for which comparisons can be made; weighted criteria’s or corresponding. [34]

A downside to the tool is the uncertainty of the result when the valued criteria represent when they approach indifferent values, as a matter of fact: the closer the values are to each other, the more uncertain the practitioner should be. However, this can be fixed with additional criteria’s which differentiates the result. [34] Another downside to the AHP is the requirement of redoing the process when new alternatives are introduced to the process. Apart from the time needed to implement the new alternative in the AHP; the old criteria are changed based on the new ones introduced with the alternative, which implies other issues. [35]

Quality function deployment
Quality function deployment is a general tool for achieving the step from customers’ needs to quantify technical engineering characteristics of a product [36, p.463]. The QFD is sometimes referred to as an upgrade of the Pugh-Matrix that is mentioned in a section above [37, p.59]. QFD is used as a design-in tool, rather than an inspect-in tool. This means that rather than having a product that you want to inspect and make better, you can use it to develop new ones based on customer needs [36, p.469]. This makes QFD a valid tool for decision-making; in this field, it is used to make analysis based on customer and market preferences [36, p.470].

EVOKE
EVOKE is a concept development tool mainly used to assess value amongst different concepts and to aid the user in concept selection. The tool can compare, benchmark and simulate a variety of concepts on the same plain field [38, p.3]. Customer buying criteria - CBC, or value drivers - VD, are put up against hardware attributes called engineering characteristics - EC. By utilizing the ability to define element parameters as optimal and neutral the input generates a so-called design merit value. As a percentage, this illustrates the quality of each characteristic value of respective solution with 100% regarded to be the result of an ideal concept. The design merit usually reacts differently to changes on various value drivers so the ultimate task is to identify the compromises achieving the maximum total score in terms of all summer up design merits.
The method of EVOKE is especially favoured when evaluating complex products (i.e. solutions involving many interfering systems and designed by many corresponding teams.). [38]

**QFD vs. EVOKE**
Both tools aim to create a relation between customer needs and engineering parameters [39]. The main difference between the QFD and the EVOKE in terms of this relation is the mathematical assumptions behind it. The QFD uses a linear approach, as the EVOKE embodies a non-linear. The non-linear functions depict reality in a preferable manner. Another point that differentiates the QFD from the EVOKE is the lack of design optimisation. QFD does not vary input value to record the trade-off a certain design. [38, p.11-12]

**Number of criteria’s**
The result of AHP and likewise methods differentiate very little when comparing different number of criteria [12, p.519]. TOPSIS and methods alike are different from AHP-like methods. These tend to have better result dependant on the number of criteria used. The optimal number of criteria is around 20 [12, p.519].

**Technology Roadmap**
A technology roadmap [15] can be applied to a project to structure and depict activities and relationships within e.g. applications and technology. The methods promote decision-making through improved activity coordination and planning. It can be used to locate and define possible objectives and in turn identify sectors with the highest potential.

**Bill of Materials**
Depending on the application a bill of materials can take different shapes, the archetype used for manufacturing differentiates from the one used in design of a product. A design BOM usually consists of larger subsystems as the manufacturing one is structured of the subsystems and their parts included. What they have in common is that they are used to display what components or raw materials that are needed to produce a product. The list generally includes two building blocks; items and relationships. The items are as mentioned a component or raw materials that are a part of the complete product. Relationships are a way to display the items connection to the holistic product (i.e. quantity of the component needed, component hierarchy in the product structure). A BOM can also include product definition, engineering change control, manufacturing instructions, order entry facility, costing and pricing. [16, p.3-4]

### 3.3.2 Quantitative methods for concept selection
As a project progresses and the knowledge-based extends with improved data quality the possibility to apply a quantification of value contributors into a monetary denominator. [40] By defining the provided value in economic terms it is easier from an engineering standpoint when comparing value and considering trade-offs. In addition, the monetary metric it is easier communicated to other actors or decision-makers connected to the work. [25]

**Cost-benefit analysis**
Cost-Benefit Analysis - CBA [41] can be used to weigh positive and negative financial aspects of a solution, e.g. to assess potential risk and uncertainty or potential advantages of an investment related decision. [42]
**Total Benefits of Ownership**
Total Benefits of Ownership - TBO is an evaluation tool assessing potential benefits of the implementation of a solution or decision. [41-42]

**Total Cost of Ownership**
An approach for collective representation of gathered monetary value is the Total Cost of Ownership, TCO. [43] Quantified parameters ranging from investments to operational and disposal costs are calculated and displayed for decision makers to determine what solution is beneficial to strive for. The lack of significant so called “ileitis” in the TCO has led to criticism as it is believed to result in a false representation of values. This gap can however be covered by incorporating soft parameters which are put in equations to generate a quantified measurement that can be included in the model. [25]

**Total Benefit of Ownership vs Total Cost of Ownership**
TBO and TCO share a common basis in the assessed value of an investment and operational costs however they are at opposite sides of the spectrum. The TBO depicts the benefits while the TCO is useful for identifying the increased cost of a solution or system. [44]

**Supporting tools for quantitative modelling?**
A so called F.A.S.T. [45] model can be applied to identify and determine functions within a solution. It is conducted by tracing function relationships breaking it down by reflection in terms of “how and why”. A verb and a noun is used to define each function. [46]

Significant hardware elements can be identified and depicted by conducting functional/structural decomposition. [47] The method consists of a hierarchical structure starting at the main product followed by its components, their subcomponents and so on.

**3.4 Data gathering & Research**
Ulrich and Eppinger [19] writes about three main methods when gathering data. The first being interviews, followed by focus groups and in-use product observations. The amount of research or number of interviews necessary to be conducted for a valid result is discussed and two different studies pointed towards the conclusion that they should be kept within the range of 10 to 50 interviews. One study stated that 90 percent of their primary data was gathered in their first 30 interviews and another one that 25 hours of data gathering had resulted in 98 percent of their applicable input.

Interviews act as a qualitative research approach where subjective thoughts can be obtained and discussed [48]. Together with the external research sources this method allows all aspects of the issue at hand to be considered. According to Kvale, there is no ideal way of conducting an interview. This simply depends on who you are interviewing, what the topic is and the goal of the interview [48, p.77].
4 ELECTRIC-DRIVEN COMPACTION EQUIPMENT ASSESSMENT

The purpose of the study is to assess road compaction vehicles, mainly the concept roller, Dynapac CC900E, using the Dynapac CC900 as a baseline. Four markets are analysed, Sweden, South Europe, North America and Australia. The markets all have different values and standards regarding environmental, social and financial matters and therefore the value provided by the rollers will be weighed differently with regards to the diverging preferences.

4.1 Comparison of diesel-driven asphalt roller (CC900) with electric-driven asphalt roller (CC900E)

Due to a lack of information in the beginning of the study, the began with qualitative methods to identify important drivers promoting value to a customer. After this stage the process transitioned into a TCO quantification of the relevant aspects emerging from the qualitative models. Steps of both the qualitative and quantitative approach are iterated multiple times. The upcoming paragraphs will explain the methodology.

4.1.1 Overall trends and assumptions for the 4 markets considered

Initial research yielded several assumptions and trends for respective market. Table 3 below represents some of the factors studied for the selected targets which will be used as founding preferences in upcoming evaluation steps.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Sweden</th>
<th>South Europe</th>
<th>North America</th>
<th>Australia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment focus</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Environmental focus</td>
<td>High</td>
<td>Medium</td>
<td>Minimal</td>
<td>High</td>
</tr>
<tr>
<td>Safety restrictions</td>
<td>High</td>
<td>Medium</td>
<td>Minimal</td>
<td>High</td>
</tr>
<tr>
<td>Social priority</td>
<td>Maximal</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Image focus</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Minimal</td>
</tr>
<tr>
<td>Quality requirements</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Repair vs. new work</td>
<td>Mainly repair work</td>
<td>Mainly repair work</td>
<td>Mainly new</td>
<td>Varying</td>
</tr>
<tr>
<td>Operator influence</td>
<td>Maximal</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Road application</td>
<td>Medium/Small</td>
<td>Varying</td>
<td>Varying</td>
<td>Medium/Small</td>
</tr>
<tr>
<td>Diesel cost</td>
<td>Maximal</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Electricity cost</td>
<td>Low</td>
<td>Maximal</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>------------------</td>
<td>-----</td>
<td>---------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>Salary trends</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Sick leave benefits</td>
<td>High</td>
<td>High</td>
<td>None</td>
<td>Maximum</td>
</tr>
<tr>
<td>Health care costs</td>
<td>High</td>
<td>High</td>
<td>Minimal</td>
<td>Medium</td>
</tr>
<tr>
<td>Electricity source (CO2)</td>
<td>Minimal</td>
<td>Medium</td>
<td>High</td>
<td>Maximal</td>
</tr>
</tbody>
</table>

### 4.1.2 Qualitative assessment

Figure 7 below illustrates the resulting process for the qualitative assessment. A problem is defined followed by a need finding phase where data was collected through research, interviews and observations. Next an EVOKE was conducted, with criteria gained from a pairwise matrix applied in a CODA model. The results were then validated and the initial stages were iterated before the result was visualised and gathered to support further assessment.

A pairwise matrix was used to generate percentages weighing the impact of each criteria assessed in the study. Each criteria was weighed in relevance to the others gaining a normalized value of its importance. For example, figure 8 below displays that criteria B, low fuel cost, is deemed more important than A, the purchase price, in the Swedish market. This yielded results for a set of VDs depicting the preferences of each respective market analysed per figure 12. The result from the pairwise comparison is then explained in a normalized percentage, illustrated with spider diagrams in figure 9-10 below. For example, the Swedish value drivers indicate that Safety, Reliability and Ergonomy are parameters with great impact for a decision to be made on this specific market.
As figure 13-14 illustrates, several value drivers displayed consistency through the different markets. Reliability, long operating time and user safety were highly prioritised whereas image and upgradability had a notably low impact. The more intangible parameters such as social impact diverged as these criteria showed great importance in Sweden, Australia and to some extent in South Europe, but was in general overlooked in the North American market in favour of drivers pointing towards financial gain.

