CHALMERS
UNIVERSITY OF TECHNOLOGY

User-friendly method for estimation of the cost and weight of passenger cars' electric system layout

Master's thesis in Product Development

AXEL JYRKÄS
GUSTAV LJUNGQUIST

DEPARTMENT OF INDUSTRIAL AND
MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020
www.chalmers.se

Master's thesis 2020

User-friendly method for estimation of the cost and weight of passenger cars' electric system layout

AXEL JYRKÄS
GUSTAV LJUNGQUIST

Department of Industrial and Materials Science
Product Development
Chalmers University of Technology
Gothenburg, Sweden 2020

User-friendly method for estimation of the cost and weight of passenger cars' electric system layout
AXEL JYRKÄS
GUSTAV LJUNGQUIST

Supervisor: Niklas Höglund, Volvo Car Corporation
Supervisor: Thomas Krusell, Volvo Car Corporation
Supervisor: Robert Weicker, Volvo Car Corporation
Supervisor: Johan Malmqvist, Department of Industrial and Materials Science
Examiner: Johan Malmqvist, Department of Industrial and Materials Science

Master's Thesis 2020
Department of Industrial and Materials Science
Product Development
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Volvo XC40 Recharge powertrain. Courtesy of Volvo Car Corporation press material.

Typeset in LaTeX
Printed by Chalmers digitaltryck
Gothenburg, Sweden 2020

User-friendly method for estimation of the cost and weight of passenger cars' electric system layout
AXEL JYRKÄS
GUSTAV LJUNGQUIST
Department of Industrial and Materials Science
Chalmers University of Technology

Abstract

Volvo Car Corporation follows the current trend of electrifying cars. A consequence of the heavy investments put into electrification is uncertainty regarding the evaluation of where the high voltage system components are placed in the car. By placing a component in the front of the car, while the rest of the high voltage components are in the back, will result in a high voltage cable being run from one end to the other. This lengthy high voltage cable will drive both the cost and weight of the car. Evaluation of the placement in terms of cost and weight has not been done before to the degree which this thesis has done. Influenced by 11 articles and 6 software, a simple yet effective evaluation tool was developed. The tool is divided into two parts, a calculation interface for showing the cost and weight, and a graphical interface which allows the engineer to try varying positions for the components in the car. The calculation interface was developed into a proof of concept/minimum viable product to quickly achieve feedback in the agile development. The results are promising, as it accurately shows the cost and weight of the connection between two, or more, components in the car. With this evaluation tool, concept development will be made more efficient and quickly deliver results.

Keywords: Concept development, Electric system layout, Electric vehicle, Evaluation method, Evaluation tool, High voltage system, Mechanical engineering, Method development, Product development

Acknowledgments

This thesis serves as the final assignment in the completion of a master's degree. The thesis itself is an accomplishment, but so is the road leading up to this point. It has been a journey of ups and downs but in the end, it was all worth it. Considerably so, since we have gotten the opportunity to complete this final assignment together with Volvo Car Corporation. We, therefore, wish to thank everyone involved with this thesis, even answering the most elementary questions such as ”does an electrical engine require AC or DC?”.

Some, more than others, have been extra involved and important for the thesis to progress. Thomas Krusell, thank you for being our go-to-person. Not only have you always provided quick and tremendous feedback, but you have also been part of the development of the scope of the thesis. This can also be said for Niklas Höglund and Robert Weicker. Without you three, supporting and enlightening us, this thesis would have not been possible to complete. Also thank you Tomas Åhlen for letting us be part of your group while conducting the thesis at Volvo Car Corporation.

Your input, Henrik Larsson, made the cost calculations possible. Your quick responses and happy-to-help attitude have proven very useful to us. Always invested and answering the most elementary questions to more advanced ones is a key factor for the progress of this thesis. Thank you!

Without academic guidance from Professor Johan Malmqvist, this thesis would have lost itself along the way. Providing thoughtful ideas and new angles on the problem at hand and our strategy forward is certainly a strength of yours. Thank you for supervising us!

Thank you all involved, once again!

Axel Jyrkäs & Gustav Ljungquist
Gothenburg, June 2020

Contents

List of Figures

List of Tables

1 Introduction

This chapter describes the foundation for the thesis. The chapter includes the background for the current situation, what the thesis aims to accomplish, and what it does not aim to look at. At the end of the chapter, the thesis structure is summarized.

1.1 Background

The trend of electrifying cars was spotted as early as a decade ago when McKinsey & Company released an article in their quarterly review, projecting a new market for batteries and their applications alike (Hensley, Knupfer, & Pinner, 2009). In the competitive world of car manufacturers, it is important to take this into account, as the amount of electric vehicles (EVs) in the coming decade is expected to threefold. More recent analyses from McKinsey & Company confirms this projected development (Gersdorf, Hensley, Hertzke, Schaufuss, & Tschiesner, 2020).

The premium car maker Volvo Car Corporation has stated that every new Volvo car launched from 2019 and onwards will have an electric motor (Volvo Car Corporation, 2017). This transition has created new opportunities but at the same time also brought new challenges. As with most car manufacturers working with this transition, it becomes important for all car manufacturers to not fall behind its competitors. The transition includes that the car manufacturers must create new platforms for their cars which are completely made for electric propulsion. These new platforms improve the electric system layouts for the cars but they are time-consuming to create.

1.2 Problem description

There are several components needed in an EV. To exemplify, a few of these are represented in Figure 1.1. The boxes with the letters A to E represent components. The arrows between the boxes represent the connection between the components. For example, the arrow connecting A to C indicates that component C needs to be connected to component A to fully function. An analogy for the connection between component C and component D. However, component A only works if it is connected to component E.

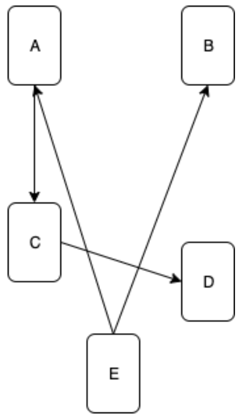


Figure 1.1: Fictive representation of components inside the car.

The representation is a fictional scenario and should not be used to fully replicate the actual component layout of the car. The representation highlights the fact that the components required are placed in such a way that it does not take account of the length of the arrows. The reduction of length of the arrow is sought after. Analogy for the car, as the cable (arrow) between the components (boxes), contributes to an increased cost and weight of the car (representation). Generally, the cost and weight of the electric system layouts are around 500 euros and 15 kilograms.

What is needed is therefore an evaluation tool that can calculate cost and weight for the connections within the electric system. Furthermore, suggestions on how the connections can be made within the car. A visual representation of how the connections can be made is also wanted. The method which will be the foundation for the evaluation tool will be developed in this thesis. The method will include all relevant information to build an evaluation tool and no further research should have to be done other than that for programming the evaluation tool.

The problem formulation for this thesis is then developed into the following:

“Develop a method which aids in the creation of the electric system layout, for cost and weight”

1.3 Scope and aim

Further information regarding the cost and weight of the electric system layout in the early design phases is needed. This information is needed to create an electric system layout which is as optimized as possible. The scope of this thesis is, therefore, to develop a method that aids in the creation of the electric system layout, for cost and weight.

1.4 Limitations

The limitations of this thesis have been identified as the following:

- The thesis will be limited to the electric system of the car. However, the electric system of the car is a widely used term. To further specify, the electric system will only concern the 400V system (commonly known as the high voltage (HV) system), the 12V battery, and the cabling required to charge the 12V battery.
- Due to the evaluation tool should be easily understood and should only be used in the early design phases, the method developed will be for an evaluation tool in 2D.
- Simplification of the cost formula, where the actual precise formula for calculation is not used. This due to the actual formula is market-price regulated.

1.5 Goals

The finished method should encompass the following characteristics. These characteristics are henceforth referred to as the goals.

- Specific and total values for the connections:
  - Cost
  - Weight
- Accurate in the result it produces
- User-friendly proof of concept for the method
- Software plan to develop an evaluation tool

The above-mentioned goals are meant to provide guidance and a framework to act within the development of the method. The characteristics are meant to both consider the engineer using the method as well as the result in which the method produces.

1.6 Outline of thesis

The thesis starts with the *Introduction* and describes what the project entails to study. From a wide perspective, the background is presented and justifies the reason why the thesis took place. To limit the scope and make it manageable, goals and limits are introduced to create the structure. Succeeding the *Introduction* is the *Methodology* used throughout the thesis. It describes the usage of an agile development process, which is incorporated into a waterfall approach. Following the *Methodology* is the *Theoretical framework* which aims to provide the reader with all information to understand the problem formulated in the *Introduction*. The chapter addresses the system as a whole, analyses available literature, and the available software. The chapter ends with a section concluding the most important elements in and formulates the principles for the evaluation tool. This leads to the *Results*, which starts by analyzing the system and dividing the evaluation tool into two distinct parts, namely the *Front end* and *Back end*. A proof of concept (PoC) is developed from parts from both the *Front end* and *Back end*, with a section verifying the PoC. Following is a discussion regarding the outcome of the *Results*, the PoC verification, and an analysis of the *Methodology*. The final chapter concerns the conclusions drawn in the thesis as well as recommendations for future work.

2
Methodology

This chapter describes the methodology which is used in the thesis. The methodology is divided into four distinct phases, namely *Pre-study*, creating the *Theoretical framework*, *Method development*, and obtaining the *Complete method*. These are visualized in Figure 2.1. The overview aims to give the reader a brief understanding of the development process from the beginning to the final proposed solution. As the visualization shows, the methodology follows a waterfall development process with an agile development process incorporated.

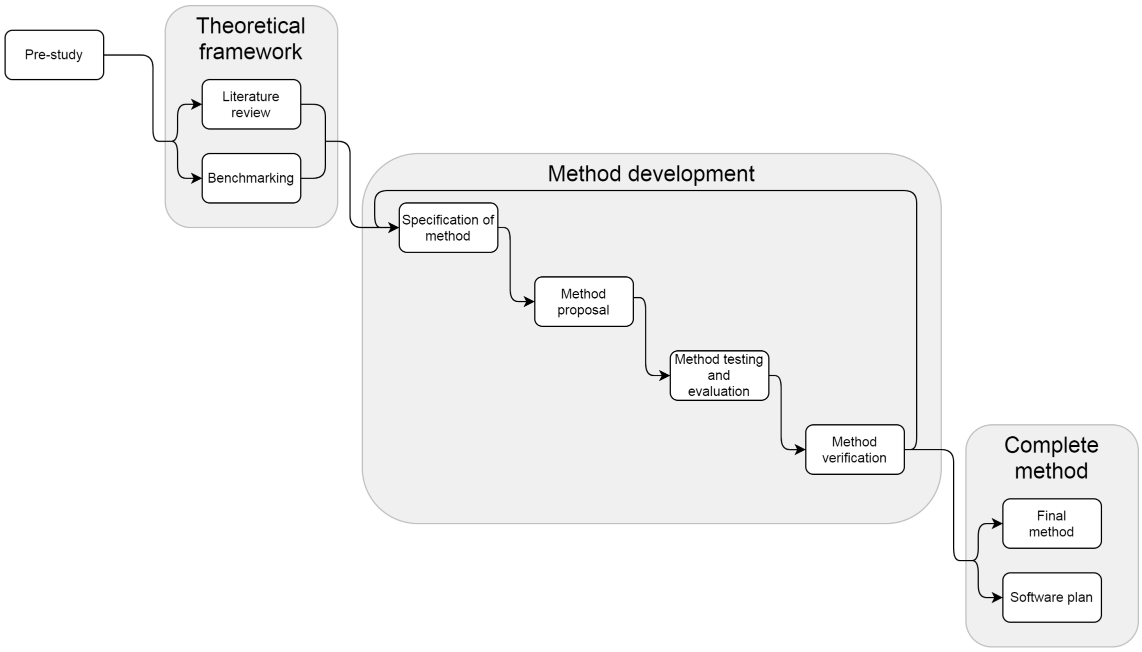


Figure 2.1: Overview of the methodology used in the thesis.

2.1 Pre-study

The pre-study contains generic elements related to the startup of any project. These are getting access to relevant software, obtaining knowledge of the current electric vehicles (EVs), and high voltage (HV) electricity, to name a few. This knowledge is required for the method evaluation later on. The method used to obtain this reference was a combination of CATIA and Teamcenter, software in CAD and PLM systems respectively. Furthermore, other references, such as automotive benchmarking tools, were used.

Apart from creating a reference, the requirements in the thesis started to unravel themselves. The black box strategy was used to find the requirements, both for the method and the components in the electric system layouts. This procedure means examining the functionality of the product itself, rather than the structure. This strategy is common practice in the Japanese automotive industry, in the sense that the supplier of a component only gets a specification on what the component's function must result in (Clark & Fujimoto, 1991). The interfaces that the components need to match is in many cases specified in the specification. The result of utilizing this strategy is the extensive maneuverability for the developers, as they are not are bound by the process for the project to reach a satisfying result (Ulrich & Eppinger, 2012). A black box has inputs and outputs which are given, but the translation from the given inputs and outputs does not have to be specified (Black & Wiliam, 2010; Clark & Fujimoto, 1992). Ulrich and Eppinger (2012) exemplify this strategy by analyzing a common handheld nailer seen in Figure 2.2. The figure shows the inputs and outputs, but the translation in the black box, which in this case is a handheld nailer, is not specified.

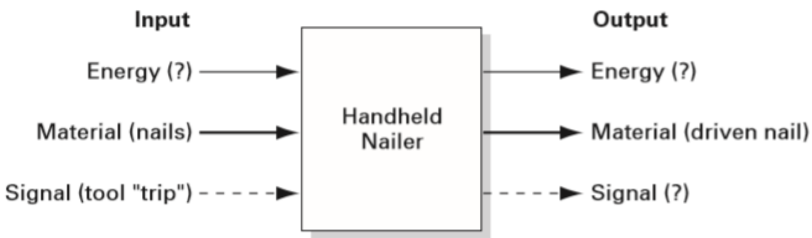


Figure 2.2: Example of a black box (Ulrich & Eppinger, 2012).

The information gathered from the analyses of the requirements were put in spreadsheets. This to map the components in the cars to find synergies and other types of combinations, considerably so since the majority of the synergies are imperceptible to the inexperienced. Studies were done on previous generations of cars, using similar methods mentioned earlier, to obtain knowledge and understanding of what has been done. However, as previous generations were not electrified to the same extent as the current cars, the relevant knowledge obtained from earlier generations started to deteriorate quickly.

The result of using the spreadsheets meant that there was a database now available. To obtain a sense of understanding of the requirements, the functions had to be identified. This meant connecting the functions and the components, as the components of the cars are the means for the functions, i.e. functional decomposition (Liedholm, 1998). The functions can be solved by several means and one mean can include several functions. This can be arranged in a tree, where each function is placed on top of each means. Scenarios where one function has several means beneath it is used primarily in concept development. A basic function-means tree can be seen in Figure 2.3 (Andreasen, 1980).

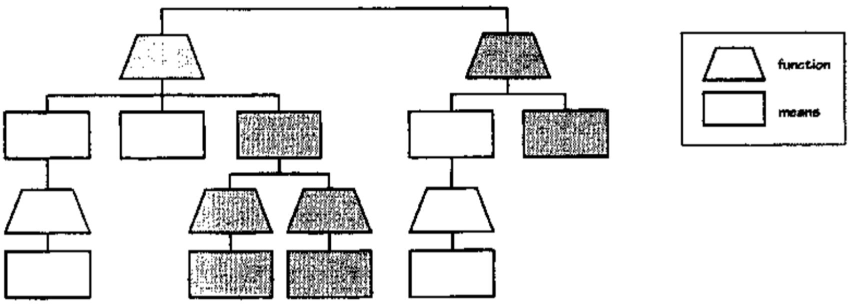


Figure 2.3: A basic function-means tree developed by Andreasen (1980), as cited in Liedholm (1998).

As Figure 2.3 shows, a function can have several means and the means can in turn realize several functions. The left highlighted tree has a means as the local top level. The means in this case is connected to two functions. The highlighted tree to the right has a function as a local top level. This function is realized by two means.

2.2 Theoretical framework

This section aims to provide the reader with the process of how the literature and benchmarking study was done. The theoretical framework consists of searching through the available scientific articles, obtaining data sources, and learning from others to name a few reasons. This scientific contribution, in conjunction with the benchmarking, formulated the principles in which the thesis was decided to pursue. Both the literature study and competitor tool analysis heavily relied on Internet sources.

2.2.1 Literature review

Academia provides a lot of information, particularly in terms of the mathematical science behind pure algorithms. It was therefore deemed to be of interest to investigate related scientific contributions in the same area as this thesis. The scientific contribution was found by mainly using Google Scholar. Terms such as "optimization", "cable", "harness", "length", "method", "tool", "architecture" were used as keywords which generated a considerable amount of scientific contributions. Especially so with terms related to material properties such as "weight", "cost", and "density". This resulted in a large amount (50+) articles that were reviewed. Not all articles were deemed relevant, however. Though it can be said that an amount of 11 articles were deemed relevant and to have nature which is directly or indirectly related to the scope of this thesis. The articles were then organized into three themes where each theme showed similarities. To exemplify, *Routing algorithms* are directly linked to the scope of the thesis. However, there is no direct link between a generic algorithm and finding the length of a cable, i.e. connecting two or more components, in an automotive application. Though by tweaking the algorithm, this can be achieved, hence the categorization. Another theme of interest is similar cases found in other various application areas.

2.2.2 Benchmarking

As described in the introduction, there are a considerable amount of car manufacturers who are creating EVs of their own. This may indicate that there already are methods present that aims to fulfill the same objectives as this thesis aims to do. Therefore, it is of interest to investigate the competitors.

The procedure of benchmarking is at its core a simple step in the development of a product (Ulrich & Eppinger, 2012). It essentially involves analyzing the competitors' products and arranging the performance in a relevant matrix. Though, as Ulrich and Eppinger (2012) argue, this process is very time consuming but at the same time of utmost importance as it is said that no product development team can create a successful product without conducting it. Furthermore, it is important to consider the accuracy in the information displayed in various product catalogs and other types of sources as it may be biased.

A parallel way of working has been applied throughout the thesis. This allowed efforts to be put into investigating current tools for routing cables between components while conducting the literature study at the same time. Investigation of the industry-standard tools was delved into similarly. This as to take note of the current way of working and obtaining a deeper sense of understanding of the problem. Other software was investigated as well. The Internet was the primary source of finding these. Keywords such as "industrial", "cable routing software", and "routing software" were used and resulted in a handful of software. As the website of each software was primarily used to market the software in question, these had to be investigated with caution, as they will most likely be biased as previously mentioned. Efforts were made to reach out to the developers of the software to get a deeper understanding. Not every developer answered and even fewer explained how their software works.

2.2.3 Identification of the principles for the tool

Having the goals of the thesis in mind, the plan was to investigate and map what others have achieved to provide guidance. The goals can be seen as one input for the principles of the tool and the available information can be seen as another. Both of these inputs are from different ends of the spectrum, where the goals are mainly focusing on the output and available information can be seen as potential inputs. The literature study and benchmarking revolved around creating the foundation of the tool, whereas the interface of the tool is developed with respect to the goals. The principles of the tool were achieved by combining these two.

2.3 Method development

The purpose of this section is to provide the reader with information about the agile development for the method. The iteration starts by defining the method, with the inputs, outputs, and the translation from input to the output, i.e. the specification of the method. The second step is the method proposal, which is the formulation of the method itself. The third step is defined as the method testing to obtain an index for the method. The fourth and last step evaluates the method.

2.3.1 Specification of method

A parallel way of working for the specification of the method is achieved by using a work breakdown structure. The method is therefore divided into three distinct segments, namely inputs, outputs, and the translation between inputs and outputs, where the translation is hereafter referred to as the evaluation tool. Using the work breakdown structure in this manner allows for the segments to be addressed individually as long as the other segments are clearly defined.

Inputs
Carefully considering the goals of the thesis meant obtaining and determining which elements are requested of the tool. By analyzing the requests, the inputs for the system can, therefore, be determined. To exemplify, finding the total cost for an assembly requires the cost as an input of each part of the assembly. Each request is therefore said to be linked to at least one input. These inputs are therefore of interest to identify.

Outputs
The requests which the thesis is built on are dealt with as outputs for the system. These are very critical indeed, as if the engineers' opinions are not taken into consideration, the thesis as a whole fails. Introducing new elements to the current way of working for the engineers tend to require an effort, in the beginning, to get familiar with the addition. Therefore, the outputs must outweigh the efforts invested by the engineers using the tool.

Evaluation tool
In essence, the evaluation tool is meant to act as a translation for the input to the output. This meant that the feedback regarding the evaluation tool is limited, which required a thorough analysis. As a goal was to utilize a parallel way of working, the evaluation tool had to be broken down into smaller segments, utilizing a work breakdown structure.

2.3.2 Method proposal

As mentioned previously, the evaluation tool is meant to translate the inputs to outputs while at the same time be general as possible. Hence the need for a generic algorithm for the calculations. Considering an algorithm is defined as a series of well-defined steps, applying an algorithm as translation should yield a satisfying result. This implied the need to construct a database. However, since the database is the resource for the cost and weight, it is strictly confidential.

2.3.3 Method testing and evaluation

A considerable amount of time was spent analyzing the current electric fleet and alternative designs in the pre-study phase. This was the input to test the method on the available electric system layouts. This served several purposes. Firstly, if the method is applied, it is verified to be working as intended. Secondly, it acts as a data extraction tool. Thirdly, it provides the ability for feedback as the data extracted can be analyzed.

2.3.4 Method verification

The extracted data in the previous step allows for an evaluation to take place, as the evaluation is directly linked to the performance of the electric system layout via indexing. As the method is defined, tested, and evaluated in several iterations, the index can be used to compare alternative electric system layouts. Each iteration can be seen as a sprint in agile development. Agile development heavily relies on communication to ensure that the sprints are on a desirable path. Agile development stops when satisfying results have been reached.

2.4 Complete method

Once the result from the agile development is satisfying, it marks the end of the thesis. This means that the method has the characteristics of the attributes mentioned in *Goals*. Therefore, the method is, with the characteristics taken from the *Goals* in Section 1.5, accurate in the calculations of the cost and weight. The proof of concept developed to realize the method is user-friendly and a software plan is provided to ensure a complete method.

Following the end of the method development is the finalized method where the software programming for the tool will take place. The thesis is meant to provide all necessary information and instructions for how the tool is meant to be shaped, without including the necessities of software development e.g. language, libraries, environments.

3

Theoretical framework

This chapter presents the theoretical framework which is used in the thesis. The theoretical framework includes system description, literature review, and benchmarking of current software. The chapter ends with the principles for the method.

3.1 System description

This section aims to provide the reader with all the overview of the total system and how the components inside them are connected, as there are several variants.

3.1.1 Overview

The high voltage (HV) system inside the electric vehicle (EV) serves several purposes namely to provide propulsion in either direction, charge the 12V battery, and provide both hot and cooled air for the passenger compartment. The air can be used for other application areas in the car as well (Avnet Incorporated, 2017; Professional Motor Mechanics, 2015; Webasto Thermo & Comfort SE, 2014). Furthermore, this thesis also covers 12V battery storage. These functions require both alternating current (AC) as well as direct current (DC).

By referring to the HV system as a black box, see Section 2.1, it provides a tool to analyze the input as well as the output for the intended function. For the car to provide the aforementioned propulsion, the car has to provide a way of storing electricity for which the HV system can utilize. However, an issue that arises is the fact that the input for the storage can only be 400V DC. Depending on the model, the car can receive AC, at different voltages, and 400V DC. The AC electricity, therefore, needs to be converted to 400V DC. Furthermore, considering the onboard electric motors run on AC, the electricity from the main battery needs to be converted from 400V DC to 400V AC. Aside from the propulsion, the 12V battery is to be charged using the electricity from the main battery. Therefore, the voltage needs to be converted from 400V DC to 12V DC. The 12V electric system is used in peripheral devices which a conventional combustion engine car utilizes as well, i.e. radio, windscreen wiper, and lights both inside and outside of the car. The components which provide hot and cool air for the passengers run on 400V DC.

3.1.2 Connections

The functions mentioned in Section 3.1.1 require electricity that is transferred, between the different components, by either cables or busbars (Zhu, Su, Zhang, & Li, 2006). The material used in both of these alternatives is some kind of metal that conducts electricity well, e.g. copper or aluminum. The choice between either a cable or a busbar depends on the type of electricity, available space, and its destination as well as origin. Depending on which type of connection between the components the engineer chooses, the outcome is different. Generally, cables are more expensive than busbars per meter used for a specific current. Furthermore, cables are flexible whereas the flat design of the busbars makes it not as flexible (Grandvuillemin, Chamagne, Tiraby, & Glises, 2008; Zhu et al., 2006). A busbar is seen in Figure 3.1.

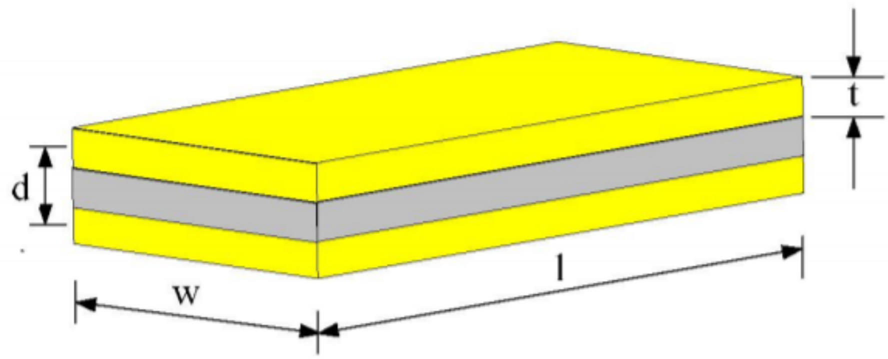


Figure 3.1: Layers of a busbar (Zhu et al., 2006).

The busbar is structured in this way because it lowers the stray inductance and increases the stray conductance which will reduce the electric and magnetic emissions (Zhu et al., 2006). The layering is achieved by having the top and bottom, t in Figure 3.1, of the busbar as conductors and the middle, d in Figure 3.1, as insulation. Furthermore, since the busbar is essentially a flat conductor, there is no need to have connectors between the end of the busbar and the receiving component.

As cables are a wide definition and may be interpreted differently, a definition of the cable connection is given. The elementary part of the cabling between two nodes is the cable. The cable consists of the conductor core, which is transmitting the electricity, and an insulator, protecting the conducting core. The insulation is henceforth referred to as the shield, where there is a distinct difference in terms of numbers of conductor elements in the cable. The notation *wire x area* will be used throughout the thesis, where *wire* indicates the number of conductor elements in the cable and *area* indicates the cross-section of each conductor in [mm^2]. To exemplify, the cable *4x4* is a multicore cable in which an application area normally associated with lower voltage, amperage, and/or effect. On the other hand, the cable *3x50* is a single shield cable that is normally associated with higher voltage, amperage, and/or effect.

3.1.3 Connectors

To fasten and properly transmit the electricity, the cable has to have one connector attached at each end of the cable. The terminology for the cable having two connectors is henceforth referred to as cable assembly. Two different connectors are used for the HV cables and these are headers and ring terminals. Examples of how these can look can be seen in Figure 3.2.

(a) Header (TE Connectivity, 2020)

(b) Ring terminal (in-Tec Bensheim, n.d.)

Figure 3.2: Examples of header and ring terminal

A header includes a male and a female component with the male component, being a pin header, which is mounted on the component and the female component, being a socket, which is mounted on the end of a cable. A ring terminal requires fewer components and it is attached to the component through a screw. Because the ring terminal requires less complicated components, the number of materials for the ring terminal is less than for the headers. The assembly cost is higher for the ring terminal because it is more complicated to assemble. After all, the header's components easily slide into each other.

3.1.4 Split boxes

The split box is a component that is used in some HV systems. A split box is a component which distributes electricity. The HV system for the Chevrolet Bolt EV is an example where Chevrolet uses a split box. They call it High Power Distribution Module (Liberty Access Technologies, 2018). The High Power Distribution Module is connected to the main battery and distributes the electricity to HV components in the front of the car. Other components in the car can also be used as a split box as in adding the split box on top of with an existing component.

3.2 Literature review

The available literature regarding various ways to solve the routing issue and their application alike are given in this section. Firstly, there is an introduction to algorithms and how they are related to the routing issue. Secondly, literature regarding algorithms applied to similar cases is put forth. Thirdly, literature in regards to other application areas is presented. Lastly, a literature review summary is presented.

3.2.1 Routing algorithms

An algorithm is defined as a finite series of well-defined steps used to solve a specific set of problems. The issue with wire-routing could be solved using algorithms, which previous studies have shown. Kloske and Smith (1994) presented a genetic algorithm to aid in designing overall cable routing by identifying the non-trivial routing in large projects such as in designing power plants. The usage of genetic algorithms in this scenario is common as Conru (1994) points out. Both of these were released the same year, currently more than two decades ago. Several other studies have been done in terms of using algorithms as a means of finding the shortest path, route, or other means of connections between several set points (Coulston & Weissbach, 2003; Lin, Rao, Giusto, D'Ambrosio, & Vincentelli, 2014; Ma et al., 2006).

The approach for the different algorithms for the aforementioned studies varies. A common approach found in the studies is the usage of Steiner trees. By formulating the wire routing issue such as this, Lin, Rao, Giusto, et al. (2014) managed to develop an algorithm that aims to minimize the weight of the wiring system in automotive systems. Their algorithms work in three steps, a transformation of the problem to a Steiner tree definition to minimize length and weight, relocation of Steiner vertices, and segment sizing. The latter two are used to keep the parameters within the constraints and to link the length to the weight (segment sizing). The constraints are set by the authors themselves, as the algorithm is generic and may otherwise give unfeasible results. The usage of Steiner tree problem occurs in other studies as well. By applying the Steiner tree problem to power transmission grids, Coulston and Weissbach (2003) tried to minimize the routing costs between several set nodes in the power grid. The power grid was generalized into a partitioned hexagonal pattern where moving across one cell to another generated a cost. To minimize these costs, a genetic algorithm was used. The genetic algorithm was used as a means of iterative optimization to find the lowest possible connection between the set points.

The aforementioned studies both used real empirical data as input for their Steiner tree problem. As reference input, Lin, Rao, Giusto, et al. (2014) put an experienced designer to the test and the result is shown in Table 3.1. As the table indicates, their algorithm manages to shorten the total routing length by roughly 4 % and the total weight for the cabling by approximately 10 %. The authors do not explicitly discuss this outcome. In another fashion, Coulston and Weissbach (2003) did

Table 3.1: Comparison of designer experience and algorithm output (Lin, Rao, Giusto, et al., 2014).

	Experienced designer	Algorithm-based
Routing length [mm]	297 310	285 010
Comparison [%]	1,000	0,959
Weight [kg]	3,031	2,707
Comparison [%]	1,000	0,893

not use real empirical data to demonstrate the potential of their algorithm, aside from the sample lattice which the authors themselves created. Testing the algorithm in a real scenario along with varying costs for each cell, which would in the real scenario indicate a rougher terrain to build power grids on, is left as future work.

Genetic algorithms, which were used by Coulston and Weissbach (2003), tries to mimic the natural selection in evolution. In short, the algorithm intends to follow the biologically inspired variants generated by combinations of mutations, crossovers, and selection of feasible options. It is frequently used in optimization problems, supported by the extensive usage of this type of algorithm in previous studies (Conru, 1994; Kloske & Smith, 1994; Ma et al., 2006). Conru (1994) states that it is not possible to use the Steiner tree problem definition to solve the wiring routing issue with certain routing objectives. He draws this conclusion from the actual wiring harness itself as the costs for each wire passing through the connection adds a cost. Using a genetic algorithm, in this case, would have taken account of a variable routing cost (Conru, 1994). Depending on the scope, this may or may not be the case for other studies done using genetic algorithms where there are other routing objectives. For instance, Kloske and Smith (1994) addressed the overfill of the cabling raceway, weight of the cabling raceway, and voltage drop inside the cabling as three routing objectives alongside the primary cost objective. These four must be addressed simultaneously since each objective is dependent on one another. By describing the objectives mathematically makes it possible to utilize them as input for the genetic algorithm. Later works, Ma et al. (2006), emphasize objectives/constraints as the main cause for introducing genetic algorithms. In a Euclidean space, the shortest path between two nodes is given by the Dijkstra algorithm (Ma et al., 2006). In similarity to Kloske and Smith (1994), the main constraint which has been addressed in the works of Ma et al. (2006) consists of the cabling tray and its properties. Though finding the optimal solution for the cabling tray is only one part of the problem. The other being searching for feasible cabling routes.