Figure 8. Pairwise comparison of VDs dependant on geographical location.

Figure 9. Impact of Value Drivers on the Sweden and North America markets.
Engineering Characteristics, EC, were inserted into the model and weighed against the VD’s to identify merit values for respective criteria and the summed up for the complete solutions. When composing the EC’s for the qualitative assessment the aim was to find objective, easily understood elements that are directly connected to alterations in the design concept, for example, the height of the hood, operating mass, torque and rpm. Something that proved to be difficult was to only generate ECs that would make sense on both proposed concepts as the rollers in question had completely different solutions in terms of drive. Therefore, to avoid such bias in the assessment, the authors of this study proceeded in this way: all aspects that were considered relevant to e.g. the CC900 would therefore have to be complemented with ECs covering similar problems in the electrical version. An example of this present in figure 11 blow, is having a fuel tank in one roller and a battery in the other, thus an EC for each of these was included.

The EC’s were implemented accordingly with figure 11 above. An upper and lower boundary is also set describing values that are not possible to exceed.
Figure 12. EVOKE correlations; VD’s/EC’s.

Figure 12 above visualizes an example of how correlations between VD’s and EC’s were mapped in the EVOKE model. A merit value between the EC and VD is generated through correlation accordingly for respective market criteria.

**First draft**

Based on initial assumptions and information received at the initiation of the study the result in figure 13 was generated. The result strongly favoured CC900E on all the markets in terms of merit value. Since the Swedish and Australian markets has intentions favouring sustainable drive, these are explainable. However, the other markets result was found misleading because of CC900E’s superior score on the other two markets. The goal from this point in the study was to reassure that the EVOKE evaluates the two products equally. Thus, if one of the products had a VD or a EC that favoured this certain product, it was secured that it had a counterpart or that the other product had an equally favouring element in the same category.
Second draft

Discussions with the project advisor at Dynapac compaction AB at Dynapac compaction AB made it clear that some assumptions and VD/EC’s in some instances needed to be alternated in the EVOKE. Some of the assumptions were harshly made and the differentiation between some VDs and EC’s were sometimes insignificant and had to be reformulated. New results were generated and are displayed in figure 14 below.

Figure 14. Second draft EVOKE result.
**Final draft**

Following several interviews with Dynapac engineers, yielding market- respective construction-expertise any potentially questionable inputs were reconsidered to produce a final validated result. The result is illustrated in figure 15 below. The result depicts that the CC900E model is favoured in all the market segments. The most favoured segments for the roller in question is the Swedish and Australian market with around 6 percent increase in merit value. On the South European segment the roller has a 3.5 % increase compared and the North American market only 1.45%. This would mean that North American segment would be a bad market to start selling such a roller, but still that it is favoured for future exploitation.

![Figure 15. Final EVOKE result.](image)

The North American market generates low merit on both options mainly due to the lack of priority in the social and environmental factors. These factors are highly sought after in the Swedish and Australian markets which are the ones displaying the highest increase of merit when viewing the electrical roller.

The diesel-powered roller had the best result in South Europe most likely due to the impact of financial aspects counterweighting other criteria. Beyond that fact, accordingly to the value driver distribution it takes the middle ground of the markets in terms of percentage differentiation between the two rollers. In conclusion, this would previse that the market segments that you generally want to focus on per the parameters utilized in this study is the Swedish, South European and Australian.
**Relevant dimensions taken further for TCO calculation**

The Qualitative assessment was used to bring out and identify what aspects in terms of CBC that would be important to take into consideration. The highest scoring, so called, value drivers were selected going further into the work. The most impactful VDs across markets are selected for the upcoming TCO calculations and simulations. The chosen VD’s are highlighted green in figure 16 below.

![Merit value diagram]

*Figure 16. Illustration of selected merit values accordingly with VD’s and respective solution for all the markets.*

All value drivers regarding Safety, Ergonomy and Performance achieved a high score on our readings. The Value drivers; Quiet operations for surroundings, Visibility of surroundings during day and night and Easy manoeuvring are associated with performance and human health, thus a high rating. Furthermore, the value drives regarding reliability, service, troubleshooting and operation time can all be associated with the result of the compaction, without the roller compacting there will be no result.

Some value drivers regarding costs were also highly rated because of their continuous impact; Low fuel cost and Low fuel consumption. However, Low purchase price generally fades in comparison to the others. The purchase price is a small fraction of a result generated over several years. Furthermore, the price of the rollers is consistent throughout markets. The final value driver that was excluded was Image. This VD received a low score because the performance oriented industry, the rollers only criteria in the matter is that they look heavy and robust.
Several lower scoring criteria were also chosen for the next steps of the evaluation as, even though there were less attractive to a potential customer, they were considered important to depict the true value of each product when considering the total cost of ownership or simulating potential changes in future markets. The extra criteria are highlighted blue in figure 16.

VDs regarding recharge/refill speed and compaction performance were not considered important from the customer’s perspective but a reason behind this is most likely since both attributes are currently taken for granted. Customers see compaction performance as something that will fulfil a certain standard no matter what and with today’s rollers consisting solely of petrol driven variants the refill speed is roughly the same. In a more in depth assessment, depicting long-time use, the compaction performance could have a great impact on the result. The fuel refill speed may not influence today’s process in any notable manner but when looking at an electrical drive which may have a battery demanding several hours of recharging time the situation changes drastically. Since only diesel vehicles are used on today’s market with on-demand supply and arbitrary flow of fuel in the fuel pumps, this is not a prioritized value for the customer. The only case where this is to be relevant in for the customer today is on remote construction sites and even on these the team has tank trucks with them.

Environmental impact from fuel production was another VD that did not make the top scoring selection but was also reconsidered and chosen for further work as it has great potential in the future with environmental legislation getting stricter. This was also one of the possible arguments against the CC900E as it shows that the electricity is not 100% emission free when approached from a well to wheel perspective. Therefore, the electrical roller could potentially be less environmental friendly than its diesel opponent in a market where the electricity is produced by unsustainable means.

Lastly upgradability was also chosen for consideration as optional criteria since potential advances in technology and shifting legislation may provide an opportunity for adaptable solutions to be beneficial to the point where you would otherwise be inclined to purchase a new machine. In terms of resources on earth, a pint might come where steel and other necessities to build new rollers are scarce. This would increase the price of a new roller to a point where upgrading existing ones are the only viable option for the customer.

4.2 Quantitative assessment
The illustration below describes the quantitative stage of the study, see figure 17. The process begins with identification of the product structure and then of main components. Together with these components and result from the qualitative process, the functional model is generated. The functional model represents correlations between functions and components, which then is transformed into monetary means in calculations. From this result the practitioners can identify potential problem areas which improvements of the products can grow. This result is then validated and the models are improved. The last step of the process is to display the iterated result.
4.2.1 Combine hardware and functional decomposition and define their correlation functions

To identify and structure the equations to be used in the cost calculation, functional and hardware decompositions were applied. Draw.io™ was used for illustrate the functional decompositions that was implemented into Excel™. The hardware decomposition was directly integrated into Excel™. Excel™ was the main input where these decompositions were combined and correlated to create the Total Cost of Ownership.

![Hardware Decomposition Diagram](image)

**Figure 18. Functional modelling process.**

Figure 18 above presents a simplified overview of the complete process from composing the functional models to presenting the results. Each step is described more thoroughly in the following sections.

**Hardware decomposition**

The hardware components were defined through a hardware decomposition. Starting at the roller the main systems was divided into subsystem groups, e.g. the engine system seen in figure 19 below, and then further separated into the components to be used. The number of elements was limited to stay within a reasonable level for the time frame of the project. Thus, mainly the elements that have a direct impact on the functionality were chosen and in many cases these were subsystems containing several components.

---

As the solutions studied have major differences within their hardware structure two separate decompositions were conducted to support the functional model. To depict the same value despite the structure changes equivalent components were identified fulfilling the same function. An equivalent to the CC900’s engine system can be found in the CC900E’s electric system as seen in figure 20. The fuel tank is replaced with a battery, the combustion engine with an electrical version and so on.

**Functional decomposition**

The value drivers selected from the qualitative assessment were applied in a F.A.S.T. - Functional analysis system technique [45]. By doing so each VD was broken down into supporting functions until the core functions could be identified, supporting the functional model, where they connect with respective hardware component. As the VD applied in the model breaks the traditional structure of activities usually used when conducting the F.A.S.T. method it came to be problematic keeping the usual format, using solely a verb and substantive as function descriptions. The VD in this case is a desired performance, rather than an activity, e.g. the desire to reduce fuel consumption or improve ergonomy rather than a description of a task that is being performed. An example of a finalized VD is the desire to obtain an ergonomic workspace which is fulfilled by the action of reducing worker strain. In turn negative impacts on the worker are reduced by reducing noise levels, toxic fumes and making it easier to view the compaction point without the involvement of non-ergonomic positions. The mentioned example can be seen in figure 21 below.
By combining the flow block model from the F.A.S.T. and hardware models the different parameters identified in each assessed roller a series of correlation functions can be defined. For example, the engine affects the fuel consumption through parameters such as weight, power and efficiency, see figure 22.
The phase resulted in values that could be combined with input data illustrating shifting external factors such as wages, taxes and medical expenses. A large sheet was dedicated for the transitional formulas covering every market and presenting the currently selected scenario before sending the outcome forward to the user interface.

4.2.2 Total Cost of Ownership calculation
From the functional model, it is now possible to generate monetary result. The methodology of transforming a functional value to a cost does in this case always involve either transforming it directly to currency or indirectly by transforming into time. This transformation is done by various methods depending on the functional correlation. This can depend on which of the rollers that are assessed; an electric roller does not consistently have the same functions and components as a diesel one.