3.2.2 Applied algorithms

There have been several studies done in terms of applying algorithms, models, or other types of tools to find a minimum or maximum for a certain variable (Axelsson, 2000; Castorani, Cicconi, Mandolini, Vita, & Germani, 2018; Lin, Rao, D'Ambrosio, & Sangiovanni-Vincentelli, 2014). The variable(s) can be measured in terms of the performance concerning weight, cost, or computational time. Often in a combination of each other. Keywords such as ”simulations”, ”optimization”, ”estimation”, and more applied concepts such as ”Design for Cost”, are common in the studies. Furthermore, the aforementioned keywords are often found in conjunction with studies in the early stages of product development.

Models for calculating the cost of the electronic architecture was studied as early as two decades ago, as shown by Axelsson (2000). An absence of a method, which is focused on costs, were identified. The method was intended to evaluate and compare different solutions in systems engineering as the absence of such a tool will generate costs. Considerably so in the early stages of product development, as there are large uncertainties when addressing the different areas in engineering. During this study, the main focus was put on electronic control units and their physical location on the vehicle. Although the empirical studies were done in collaboration within the automotive industry, Axelsson (2000) argued that the model approach was general, and the results could be extended to include other attributes as well. Later works confirm the absence of such a method (Castorani et al., 2018; Lin, Rao, D'Ambrosio, & Sangiovanni-Vincentelli, 2014). The absence of such a method was confirmed here as well to increase the costs. The need for a proper architecture was identified, and developing a complete method will solve this, as manual calculation by hand is too extensive of a task. Axelsson (2000) argues the total lack of both modeling and evaluating the cost for a particular architecture. This in contrast with later works (Castorani et al. (2018); Lin, Rao, D'Ambrosio, and Sangiovanni-Vincentelli (2014)) as their argument lies in the lack of a complete method for evaluation. Complete is in this sense referred to as being part of the tools in which the designer uses regularly, i.e. a CAD software.

The attribute in which the method calculates is similar for the cases studied. The studies were done (Axelsson (2000); Castorani et al. (2018); Lin, Rao, D'Ambrosio, and Sangiovanni-Vincentelli (2014)) by applying a variant of a system breakdown structure. By using this method, a precise and accurate method can be achieved. To exemplify, Axelsson (2000) calculates the wire cost as a function of the length of the cable and the cost per length: $f(L) = L * C$, where L is the length of the cable in meters [m] and C is the cost per meter [\$/m]. The calculated cost in this example only addresses the wiring inside the harness. The total cost for the harness is a function of the wiring cost and the peripheral cost. The peripheral cost is defined by Axelsson (2000) as the combination of the necessary costs associated with the wiring for a complete component.

Using the method developed gives an estimate in the early stages of product development (Axelsson, 2000). The goal set by Axelsson (2000) was to develop an easy-to-use method that takes account of the cost, but still being general in the sense that other attributes can be used. The author concluded that this was achieved, and the method could be used stand-alone or included in relevant software. Later works (Castorani et al. (2018); Lin, Rao, D'Ambrosio, and Sangiovanni-Vincentelli (2014)) has achieved the same result where the respective method developed takes account for the costs associated. Each paper's future recommendation corresponds with one another with the reasoning to investigate the opportunity to incorporate their respective method in software which the designer uses daily.

3.2.3 Various application areas

The application area for which the target is to find the shortest path between at least two in a given Euclidean space is many. Few examples of these application areas are wind farms, electrical panels, and aerospace design (Hu, Chen, & Hou, 2016; Ittner, de Sá, & Sasse, 2007; Van der Velden, Bil, Yu, & Smith, 2007).

In their article, Hu et al. (2016) shed light on the issue of having offshore wind farms. As wind farms generate noise pollution, it is sought after to construct these far from society. Furthermore, offshore wind farms have a higher efficiency than onshore wind farms. Though the drawback of having the wind farms far away from society, generating electricity far away from where it is being used, is the increased cost for cabling required. Hu et al. (2016) aimed to develop a method to minimize the cost associated with this. To do so, they proposed a dynamic variant of the minimum spanning tree. The minimum spanning tree is a variant of the previously mentioned Steiner tree problem, but each vertices acting as terminals with different properties. An illustration of this is given in Figure 3.3 with six fixed vertices, vertex A to vertex F.

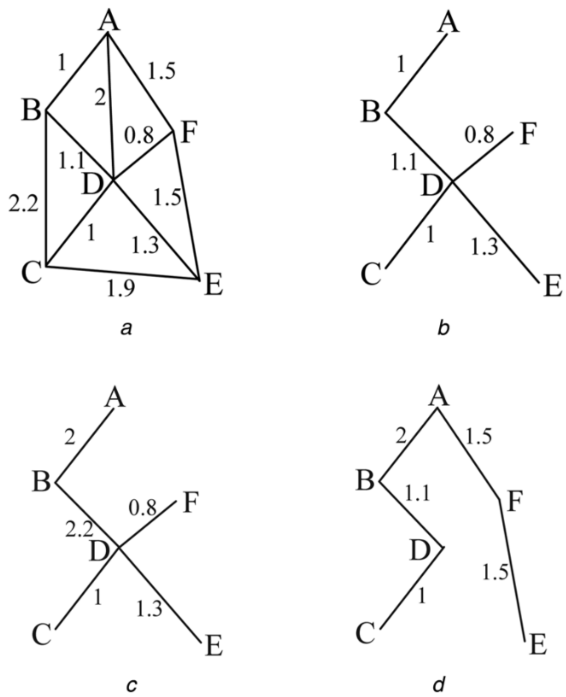


Figure 3.3: Illustration spanning trees (Hu et al., 2016).

In the figure, there are four illustrations of spanning trees (Hu et al., 2016). The illustrations represent (a) six vertices graph with varying weight (b) minimum spanning tree with a maximum of one connection per vertex (c) minimum spanning tree layout with an assumed double weight, if one vertex is connected to more than one (d) the proposed dynamic minimal spanning tree. With this assumption (d), Hu et al. (2016) concluded that the dynamic minimal spanning tree approach is better than the minimal spanning tree approach. Future works given by the authors include practical application factors such as transformers, circuit breakers, and cable installation to be accounted for.

Another area of interest is the installation of the cabling between the components inside electrical panels (Ittner et al., 2007). Each panel consists of dozens or hundreds of components. These components have to be linked one way or the other. It takes a lot of effort from the designer of these panels as there is a direct correlation between the cost and the aforementioned connections. The iterative process of finding the optimal placement for the connections is stressful, repetitive, and prone to errors. Therefore, there is a need to ease this process. As mentioned, the panels consist of dozens or hundreds of components which makes the problem complex very quickly, as several variables determine the cost for the connections. These range from the properties of the cable in use, e.g. gauge, color, insulation voltage to the specification of the cable conduit, e.g. wire ducts, raceways, cable trays. The proposed method by Ittner et al. (2007) is developed with a system breakdown approach to ensure that every variable is accounted for. The breakdown allowed for the developed algorithm to function in the following way: (1) cable conduit splitting, (2) iterate through a list of cables, inserting them into the panel with descending order of cost and routing according to the shortest path while calculating remaining cross-section area for the cable. The result is a cost minimization due to having the most expensive cable being the shortest, at the cost of having a cheaper cable being longer. The finished method is tested by a case study and showed promising results. As a future recommendation, the authors recommend comparing this method with a genetic algorithm.

A third area of interest is the wiring routing within aerospace (Van der Velden et al., 2007). Within aerospace, there are heavy amounts of laws and regulations which the designer for the cabling harness has to take into consideration, as they are determined manually. This iterative process of finding an optimal solution is exhausting and difficult but also a prime candidate for applying knowledge-based systems. Knowledge-based systems are the software that allows for a knowledge-based engineering method to aid in product development. To obtain a satisfying result with the routing, Van der Velden et al. (2007) proposed the usage of the A* (A Star) algorithm. It is said that the A* algorithm is a refined version of Lee's breadth-first maze algorithm and proven useful in areas of rule-based routing systems. Although extending the algorithm to allow for three-dimensional routing, a solution was found in conjunction with the usage of multiple CAE tools.

The objective set by Van der Velden et al. (2007) was to create the prerequisites for a knowledge-based system, by having the routing done automatically. This was meant to be implemented in the CAD tool as the output was meant to be the CAD geometry. This was deemed successful as the method which was developed draws a wiring path in a Euclidean three-dimensional space.

3.2.4 Literature review summary

There are plenty of algorithms that can be applied to the problem in this thesis. Furthermore, there are very similar cases, such as aerospace, which confirms the result of using algorithms such as the ones mentioned in Section 3.2.1. To summarize, Table 3.2 is meant to provide readability for the reader.

Table 3.2: Summary of the cited works in the literature review

Article	**Identified gap**	**Generic approach used**	**Future recommendation**
Coulston and Weissbach (2003)	Lack of complete evaluation method	Steiner tree and genetic with 1-level optimization	Using the proposed method in real scenarios
Lin, Rao, Giusto, et al. (2014)	Lack of evaluation method	Steiner tree with 3-level optimization	Further testing using the proposed method
Ma et al. (2006)	Lack of evaluation method	Genetic with 2-level optimization	Using the proposed method in real scenarios*
Conru (1994)	Lack of evaluation method	Genetic with 2-level optimization	Further refinement of the proposed method
Kloske and Smith (1994)	Lack of evaluation method	Genetic with 2-level optimization	Using the proposed method in real scenarios*
Axelsson (2000)	Lack of rough evaluation method	System breakdown approach	Integration of method to other software(s)
Castorani et al. (2018)	Lack of complete evaluation method	System breakdown approach	Integration of method to other software(s)
Lin, Rao, D'Ambrosio, and Sangiovanni-Vincentelli (2014)	Lack of complete evaluation method	System breakdown approach	Integration of method to other software(s)
Hu et al. (2016)	Lack of complete evaluation method	Modified minimal spanning tree (Steiner tree variant)	Further testing using the proposed method
Ittner et al. (2007)	Lack of evaluation method	System breakdown approach	Further testing using the proposed method
Van der Velden et al. (2007)	Lack of complete evaluation method	Knowledge-based engineering and A*	Further testing using the proposed method

By addressing the columns in Table 3.2 from left to right, it seems as though the reason for conducting the study, ”Identified gap”, is more or less the same. The major differences between the studies are different attributes, i.e. weight, cost, electrical capacity, which the study intends to optimize/minimize/maximize. The term ”complete” refers to a study where the authors are addressing the future recommendations given in another study, and formulating a new one, further refining the initial scope. For example, the literature study done in a particular article shows that there have been studies done on a specific attribute but not in the area of interest for that article. The term ”rough” in this sense refers to having identified a total lack of study done in that particular field or by using that particular algorithm.

The method of calculation for how others have done in adjacent studies varies a lot. Though it can be summarized that the most common approach for finding an optimal/minimized/maximized attribute is the usage of a genetic algorithm. If the attribute can be divided into sub-attributes, e.g. total cost and sub-cost, the most common approach is by systematically break down the chunk into smaller segments and then summarize the segments, once calculated.

The future recommendation for each study reviewed differs somewhat. Although they somewhat coincide with each other in terms of testing the proposed method in further studies. Two of the articles in Table 3.2 are marked with an asterisk (*). This indicates that the study used experimental empirical data, meaning that the proposed method has not been tested on a real scenario. These are therefore marked with an asterisk as using them first in a real scenario would be the best approach forward. Concluding the summary, it seems as a recurrent recommendation given is the integration for the proposed method in other software and mainly the software for which the designer (design engineer) is already using.

3.3 Benchmarking

The benchmarking was done on tools and software which aims at working with connections, such as cables and busbar. The different tools and software which were found are described with both texts and figures with the interface of the tool or software. In the summary of the benchmarking, a comparison was made between the different tools and software.

3.3.1 Industrial Path Solutions

Industrial Path Solutions (IPS) is a software that can be used to do FE analyses on for example cables (Fraunhofer Chalmers Centre, n.d.). IPS is currently being used to conduct FE analyses on cables. The way it looks when doing FE analyses on cables in IPS can be seen in Figure 3.4.

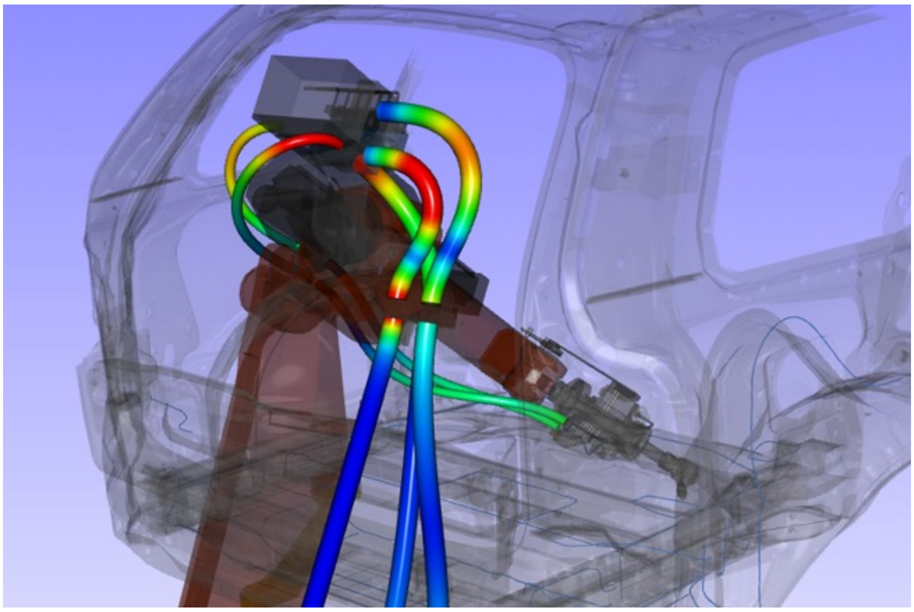
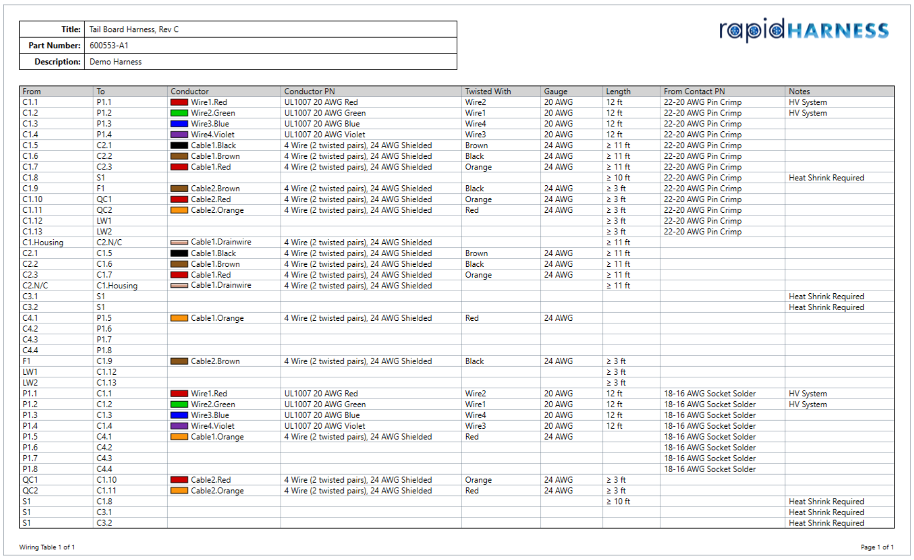


Figure 3.4: FEM-analysis on cables in IPS (Fraunhofer Chalmers Centre, n.d.).

Input from the front end users of IPS and Fraunhofer research centre at Chalmers, which develops IPS, it can be understood that the length of the different connections between components can be found in IPS, but IPS are not used to calculate cost or weight at the moment. In IPS there is a possibility to assign properties to the cables to differentiate them from each other (Fraunhofer Chalmers Centre, n.d.).

3.3.2 RapidHarness

RapidHarness is a software, according to their website, used to draw schematics automatically in real-time (RapidHarness, n.d.). In the example interfaces on RapidHarnesses' website, it can be seen that their program calculates the length of different harnesses, but the numbers are not precise, as can be seen in the "length" column in Figure 3.5.



Title:	Tail Board Harness, Rev C
Part Number:	600553-A1
Description:	Demo Harness

From	To	Conductor	Conductor PN	Twisted With	Gauge	Length	From Contact PN	Notes
C1.1	P1.1	Wire1.Red	UL1007 20 AWG Red	Wire2	20 AWG	12 ft	22-20 AWG Pin Crimp	HV System
C1.2	P1.2	Wire2.Green	UL1007 20 AWG Green	Wire1	20 AWG	12 ft	22-20 AWG Pin Crimp	HV System
C1.3	P1.3	Wire3.Blue	UL1007 20 AWG Blue	Wire4	20 AWG	12 ft	22-20 AWG Pin Crimp	
C1.4	P1.4	Wire4.Violet	UL1007 20 AWG Violet	Wire3	20 AWG	12 ft	22-20 AWG Pin Crimp	
C1.5	C2.1	Cable1.Black	4 Wire (2 twisted pairs), 24 AWG Shielded	Brown	24 AWG	≥ 11 ft	22-20 AWG Pin Crimp	
C1.6	C2.2	Cable1.Brown	4 Wire (2 twisted pairs), 24 AWG Shielded	Black	24 AWG	≥ 11 ft	22-20 AWG Pin Crimp	
C1.7	C2.3	Cable1.Red	4 Wire (2 twisted pairs), 24 AWG Shielded	Orange	24 AWG	≥ 11 ft	22-20 AWG Pin Crimp	
C1.8	S1					≥ 10 ft	22-20 AWG Pin Crimp	Heat Shrink Required
C1.9	F1	Cable2.Brown	4 Wire (2 twisted pairs), 24 AWG Shielded	Black	24 AWG	≥ 3 ft	22-20 AWG Pin Crimp	
C1.10	QC1	Cable2.Red	4 Wire (2 twisted pairs), 24 AWG Shielded	Orange	24 AWG	≥ 3 ft	22-20 AWG Pin Crimp	
C1.11	QC2	Cable2.Orange	4 Wire (2 twisted pairs), 24 AWG Shielded	Red	24 AWG	≥ 3 ft	22-20 AWG Pin Crimp	
C1.12	LW1					≥ 3 ft	22-20 AWG Pin Crimp	
C1.13	LW2					≥ 3 ft	22-20 AWG Pin Crimp	
C1.Housing	C2.N/C	Cable1.Drainwire	4 Wire (2 twisted pairs), 24 AWG Shielded			≥ 11 ft		
C2.1	C1.5	Cable1.Black	4 Wire (2 twisted pairs), 24 AWG Shielded	Brown	24 AWG	≥ 11 ft		
C2.2	C1.6	Cable1.Brown	4 Wire (2 twisted pairs), 24 AWG Shielded	Black	24 AWG	≥ 11 ft		
C2.3	C1.7	Cable1.Red	4 Wire (2 twisted pairs), 24 AWG Shielded	Orange	24 AWG	≥ 11 ft		
C2.N/C	C1.Housing	Cable1.Drainwire	4 Wire (2 twisted pairs), 24 AWG Shielded			≥ 11 ft		
C3.1	S1							Heat Shrink Required
C3.2	S1							Heat Shrink Required
C4.1	P1.5	Cable1.Orange	4 Wire (2 twisted pairs), 24 AWG Shielded	Red	24 AWG			
C4.2	P1.6							
C4.3	P1.7							
C4.4	P1.8							
F1	C1.9	Cable2.Brown	4 Wire (2 twisted pairs), 24 AWG Shielded	Black	24 AWG	≥ 3 ft		
LW1	C1.12					≥ 3 ft		
LW2	C1.13					≥ 3 ft		
P1.1	C1.1	Wire1.Red	UL1007 20 AWG Red	Wire2	20 AWG	12 ft	18-16 AWG Socket Solder	HV System
P1.2	C1.2	Wire2.Green	UL1007 20 AWG Green	Wire1	20 AWG	12 ft	18-16 AWG Socket Solder	HV System
P1.3	C1.3	Wire3.Blue	UL1007 20 AWG Blue	Wire4	20 AWG	12 ft	18-16 AWG Socket Solder	
P1.4	C1.4	Wire4.Violet	UL1007 20 AWG Violet	Wire3	20 AWG	12 ft	18-16 AWG Socket Solder	
P1.5	C4.1	Cable1.Orange	4 Wire (2 twisted pairs), 24 AWG Shielded	Red	24 AWG		18-16 AWG Socket Solder	
P1.6	C4.2						18-16 AWG Socket Solder	
P1.7	C4.3						18-16 AWG Socket Solder	
P1.8	C4.4						18-16 AWG Socket Solder	
QC1	C1.10	Cable2.Red	4 Wire (2 twisted pairs), 24 AWG Shielded	Orange	24 AWG	≥ 3 ft		
QC2	C1.11	Cable2.Orange	4 Wire (2 twisted pairs), 24 AWG Shielded	Red	24 AWG	≥ 3 ft		
S1	C1.8					≥ 10 ft		Heat Shrink Required
S1	C3.1							Heat Shrink Required
S1	C3.2							Heat Shrink Required

Wiring Table 1 of 1

Page 1 of 1

Figure 3.5: Information about a demo harness in RapidHarness software (RapidHarness, n.d.).

In RapidHarness, different properties, as which type of shielding, for example, can be applied to the different harnesses. There is a database that stores these properties. The database is there to save time when designing the harnesses. RapidHarness is designed in the way that the systems which are created can be disassembled into smaller systems to be able to look at the system from a different angle. After mail correspondence with the creators of RapidHarness, it was concluded that their software could not calculate either the cost or weight of the harnesses.

3.3.3 netTerrain

The goal which Graphical Networks has with its software (netTerrain) is to offer a way out of using, for example, out-of-date spreadsheets to manage cables and circuits (Graphical Networks, 2020b). Graphical Networks emphasize that netTerrain allows the engineer to assign properties to different cables and circuits. The information about how the different properties change over time is also stored as revisions. Among the properties, the cable type and length are included.

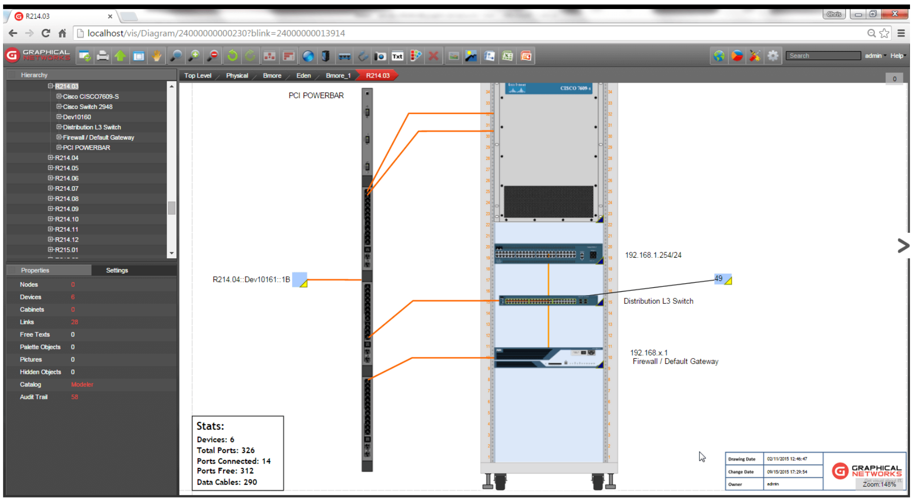


Figure 3.6: Interface of netTerrain (Graphical Networks, 2020b).

Some of the users of netTerrain are Bell, UBL, and GE. What they share in common, is that they all say that they save time and money when using netTerrain (Graphical Networks, 2020a, 2020d, 2020c). After mail correspondence with Graphical Networks, it was concluded that their software could not calculate either the cost or weight of the harnesses.

3.3.4 Bentley Raceway and Cable Management

One of the things that Bentley emphasize with their software is that it helps in the early phases of project planning. The software has a conceptual design mode that can be used in the early phases of project planning. What can be seen in Figure 3.7 is that different properties can be assigned to different cables. It can also be seen that in detailed design the length and weight of the cable can be calculated (Bentley Systems Incorporated, 2020).

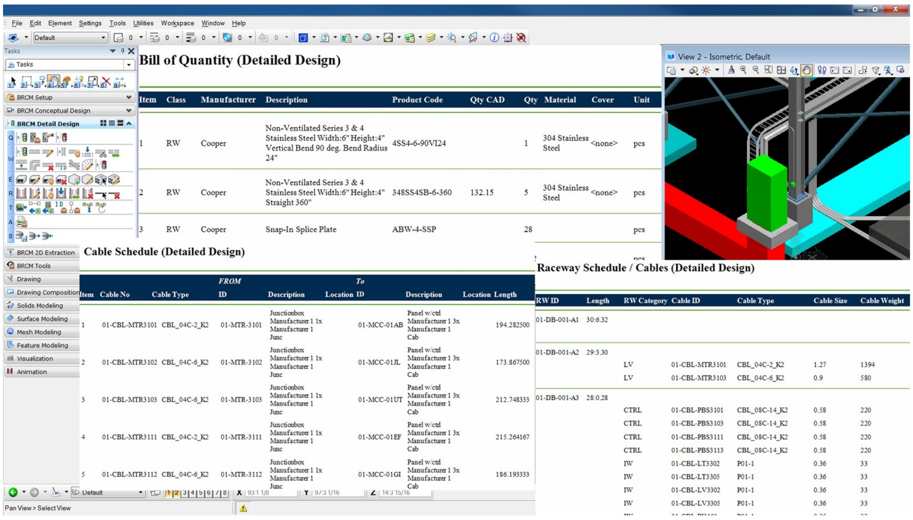


Figure 3.7: Information that can be collected through Bentley Raceway and Cable Management (Bentley Systems Incorporated, 2020).

Bentley Raceway and Cable Management can transform 3D models into a 2D drawing to reduce the number of errors that are delivered from projects. The 2D drawings are easily updated through only republishing of the drawing when changes to the corresponding model have been made. Both automatic and manual cabling can be done with the help of Bentley Raceway and Cable Management (Bentley Systems Incorporated, 2020).

3.3.5 E3.series

E3.series is developed by Zuken. It includes many different ways of handling and documenting of electrical and fluid planning (Zuken, 2020a). E3.series is built through different core products and optimal products. The ones that are used for similar aims as this thesis are E3.schematic, E3.panel, E3.topology, and E3.WiringSystemLab. With E3.schematic the foundation and the rules for the system are set (Zuken, 2020b). To place the components where they should be and route connections between them, E3.panel is used (Zuken, 2020d). When connections have routed a calculation of their length is done. To fit the connections in the physical world, E3.topology is used. Different configurations of the connections can be tested. The cost and weight of the connections can be calculated with the help of E3.topology (Zuken, 2020c). To combine CAD drawing with the topology E3.WiringSystemLab. Modification of the topology can be done in E3.WiringSystemLab, like for example adding connectors (Zuken, 2020e). In Figure 3.8 an example of how the interface looks in E3.WiringSystemLab, with the weight of the connections shown in the bottom left corner.

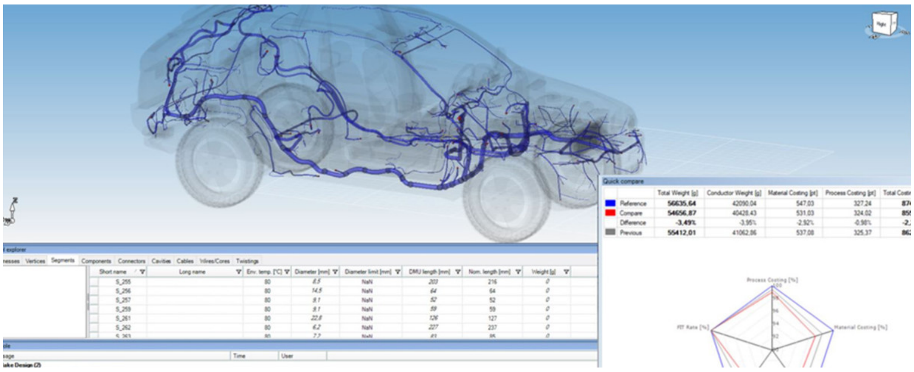


Figure 3.8: Interface of E3.WiringSystemLab (CCS Group, n.d.)

3.3.6 Cable Routing & Schedule

Cable Routing & Schedule (CRS) is developed to be a supplement to engineering software, e.g. CAD systems, which do not have cable routing built-in (Keppel FELS Baltech Ltd., n.d.). CRS automatically routes cables between different equipment, where one equipment can be a heat detector for example. These equipment are connected to locations, which are reference coordinates and distances. The inputs to the software, which the locations are one of, are put into the software through a ".CSV."file which is built into the software. The other inputs are for example the type of cable. The interface where the input is done can be seen in Figure 3.9.

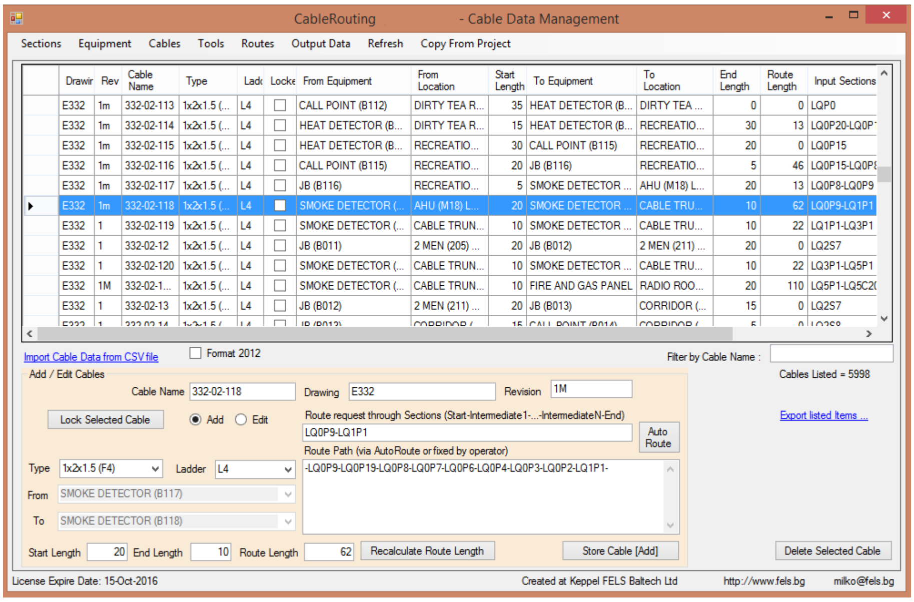


Figure 3.9: Interface of Cable Routing & Schedule software (Keppel FELS Baltech Ltd., n.d.).

The software automatically generates a cable schedule and a cable bill of material (Keppel FELS Baltech Ltd., n.d.). Data that is generated by the CRS software is said to have the ability to be imported electrical 2D drawings or other documents. The cable weight can be seen to be calculated in CRS but the cable cost can not.

3.3.7 Benchmarking summary

The benchmarking showed that there is a plethora of available software to calculate the length between components. Although not all software can use the length to consider other aspects as well e.g. cost and/or weight. The usability of the other available software is therefore of interest. Furthermore, there is a range in simplicity of the available software. These range from basic ".CSV" data files to more extensive and graphical software such as E3.series, requiring a complete CAD model.