Cost allocations and assumptions in the TCO model
The following list describes cost allocations that occur in the TCO model. All the allocations are represented in the upcoming result oriented section of the report. This list exists to introduce and guide the reader in their analysis of the result.

Table 3. Description of cost allocations.

<table>
<thead>
<tr>
<th>Cost Allocation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>The annual amount of fuel consumed.</td>
</tr>
<tr>
<td>Ergonomics</td>
<td>Considers the effect that noise, emissions and operator sight has on the amount of sick days that the operator takes.</td>
</tr>
<tr>
<td>Society Noise</td>
<td>The effect that the specific rollers noise has on nearby society's.</td>
</tr>
<tr>
<td>Safety</td>
<td>Considers the effect that noise, emissions and operator sight has on the amount of accidents experienced in connection to the specific roller.</td>
</tr>
<tr>
<td>Emissions</td>
<td>The cost/gram of CO2-equivalent in the operations of the roller.</td>
</tr>
<tr>
<td>Manoeuvring</td>
<td>The lower cost that faster manoeuvring represents. This is dependent on roller lamp illumination during night, operator sight and weight of the roller.</td>
</tr>
<tr>
<td>Reliability</td>
<td>Considers how often the roller needs to be repaired and then the cost of the repair.</td>
</tr>
<tr>
<td>Interruptions</td>
<td>The amount of time that it takes to service the roller. This includes tanking fuel and water and is dependent on refill flow and size of respective tanks.</td>
</tr>
<tr>
<td>Upgrading</td>
<td>The cost of upgrading the roller. Depends on the options toggled for this cost allocation.</td>
</tr>
<tr>
<td>Troubleshooting</td>
<td>The amount of time that is needed to assess damage when the roller may be broken.</td>
</tr>
</tbody>
</table>
Operations
The time that the specific roller must spend on compaction operations by using a specific force to affect the asphalt.

Initiation Time
The time before the roller can be used each session.

Concept Investment
The initial investment cost of each individual concept that is applied to the model and their circumambient services.

Depreciation
The investment of the roller and how much it degrades over time.

Resale
The resale price based on initial investment and depreciation.

The TCO evaluation, is ultimately composed of several functions transforming all different parameters into one common denominator, cost. The formulas are composed by combining literature studies and assumptions, as can be seen in table 4. Table 4 describes the assumptions and the section after this will describe some calculations deliberately.

Table 4. Assumptions made in TCO calculations.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Description</th>
<th>Unit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Assumptions:</td>
<td>Operator salaries</td>
<td>Sweden</td>
<td>South Europe</td>
</tr>
<tr>
<td></td>
<td>14.59</td>
<td>9.6</td>
<td>18.17</td>
</tr>
<tr>
<td>Fuel Assumptions:</td>
<td>Diesel prices</td>
<td>1.44</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td>Electricity prices</td>
<td>0.73</td>
<td>1.40</td>
</tr>
<tr>
<td></td>
<td>Fuel consumption</td>
<td>The fuel consumption is based on measurements from the CC900 respective CC900E</td>
<td></td>
</tr>
<tr>
<td>Safety Assumptions:</td>
<td>Cost of injury</td>
<td>6761</td>
<td>1970</td>
</tr>
<tr>
<td></td>
<td>Accident probability</td>
<td>Due to a lack of data the probability of accidents was assumed to be equal to the probability of factors within</td>
<td></td>
</tr>
</tbody>
</table>
ergonomics mentioned below. This should be complemented with justified data when possible.

**Ergonomics**

**Assumptions:**
Cost of ergonomics is estimated with foundation in the economic impact brought by sick leave. The sick leave is a result from continuous exposure to pollution, noise and back problems.

**Pollution**
Pollution from roller emissions are based on measurements on respective roller.

**Noise**
Noise originating from vibrations and engine noise are based on measurements from Dynapac and literature. [58]

**Back problems**
Back problems are assumed to be dependent on the operator leaning when having bad vision over the hood. The calculation is based on the resulting viewing angle.

**Sick leave benefits**
A percentage of the worker salaries are applied to illustrate sick leave. The percentages are based on research. [59]

<table>
<thead>
<tr>
<th>Percentage</th>
<th>80</th>
<th>90</th>
<th>0</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Emissions**

**Assumptions:**
Cost of emissions are gathered from use of fuel, emissions from fuel production and component production. These values are then multiplied with an estimated cost of a CO2 equivalent. In addition, an annual adder is implemented to project future changes.

**Emissions from diesel production**

<table>
<thead>
<tr>
<th>CO2/litre</th>
</tr>
</thead>
<tbody>
<tr>
<td>421.4</td>
</tr>
<tr>
<td>421.4</td>
</tr>
<tr>
<td>421.4</td>
</tr>
<tr>
<td>421.4</td>
</tr>
</tbody>
</table>

**Emissions from electricity production**

<table>
<thead>
<tr>
<th>CO2/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
</tr>
<tr>
<td>484</td>
</tr>
<tr>
<td>567</td>
</tr>
<tr>
<td>885</td>
</tr>
</tbody>
</table>

**Cost of CO2**
32 Euro per ton CO2 and an annual adder of 1 € per ton CO2 is initially used for the calculations, based on literature. [60]

**Manoeuvring**

**Assumptions:**
Manoeuvring is based on the roller weight, dimensions and operator vision. The operator vision is estimated as the viewing angle achieved with given roller dimensions and the luminance depending on day/night work.

**Reliability**

**Assumptions:**
Reliability is depicted in the TCO as the cost of eventual replaced parts when faced with failing components. Component failure is estimated using the reliability function mentioned in interruptions. The cost of parts [62]
### Component cost
Being replaced is a mean value of usually changed parts.

The cost of replaced components is based on the cost of spare part kits from Dynapac CE.

### Meantime to failure
Meantime to failure is calculated with probability functions using documented service intervals.

Interruptions

**Assumptions:**
The cost of interruptions is based on the time consumed on halts in the operations due to fuel/water refill and/or problems occurring resulting in repair and maintenance delays.

**Refill time**
The time required to refill fuel or water is calculated on the fuel/water tank size and the recharge/refill flow.

**Maintenance and repair**
Maintenance and repair delays are estimated with a probability function depicting the possibility of failing components.

**Meantime to failure**
Meantime to failure is calculated with probability functions using documented service intervals.

### Troubleshooting

**Assumptions:**
Cost of troubleshooting is based on an estimated time for detecting problems when faced with failing components. This time is in turn based on the free volume under the roller hood and the number of components inside. Reduced free space and increased number of components results in increased troubleshooting time and cost.

### Upgrading

**Assumptions:**
Upgrading is optional and allows the user to invest in a performance enhancing upgrade to the roller. It is greatly inspired by literature.

**Settings**
Upgrade interval, investment cost, geometrical impact and a technology advance rate depicting the performance increase are all modifiable to desired scenario.

**Constraints**
The upgrade is dependent on the geometrical impact of upgrade and free hood space on respective roller. If the hood space is smaller than the geometrical impact no upgrade is made.

**New roller**
Optionally, in case of too great geometrical impact, a new roller can be purchased.
<table>
<thead>
<tr>
<th><strong>Operations</strong></th>
<th>Assumptions:</th>
<th>Operation time is calculated by combining the operation speed and compaction force with the worksite area and required compaction force.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compaction force</strong></td>
<td>Assumptions:</td>
<td>The compaction force and required force is calculated by combining several equations, literature and roller parameters. A detailed description can be found further down in the report.</td>
</tr>
<tr>
<td><strong>Operation speed</strong></td>
<td>Assumptions:</td>
<td>The operation speed was estimated with a base-speed of 3 km/h. The speed was then reduced slightly depending on factors such as machine weight, dimensions and operator vision.</td>
</tr>
<tr>
<td><strong>Initiation Time</strong></td>
<td>Assumptions:</td>
<td>The initiation time cost is based on the time loss when required to heat up the roller before initiating the operations.</td>
</tr>
<tr>
<td><strong>Heating time</strong></td>
<td>Assumptions:</td>
<td>The time is based on the time to heat oil in the CC900's hydraulic system.</td>
</tr>
<tr>
<td><strong>Depreciation</strong></td>
<td>Assumptions:</td>
<td>The investment of the roller with a periodic decaying value. Half of the price is a constant delay, while the other half is dependent on the amount of usage.</td>
</tr>
<tr>
<td><strong>Resale</strong></td>
<td>Assumptions:</td>
<td>The resale price is calculated by each year deducting a depreciation cost from the initial investment value. The depreciation is based on an exponential function resulting from web scraping where the resale price was compared to the hours of operation on multiple second hand rollers. The resale value only occurs in the TCO if a user has chosen to perform an upgrade without success.</td>
</tr>
<tr>
<td><strong>Society noise</strong></td>
<td>Assumptions:</td>
<td>Society noise is a cost that is included in different extent depending on the road type. The noise generated by the rollers are multiplied with an estimated society noise cost value.</td>
</tr>
<tr>
<td><strong>Society noise cost</strong></td>
<td>Assumptions:</td>
<td>The cost is based on literature pointing out the cost of noise exposure at different levels.</td>
</tr>
</tbody>
</table>
Initiation time

The initiation time cost is based on the heating time for oil in the CC900's hydraulic system [68]. It is dependent on the surrounding temperature and can be calculated as follows.

\[ Q = c \times m \times \Delta T / W \] (1)

- \( Q \) = Energy required in Joules
- \( c \) = Specific heat capacity in Joules per gram per °C
- \( m \) = Mass in grams
- \( \Delta T \) = Temperature rise in °C
- \( W \) = Wattage of the element

Upgrading

Upgradability is based on multiple aspects, many of which originated from [63]. If the user chooses an upgrade interval within the scope of the study the action will be applied to the assessment. The algorithm is displayed in figure 23 below.

If a geometrical impact is selected with a lesser volume than the free hood volume an upgrade is implemented. If the geometrical impact of the upgrade is greater than the available space the current roller is sold and replaced with a new one.

A technology advance rate sets the improvement ratio on which the roller's performance is improved, thus reducing the total cost of ownership. The investment cost for a new roller respective a new upgrade is selected by the user of the TCO model.
**Emissions**

Cost of emissions are gathered from use of fuel, emissions from fuel production [60-61], and component production. These values are then multiplied with an estimated cost of CO2. In addition, an annual adder is implemented to project future changes. [62]

\[
E_C = E_X (C_{EMI} \times C_{TAX})
\]  

\(E_C = \text{Emission costs in euro}\)
\(E_X = \text{CO}_2 \text{ equivalent in gram}\)
\(C_{EMI} = \text{Cost of CO}_2 \text{ equivalent per gram}\)
\(C_{TAX} = \text{Taxes of emissions per gram/Euro}\)

**Society Noise Impact**

Society noise is a cost that is included in different extent depending on the road type. E.g. and urban road is assumed to have nearby residences so there the impact is greater. The noise generated by the rollers are multiplied with an estimated society noise cost value [69].

**Ergonomy**

Cost of ergonomy is estimated with foundation in the economic impact brought by sick leave. Aspects that may impact the worker’s health are all weighed as probabilities with individual reliability functions [57], an example of the functions can be seen in figure 24.

![Figure 24. Probability density functions. [70]](image)

Health impact from vibrations, back strains, pollution and noise [58] were all individually turned into reliability functions depicting the probability of forcing a worker into sick leave throughout each year. The factors are then summed up into one total probability. In the reliability function the lifetime of the roller is used as a characteristic life for the equations, the cycles of which the operators can be exposed to the elements are then set according to [70]. This generates a probability for the operator to be damaged by the specific element.

**Density function**

\[f_\chi = \frac{\beta}{\alpha^\beta \Gamma(\beta)} x^{\beta-1} e^{-\frac{\chi}{\alpha^\beta}}\]  

(3)
Distribution function

\[ F(x) = 1 - e^{-(x/\alpha)^\beta} \]  

\( \alpha = \text{Scale parameter} \)
\( \beta = \text{Shape parameter} \)

The calculated percentage is combined with a mean value of the salaries in respective market [49] and their sick leave benefits [59] to achieve a simplified value loss for the employer.

\[ ERG\text{COST} = H_{\text{operations}} \times P_{\text{sick}} \times C_{\text{worker}} \times P_{\text{sickmarket}} \]  

\( H_{\text{operations}} = \text{operations hours/year} \)
\( P_{\text{sick}} = \text{Probability of taking a sickday in \%} \)
\( C_{\text{worker}} = \text{Worker salary in euro} \)
\( P_{\text{sickmarket}} = \text{Probability of taking a sickday on the specific market in \%} \)

The level of back strain is estimated with basis in the viewing angle achieved for the roller operator looking over the hood. The operator is assumed to be forced into leaning more frequently as the hood grows higher, thus causing increased back strain. The viewing angels are calculated with trigonometry according to figure 25.

*Figure 25. Roller operator viewing angle.*
**Compaction performance**

Compaction volume is used as input defined by the choice of work type.

\[
A_{\text{comp}} = \frac{V_{\text{comp}}}{W_{\text{drum}}}
\]  

\(A_{\text{comp}} = \text{Compaction area}\)

\(V_{\text{comp}} = \text{Compaction volume (m}^3)\)

\(W_{\text{drum}} = \text{Drum width (m)}\)

The compaction area is used as input in the formula [64] below to calculate the angle of a triangle with a base covering the width of the drum segment compacting the ground.

\[
A_{\text{drum}} = \frac{1}{2} R_{\text{drum}}^2 (\alpha - \sin \alpha)
\]  

\(A_{\text{drum}} = \text{Vertical area of compaction seen from the side of the drum}\)

\(R_{\text{drum}} = \text{Drum radius}\)

\(\alpha = \text{Angle to projected drum area}\)

By using the law of area [65], area and angle can be used to obtain the compaction width \(b\).

\[
A = \frac{absiny}{2} = \frac{acsin\beta}{2} = \frac{bsina}{2}
\]  

\(A = \frac{R_{\text{drum}}^2 \sin \beta}{2} = \frac{bR_{\text{drum}} \sin \alpha}{2}
\]  

\[
b = \frac{R_{\text{drum}} \sin \beta}{\sin \alpha}
\]  

\[
\beta = \frac{180 - \alpha}{2}
\]

By breaking out \(F_b\), compaction force, from H. Hertz formula cited in [66, p.41] the compaction width, \(b\), can provide the required compaction force, \(F_{\text{req}}\), at given compaction volume.

\[
b = \sqrt{\frac{16}{\pi} \frac{R_{\text{drum}}(1-v^2)}{E} \frac{F_{\text{req}}}{W_{\text{drum}}}}
\]

\(v = \text{poissons ratio}\)

\(E = \text{Modulus E for the asphalt (Pa)}\) [30]

\(F_{\text{req}} = \text{Compaction force from the roller (N)}\)
\( W_{\text{drum}} = \text{Length of the drum} \ (m) \)

The modulus \( E \) is retrieved from a paper researching the modulus \( E \) of different types of asphalt [67, p.22].

The roller compaction force, \( F_{\text{roller}} \), is calculated using a formula cited in [66, p.38].

\[
F_{\text{roller}} = m_u r_u \Omega^2 + m_{\text{roller}} g
\] (13)

\( F_{\text{roller}} = \text{required compaction force} \ (N) \)

\( m_u = \text{unbalanced mass} \ (kg) \)

\( r_u = \text{radial distance to } m_u \)

\[
\Omega = 2\pi \times f
\] (14)

\( f = \text{vibration frequency} \ (Hz) \)

\( m_{\text{roller}} = \text{mass of the roller} \ (kg) \)

\( g = \text{gravitational acceleration} \ (m/s^2) \)

The required force, \( \text{Freq} \), multiplied by given work site area are divided by the roller compaction force, \( F_{\text{roller}} \), multiplied by the roller’s velocity, \( v \), and the width of the drum, \( W_{\text{drum}} \). The result obtained is a simplified manner for the time it takes the roller to perform a defined task.

\[
P_{\text{comp}} = \frac{\text{Freq} A_{\text{comp}}}{F_{\text{roller}} v_{\text{roller}} W_{\text{drum}}}
\] (15)

\( P_{\text{comp}} = \text{Compaction performance} \)

\( v_{\text{roller}} = \text{Velocity of the roller} \ (m/s) \)

The compaction performance value is lastly multiplied with respective salary [49] to retrieve the resulting cost.
**Market/application scenario modelling**

In the qualitative assessment, four markets are studied: Sweden, South Europe, North America and Australia. The South Europe market is viewed upon as France, Italy and other Mediterranean countries. The assessment is done looking at the whole lifecycle of the product.

The model includes several scenarios that make simulations possible, all illustrated in figure 26. The scenarios were integrated to broaden the result, hence discover the benefits and drawbacks of the assessed machines in different situations. The different market or application scenario were implemented as a user interface (UI) in Microsoft Excel™. The user can vary such scenario parameters along three main domains and assess the total cost implication for both the CC900 and CC900E. The following paragraphs briefly explain these domains and the parameters involved.

![Compaction Method Diagram]

- **Compaction Method** refers if the work that the roller is performed with or without any kind of vibrational aid. The practitioner can here choose the amount of vibrational work that the roller performs, the residual value is referred to as work with static load. When vibrational work is increased, this accumulates more noise but makes for faster work with a higher force, thus has a lower cost related to fuel consumption and a higher one to ergonomic aspects.

![Work Conditions Diagram]

- **Work Conditions** for the desired scenario; day/night and indoor/outdoor. The practitioner can choose how much of the work is done at day respective night. The **Operation and Ergonomy** cost is increased based on how well the operator sees the result and surroundings, hence an increased cost with nightly work depending on the lights of the specific machine. Per same methodology the practitioner can choose the quantity of indoor work. The "Indoor" alternative increases cost of **Ergonomy** based on noise and local emissions that the operator and close workers must endure.

One of the most important aspect that the practitioners can customize in the TCO model is the **applications** that the rollers perform during the lifecycle; urban road, highway and parking lot. This aspect can be customized freely by choosing how many percent of each application that the roller performs. What differentiates the applications from each other is the importance of **society noise**, **manoeuvring** and **performance aspects**.

![Applications Diagram]

![Upgrades Diagram]

![Increased diesel price/year]

![Increased electric price/year]
Urban road: represents winding roads with urban societies. These factors make noise and manoeuvrability factors more important in the calculation.

Highway: represents moderate amount of asphalt that needs to be compacted. Neither manoeuvrability nor noise are important factors as the road is straight and there are no nearby residents.

Parking lot: a large rectangular area of asphalt that needs to be compacted. As there are no obstacles manoeuvrability is not an important factor, however the parking lot has residents living nearby which makes noise moderately important.

The possibility to run upgrades on the machine is available to the user of the TCO model. The user has five different parameters that can be varied. These will all represent a summarized cost in the model depending on the input of the options. The method and options are inspired by previous research [72].

- **Geometrical impact:** The size of the upgrade under the hood of the roller.
- **Upgrade interval:** The amount of years that is in between the upgrades.
- **Technology advance rate:** The technology advance rate is the percentage of increased performance that the upgrade represents.
- **Required investment:** The Required investment that the upgrade represents each time it upgrades.
- **New roller cost:** The cost for a new roller, this only comes into play if the upgrade is too large to fit under the hood of the assessed roller.