An attempt to identify the range has been done, where each software has been given a rating, of 1 to 5 in terms of simplicity and usability. Simplicity is in this sense a weighted sum of two contributions. A contribution to this is the graphical interface where it is given a low rating if the software requires several windows to be open at once. Another contribution to simplicity is the number of steps that the user needs to conduct for the software to present the information asked for. The software may for instance require a complete CAD model. Furthermore, usability in this sense refers to which degree the software is relevant to this thesis. It is given a low number if the software presents, for instance, the center of gravity for the harness but not the weight in an unambiguous manner. Conversely, it is given a high number if it presents the cost and/or weight in such a way that it is user-friendly. This is visualized in Figure 3.10.

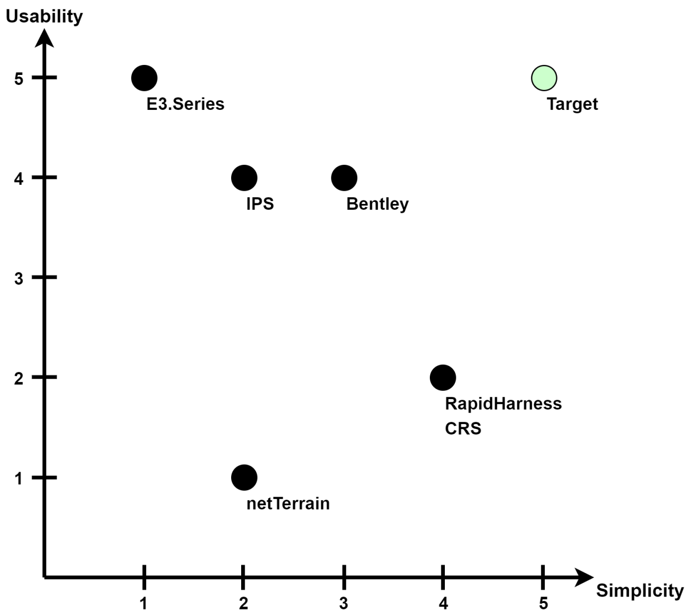


Figure 3.10: Software comparison in a graph

Figure 3.10 displays the simplicity and usability on separate axes. Each software is then, via their ratings, placed in the graph. For instance, E3.Series is given a rating of 1 in simplicity and 5 in usability. Figure 3.10 also shows a green circle marked "Target". This highlights the fact that there is a lack of available software that is usable in the scenario for this thesis. The "Target" is meant to have a high usability rating and still be easy-to-use and understand, i.e. having a high simplicity rating.

3.4 Conclusion of literature review and benchmarking

The conclusion from the *Literature review summary* is that using a system breakdown approach and working towards incorporating the method in an existing software is favorable. The *Benchmarking summary* shows potential in available software, although they are of varying relevance. As the method is meant to be user-friendly, and at the same time produce adequate results, it becomes apparent that the principles for the method from this time forward must hold the traits of the ”Target” mentioned earlier. To achieve this, new software must be developed despite not following the conclusion from the *Literature review summary*.

4
Results

This chapter presents the results of the thesis with a deconstruction of the results. The chapter includes a systematic analysis of the system described in Section 3.1, a description of what is included in the evaluation tool, a description of a proof of concept, and proof of concept verification.

4.1 System analysis

An identification of the system needs to be completed to understand the reason for including the components which this thesis concerns. This has been done in this section and then these needs have been connected to the different components that solve these needs. The components have then also been analyzed to be able to show which voltage level they require and if they require alternating current (AC) or direct current (DC).

4.1.1 Identification of needs

Based on the description portrayed in Section 3.1, a couple of them are identified as standard across every electric vehicle (EV). These standard needs are categorized and presented in Table 4.1.

	Needs
1	**General**
1.1	Store 400V DC
2	**Prior to storage of electricity**
2.1	Receive AC in different voltages
2.2	Receive 400V DC
2.3	Transform AC to 400V DC
3	**After the storage of electricity**
3.1	Transform 400V DC to 400V AC
3.2	Transform electricity into mechanical energy
3.3	Transform 400V DC to 12V DC
3.4	Store 12V
3.5	Heat passenger compartment
3.6	Cool passenger compartment

Table 4.1: The needs of the system.

To fulfill these needs there are standard components that are used in many different cars, for example, the Chevrolet Bolt EV (Liberty Access Technologies, 2018). Although, these components are not shared between all cars but rather the functionality of the components. To exemplify, some components which solve the different needs are shown in Figure 4.1. In the figure, discharge electricity from EV is shown. Although, since this feature is not used in existing cars, it will not be included in further analysis.

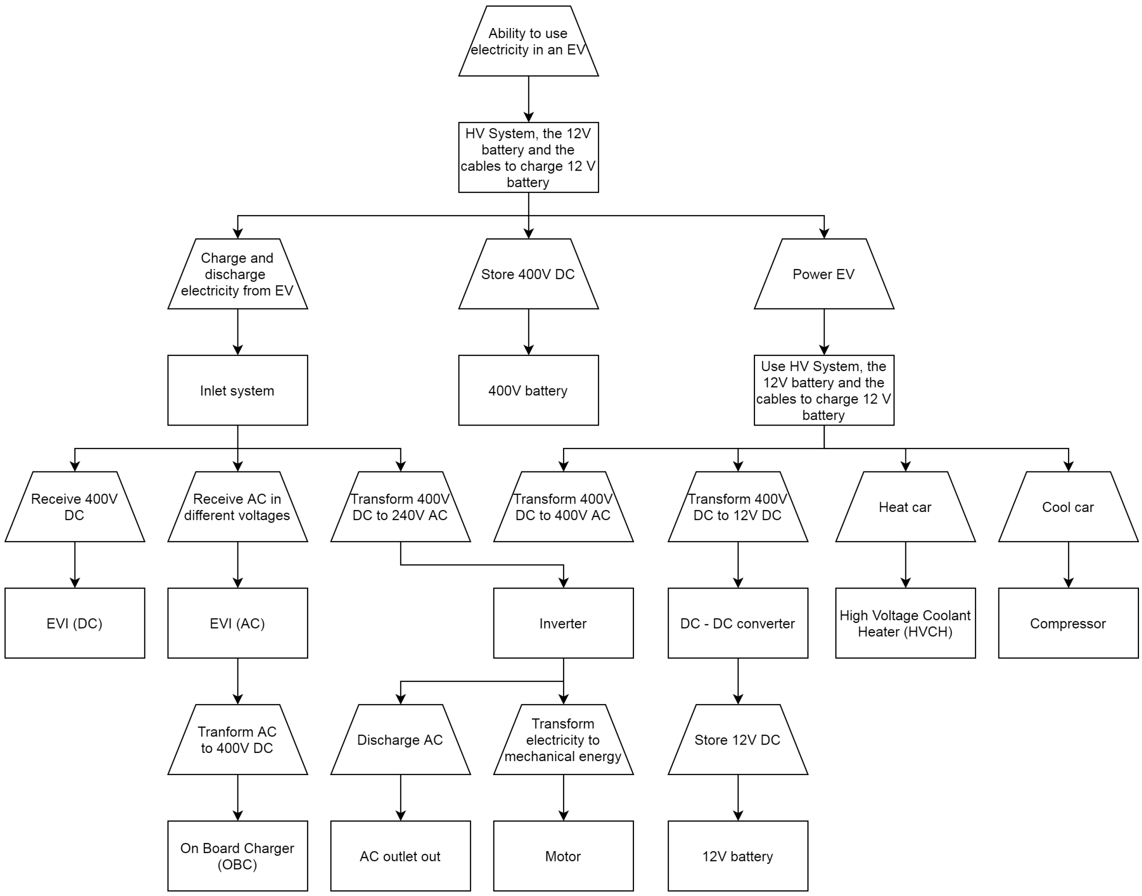


Figure 4.1: Function-means tree of needs and components.

As described in Section 3.1, the electric motor needs 400V AC but the 400V battery, which is the main battery, only stores 400V DC. To solve this problem an inverter has been added to transform 400V DC to 400V AC. This is shown in Figure 4.1.

4.1.2 Connecting needs to components

Having identified one set of necessary components in Section 4.1.1, the different components which are included in the system is, therefore, the following:

- Electrical Vehicle Inlet (EVI)
- On-Board Charger (OBC)
- 400V battery
- Inverter
- Motor
- DC – DC converter
- 12V battery
- High Voltage Coolant Heater (HVCH)
- Compressor

The motor can be used in three scenarios, solely electric front-wheel drive (EFAD), solely electric rear-wheel drive (ERAD), or a combination of both EFAD and ERAD. Furthermore, these components require different voltages and currents. They also send out different voltages and currents. As mentioned in Section 3.1, the black box theory will be applied as there is no need to investigate the components in detail. At this level, there is no need to understand the specifics for a generic three-phase electrical system, for instance. The significant contribution by the components is the input and output, i.e. the voltage and the current. The above mentioned necessary components are one example of a set of components that solves the different functions. As mentioned in Section 4.1.1, the components are different between car manufacturers, but the functionality of the components stay roughly the same. The connections mentioned in Table 4.2 are meant to bridge the gap between the needs of the system and the components.

Connections	
From:	**To:**
EVI (AC)	OBC
OBC	400V battery
EVI (DC)	400V battery
400V battery	Inverter ERAD
Inverter ERAD	Motor ERAD
400V battery	Inverter EFAD
Inverter EFAD	Motor EFAD
400V battery	DC-DC converter
DC-DC converter	12V battery
400V battery	HVCH
400V battery	Compressor

Table 4.2: Diagram for how the components are connected

Table 4.2 justifies the usage of the various components. To exemplify, the connection between the inverter and the motor is needed for the motor to properly function. However, it does not portray the property of electricity. Figure 4.2 visualizes the connection between the components and at the same time provides the property of the electricity. Do note however that the physical connection, using split boxes, can be different. The required property of the electricity is still the same, however. Avnet Incorporated (2017); Professional Motor Mechanics (2015); Webasto Thermo & Comfort SE (2014) describes more in detail the property of the electricity associated with each component.

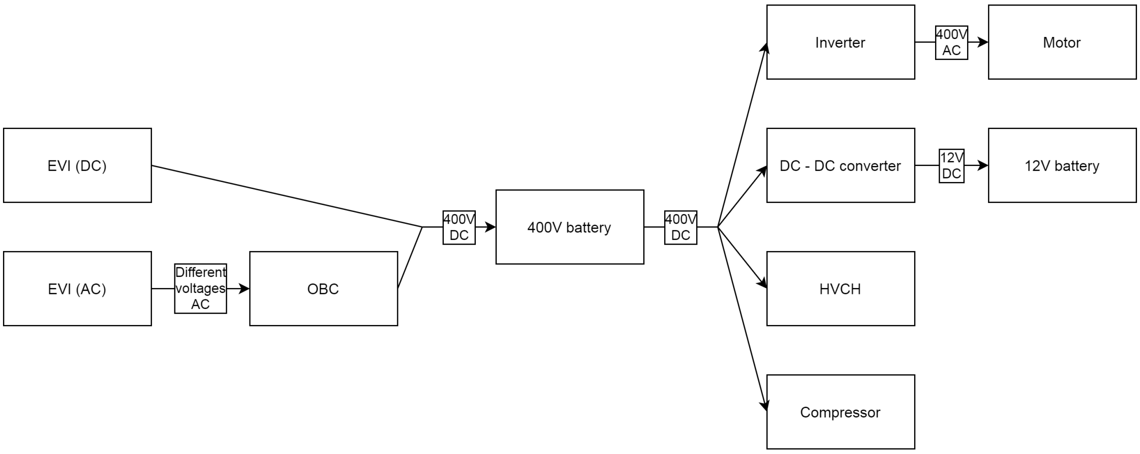


Figure 4.2: Property and connection between the components

4.2 Front end

Figure 4.3 shows the evaluation tool which is asked for. This evaluation tool is hereafter referred to as ”Evaluation Tool for Cost and Weight”, abbreviated ETCW. This section will focus on the front end of ETCW. This means analyzing the inputs and outputs and their relation to the user. This in turn justifies the calculation-, graphical, and the complete interface.

Figure 4.3: Black box adaption for the evaluation tool

4.2.1 Input and output

The outputs which ETCW will include are pointed out in the *Goals*, see Section 1.5. ETCW will calculate the cost and weight of the system, therefore there is a need to calculate the different connections' specific costs and weights. Because of this, the outputs have been defined as the following:

- Costs
  - The specific cost for each connection
  - Total cost for all connections
- Weights
  - The specific weight for each connection
  - Total weight for all connections
- Visualizations
  - Visual representation of where the components are placed
  - Visual representation of how the connections between the components have been made

These outputs require a specific set of inputs that are at this point unknown. To obtain these, the necessary information to identify these inputs is needed. There is more to it than the inputs that will be put into ETCW each time it will be used. There are two types of inputs that are needed. The first inputs are the ones that are changed every time ETCW is used. These are the user inputs. These can for instance be the component placement. The user inputs will be grouped to make the explanation of them more understandable. The second inputs are the resources in the form of numbers, which represent the different costs and weights for the connections' different parts. These will be in a database. The resources in the database consist of:

- Connection costs
- Connection weights

After iterations of the inputs had been done through agile development, the following inputs were decided upon:

- Locations of the different components
- Size of the different components
- Choice of connections
- Choice of connectors on cables
- Ability to add off-limit areas
- Ability to add points which the connections must go through
- Ability to add split boxes or use already existing components as split boxes

The locations of the different components are where the components, which are defined in Section 4.1.2, should be placed in the car. The size of the different components will be decided by the user to have a shape and size that corresponds to the real shape and size of the different components. These two inputs can be grouped as the *Component information*. Because there are different kinds of connections that can be chosen between the user has to make a choice in which kind of busbar or cable they want to use for a certain connection. These choices need to be done for the connections shown in Table 4.2. The different kinds of connectors can be chosen on each end of the cables as mentioned in Section 3.1.3. Together with the choice of connections the choice of connectors can be grouped as the *Connection information*. The cost of the connectors is to be included in the connection costs resource. The weight of the connectors is deemed negligible. Off-limit areas are areas where a busbar or a cable cannot be inserted. These are areas which are already decided to contain something else than a connection. It could for example be the cooling system. Points which the connections must go through will be able to add to make the connections more customized for the engineer working with the tool. Split boxes will be able to be added because the electricity may want to be gathered or separated through a split box rather than directly to and from components. With the additional choice of using split boxes, not only adding a separate split box can be used as a split box but an already existing component can be used. Therefore changing from where components' connections should go will be available to be changed. These three extra choices can be grouped as *Extra customization*.

With the added information, Figure 4.3 can be updated. ETCW can, therefore, be updated to Figure 4.4, having the newly added information.

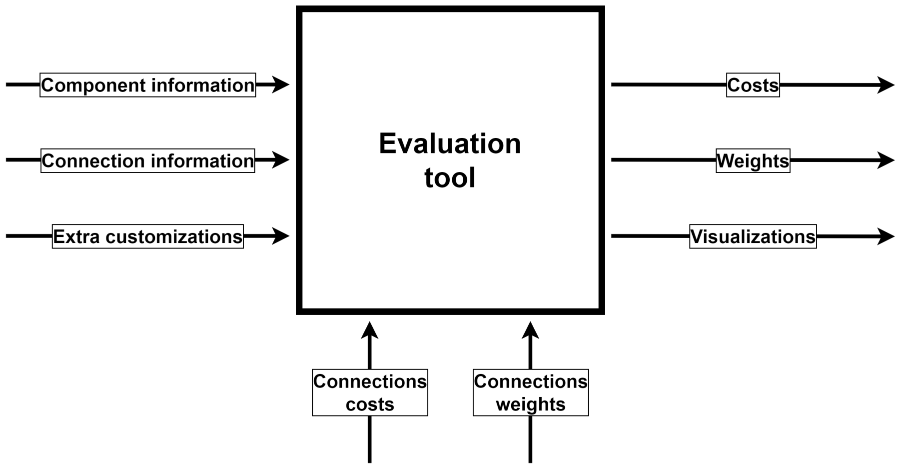


Figure 4.4: Evaluation tool with defined inputs and outputs.