Thus, depending on these options the upgrade cost differs. After choosing the Upgrade interval, for each year that an upgrade is scheduled, Geometrical impact of the new technology is overlooked. If the volume is larger than the space under the hood of the roller the model simulates the acquiring of a new roller. When an upgrade is accepted, the Required investment takes place, on the other hand if a new roller needs to be acquired the New roller cost is. Technology advance rate improves the performance of the roller upgraded.

The final option that is available to the practitioner is future fuel prices; electricity and diesel. These can be increased and decreased in percent depending on the annual development that is sought to be simulated. The pre-set values for the simulations that is done bellow is 5% diesel increase and 8% electric increase.
First draft

The following result is simulated with 55% vibration, thus 45% of the work is done with static load. The work is done exclusively at day and outside and the applications are equally performed. No upgrades are included in the generation of this result. This version was established through verbal confirmation of compaction experts.

All results from the TCO model are displayed in detail in a five-year interval depicting what factors are affecting the cost. This is followed by a rougher 10-year interval where the total cost is compared in the different markets. The future perspective involves increasing diesel, electric and emissions costs. Two of the largest assumptions made in the model is the amount of work that a roller in this machine range completed per day during its lifetime. Originating from the initial interviews, the assumed hours of work per year are 3 hours a day in 40 weeks and the lifetime for respective roller is estimated to 6000 hours.

The first market investigated is Sweden, result for both CC900 and CC900E is available in figure 28. Studying the result, the main cost contributors in this segment is Ergonomy, Safety, Operations and Reliability. One can observe in the figure 27-28 that the factors that differentiate between the models are primarily Fuel, Ergonomy and Safety. The depreciation cost of the rollers is consistently and higher for CC900E throughout all the market segments.

From the qualitative assessment, the Swedish market values human health. The cost of sick days for a company and the amount that a company must pay if an operator is injured is large. The logic behind the higher cost of CC900 is because the diesel engine accumulates higher noise and local emissions, which both can be translated directly into a higher cost in terms of Ergonomy and Safety. Furthermore, the cost for diesel and its consumption has a substantial effect on the result.

If one examines the cost per year graph in the lower half of figure 27-28, the first year stands out. The first year of this five-year interval is the only year were the diesel driven alternative is comparable in cost to the electric one. This might be one of the reason why electric alternatives are not present on this the market yet. Interviews proved that most customers investigate solely the investment price, which is undoubtedly higher for the electric alternative. But even apart from this the alternatives have comparable costs on the first year of usage, which could mislead buyers to a trending cost that continues throughout the years. However, the periodic cost of the diesel alternative (CC900) is gradually increasing at a higher rate.
Figure 27. Result in a 5-year period of the Swedish market for CC900

Figure 28. Result in a 5-year period of the Swedish market for CC900E.
The second market assessed is the South European one present in figure 29-30. The total costs of the machines are closer on this market compared to the Swedish market. The reason for this seems to be that major cost aspects on the Swedish market (i.e. Ergonomy and Safety) are here less prioritized criteria. The trend indicates that the CC900 will be more expensive over time as it is increasingly so. However, within the initial five-year period the costs are arguably comparable, solely the result from this time perspective would not make the transition from diesel to electric alternatives convincing.

The reason for the similar costs of the alternatives that the Investment cost of the electric alternative (CC900E) is large compared to the other costs, this because the increasing periodic costs of the diesel alternative (CC900) is yet to accel on this soft five-year period. Hence, the Investment cost of the diesel alternatives costs is even less in comparison to its other cost allocations. This can be pinpointed back to the market properties; the cost of electricity is high on these markets and based on the qualitative result sick days/accident coverage are not prioritized. These are differentiating factors on the other markets and the impact here is lower.

*Figure 29. Result in a five-year period of the South European market for CC900.*
The result of the North American market is displayed in figure 31-32. This market differentiates from the other markets; the cost of the machines is even closer in terms of total cost costs as the drawbacks of the CC900 affect criteria that are here less prioritized.

The main contributors to these diverging results is the non-existent *Ergonomy* and *Safety cost*. According to the qualitative assessment this market seldom has the same driver from day to day and does usually not offer paid sick leave. However, the safety cost is still large; this cost is here counts for the many cases which accidents leads to a lawsuit of the employing company. Another reason for the similarity in overall cost is the similar fuel costs of the alternatives. Usually the diesel prices overdues the electric ones, this is not the case here.
Figure 31. Result in a 5-year period of the North American market for CC900.

Figure 32. Result in a 5-year period of the North American market for CC900E.
The final market segment that is assessed is Australia, the result of which is illustrated in figure 33-34. This market has the highest overall costs for both alternatives. The *Ergonomy* and *Safety* cost aspects are once again amongst the dominating factors for the overall cost. Furthermore, on this market segment they are larger, resulting in the consistently higher cost over the course of the five years assessed.

The reason for this are the sustainability related market properties. Human health and safety is overall prioritized on the market. Accordingly, the electric alternative has an advantage; less noise and local emissions. However, the Australian market has a high cost for accidents and sick days, thus an overall increased cost in comparison to the Swedish market.

*Figure 33. Result in a 5-year period of the Australian market for CC900.*
Figure 34. Result in a 5-year period of the Australian market for CC900E.

Figure 35 displays the result over a period of 10 years rather than 5. According to the same methodology as with the previous illustrations the result to the left in the picture represents CC900 and the other CC900E. All the market segment is here displayed in the same graph to get a reasonable comparison.

The immediate conclusions that can be made from this result is the disparity between the costs of the Swedish and Australian market segments on the diesel alternative compared to its electric equal. This indicates that these markets prone to benefit from an electric alternative.
4.3 Validated and final TCO model experimentation

After validating the final version of the TCO model could be generated. The following section of the report will explain the validations and the result of several simulations that was performed.

4.3.1 Model validation by expert opinion input data

To gather reliable data for the TCO a set of interviews were conducted with people possessing expertise from various areas of the compaction industry. From Dynapac engineers to several posts within the customer segment (Companies operating the rollers).

A questionnaire was composed containing questions regarding a user scenario containing smaller asphalt rollers, ranging between 1.5 and 2 tons. Answers were collected using Google Forms™, figure 36. A first sheet of background information regarding the interviewee could determine the expertise and validity of certain answers.

![Figure 36. Questionnaire for input validation.](image)

The questionnaires resulted in input data for the TCO regarding the use scenario, for instance operational parameters. A major of the expert opinions pointed towards settings such as a 50%-percentage split between vibration and static load, six overruns for adequate compaction results.

In addition to the questionnaire results a semi structured interview made it clear that a higher level of adaptability regarding hours of operation and cost of emissions would greatly benefit the model for multiple user scenarios to be tested as these variables may diverge drastically in different markets.

Experimenting the TCO model after the data collected from the questionnaires, some input data were modified from the previous run. According to the validation the values which operations are done with vibrations are changed from 55 % to 50 % and the amount of overruns the that is required per area unit is increased from 1 to 6. Slide bars were implemented in the user interface so that the model enables adjustment of the operating hours per year and the pollution taxes per figure 37. Previously the inputs had constant values of 600 hours/year respectively 32 € per ton CO2.
The pre-set values for the upcoming result for the given options are set with an annual adder of 40 € per ton CO2 and 300 hours/year. The taxes of CO2-equivalent/grams are set to this value to achieve the futuristic perspective with radical climate prioritization that is sought in the assessment. The operating hours is a product of the validation. Instead of 600 hours/year (3 hours/day), the machines are validated to be used 150-300 hours/year (1-2 hours/day).

The result from the market segments are once again present in figure 38-45, it is now adjusting per the validation. Per the result the overall costs of both alternative have been decreased drastically. This since the adjustment from the validation was large and regarded factors that is dependent on most the cost allocations; operation hours. These drastic adjustment is present on all the market segments. The integration of increased pollution taxes has now increased the percentage gap between the two alternatives across all markets.

Apart from the emission cost, an allocation that previously was very low, the placement of the total cost is similarly divided. The dimidiation of operation hours has made the previously dominant Ergonomy and Safety allocations to be less so. These costs are heavily dependent on to what extent the machine is used; as the operator works more, the individual is more likely to be exposed to health diminishing factors. As these previously radically dominant allocations has been reduced to merely dominant, they are more comparable with the less periodic ones such as fuel, investment and operation cost. This makes the overall cost of the machines comparable accordingly.
Figure 38. Validated result in a 5-year period of the Swedish market for CC900

Figure 39. Validated result in a 5-year period of the Swedish market for CC900E.
Figure 40. Validated result in a 5-year period of the South European market for CC900.

Figure 41. Validated result in a 5-year period of the South European market for CC900E.
The North American market segment is the only market where the diesel alternative has a lower cost than the electric one, according to figure 42-43. All the market segments are as mentioned above further similar in terms of costs, however the non-existent *Ergonomy* cost reduce the costs enough to bring it under the electric alternative with the lowered operation hours.

*Figure 42. Validated result in a 5-year period of the North American market for CC900.*
Figure 43. Validated result in a 5-year period of the North American market for CC900E.

Figure 44. Validated result in a 5-year period of the Australian market for CC900.
Figure 45. Validated result in a 5-year period of the Australian market for CC900E.

Figure 46 displays the validated result but over a 10-year period, this provides similar result in terms of distribution compared to the result before the validation; in figure 32. The Swedish market still shows the greatest cost reduction when introducing the CC900E. This is followed by Australia, South Europe and last North America, where the diesel alternative is not far behind. Overall the costs are more equal with the validated result. This is because of the lowered operation hours per year. The periodic costs of the diesel alternative in comparison to the electric one is yet to accel with this amount of usage.

Figure 46. Validated result of a 10-year period (CC900/CC900E)
4.3.2 Experimentation

Model validation by Sensitivity analysis

By applying the Morris method [18] and altering respective input parameter individually from its maximum to its minimum value any abnormalities or unrealistic results could be located and eliminated. The approach resulted in the identification and determination of various deviations e.g. in hours of operation where any values beneath 100 hours caused misleading cost in the TCO output.

Simulation

All the upcoming simulations are performed on the Swedish market segment. This since on this market the electric alternative was most favourable. When the diesel alternative was less expensive than its equal on this market, this was the case on all the other segments.

To cover a wide range of potential outcomes, several different scenarios were studied by experimenting and altering input data. Quantity of operation hours, CO2-equivalent cost and work conditions per year was composed in multiple combinations until trends pointing towards favourable use of a certain roller could be associated with specific setups. All of which was at operating hours around 100 hours, this makes depreciation look like a dominant cost allocation but this is just the case in comparison to the other costs at low operation hours/year.

For the following result, represented in figure 47-48, the annual emission tax adder was increased from 40 to 400 € per ton CO2. By raising the emission impact the cost of the diesel roller rapidly increases making it further unfavourable. This depicts the outcome in an exaggerated projection of future increase in environmental focus.

![Figure 47. Result represented with the input 48 operation hours and increased emission taxes of 0.0004 euro/year for CC900.](image-url)
Figure 48. Result represented with the input 49 operation hours and increased emission taxes of 0.0004 euro/year (CC900/CC900E).

Any indoor operations are favourable for the CC900E as the increased effect of emissions greatly increases the disadvantage of using a diesel-powered roller. In addition to this the electric engine operates at a much lower noise level than the one of the CC900, providing an even greater advantage when used in a closed space.

Setting the input to a scenario with comparatively high amount of indoor and night work is as mentioned above favourable for the electric alternative. However, at operation hours of 93 per year the diesel alternative still has an edge per figure 49-50.
Figure 49. Result represented with the input 93 operation hours and 50% indoor/outdoor respectively night/day work for CC900/CC900E.

Figure 50. Result represented with the input 93 operation hours and 50% indoor/outdoor respectively night/day work for CC900E.
In future scenarios, the electrical roller benefits from the increased cost of CO2. In comparison, the electricity cost is estimated to rise, but even with this in mind the CC900E roller will maintain a lead in relation to the CC900 as the diesel prices follow the same trend. If one on the other hand simulates the input of tangible increase in fuel prices the result in figure 51-52 is generated.

The annual increase in fuel prices is here set to 5% for both electricity and diesel. On the perspective of 200-300 operation hours per year the electric alternative has an edge. However, there is still a scenario where the diesel alternative is favourable; at 84 operation hours per year. Since the prices of electricity are lower to begin with, having a scenario where the diesel alternative is cost effective is intriguing.

Figure 51. Result represented with the input 84 operation hours and 5% increase of both electric and diesel costs/year for CC900.
Figure 52. Result represented with the input 84 operation hours and 5% increase of both electric and diesel costs/year for CC900E.

Accordingly, the same methodology as with the previous input values, the annual increase in fuel prices is tampered with. In this case the diesel prices are set to increase by 6% per year and the electricity to 16% per year. With this input one can also achieve a result where the diesel alternative is favourable compared to the electric one; at 85 operation hours per year, see figure 53-54.
Figure 53. Result represented with the input 85 operation hours and 6% increase of diesel respectively 16% electric costs/year for CC900.

Figure 54. Result represented with the input 85 operation hours and 6% increase of diesel respectively 16% electric costs/year for CC900E.
The CC900E is estimated to require a heavy investment in relation to the current diesel powered CC900. The complete duration of compaction work would have to exceed a certain number of operational hours for the benefits of the electric roller to scale enough to cover this initial financial gap.

The scenario where the investment of the electric alternative overcomes the operational costs of the diesel one is represented in figure 55-56. This is achieved with the input of 91 operation hours per year.

*Figure 55. Result represented with the input 91 operation hours for CC900.*
To examine the impact that upgrading has on the result, an upgrade was implemented on the diesel alternative that made a 5% increase in performance and had the cost of 1000 € the third year of usage, see figure 56. One can identify the shift in costs from the third year and beyond for this alternative. However, this was not enough to justify the alternative with the input of 300 operation hours. If the operation hours where to be lowered significantly, one would eventually receive a result that was favourable for the diesel alternative per the other scenarios.
Figure 57. Result represented with the input 300 operation hours and upgrade for CC900.

Figure 58. Result represented with the input 300 operation hours and upgrade for CC900E.
The overall conclusions that one can make from this experimentation of scenarios is that the diesel alternative in many cases are favourable at low quantity of operations hours per year. If a roller is to be implemented on a market segment that is to use the roller at similar quantity, one should consider the diesel alternative. This roller would be monetarily beneficial per the model and not require the integration of new infrastructure to function.

4.3.3 Favourable scenarios per roller
As stated in previous section certain situations favour different solutions. A list of scenarios that stand out as particularly beneficial to respective roller is presented below.

CC900:
- Operations exceeding 9-hour work shift demanding the CC900E to be recharged.
- Total hours of operation lower than 91 hours.

CC900E:
- Operations exceeding 91 hours in total, but not exceeding 9 hours per shift.
- Indoor operations.
- Urban roads (near residences).
- Markets with high CO2 tax.
- In future scenarios with more strict sustainability oriented legislation.

4.4 Development of PSS solutions

To further enhance the assessed asphalt rollers from an economic standpoint; services that could complement them was created. These service concepts were developed and selected depending on assessed problem areas within the total cost of ownership model. The following paragraphs will explain the development and content of the solutions, also why they are enhancing the current products.

4.4.1 Ideas & concepts

Services to integrate into the existing physical products was generated through traditional brainstorming. In the first sessions, many radical ideas were generated through discussion and mind mapping. In the later sessions ideas was generated that had a significant impact on the result in the TCO model.

The largest cost represented in the TCO model has the following allocations:

- **Investment**
- **Ergonomics**
- **Safety**
- **Reliability**
- **Operations**
- **Operational interruptions**

When the following allocations was established, ideas were generated that i.e. changed the way you pay the investment cost of the machine or that somehow relates to this. Finally, as a first sift of the solutions, ideas that didn't have a relevant relation to the TCO model was excluded.
4.4.2 Pugh
The concept selection is a two-stage process that is divided into: Pugh and the IPA based method. To sift the generated concepts the first method used is Pugh-matrix. To make the tool relevant in terms of criteria and weight, it is based on TCO results. The VDs used in the TCO is integrated as criteria and the weight of the criterion is calculated based on the relative cost amongst the VDs in the TCO, the weight result is a mean result between the CC900 and CC900E cost result. The criterion and their respective weights can be seen in figure 59.

![Figure 59. Criteria and weights of the Pugh-matrix.](image)

Per the criteria and their weights twelve concepts was evaluated, see figure 60. The concepts that received a high score and combinable concepts that had a moderate score was accepted to the next stage of the process.

![Figure 60. Overview of the Pugh-matrix.](image)
The following concepts that bypassed to the stage of the process:

**Concept 1:** Solar panels attached to transportations, directly on roller or at charging stations/site hubs.

**Concept 2:** Expand the intranet of charging post that exist around cities to provide means for the electric rollers and make a profit not only for rollers but for charging of electric cars. Co-ownership exist where the roller customers pays for charging post and earns a percentage of the distribution of electricity and makes it easier for themselves to charge their roller. The solution additionally allows them to refill water and fuel at the same place. These are only available to customer on demand. Make it easier to recharge with specific outlets and custom stations. Another alternative to this concepts is "Energy delivery", this would mean that you buy a service that makes Dynapac provide charged batteries or fuel/charging stations that are portable either at a truck or ones that you can carry.

**Concept 3:** Pay for X years of “future proofing”. Any new upgrades are installed for free or heavily discounted. If paid for the service includes having spare parts ready at a local proximity, this also means having someone ready to repair if needed.

**Concept 4:** The customer can choose as he/she pleases to pay for the roller. The roller could be paid for partially at first and then over several months or however the customer pleases. The customer could also lease, rent or buy whichever of the components that is pleased. If the customer chooses to rent or lease EOL disposal is taken care of by the company, the house the service.

**Concept 5:** Providing a software that recommend machine usage, provide information and functions to the operator/roller to lower fuel consumption. The software includes a heat and cooling timer to increase compaction efficiency and can start whenever. The software can also work as a “black box”; it records accidents in database and warns the operator if the upcoming task has high accident ratio. To further the security sensors on the roller to decrease accidents and increase roller lifecycle time.

### 4.4.3 The IPA based method

As a second and final step of the concept selection process, before concepts are integrated to the TCO model, a IPA based method was used. The method uses pre-set criteria based on [48], that is customized for service and PSS concepts, thus this method was used. Another reason why this method was used is that it illustrates the result from a provider and society perspective. The weights of the criterion were based on the information gathered in previous parts of the project.

The provider part of the method is displayed in Figure 61. The picture displays the criteria’s, their weights and concept 1 as an example.
Figure 61. Provider matrix.

The society part of the method is displayed in Figure 62. The picture displays the criteria’s, their weights and concept 1 as an example. The criteria for this matrix are not the same; this is to fit a “society perspective”.

Figure 62. Society matrix.

The perspective in the evaluation the provider is asphalt companies and the society is the users of the rollers and other humans that come in close contact with the rollers.

The result of the method is displayed in figure 63 which is a provider/society-matrix. The goal of the method is to look for solutions that end up in the second quadrant of the matrix, in this case all the solution ended up there. This lead to believe that all concepts had potential, hence other means of decision-making was needed. Instead concepts that had the highest provider respective society score was selected.
For this final selection concept 2 and 5 was chosen to advance to the integration in the TCO model. Concept 4 show promise in provider satisfaction, the concept did not meet the same satisfaction on the society spectrum and was therefore discarded. Concept 2 was divided into two concepts because of its diversity in terms of function. The separation was also done to make sure that concept was advanced that benefitted both assessed rollers; electric charging stations would not benefit the CC900 model. However, the part of the concept that represented “energy delivery” could, thus the concept was separated into two.