4.2.2 Calculation interface

The origin and the end of the connections are to be decided in the calculation interface. The calculation interface is where the choices of connections are to be made. The choice of connectors is also to be made if a connection will be done through a cable, as busbars do not require a connector. The addition of a split box will be made in the calculation interface as well. This is to connect the added split box or to make one of the already existing components into a split box. The cost and weight of the systems' connections will be presented in the calculation interface.

The calculation interface will include:

- Choice of connections
- Choice of connectors on cables
- Ability to add split boxes or use already existing components as split boxes
- The specific cost for each connection
- The specific weight for each connection
- Total cost for all connections
- Total weight for all connections

The different connections will be color-coded, to be separated easily. To construct the connections the components which the connection goes from and to is to be defined. The type of connection the connection is to be done with needs to be chosen also, either it being a busbar or a cable. Because there are different kinds of busbars and cables, the connections that can be done with a drop-down list with all different busbars and cables will be available in the spreadsheet. If the connection is to be done with a cable a header on each end of the cable needs to be chosen. There will be a similar drop-down list for the connectors as for the choice of the type of connection. To add a split box is done through choosing the split box as either where the connection comes from or goes to. To use an already existing component as a split box it is chosen as the component which the connection comes from or goes to. The different individual costs and weights for the connections will be shown in the same spreadsheet. The total length, cost, and weight of systems' connections will be shown in a separate spreadsheet.

All the choices that need to be done in the calculation interface can be summarized in a product structure for a certain connection. The product structure can be seen in Figure 4.5.

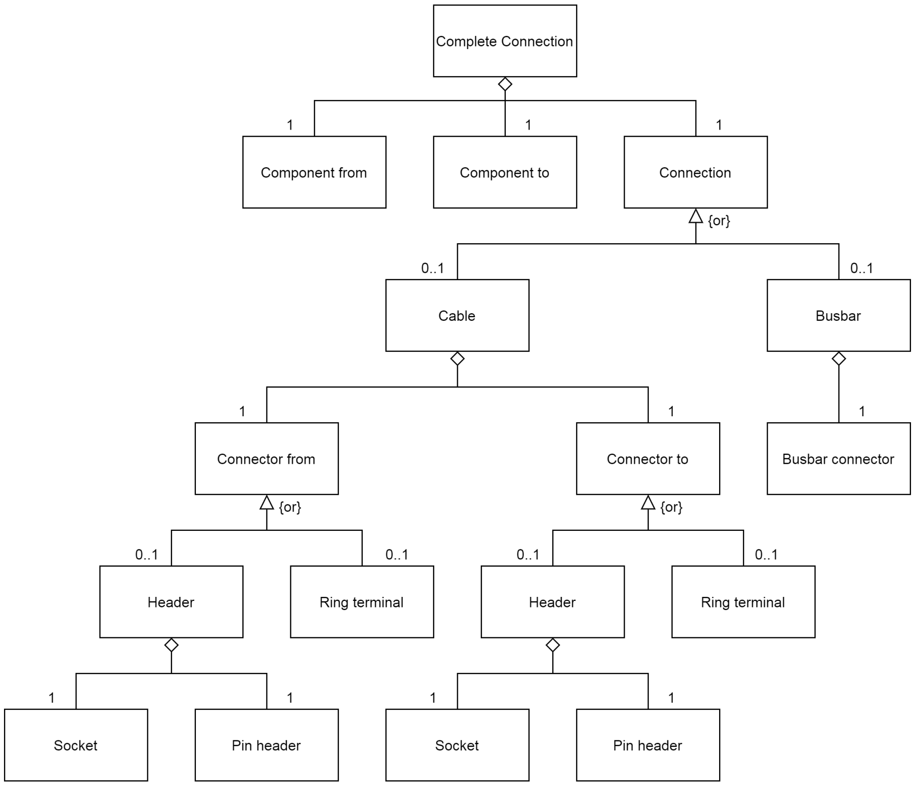


Figure 4.5: Product structure for a certain connection.

4.2.3 Graphical interface

The graphical interface will include how the different components and connections look. The components' location and size will be decided in the graphical interface. The split boxes are handled as the other components in the graphical interface. If any off-limit areas or any points which the connection must go through are to be added, this is to be done in the graphical interface.

The graphical interface will include:

- The choice of locations for the different components
- The choice of size of the different components
- Ability to add off-limit areas
- Ability to add points which the connections must go through
- Visual representation of where the components are placed
- Visual representation of how the connections between the components have been made
- Visual representation of the off-limit areas

The graphical interface will be presented in a window in ETCW. In the window, the different components will be presented as boxes. The size of the boxes will as been said in the list previously, be decided by the user to have a corresponding shape and size to the real-life shape and size of the different components. The boxes which represent the components are put to their, by the engineer, intended location. To make the tool as unambiguous as possible the different components will have text on them to show which box is which component. The off-limit areas will be able to be put into the graphical interface by marking the off-limit areas. To add a point which a connection must go through, the point and the connection is selected. To go into the modes of marking the areas which are off-limit and adding points which the connection must go through there will be buttons to mark. The connections are to be made automatically after the different components have been set into their intended locations, the connections will be color-coded in the same colors as in the calculation interface.

The visual representation of how the components have been placed and how the connections have been made is there to make it easier for the engineer to present the different layouts for placements of the different components. It is also there to help the engineer that places the components and connections in the real CAD model of the car.

4.2.4 Complete interface

The complete interface will include everything that is included in both the calculation interface and the graphical interface. It will include all the choices which are shown in Figure 4.5 where the information about the components' location and size is decided in the graphical interface. It is decided in the calculation interface which components are connected.

The complete interface can be seen in Figure 4.6. Examples of how the components and connections can look can be seen in the graphical interface in the figure. The graphical interface then returns the value of the length for the connections. The numbers are in this case of course purely fictional.

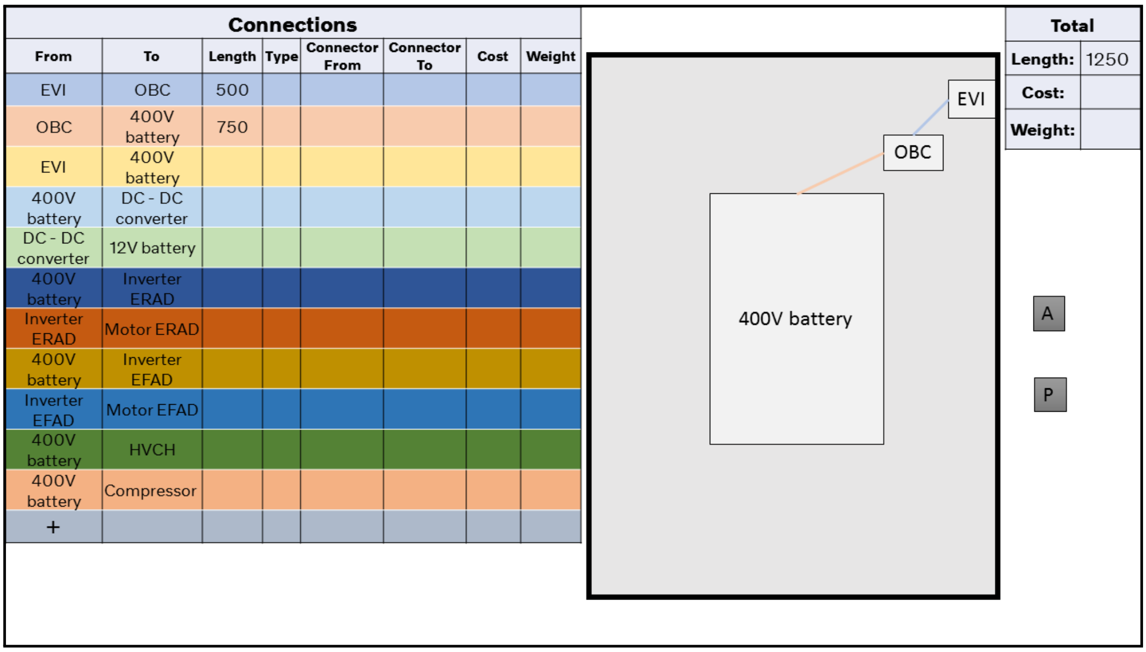


Figure 4.6: The complete interface with two connections.

To the left and the upper right corner the parts that are included in the calculation interface can be seen. In the gray window, the parts that are included in the graphical interface are to be put in and then also be shown. To the right, the two buttons which are mentioned in Section 4.2.3 can be seen. Some components are written in the columns "From" and "To" to show examples of connections.

4.3 Back end

This section puts forth the necessities for the data layer. The section starts by addressing the proposed algorithm to obtain and draw the connection between the components is presented. Once the length of the connection is obtained the cost and weight calculations are put forth, essentially the translation from knowing the length of the connection to the cost and weight of the connections. The section ends with pseudocode for a software to be developed and implemented.

4.3.1 Calculation of length

To obtain the length between two components in the graphical interface, a path between these two components needs to be calculated. An algorithm will be applied to calculate the path. After having researched multiple different algorithms in the literature review, see Section 3.2, the A* algorithm has been proposed as the algorithm that will be used. A* is proposed because it is a well-known algorithm that is easy to understand and follow. Furthermore, A* is proposed as the algorithm is already in use by other studies. This is highlighted in the *Literature review summary*. Further developments for the algorithm are put forward in other studies as well (Duchon et al., 2014), which can be implemented in ETCW to further enhance the performance. The A* algorithm calculates the lowest value and therefore shortest path between two points, by dividing up the space between the two points into a grid. Each node in the grid has a value (most times written as $f(v)$) which is built upon two other values. One is the distance from the starting point to the current node (most times written as $g(v)$). The other is the distance to the endpoint (most times written as $h(v)$). $f(v)$ is calculated through $f(v) = h(v) + g(v)$. The algorithm then chooses its path through the nodes with the lowest $f(v)$.

4.3.2 Calculation of cost

To calculate the total cost for the electric system layout, a systematic breakdown approach was applied. The total cost is then calculated as the sum of all the connections. Mathematically this is defined as:

$$C_{total} = \sum_{i=1}^{n} c_i(L) \tag{4.1}$$

The function c_i acts as the translation from each connection L, where the electric system layout is built upon n number of connections, to the cost of each connection. The formula for calculating the cost, i.e. function c_i, is heavily dependent on an assessment done by a cost engineer. The cost engineer responsible for the scope of this thesis uses the following formula to obtain the cost for a connection[1]:

$$c_i(L) = BoM(L) * MoH + VA_{rate} * LM \tag{4.2}$$

Where BoM indicates the bill of material for the cable assembly. To exemplify, the BoM for a particular cable assembly can consist of a *2x50* cable, 2 sockets, and 2 pin headers. MoH indicates the agreed-upon material overhead (MoH) with the supplier. VA_{rate} is the fixed cost for cutting, splicing, and other types of mechanical changes to the cable. LM is the added time it takes to mount the cable inside cable harness. Though, as literature within the same area of field argues, see Section 3.2, it is often better to provide a quick estimation rather than an extensive complete answer in the early stages of product development. Calculating the exact impact of LM and VA_{rate} is exhausting and difficult to do, considerably so in the early stages of product development. Simplification for Equation 4.2, proposed by the cost engineer, is the following equation:

$$c_i(L) = BoM(L) * MoH + \varepsilon \tag{4.3}$$

Where BoM and MoH refer to the same previously mentioned cost items. However, ε refers to an estimation of the costs of personnel costs, manufacturing, etc. To exemplify the now derived cost calculation, a simple exercise is given below.

[1] The numbers for the cost of each connection has been tampered with to preserve the confidentiality. The full numbers list can not be released as this thesis is published. This will, however, not affect the results, as the rest stays the same.

A 4x4 cable with a length of 2 meters is required between component A and component B. The socket which are mounted on each end of the cable cost 13 euro apiece. To fasten the socket on the components, pin headers are required. Pin header amount to 10 euro apiece. Given the cost of the cable per meter is 6 euro, calculate the total cost between component A and component B.

Given the scenario above, the bill of material, BoM, is formulated as:

$$BoM_{AB} = 2 * 6 + 2(13 + 10) = 58 \tag{4.4}$$

Given the MoH is 8% and ε is 7 euro, the total cost is calculated as:

$$c_i(L_{AB}) = 58 * 1.08 + 7 = 69.64 \tag{4.5}$$

The resulting total cost for the connection between component A and component B is therefore 69.64 euro.

4.3.3 Calculation of weight

The calculation for the weight will be done similarly to that of the cost calculation, where a systematic breakdown structure was used. The total weight is defined as:

$$W_{total} = \sum_{i=1}^{n} w_i(L) \tag{4.6}$$

The function w_i acts as the translation from each connection L, where the electric system layout is built upon n number of connections, to the weight of each connection. The formula for calculating the weight, i.e. function w_i, is dependent on the specifications for each connection. Via the cost engineer, who provided information on calculating the cost, information regarding the weight of each cable type was provided. As previously mentioned, the weight of the socket and pin header is negligible. It was said that the majority of the weight originates from the cabling.

The weight of the busbar equivalent for a cable is calculated by utilizing the density of copper and the specification of the counterpart cable, i.e. if the connection requires a *3x50* connection, it can either be a *3x50* cable or the equivalent for the busbar. The exact figure for the difference in weight for a busbar equivalent of a cable can not be presented due to confidentiality[2]. However, the weight equivalent of the busbar is calculated to be roughly 65 percent of the weight for if a cable would have been used. Furthermore, the busbar does not have any socket or pin header, but rather utilizes the busbar for the same function. To exemplify the weight calculation, a simple exercise is given below.

[2]The numbers for the weight of each connection have been tampered with to preserve the confidentiality.

> *A 4x4 busbar with a length of 2 meters is required between component A and component B. Given the weight of the busbar per meter is 0.32 kilogram, calculate the total weight between component A and component B.*

Given the scenario above, the weight between component A and component B is calculated using Equation 4.6. This is formulated as:

$$w_i(L_{AB}) = 2 * 0.32 + 2(0 + 0) = 0.64 \tag{4.7}$$

The resulting weight for the connection between component A and component B is therefore 0.64 kilograms. The zeros are included in the equation to provide similarity with the example given in the cost equation.

4.3.4 Pseudocode and implementation

This section aims to provide the software programmer with the principles of ETCW. The pseudocode for ETCW was deemed to be the best way of delivering this information.

Step 1: Initialization
The user inputs, along with the database of the resources, provide all necessary information.

Step 2: Calculating the length
By using, in this thesis, the proposed algorithm, the connection length between the components can be calculated.

Step 3: Database connection
Depending on the choices made earlier, the tool has to fetch different resources in the database. If, for instance, the engineer picks a 4x4 cable with ring terminals, the tool must fetch the cost and weight for the cable and the cost for the ring terminals.

Step 4: Calculation of cost and weight
Having the length and appropriate information available, the tool is then able to calculate the cost and weight for each connection.

Step 5: Presentation of the results
With the cost and weight calculated, for each connection and the total sum, this information is to be presented. It is meant to be returned to the same spreadsheet where the engineer decided on the user inputs. The total sum for the cost and weight is to be displayed in a separate spreadsheet. See Section 4.2.4 for a visualization of the complete interface.

4.4 Proof of concept

A proof of concept (PoC) has been developed to be able to test parts of the method developed. It was decided that PoC was to mimic the calculation interface which can be seen in Section 4.2.4. The PoC has been developed in Microsoft Excel.

4.4.1 Front end

The front end of the PoC is very similar to the final concept of the calculation interface but with added columns. The first of these added columns are where the length of the connections can be inserted. The other columns are where the $€/mm$, kg/mm, and assembly cost in euro for connections are shown plus the connectors different parts unit costs in euro are shown. The column for the length of the connections was added because in the PoC the length is manually entered as opposed to ETCW, where the length is retrieved from the graphical interface and in turn the algorithm. The columns with the individual costs were added to make the results more understandable.

To make comparisons between different electric system layouts which are inserted into the PoC easier, charts which include the lengths, the calculated costs, and the calculated weights for the specific connections have been added. This is something that can be added to ETCW if wanted. It was added to the PoC because of the simplicity of creating charts in Excel. The charts are therefore an extra output from the PoC.