### 4.4.4 Charging solutions - Charging Post Co-ownership

![Illustration of co-owned charging post.](image)
This solution consists of a customer investment based development of the charging posts infrastructure. The concept is built around Dynapac controlling a custom expansion of electric charging posts. Customers are offered to invest in a charging post on a location of their choice where they would gain greatly reduced electricity cost as well as “Co-ownership”, meaning they are granted a percentage of any revenues brought by the new station’s distribution.

The posts are not only intended to be used for rollers but also to be available for the society, with increasing numbers of electric cars, resulting in an increased revenue stream and improved public relations. A water outlet is available at the post to cut time loss during refill. The water outlet is fit with a clamp fixating the hose to the roller, making an increased flow possible and further reducing refill time.

The solution would require an investment of:
- 15000 Euro

The solution would attack the following aspects identified in the TCO:
- Fuel cost (For CC900E)
- Water refill time

**4.4.5 Charging solutions - Energy delivery**

The solution consists of a portable energy stations available to the user either by a truck, or handheld modules transported to the site and then dragged/pushed to the roller. The service is provided through rent/lease or with an additional cost order the energy delivery on demand. Just like the previous concept the stations will also carry water and outlets are fitted with clamps to fixate the hoses while refilling or refuelling.

The solution would require an investment of:
- Monthly subscription: 350 Euro

The solution would attack the following aspects identified in the TCO:
- Water refill time
- Fuel re-fill/charge time

*Figure 65. Illustration of charging truck and a usual tool bearing truck at a site.*
4.4.6 The software

This solution involves developing a software that provide information to the operator in multiple instances. Its main purpose is to increase safety and ergonomy by lowering: noise, vibrations and emission levels. This is achieved by functions such as auto turn-off, recommended usage and displaying current levels of resource consumption. The same software should also be able to function as a “black box”, collecting data throughout the operations. This to prevent accidents from happening by tracking injuries and accidents to determine where and they happened, and warning the operator during similar scenarios. The software warns the operator if the upcoming task has a high accident ratio or if it potentially promotes non-ergonomic use.

The software can by the same mechanism calculate the reliability that certain components must fail. Parts near their EOL are flagged for troubleshooting.

The front, rear and sides of the roller is outfitted with motion detecting sensors to avoid collisions, roll-over accidents and injuries. In addition, a heat and cooling timer is integrated to increase compaction efficiency: by being able to start whenever.

The software can be selected as an add-on in the purchase of a new Dynapac roller or acquired and installed separately as an upgrade on an existing machine.

Figure 66. Illustration of software solutions concept.
The solution would require an investment of:
- Monthly subscription of 100 Euro

The solution would attack the following aspects identified in the TCO:
- Ergonomy
- Safety
- Society noise
- Troubleshooting
- Maintenance

4.5 Evaluations of new solutions
To further test the solutions and to do a monetary comparison, all concepts was integrated into the TCO model. This was done based on the cost allocation that that the respective solutions have a significant impact on and the qualifications of the solutions.

4.5.1 Total Cost of Ownership of Concepts
Under the following captions the decision-making behind the solutions cost allocations differentiation will be argued and explained for. The monetary result of the solutions will also be displayed. Apart of the altering of the result that the specific solution represents, all the result is generated per the same input values as the first validated result.

**Concept 1**
As the concepts represent an investment in electric charging posts the investment cost in the model has been increased. This is done by an approximated investment of 15000 €. An invested charging posts means a revenue that is approximated to 1200 € per year at this investment. To simulate the lower refill time that charging electricity and water at the same time represent, this refill time is decreased by 2 minutes from 20 minutes. These aspects make the solution affect the investment cost allocation to be higher but then the result is successively gained back each year. Also, as the refill time is lowered the interruption cost allocation is decreased. This concept only regards the electric alternative in the TCO model as the CC900 does not benefit from any reduced electricity cost or electric refuelling modifications. However, an implementation would still generate the potential revenue that is generated through the co-ownership, meaning total decrease of 1200 € per year. Figure 66-74 presents the results for the concept applied on the CC900E.

This concept is especially favourable on markets where the electric price is substantial; North American and Australian. The income from the charging posts makes the electric alternative favourable over the diesel one on all the markets.
Figure 66. Result from concept 1 in a 5-year period of the Swedish market for CC900.

Figure 67. Result from concept 1 in a 5-year period of the Swedish market for CC900E.
Figure 68. Result from concept 1 in a 5-year period of the South European market for CC900.

Figure 69. Result from concept 1 in a 5-year period of the South European market for CC900E.
Figure 70. Result from concept 1 in a 5-year period of the North American market for CC900.

Figure 71. Result from concept 1 in a 5-year period of the North American market for CC900E.
Figure 72. Result from concept 1 in a 5-year period of the Australian market for CC900.

Figure 73. Result from concept 1 in a 5-year period of the Australian market for CC900E.
According to figure 74, the mentioned improvement on the Australian and North American markets are distanced when observing the result from a 10-year period. If this result is compared with the result of no concept available in figure 46 previously in the report, one can see that these markets has a substantial decrease in cost. The result has not shifted slightly from the qualitative one as there is a larger difference between the South European market and the North American one.

**Figure 74. Result from concept 1 in a 10-year period (CC900/CC900E).**

**Concept 2**

As mentioned above this concept represents portable refuelling. This solution is payed for in the model as a continuous payment/year. Equally to the previous solution, this concept decreases the refilling time of both water and fuel. However, this solution decreases the refill time further since the portable “station” can be placed in a significant local proximity to the rollers. To simulate the annual payment of the portable charging station a cost at the concept investment allocation is set to 4200 €/year. The refill time is decreased from 20 to 16 minutes, which decreases the interruption cost allocation significantly.

The result from this concept in the model is available in figure 75-83. This concept represents a substantial decrease in refill time for both fuel and water, however it is not monetarily justifiable per the TCO model. The current yearly cost for the solution is overshadowing the benefits of low refill times on all the markets.
Figure 75. Result from concept 2 in a 5-year period for CC900.

Figure 76. Result from concept 2 in a 5-year period for CC900E.
Figure 77. Result from concept 2 in a 5-year period for CC900.

Figure 78. Result from concept 2 in a 5-year period for CC900E.
Figure 79. Result from concept 2 in a 5-year period for CC900.

Figure 80. Result from concept 2 in a 5-year period for CC900E.
Figure 81. Result from concept 2 in a 5-year period for CC900.

Figure 82. Result from concept 2 in a 5-year period for CC900E.
According to figure 83, the concept does not improve in profitability over a 10-year period either. The result is equal to the no-concept 10-year result in partition, see figure 48.

![Figure 83. Result from concept 2 in a 10-year period (CC900/CC900E).](image)

**Concept 3**

Concept 3, the Software solution directly benefits the *Safety, Ergonomy* and *Society noise* cost allocations impact by increasing attention and warning the operator about potential risk factors throughout the work process. In addition, the program is estimated to reduce cost from troubleshooting and maintenance as it constantly analyses the machine and provides feedback foreseeing anticipated component failures.

A monthly subscription of 100 € is projected in the TCO model. The concept affects 5 different cost allocations: *Ergonomy, Safety, Society noise, Troubleshooting* and *Maintenance*. These costs are decreased based on the properties of the solutions and illustrated in figure 84-92. On some markets the solution is better than others. The solutions are especially good on the Australian market since this market originally has a high cost on the safety allocation.
Figure 84. Result from concept 3 in a 5-year period for CC900.

Figure 85. Result from concept 3 in a 5-year period for CC900E.
Figure 86. Result from concept 3 in a 5-year period for CC900.

Figure 87. Result from concept 3 in a 5-year period for CC900E.
Figure 88. Result from concept 3 in a 5-year period for CC900.

Figure 89. Result from concept 3 in a 5-year period for CC900E.
Figure 90. Result from concept 3 in a 5-year period for CC900.

Figure 91. Result from concept 3 in a 5-year period for CC900E.
The same kind of decrease in cost can be observed in the 10-year period result for both alternatives in accordingly with figure 92. The costs do not simulate exponentially nor do the price of the solution decrease/increase.

Figure 92. Result from concept 3 on a 10-year period (CC900/CC900E).

Concept 3 had the most beneficial monetary result of the three solutions per the TCO model. This considering all market segments and both roller alternatives.

4.5.2 Technology roadmap
To get a sense of when and what to be expected of each solution, before and after implementation, a type of timeline, a simplified technology roadmap, was composed. The solutions are illustrated by respective line in Figure 93 and different milestones depict events such as investments, time until implementation, customer acceptance and increased revenue streams.

Figure 93. Technology roadmap of concept 1-3.
The charging post solution, illustrated in yellow in figure 93 above, requires a large initial investment and is halted for a time until permits are approved for the new charging stations. When approved, the construction is a lengthy work, putting the finished implementation a year later. The business model included is based on a share of the revenue stream delivered by the charging post when used by the public. Thus, the revenue will grow as the electric cars are standardized into society.

Energy Delivery, depicted in orange above, demands an initial investment and will start with a development/manufacturing phase the first year while being promoted and displayed on a concept stage to the customers. Customer acceptance in the Swedish market is estimated to the fall of 2019 which will initiate product distribution. A year of successful implementation would result in a spread across the European market and eventually to the North American market.

The Software solution would require an initial investment for the necessary hardware and installation followed by a monthly subscription for the service. The technology is already existing and would only require minor modifications to today’s rollers. The operators will probably not adopt the changes right away so acceptance is estimated to be achieved by the summer of 2018. As the concept is built upon a prospective national intranet of data regarding use of asphalt compaction vehicles and necessary facts about the potential work site areas it is estimated to take several seasons before sufficient data has been gathered. Optimal functionality is projected in the spring of 2020.