To easily understand how to use the PoC, a user manual has been developed. The user manual describes every step to get a cost and weight for a connection. It also describes where to find the different outputs of the PoC. This can be seen in a sheet in the PoC.

4.4.2 Back end

The back end of the PoC is a database of the lists that the drop-down lists are made up of and the costs and weights for connections' different parts which are shown in the front end. The costs and weights for connections' different parts are the specific resources that are mentioned in Section 4.2.1. The lists include lists of the components, the different types of connections, and the different connectors. The lists with the types of connections and the connectors are dependent on one another. The dependence is constructed in such a way that a header or a ring terminal is the only option for when a cable is picked a connector.

To have the costs and weights for connections' different parts shown in the front end they are stored in different sheets with the connections' numbers in one sheet and the connectors' numbers stored in one sheet. The connections individual numbers are stored as [$€/mm$], [kg/mm], and assembly cost in euro. The connectors' numbers are the costs for the part of the connector which is on the cable, on the component which the cable connects to and the assembly costs. All the costs for the connectors are in Euro.

To easily be able to update the database, a sheet with how to update resources has been made. This sheet includes information to add and/or remove connections for example. It also includes how to refer to the different connections.

4.5 Proof of concept verification

As seen in Section 2.3.3, the methodology for the verification is determined by the ability to test, verify, and evaluate. The testing will be performed here and will result in two tests. The first test looks at the previous and current electric system layouts. The second test analyses the electric system layouts of several original equipment manufacturers (OEMs). The evaluation is left to the *Discussion* chapter in the thesis.

4.5.1 Testing on previous and current electric system layouts

Equations for cost and weight have been developed. These can be verified by using them in real scenarios, i.e. previous and current electric system layouts. The verification will utilize indices for comparison. The validation therefore can not be addressed in absolute terms, as using this approach will result in relative measurements. Furthermore, as the confidentiality of the results gathered must be preserved, the individual connections between the components can not be addressed. This will result in a combined index for each electric system layout, where the combined index refers to the sum of all connections between the components. This in terms of length, cost, and weight.

Each electric system layout is assumed to have different functionality, hence different components that fulfill them. Some electric system layouts may for instance combine the functionality of the DC-DC converter and the Inverter, a "CIDD", whereas others will not. To make a proper comparison, only the functionality which is shared across the different electric system layouts will be addressed. Each electric system layout analyzed does not have the ability for all-wheel drive, which is why only the ERAD will be addressed. Furthermore, each functionality is assumed to share the same specification for the connection required. This may not be the case in a real scenario, as the previous electric system may use a different connection. The assumption is based on the current system layout. The assumption leads to the same cost and weight per meter for each cable, pin header, and socket being used on each electric system layout. The functionality shared across the different electric system layouts are fulfilled with the connections presented in Table 4.3.

Table 4.3: Connection and assumed specification for the shared functionality of index_{A}.

Connections		**Assumed specification**
From	**To**	**Wire x area**
EVI (AC)	OBC	*4x4*
OBC	400V battery	*2x6*
400V battery	Inverter	*2x50*
Inverter	Motor	*3x50*
Regenerative charge	Inverter	*2x6*
400V battery	Compressor	*2x6*
400V battery	DC-DC converter	*2x6*
DC-DC converter	12V battery	*1x50*

Although the functionality remains the same, the electric system layout to achieve the functionality through the connections does not. The result of this is a varying length, cost, and weight due to varying utilization of split boxes between the architectures. There is also a difference in which connector is being used as there is an option to use a header or a ring terminal. This results in different performance and therefore index. The PoC has been used to calculate the indices. The base index is given to the first electric system layout, which is henceforth referred to as layout 1. For the sake of simplicity, the index for this electric system layout is set to 100. As four different electric system layouts have been analyzed, there are a total of four electric system layouts. These are referred to as similar to that of the first electric system layout, i.e. layout 2, layout 3, and layout 4. The index for the complete list, ranging from layout one through four are plotted in a bar chart diagram, see Figure 4.7. The length, cost, and weight for each electric system layout are displayed in different colors. The X-axis shows the electric system layouts, from one through four, whereas the Y-axis shows the index. The individual index is later referred to with their number as a subscript. To exemplify, $\text{index}_{\text{A},1}$ refers to layout 1 in the first (A) study.

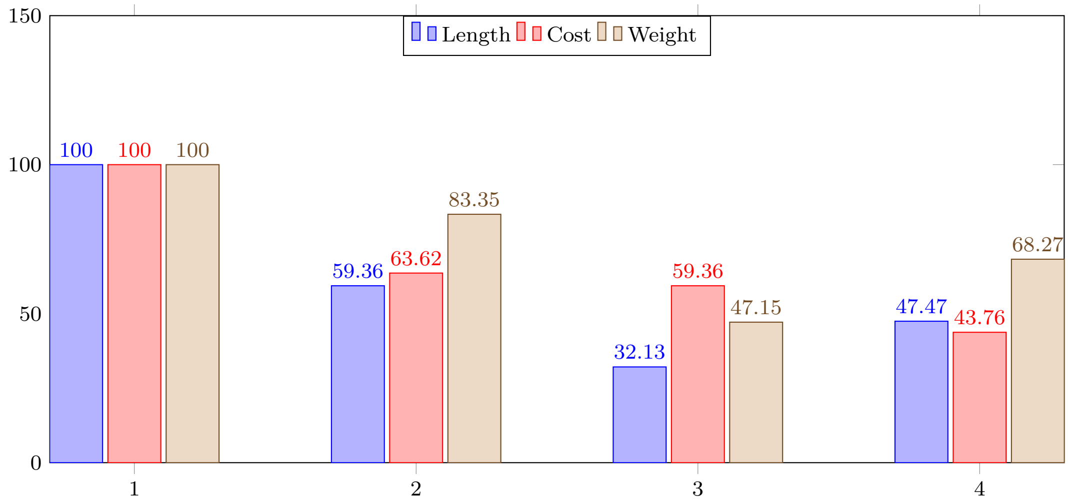


Figure 4.7: Properties for layout one through four.

4.5.2 Testing of alternative electric system layouts

As the pre-study provided a lot of information on alternative electric system layouts, similar calculations done in Section 4.5.1 can be performed. By assigning the base index as 100, and using "layout 4" from the previous study as the reference, henceforth referred to as $\text{index}_{\text{B},1}$, the alternative electric system layout performance can be mapped. This comparison will use numbers based on the electric system layout from several OEMs.

A problem poses which is similar to that of the functionality issue found in the previous study. Not every electric system layout addressed in this study allow for EFAD and ERAD. $\text{Index}_{\text{B},1}$ and $\text{index}_{\text{B},2}$ both allow for EFAD and ERAD, although $\text{index}_{\text{B},3}$ does only support ERAD. To make a proper comparison, the EFAD functionality has been not been considered for $\text{index}_{\text{B},1}$ and $\text{index}_{\text{B},2}$. Table 4.4 shows the connections which fulfill the functionality and is shared across the three alternative electric system layouts. The assumed specification column in this study has the same definition as the one used in the previous study.

Table 4.4: Connection and assumed specification for shared functionality of index$_B$.

Connections		**Assumed specification**
From	**To**	**Wire x Area**
EVI (AC)	OBC	*4x4*
OBC	400V battery	*2x6*
400V battery	Inverter	*2x50*
Inverter	Motor	*3x50*
400V battery	Compressor	*2x6*
400V battery	HVCH	*2x6*
EVI (DC)	400V battery	*2x70*
400V battery	DC-DC converter	*2x6*
DC-DC converter	12V battery	*1x50*
Front of 400V battery	Rear of 400V battery	*2x50*

The indices for the second test have been done in a similar manner in which the first study was done, see Section 4.5.1. The performance indices are presented in a bar chart diagram, see Figure 4.8. Each property associated with each alternative electric system layout is given a different color and is presented on the X-axis. The index is presented on the Y-axis.

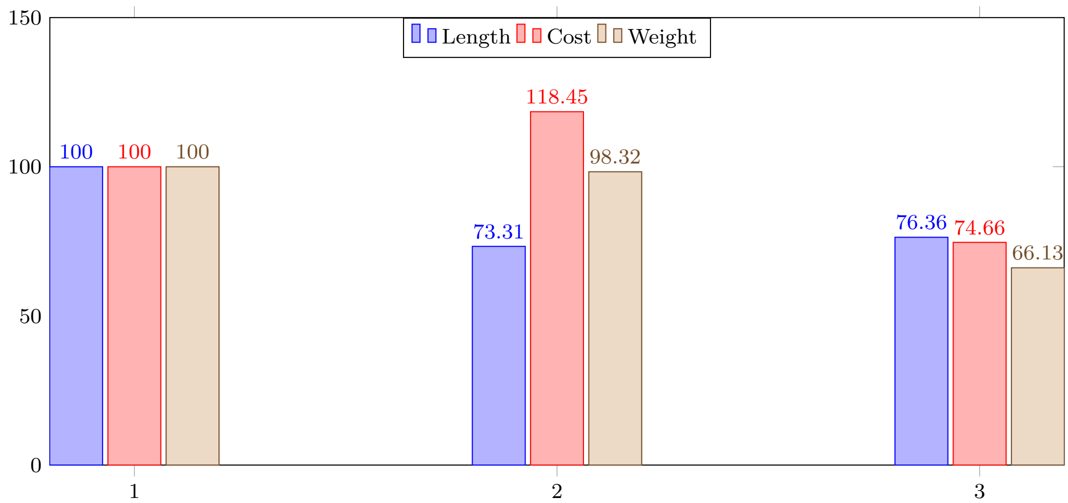


Figure 4.8: Properties between three alternative electric system layouts.

4.5.3 Front end user verification

The agile methodology utilized in the development of the method proved useful as minor updates can quickly be tested and evaluated. The evaluation was done by the authors of the thesis in parallel with front end users, it is, therefore, safe to say that every opinion has been considered to a large extent. The verification that the PoC works as intended is therefore a consequence of the merging of the PoC and the goals of the thesis.

5
Discussion

This chapter critically discusses the outcome of the thesis and illuminate important aspects of the methodology used to obtain the results. The discussion addresses the degree in which ETCW fulfills the goals set at the beginning of the thesis, the validity of the outcome, and a reflection regarding the methodology used throughout the thesis.

5.1 Identification of principles for the method

The principles for the method were shaped after the literature studies. See Figure 2.1 for the visualization of the methodology used in the thesis. The literature review showed the potential of using algorithms as a tool for finding a satisfying connection between two nodes. The presence of algorithms was also found in other areas, such as wind farms or electrical panels. The widespread provided enough proof that this type of approach is favorable, hence the proposal of the A* algorithm in this thesis. Furthermore, a considerable amount of literature showed that utilizing a system breakdown approach is both a common and effective way to find the total sum of individual properties within a system. This resulted in the breakdown approach used in this thesis, where each connection between each component is calculated as individual elements and later on combined. Both in terms of length, cost, and weight. Therefore, after having completed the literature review, the principles for the back end of the evaluation tool were set.

The benchmarking for software which to varying degrees fulfills the same objective were many. From scouring the website and e-mailing the developers of each software, it became apparent that there is currently no software developed that solves the issue at hand. The front end of the method then became apparent. It should be user friendly but at the same time applicable.

5.2 Final evaluation tool

As mentioned earlier in the discussion, the methodology used to develop the method required intense communication with all relevant parties. This communication made sure that the method developed was on the right path and showed a satisfying result. This was achieved with both formal and informal meetings. As both of these communications methods were present, the content of the conversations was varying, hence the explicit partition between the front end and the back end. Input for the front end were often had in informal settings whereas the back end input were in the majority of the time set in a formal atmosphere such as a meeting. The distinct difference of the content may be traced back to the, still ongoing, COVID-19 pandemic.

Neither author of the thesis possesses knowledge in software programming, hence the lack of prototype for the graphical interface where the engineer would place the components. As the algorithm was to be used in the graphical interface it has not been tested in this thesis. This was, as argued before, acknowledged from the beginning of the thesis, however, hence the suggestion for future work, where a software programmer will develop the program. This awareness did not hinder the ability to produce a proof of concept (PoC) for the calculation interface. Seeing the resemblance with cells, columns, and rows, a decision was made to utilize Excel for the PoC. This decision was also encouraged by the front end users as they, to a varying degree, already possess knowledge in this software. They argued that if anything were to go wrong with the Excel workbook in the future, a person who is familiar with Excel may be able to fix it. It also provided quick and easy feedback, via the informal meetings, for further development of the PoC. To exemplify feedback gotten from one of the parties involved were the request to get the individual cost and weight for each connection. This had been overlooked in the early stages of the method development, hence the importance of communication and visual confirmation.

Tracing back to the identified principles for the tools and software, visualized in Figure 3.10, highlighted the fact that there is complex software already available. These complex software are found to requiring a complete 3D CAD model for the software to work. Having a prerequisite such as this lowers the ”simplicity” ranking by a considerable amount as well as the ”usability” as the scope of the thesis is getting less considered. It is, therefore, sought to have a 2D environment for ETCW. The obvious drawback of this is that there is no possibility to place a component in the electric system layout beneath one another. This does not infringe on the goals for this thesis, however. The accuracy of the method will still be achieved as the majority of the specific and total cost and weight stems from the placement from being in opposite ends of the car. Not the height. The target for this thesis ultimately became the development of a user-friendly evaluation tool while still being applicable, i.e. the ”Target”, mentioned in Section 3.4 as a synthesis of the literature review and benchmarking. Considering the calculation interface is developed in Excel, see the argument above, the user-friendly factor would be deemed as achieved. Although difficult to prove the applicability in this thesis, due to confidentiality, the software accounts for the latest and still in development products. This is a fact stated by the engineers themselves.

There is a discrepancy in the developed method of the evaluation tool and what was said in the literature study. The articles highlighted the importance of including the evaluation tool in existing software, a software that the engineer is already familiar with. This recommendation has been considered throughout the development of ETCW. Although, including the evaluation tool in a software that is already being used, e.g. IPS/CATIA/Teamcenter, will make it more difficult to change the database for when new cost negotiations have taken place. It can also be argued that the engineers, which the evaluation tool aims to aid, will lose control of ETCW as there will be a lot more people involved if ETCW is integrated into an already used software. The decision was, together with all relevant parties, taken to develop ETCW as separate software.

While on the topic of discussion regarding what has been said in the literature study, there are a few items to address. Figure 3.3 shows different ways of organizing the paths between components. By utilizing split boxes and combining the functionality of the components, the thesis shows a close resemblance to sub-illustration (d). Although, the difference is that coupling components together will require a connection that allows for a stronger current. This ability may make it more difficult to implement a Steiner tree/minimum spanning tree approach, hence the proposal, and no obligation, for the A* algorithm as this algorithm is not as affected.

5.3 Comparison of existing tools and software

As the graphical interface has not been developed through a PoC, it can not be tested. However, as parts of the calculation interface have been developed through a PoC, it can be used in comparisons. There are similarities between the calculation interface and a handful of the software available as described in Section 3.3. Especially CRS, as the back end of the evaluation tool in this thesis will utilize data files in the same manner. Although, the front end developed in this thesis is much more focused on increasing the simplicity and usability, in comparison to CRS. In other words, the existing tools and software fulfill the same requirements, albeit to varying degrees, which the evaluation tool with the complete interface aims to do, but the difference being that ETCW in the complete interface improves the usability.

5.4 Method verification

It can be said that proper verification of the method is difficult to achieve. This is mainly due to the lack of an absolute method to test, evaluate, and verify. The parts of ETCW that were tested were the ones included in the calculation interface as they were included in the PoC. The equations for cost and weight could, therefore, be tested and are verified by two graphs. The two graphs are derived from the indices marked with subscript A and B. Because the graphical interface had not been included in the PoC, any parts of the graphical interface could not be tested. This included the algorithm, on which the graphical interface heavily relies on.