With the roadmap containing milestones occurring the closest in time as well and referring to previous TCO results the Software solution has the highest potential of improving the activities surrounding and included in the compaction operations culminating in the lowest cost throughout its lifetime. Thus, the decision was made to define this solution further by creating a theoretical foundation for a potential physical prototype.

4.5.3 Attribute pictures
The software solution brings greater awareness of the area surrounding the rolled. As seen in figure 94, the sides, back and front of the roller has been equipped with motion detection, avoiding potential damage from collisions or roll-over injuries. Vibrations are tracked by the drum and the temperature is measured to calculate factors such as asphalt compaction characteristics and time needed to initiate work (if a diesel compactor is used and required to heat up on idle).
4.5.4 Bill of materials
Per the TCO model and the technical roadmap the most beneficial concept is concept 3; the software. To solidify and realise the concept further the following tool was applied.

Figure 95 illustrates a BOM created for the solution. This tool was used to identify the components that is needed to realise the solution. All physical components exist thus are available “off-the-shelf”. The only “component” to the solution that is not yet available is the software itself. However, creating the software is not the problem, rather the potential high cost of its creation. The BOM does not consider the development cost that Dynapac must invest to make the solution possible. For the users, the cost of the solutions is affordable if one refers to the investment in the BOM.

The components in the BOM could be released as an upgrade to a machine in use or as an addition to ones that is to be produced. If the component is released as an upgrade the company owning the machines must pay for the integrate ration of the components. This includes the wearing of wires, attaching the mount for the tablet and embedding sensors into the machine.
To complement the BOM, a tier tree and a component illustration was created, see figure 96. The left picture explains the near proximity which the components are integrated into/onto the machine and the part number for the component. The right picture explains the hierarchy of the components, the machine itself is set to tier 0 and tier 1-3 is the solution sub-system.

**Figure 95. Potential bill of materials for concept 3.**

**Figure 96. Illustration of parts and pert tier tree.**
The existing components, location of them and costs is somewhat hypothetical. Nonetheless, the above information leads to believe that the solution is possible to realise with minor modifications.

4.6 Final validation of the model results
To ensure the validity of the final TCO all input parameters were reassessed. All input controlling the simulation today and in future scenarios were evaluated and reconsidered. This time the requested answers required precise percentage estimations of each value to be entered. Instead of asking the interviewees if 20% of operations are done at night, we asked how many hours of work are done with this conditions.

![Figure 97. Questionnaire for process validation in Google Forms™.](image)

The validation showed unified opinions on most fronts. As an outcome of this several altercations were made in the TCO model, both minor and more significant changes. Some of the more notable results are presented below.

A very low usage during night-time and close to no operations taking place indoors. Approximately 60% of the operations conducted with vibration as seen in figure 98.
Almost half of the work with these smaller rollers were estimated to take place on urban roads, next to nothing on highways and the remaining, roughly 40%, on parking lots. The distribution is depicted in figure 99. The technology improvement rate was estimated to 6.4%, just slightly higher than what is used in the first TCO draft.

Furthermore, in discussions parallel to the validation made, attention was repeatedly brought to the fact that the investment cost is depicted as one lump sum in year one in place of the traditional way of cost calculations presenting the cost as it’s depreciation each year. The idea behind the current illustration originated on the presumption that the initial cost tends to be the crucial factor for decision makers choosing a new roller. However, the risk of sacrificing the legitimacy of the study by breaking a well-known pattern made the authors embrace this reoccurring advice.
4.7 Evaluation of PSS concepts

As the concluding draft of the TCO was completed a final validation was applied to establish the legitimacy of the study. A new questionnaire, figure 100, was composed in Google Forms™ where the reader was given descriptions of the three concept solutions proposed in the study and then asked to answer a set of statements. The statements revolved around the affect respective solution would bring to different parameters, for instance investment cost, environmental impact and ergonomy. The questions could be answered from a scale from one to ten, were ten is high impact and one is low.

![Figure 100. Questionnaire for concept validation](image)

The average values from the answers gathered in the validation were compared with normalized values from the initial data used for the TCO model.

**Concept 1 - Charging Post Co-ownership**

The blue bars in figure 101 below represent the results gained from the subjects interviewed for the validation and the orange is the data used for the TCO. The results pointed towards similar opinions in regards of investment and fuel cost. The validation stated a slightly higher refill time which may be feasible due to a potential higher flowrate than originally predicted. An interesting finding was the high impact on emission reduction found in the answers however this is thought to be a result of reasoning stating that the transitioning from diesel to electricity is promoted by the solution. A most valid argument however not implemented in the TCO model.
Solution 1 - Highlights

Figure 101. Comparison of validation and input data - Solution 1.

**Concept 2 - Energy delivery**

Solution 2 was perceived as a costlier investment than initially estimated. A possible reason behind this might be that the concept is foremost implemented as a rental/leasing service, reducing the impact in the TCO. The refill time is similar to the one predicted in the validation with 7 versus 8 on a scale of 10. As seen in figure 102, the validation yielded a high improvement on the compaction operations. This is thought to be since the summation of all activities will be reduced if the refill time is diminished. In the actual TCO the compaction operations only regard the moment when the roller is actively operating, leaving this factor unchanged after concept implementation.

Solution 2 - Highlights

Figure 102. Comparison of validation and input data - Solution 2.
Concept 3 - Software solutions
The validation of the Software solution was mainly satisfactory. The investment cost was predicted to be slightly higher, as was ergonomics and improved troubleshooting. Safety was anticipated to be a bit lower in the validation. A diverging element was a reduced fuel cost estimated by the validation subjects, something that is not included in the TCO model. A belief is that this result originates from the argument that the recommended use promoted by the concept would create a more sustainable way of operating the roller and in turn reduce the consumed fuel. A similar pattern could be seen in emissions. Figure 103 below depicts the mentioned highlights.

![Solution 3 - Highlights](image)

*Figure 103. Comparison of validation and input data - Solution 3.*

5 DISCUSSION AND CONCLUSION
The study originated with the objective:

“To further elaborate the value of electric asphalt compaction vehicles compared to conventional gasoline based alternatives.”.

To support the accomplishment of this aim, the following research questions were to be answered:

“What environmental, economic and social factors are affected, and how, when replacing a diesel-powered asphalt compactor with an electrical alternative?” and “Furthermore, how would an integrated service concept promote the electric concept roller?”

As the research questions caused the traditional financial assessment models to give way for social and environmental factors to be included the results pointed towards the fact that even though the electric roller brings a costly initial investment it has a lower cost throughout the whole operational life cycle. This case was most obvious in the Swedish and Australian markets possessing higher restrictions regarding these new intangible aspects but also showed itself in South Europe and North America, despite the last mentioned, in relation to the other markets, greatly lacking in terms of social and environmental consciousness.
The outcome of the study is applicable on other research fields. Even though the generated model for which the result is created is tailored for certain models of compaction machines; this can be changed to different ones or even other types of products. The general conclusion that intangible factors can have a large impact on the cost of a product is exceeded over products archetypes and alternative products. Nonetheless, the realisation that can be obtained from the result is that electric solutions has more advantages than merely fuel cost etc.

This result is proven to be even more enhanced by the integration of services in the products. By integrating the correct service and creating a PSS, electric alternatives can have even more financial potential then primarily. This can also be applied to different archetypes of rollers and alternative products. The thing is that when introducing a petrol product to a market, all the means of which this product is driven by is accessible. Not only the intranet on gas stations, but knowledge among mechanics and acceptance by the users. However, when introducing a new electric solution these means are not present. The integration of services into these products that represent the expanding of intranets and understanding of the solutions increase their benefits financially and functionally.

5.1 The approach
Both the qualitative and the quantitative assessments was respectively easy to use, even though both assessments needed iteration of input data to depict a reasonable result. However, the transition between the two was the problematic phase of the process. The transition created friction between the methods used in the assessment, i.e. the VDs that was generated through the qualitative assessment was problematic to integrate into the functional model in the quantitative assessment. A value was described that the customer wanted and how much they wanted it on each market. When this was to be integrated, it needed to be translated into a function. An example of this is the VD “lower fuel consumption”, this is not a function (substantive + verb) it's rather a value that a customer wants. In hindsight, it would had been easier to translate the primary VD into a function before trying to break this non-function into lesser ones.

When using evaluation tools like the ones adopted in the study it is important to balance the choice of criteria to avoid achieving a corrupt result. If misused the models can easily enhance the features of only one solution and show a bias score pointing towards the concept that was favoured all from the start.

To bypass this effect consistent validation iterations of input and results were made through interviews and literature research prior to and following every step of the project. Where market expertise was needed, market experts were reached out to. If there were questions regarding construction parameters, engineers possessing that knowledge were asked. In addition to this various people within different parts of the construction industry were approached. The validity of their answers to certain questions were weighed against an estimation of their experience in respective area.

5.2 Suggestions for further research
Even though the study is directed towards the comparison of smaller asphalt compaction vehicles it can in theory be adopted to various other scenarios and machines. The result itself speaks for future shifts in restrictions and legislation to pave the way for green alternatives to today’s fossil powered vehicles and by a few tweaks to the input model used for the TCO a whole new scenario could be illustrated and experimented with.
Due to the given time frame of the study the process was simulated using an excel™ interface. Taking the work further a discrete event simulation would bring a whole new level of life to the operation process. A tool such as AnyLogic™ could simulate the usage phase of the roller and create a realistic scenario with unexpected events and queuing.

To further the applications of the model it could be integrated into a CAD system. This would mean that emissions from the creation of the components can be accounted for. You could also create a mutable model that changes properties depending on the result of the TCO model. This in combination of discrete event simulation would mean the generation new product designs at a fast phase.

Assumptions made due to the lack of time implies that the validity of the result can always be improved further to ensure a justifiable result.
References