Index$_{\mathbf{A,X}}$

By putting the equations for cost and weight to test, it is possible to determine whether or not the developed method works as intended. However, this verifies only the elements within the cost and weight calculations. It does not verify the equation itself. This is achieved with other verification methods. One of these is the assumption that developing a product with a specific intent results in a higher degree of satisfaction and performance of that particular intent. Considering the growing interest of electrification, it is, therefore, safe to assume that electrification is this particular intent, and measuring the performance should yield a better performance across all properties. Considering cost and weight falls underneath these properties, the cost and weight performance index should, therefore, be lower, generating higher satisfaction, in the current cars as opposed to previous cars. The PoC obtained a lower value in length, cost, and weight as $\text{index}_{\text{A},4}$ yields higher satisfaction than basal $\text{index}_{\text{A},1}$. Furthermore, there may be an issue of the introduction of new laws and regulations when comparing previous and current versions. Time might play a significant role in this, although at this point impossible to map out. This due to the exhaustive breadth and depth of the task, a task which may serve as a master thesis in and of itself. There may for instance be a law passed in-between versions that prohibit the placement of a particular component in a particular area of the car. This has not been accounted for several reasons. One reason is revealing this restriction in-between versions will link one version to a particular year, as it is possible to fetch the year in which a particular law has been introduced. This questions the confidentiality. Using a fictional scenario as an example, a law could have been introduced in-between $\text{index}_{\text{A},2}$ and $\text{index}_{\text{A},3}$ which forces all-electric vehicle (EV) manufacturers to place the EVI on the hood of the car. The consequence of this is for example be an increased length of the connection between the EVI and OBC by fifty percent. Tracing back to the year this law was introduced will give an estimate of which year $\text{index}_{\text{A},3}$ was introduced.

Index$_{\text{A},3}$ and index$_{\text{A},4}$

Comparing $\text{index}_{\text{A},3}$ and $\text{index}_{\text{A},4}$ it becomes evident that some properties increase while others decrease depending on the electric system layout. This shows that only focusing on reducing the length is not a guarantee that the cost and weight will decrease. Comparing the third to the fourth index shows that there is an increase in length by roughly 15 points. This does not increase the cost and weight by the same amount, however. The weight increased by roughly 20 points while decreasing the cost by roughly 15 points. This highlights the importance of a holistic view as one might think reducing the length of the connector, a tangible contributor to the cost and weight, will reduce the total cost and weight of the electric system layout. Focusing solely on decreasing the total cost, $\text{index}_{\text{A},4}$ has a better electric system layout, as it has the lowest cost index of them all.

Index$_{\mathbf{B,1}}$ and index$_{\mathbf{B,2}}$
Addressing the second set of indices, each marked with subscript B, shows a difference in the three alternative electric system layouts. Comparing index$_{B,1}$ and index$_{B,2}$ shows a decrease in both length and weight, but an increase in cost. This indicates an electric system layout that aims to decrease the total connection length and weight. The consequence of doing so is an increased total cost. Depending on the aim which the engineer has, a shorter length and lower weight, might be better than an increase in cost. The opposite is also true. If the engineer aims to lower cost, index$_{B,1}$ is the preferred option.

Index$_{\mathbf{B,3}}$
The exact functionality is shared between index$_{B,1}$ and index$_{B,2}$ as both electric system layouts allow for all-wheel drive. However, as stated before, the all-wheel-drive functionality has not been considered in the second study to make it fair. This is down to the fact that index$_{B,3}$ does not have that functionality. Comparing index$_{B,1}$ and index$_{B,2}$ with index$_{B,3}$, it is obvious that the best performing electric system layout is index$_{B,3}$. An explanation for this result may be the inaccuracy in the comparison, as the removal of the all-wheel-drive capability might not translate to a 2-wheel drive. Purely electric system layout-wise, the decision to reduce the number of powered wheels may result in the different placement of auxiliary components. However, considering that the calculation interface brings forth a vastly different result, in this case, the calculation interface is deemed as accurate. All in all, these types of findings are highly valuable as they highlight the result in terms of length, cost, and weight of the difference in electric system layouts.

5.5 Analysis of methodology

The information that was gathered in the pre-study proved to be very useful as it provided the necessary information to validate the equations for which the evaluation tool uses. Considerably so, as the information which can be made public is limited, due to the confidentiality which the information addresses. The pre-study also provided information that made the literature studies easier, seeing as a lot of relevant keywords were found in the pre-study. The method development, the third phase, were decided to follow an agile methodology, rather than the classical waterfall model, as quickly providing a tangible product provides relevant feedback. Lastly, from the beginning of the thesis deciding that the finished product will be software which is developed by a software programmer, helped a lot. This meant that the focus can be placed elsewhere, as there was not any need to investigate possibilities of learning to program and use for example `Python`, `C++`, or `C#`. It also meant that stating the results early on essentially meant providing the outer structure for what the thesis had to navigate within. This type of approach, having an agile loop methodology within an overarching waterfall model, is therefore argued by the authors as a successful methodology. The methodology which was decided upon at the beginning of the thesis worked as planned. This was despite the, as of June 2020, ongoing COVID-19 pandemic.

6
Conclusions and Future work

The cost and weight aspect for the evaluation of different electric system layouts in new product development have been the focus of the authors of this thesis. The cost and weight aspect of different components are of significant value due to their contribution to the final cost to produce a particular electric system layout. It is therefore important to consider these, especially so in the early product development stages. This has not been considered before, at least not to the extent this thesis has considered it.

The proposed method which this thesis recommends is the development of new software. The software has been considered as a combination of two interfaces, namely the calculation and graphical interface. The name given by the authors to the software is Evaluation Tool for Cost and Weight (ETCW). This software has not been developed as of now. Albeit the absence of such a tool, parts of the authors' proposed software have been developed. The result of this is a proof of concept (PoC).

The PoC is deemed very satisfying and fulfills the goals set in the beginning. It is said that the finished method should be able to accurately produce the cost and weight of by the engineer asked connections. These should be presented in a visually pleasing manner. These goals are considered to be fulfilled, as the calculation interface successfully manages to implement them. The graphical interface is, however, left as a future development for a software engineer to implement. The software design is the front end of ETCW and instructions for how to carry out is given as pseudocode.

For future development ETCW, the authors suggest implementing one or more of the following identified improvement areas:

- **Develop the graphical interface.** It should be developed in such a manner that allows for the extraction of the length of the connection, which will act as input for the calculation interface. Furthermore, it is proposed to use the A* algorithm to find a suitable path between the components for the graphical interface.
- **Remove or lower the impact of the limitations.** Once the graphical interface has been completed and is working alongside the calculation interface, the completed interface should to the best of its ability work towards remove or lower the impact of the limitations which were found in this thesis. More specifically, it should look at implementing a 3D environment for ETCW, as opposed to the 2D environment.
- **Establish a connection for the database.** Without updated information regarding the cost and weight of the connections and connectors, ETCW and especially the PoC will become invalid. The recommendation is therefore to establish a separate spreadsheet of some kind, which is shared cross-functionally between departments.

References

Andreasen, M. M. (1980). *Machine Design Methods based on a Systematic Approach* (Unpublished doctoral dissertation). Lund University.

Avnet Incorporated. (2017). *Technologies and Components for Designing Electric Vehicles.* Retrieved from `https://www.avnet.com/wps/portal/us/resources/article/technologies-components-designing-electric-vehicles/`

Axelsson, J. (2000). *Cost Models for Electronic Architecture Trade Studies.* Retrieved from `https://www.researchgate.net/publication/221473953_Cost_Models_for_Electronic_Architecture_Trade_Studies`

Bentley Systems Incorporated. (2020). *Bentley Raceway and Cable Management Design Software.* Retrieved from `https://www.bentley.com/en/products/product-line/electrical-and-instrumentation-software/bentley-raceway-and-cable-management`

Black, P., & Wiliam, D. (2010). Inside the Black Box: Raising Standards Through Classroom Assessment. *Phi Delta Kappan*, *92*(1), 81–90. doi: https://doi.org/10.1177/003172171009200119

Castorani, V., Cicconi, P., Mandolini, M., Vita, A., & Germani, M. (2018, 9). A method for the cost optimization of industrial electrical routings. *Computer-Aided Design and Applications*, *15*(5), 747–756. doi: 10.1080/16864360.2018.1441241

CCS Group. (n.d.). *E³.Wiring System Lab - Modules - E³.series - CCS.* Retrieved from `https://www.ccsgroup.com/e3.series/modules/e3.wiring-system-lab`

Clark, K. B., & Fujimoto, T. (1991). *Product Development Performance: Strategy, Organization, and Management in the World Auto.* Boston: Harvard Business School Press.

Clark, K. B., & Fujimoto, T. (1992). Product Development and Competitiveness. *Journal of the japanese and international econoomies*, *6*(2), 127.

Conru, A. B. (1994). A genetic approach to the cable harness routing problem. In *Proceedings of the first ieee conference on evolutionary computation. ieee world congress on computational intelligence* (pp. 200–205). doi: 10.1109/ICEC.1994.350016

Coulston, C., & Weissbach, R. (2003). *Routing Transmission Lines via Steiner trees* (Vol. 3). doi: 10.1109/PES.2003.1267390

Duchon, F., Babinec, A., Kajan, M., Beno, P., Florek, M., Fico, T., & Jurišica, L. (2014). Path planning with modified A star algorithm for a mobile robot.

In *Procedia engineering* (Vol. 96, pp. 59–69). Elsevier Ltd. doi: 10.1016/j.proeng.2014.12.098

Fraunhofer Chalmers Centre. (n.d.). *IPS Cable Simulation–Fraunhofer-Chalmers Centre.* Retrieved from `http://www.fcc.chalmers.se/software/ips/ips-cable-simulation/`

Gersdorf, T., Hensley, R., Hertzke, P., Schaufuss, P., & Tschiesner, A. (2020). *The road ahead for e-mobility.*

Grandvuillemin, J., Chamagne, D., Tiraby, C., & Glises, R. (2008). Ampacity of power bus bars for Hybrid-Electric or Electric Vehicles. *2008 IEEE Vehicle Power and Propulsion Conference, VPPC 2008*, 1–6. doi: 10.1109/VPPC.2008.4677660

Graphical Networks. (2020a). *Bell – Customer Success Story | DCIM, Network Documentation, OSP Software.* Retrieved from `https://graphicalnetworks.com/roi-customer-success-stories/bell/`

Graphical Networks. (2020b). *Cable Management Software | DCIM, Network Documentation, OSP Software.* Retrieved from `https://graphicalnetworks.com/cable-and-circuit-management-dcim-software/?gclid=CjwKCAjw3-bzBRBhEiwAgnnLCsXKBlQqaGc0dXbGpyaGNcSb7DzYV9-I5EHzq6YlLrIjbB6bFuFZ_xoCOlEQAvD_BwE`

Graphical Networks. (2020c). *GE – Customer Success Story | DCIM, Network Documentation, OSP Software.* Retrieved from `https://graphicalnetworks.com/roi-customer-success-stories/ge-dcim-network-documentation-review-2/`

Graphical Networks. (2020d). *UBL – Customer Success Story | DCIM, Network Documentation, OSP Software.* Retrieved from `https://graphicalnetworks.com/roi-customer-success-stories/url-dcim-network-documentation-review/`

Hensley, R., Knupfer, S., & Pinner, D. (2009). *Electrifying cars: How three industries will evolve.* Retrieved from `https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/electrifying-cars-how-three-industries-will-evolve`

Hu, W., Chen, Z., & Hou, P. (2016, 5). Optimisation for offshore wind farm cable connection layout using adaptive particle swarm optimisation minimum spanning tree method. *IET Renewable Power Generation*, *10*, 694–702. doi: 10.1049/iet-rpg.2015.0340

in-Tec Bensheim. (n.d.). *High-Voltage cabling for electric vehicles with VDA-Standards.* Retrieved from `https://www.in-tec.de/en/component-assembly/high-voltage-cabling`

Ittner, A., de Sá, C., & Sasse, F. (2007). *A Heuristic Approach to the Cable Routing Problem in Electrical Panels* (Vol. 186). doi: 10.3233/978-1-58603-936-3-55

Keppel FELS Baltech Ltd. (n.d.). *Keppel FELS Baltech.* Retrieved from `http://www.fels.bg/solutions/cablerouting.html`

Kloske, D. A., & Smith, R. E. (1994). Bulk Cable Routing Using Genetic Algorithms. In *Proceedings of the 7th international conference on industrial and engineering applications of artificial intelligence and expert systems* (p. 427–431). USA: Gordon and Breach Science Publishers, Inc.

Liberty Access Technologies. (2018). *Tesla Model 3 Versus Chevrolet Bolt EV: High Voltage Components Compared - Liberty Plugins.* Retrieved from https://www.libertyplugins.com/blog/2018/12/07/tesla-model-3-versus-chevrolet-bolt-ev-high-voltage-components-compared/

Liedholm, U. (1998). Conceptual Design of Products and Product Families. *MODULARITY IN USE-EXPERIENCES FROM FIVE COMPANIES*, 93.

Lin, C. W., Rao, L., D'Ambrosio, J., & Sangiovanni-Vincentelli, A. (2014). Electrical Architecture Optimization and Selection - Cost Minimization via Wire Routing and Wire Sizing. *SAE International Journal of Passenger Cars - Electronic and Electrical Systems*, *7*(2), 502–509. doi: 10.4271/2014-01-0320

Lin, C.-W., Rao, L., Giusto, P., D'Ambrosio, J., & Vincentelli, A. (2014). *An efficient wire routing and wire sizing algorithm for weight minimization of automotive systems.*

Ma, X., Lida, K., Xie, M., Nishino, J., Odaka, T., & Ogura, H. (2006, 6). A genetic algorithm for the optimization of cable routing. *Systems and Computers in Japan*, *37*, 61–71. doi: 10.1002/scj.10250

Professional Motor Mechanics. (2015). *Why do hybrids use high voltage A/C compressors?* Retrieved from https://pmmonline.co.uk/technical/why-do-hybrids-use-high-voltage-ac-compressors/

RapidHarness. (n.d.). *RapidHarness | Wiring Harness Software.* Retrieved from https://rapidharness.com/

TE Connectivity. (2020). *AMP+ HVP 800 high voltage connector system | TE Connectivity.* Retrieved from https://www.te.com/global-en/products/connectors/automotive-connectors/intersection/amp-high-current-connector-system-hvp-800.html?tab=pgp-story

Ulrich, K. T., & Eppinger, S. D. (2012). *Product Design and Development* (5th ed.; P. Ducham, Ed.). New York: McGraw-Hill.

Van der Velden, C., Bil, C., Yu, X., & Smith, A. (2007, 6). An intelligent system for automatic layout routing in aerospace design. *ISSE*, *3*, 117–128. doi: 10.1007/s11334-007-0021-4

Volvo Car Corporation. (2017). *Volvo Cars to go all electric.* Retrieved from https://www.media.volvocars.com/global/en-gb/media/pressreleases/210058/volvo-cars-to-go-all-electric

Webasto Thermo & Comfort SE. (2014). *The innovative coolant heater for hybrid and electric vehicles* (Tech. Rep.). Retrieved from www.webasto.com

Zhu, X., Su, D., Zhang, Y., & Li, W. (2006). Bus Bar Design for EMC Performance of Power Converters in Fuel Cell Electric Vehicles. *IEEE International Conference on Vehicular Electronics and Safety*, 144–147.

Zuken. (2020a). *Electrical harness design - Wire Harness Design - E3.series - Zuken EN.* Retrieved from https://www.zuken.com/en/product/e3series/

Zuken. (2020b). *Electrical Schematic Design Software - E3.schematic - Zuken EN.* Retrieved from https://www.zuken.com/en/product/e3series/design-and-documentation/

Zuken. (2020c). *Electrical systems topology planning - Zuken EN.* Retrieved from https://www.zuken.com/en/product/e3series/e3-topology/

Zuken. (2020d). *Panel Design Software and Routing - 2D/3D - E3.panel -*

Zuken EN. Retrieved from https://www.zuken.com/en/product/e3series/cabinet-layout-and-routing/

Zuken. (2020e). *Wire Harness Analysis and Optimization - Zuken EN.* Retrieved from https://www.zuken.com/en/product/e3series/wiring-system-lab/

DEPARTMENT OF INDUSTRIAL AND
MATERIALS SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY