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Energy Storage System Portfolio Analysis for Volvo Hybrid Construction Machines

A Life Cycle Cost Optimized Approach
Master of Science Thesis

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ABSTRACT

The objective of this report is to scientifically create a base that can be used in the decision making of how to create a cost effective hybrid component portfolio. The result is based on performance fulfillment and cost parameters of different components. The cost model used has the goal to estimate benefits of economies of scale in sharing components, in this case sharing the complete Energy Storage System (ESS). The cost model regards a life cycle cost perspective of the component, taking not only component investment cost into consideration but also cost of wear and power losses, cost items are of substantial size for some of the systems.

Different types of ESSs are evaluated. The ESS types evaluated in this report are battery-, super capacitor- and combined ones.

The work is based on a literature study including variant handling and cost analysis. The procedure of how to solve the problem is developed through a set of example problems created to explain to the reader the different steps of the problem solving process.

From the large amount of different energy storage system variants present, it was not possible to evaluate all different combinations (component portfolios). Instead an evolutionary algorithm was utilized in an optimization process, to generate and evaluate different ESS portfolio proposals based on their calculated cost.

It was realized that the energy capacity is one of the most critical parameters. At soft energy requirements super capacitor ESSs are most suitable. Another key result is that the ESS component portfolio should be created from a low number of different variants to be cost effective. It was also realized that this directive loses importance when the production volume increases.

Keywords: Energy Storage System, Life Cycle Cost Analysis, Component Portfolio, Variant Reduction

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1. INTRODUCTION

This chapter describes the background and purpose of the Energy Storage System (ESS) component portfolio synthesis work.

1.1. Abbreviations

Some of the abbreviations used in this report.

CPU	=	Cost Per Unit
DC	=	Direct Cost
ESS	=	Energy Storage System
HyCC	=	Hybrid Components in Construction vehicles
IC	=	Indirect Cost
Li-Ion	=	Lithium Ion
NiMH	=	Nickel Metal Hydride
CM	=	Construction Machine
TESSS	=	Tool for Energy Storage System Synthesis
VCE	=	Volvo Construction Equipment

1.2. Background

In today's vehicle industry it is becoming more and more important to deliver vehicles with low fuel consumption. The demands for fuel efficient vehicles are driven both by customer demands and by government regulations. The market is already starting to adapt to the new demands and it is thereby not only important to deliver vehicles with low fuel consumption but also to do this cost efficiently, to fight the market competition.

Following extract from [1] describes the plan of action for developing cost efficient hybrid vehicles at VCE.

“To ensure cost efficient future Volvo hybrid vehicles it is important to minimize the number of variants of vital hybrid components (electric machines and energy storage system). At the same time, this restricted number of component variants must (with a minimum of adjustment) fit all applications and vehicle variants.” [1]

1.3. Project description

This Master thesis project is a part of the VTEC project HyCC elapsed during 2008. The objective of the HyCC project is to identify and survey VCE machines with, today not existing, hybrid components [1]. This master thesis project will evaluate the possibilities of reducing the number of different hybrid components to reach cost savings.

The current situation is that a new feature (hybrid system) is going to be added to an existing product (VCE machines). The product is already complex. Integration of a new system makes the product even more complex and thereby more difficult and more expensive to produce. By using modularization and platform strategy (according to e.g. Ulrich and Eppinger [7]) or component commonality among the different products the complexity can be reduced and cost savings made.

At the moment there are unique solutions of the proposed hybrid system, especially the energy storage systems, to each product and model. This makes the component portfolio variation large and thereby probably expensive. A high component cost is a potential problem and the initializing factor of this master thesis. A unique component to each product and model would offer a high performance to each product but the price would probably not be competitive enough on a market where similar products soon will be launched.

The objective of this master thesis project is to find a method to cost efficiently implement the Energy Storage System (ESS) in the VCE machines. Doing so, the performance requirements from the machine on the ESS attributes must be satisfactory. There will most likely be a conflict between cost efficiency and product performance. The problem concerns a limited number of VCE models and to each machine belongs a set of ESSs (a top list) developed for that particular machine (see section A2.1). The combination of all top lists creates the base from which an ESS component portfolio will be created.

A suggestion from Jonas Hellgren, project manager at VTEC, is to implement a platform strategy or modular thinking.

The idea of a platform strategy is to try to find commonality among the unique components, making it possible to share component between different machines.

There are two extreme ways of developing an ESSs portfolio;

1. Too adjusted: Portfolio consisting of only one unique ESS
2. Too specialized: Portfolio consisting of one unique ESS for each machine.

The most suitable portfolio, when both performance and cost are regarded, is probably situated in between these two extreme portfolios.

A benefit from platform thinking is the economy of scale received when fewer variants are produced in larger quantities. One of the sub tasks of this project can thereby be to express a cost model trustworthy enough.

1.4. Objectives

- The objective of this project is to explore the possibilities to share ESS components between different VCE machines. This can be done if there is commonality between the attributes and requirements of the proposed ESSs and the different hybrid VCE machines.
- Create/find an optimization method for creating a cost efficient ESS portfolio from a given top list (see Figure 14, ch. A2.1) of proposed ESSs.
- Perform literature surveys on variant handling and product cost estimation.

1.5. Purpose

The goal is to present a cost efficient and “practically useable” ESS portfolio for hybrid VCE machines. Preferably the number of ESS variants in the portfolio is going to be much smaller than the number of VCE hybrid models the portfolio is designed for.

1.6. End effects

This project will deliver guiding information about how to cost efficient implement hybrid systems in VCE machines.

A reduced number of ESS variants will also shorten the development time for the detailed design of all hybrid systems. In addition, service and after market handling can be simplified.

1.7. Methodology

The methodology of finding an appropriate ESS portfolio will be to, from the already developed ESSs, generate different portfolio proposals by combining the selected VCE machines with different ESSs.

The most appropriate portfolios are defined by the ones where all portfolio element attributes fulfill the corresponding machine requirements and concurrently cause a low portfolio life cycle cost.

To perform the generation and evaluation of portfolios, tools or methods for generating a good sample selection and to evaluate it (by attributes and life cycle cost) will be required. A cost model to estimate the life cycle cost is also needed. To find such methods or similar ones, literature surveys were performed in the areas of cost estimation and variant handling (see chapter 2 and 3).

1.8. Exclusions

- Only energy storage system is regarded. Other hybrid components like electric machines and power electronics are not regarded.
- All ESS variants are already presented/developed in [10]
- Specific VCE machines selected, see section 4.3

1.9. Structure of this thesis

Chapter 4 “Methodology” describes the process of reaching the result: the portfolio proposals. The methods are influenced by methods discovered in the literature surveys presented in chapter 2 and 3. Chapter 4 is followed by four example problems chapter 5-8 set out to give the reader deeper understanding in how the “real problem” is approached and how it can be solved. The example problems have served as simplified parts of the “real problem” to test and confirm used methods on. Chapter 9 describes the technical requirements of the VCE machines and the cost items of the ESSs.

The result of the thesis is then presented in chapter 10 “Results”. Chapter 10 present the final results selected from a larger selection of result presented in Appendix A3 and A4. The Results are followed by chapter 11 “Discussion” and 12 “Conclusion” that provides some conclusions of the result and benefits and limits of different portfolio proposals.

In Appendix the literature surveys and additional parts of the result are placed as described above. It is also containing Appendix 1 “ESS technology”, describing the different technologies of the ESSs considered in this thesis ; lists of different ESSs serving as input data: Appendix A2 “ESS selection”; a package analysis performed: Appendix A5-A7; the program structure of the cost calculation: Appendix A8; and additional equations used in the different methods: Appendix A10.

2. LITERATURE SURVEY: VARIANT HANDLING

This section describes the challenge with variant handling and also presents a method for reducing the number of variants.

2.1. Examples of variant handling

“A competitive environment forces the companies to concentrate on many smaller market segments” [2]. The smaller markets have different requirements on the product. This results in development of a range of product variants to suit the different markets. Ericsson & Erixon [2] also says that an increased number of variants are a necessary development to be able to take market shares on these competitive markets. But at the same time Ericsson & Erixon [2] also mention the problematic situation that can arise if a company loses control over the number of variants.

A large range of product variants do often result in small sales volumes for some of the product variants. One type of variant/sales mapping presented in Figure 1 can be used to analyze this type of problem. In the particular example presented in Figure 1 it can be observed that only a few of the product variants reaches high sales volumes. It can also be noticed that most of the product variant sales volumes are very low. A high cost/unit will probably be the result of that. This particular example is collected from a case in the automotive industry. Figure 2 presents the percentage of the sales volume created by the product variants that sold the most. From Figure 2 it can be realized that the number of variants can be reduced dramatically without decreasing sales volume too much.

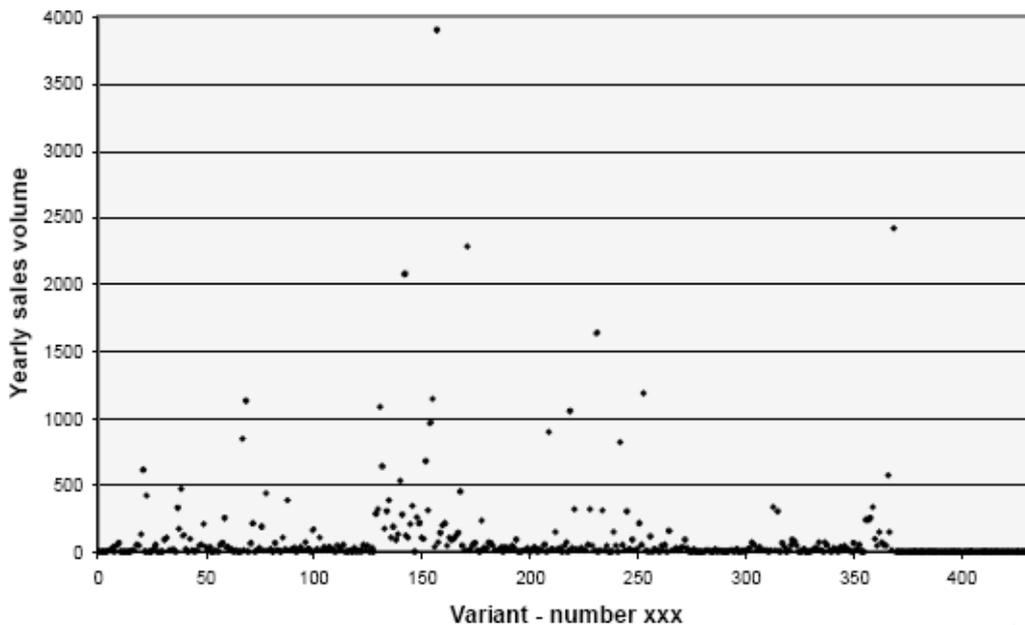


Figure 1. (Left) Mapping of the yearly sales volumes of each product variants in an example (from Magnus Persson, University lecturer Chalmers University of Technology, course material in Platform development and modularization management 07/08)

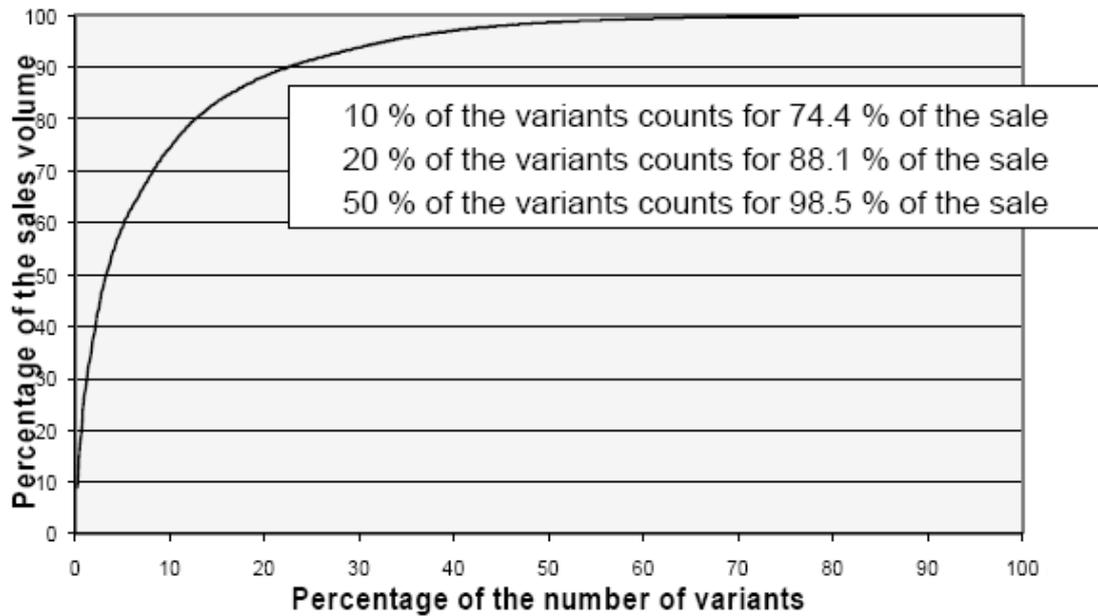


Figure 2. (Right) Diagram showing the relation of number of variants responding to the total sales volume from the example in Figure 1. (from Magnus Persson, University lecturer Chalmers University of Technology, course material in Platform development and modularization management 07/08)

Fujita et al. [5] says that “The benefits from commonalization are typically the cut-down of various cost items such as development cost, inventory cost and so forth”. This makes it possible for the company to profit from economies of scale.

The down side of utilizing common components in product design is the loss of performance due to the reduced level of customization.

Fujita et al. [5] express the struggle between pros and cons as “Commonalization affects designs to prevent them from individual optimization for different system operation and customer needs. This kind of tradeoffs should be appropriately assessed toward optimal product variety design”.

Thonemann [3] gives two examples of companies that in different ways experienced high product cost due to an ineffective of commonalization strategy.

One company ignored the cost associated with an increased number of variants and offered 14 different dashboards for a single car model. These individualized dashboards resulted in a low unit cost but even higher indirect cost (e.g. R&D and purchasing).

The other company produced an air-conditioning system. The system design was common for a complete product family, to minimize the burden of many variants. This procedure resulted in a very high cost per unit. The lesson to learn from this is that; large cost benefits can be achieved by using the strategy of platform and modularization, but to over exaggerate the commonality can result in an unnecessary high unit cost. This due to continuous implementation the most advanced and expensive module in all of the systems/products.

2.2. Method for handling variants

Thonemann et al. [3] describes a method for finding the optimal component portfolio among a highly customized range of variants. The work was inspired by a design problem in the automotive industry. A company used 136 different wire-harnesses for one single auto model, customized for each combination of engine, transmission etc. According to Thonemann [3] this lead to high cost in stock-keeping, production control, labor training etc. It, in some cases, also leads to poor assembly quality.

In the model for finding the optimal component portfolio, each product requires their variants to fulfill a certain set of requirements. In the model a matrix is holding the information of which product requires a certain attribute. The matrix was named \mathbf{v} . In matrix \mathbf{v} the element $v_{l,j}$ express if product l require attribute j or not, the answer is presented binary with 1 for yes and 0 for no.

$$\mathbf{v} = \begin{bmatrix} v_{1,1} & v_{1,2} & \cdot & \cdot & \cdot \\ v_{2,1} & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & v_{l,j} & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}$$

The rows represent different products
The columns represent different kinds of requirement

The model also expresses the attributes belonging to each variant, presented in a matrix. Thonemann [3] names this matrix \mathbf{x} . In matrix \mathbf{x} element $x_{i,j}$ tell if variant i have attribute j or not. Also in matrix \mathbf{x} the answer is expressed binary with 1 if attribute exist and 0 if not.

$$\mathbf{x} = \begin{bmatrix} x_{1,1} & x_{1,2} & \cdot & \cdot & \cdot \\ x_{2,1} & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & x_{i,j} & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}$$

The rows represent different variants
The columns represent different kinds of attributes

To be able to implement a variant i in a product l at least the requirements of the product should be fulfilled by the variant attributes, the objective could be $v_{l,j} \leq x_{i,j}$ for all j . The possible assigning of variants to products is then presented in a final matrix \mathbf{y} . \mathbf{y} describe which variants to successfully implement in each product. Element $y_{l,i}$ presents the possibility of putting variant i in product l .

$$\mathbf{y} = \begin{bmatrix} y_{1,1} & y_{1,2} & \cdot & \cdot & \cdot \\ y_{2,1} & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & y_{l,i} & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}$$

The rows represent the different products
The columns represent the different variants

The "Component design problem" (CDP) as Thonemann [3] calls it can now be expressed as equation (1). Equation (1) calculates the minimum cost of all possible portfolios.

$P_i(x, y)$, $H_i(x, y)$, $G_i(x, y)$, and $F(I)$ are all cost items estimating the final product cost. $P_i(x, y)$ express the production cost. $H_i(x, y)$ express the inventory cost. $G_i(x, y)$ express the setup cost. $F(I)$ express the complexity cost. More information about the expression behind the cost items can be found in Thonemann [3].

$$(1) \quad CDP = \min_{I, x, y} \sum_{i=1}^I [P_i(x, y) + H_i(x, y) + G_i(x, y)] + F(I)$$

2.3. Variant handling in this project

The current situation in the HyCC project is that a top list of possible ESS is present for each VCE machine. The top list consists of ESSs developed for a particular vehicle. In the top list the ESSs are placed based on cost, with the cheapest first. All ESSs with reasonable cost fulfill the performance requirements.

From all possible ESS components one optimal portfolio should be presented. The optimal portfolio should fulfill all machine requirements to the lowest total cost.

3. LITERATURE SURVEY: ESTIMATE BENEFITS FROM ECONOMIES OF SCALE

This chapter presents how to estimate the unit cost influenced by economies of scale. The result will be applied to the optimization problem of finding the optimal hybrid component portfolio for VCE machines. Cost functions for the different ESSs are necessary to be able to predict benefits of economies of scale when reducing variants and estimate the total cost of a proposed ESS portfolio.

3.1. Introduction

The benefit of reducing the number of variants, in a cost perspective, is to cut cost to make the product more competitive on the market. This is achieved by gaining benefits of economies of scale. This means that the cost per unit decreases when the production volume increases. The possible benefit of economies of scale varies for different kinds of products, all products might not benefit from economies of scale to the extent that variation (customization) should be reduced. It depends on the influence of different cost drivers.

Can cost benefits, by reducing the number of variants, be achieved in this project?

3.2. Development of a cost estimation

This section will try to answer how to develop a cost function

3.2.1. Cost drivers

The cost of the product is driven by different factors. The cost is driven by e.g. development-, design-, material-, process-, assembly-, facility-, transport cost etc.

Pahl and Beitz [6] divide the overall cost into two parts, the direct- and indirect cost. "Direct costs are those costs that can be allocated directly to a specific cost carrier, for example material and labor costs for producing a specific component. Indirect costs are those costs that cannot be allocated directly, for example the costs of running stores and illuminating the workshop"

Pahl and Beitz [6] also describe two different kinds of cost in the cost calculation, variable and fixed cost. The variable cost depends on the "number of products ordered" or "degree of facility utilization". Material- and production labor costs for example increase with larger production volumes. The fixed cost however does not change with increased production. These are costs such as interest, building rent, and management salaries. The manufacturing cost for example consists of both variable and fixed costs according to Pahl & Beitz [6]. In that sense the fixed costs could be for tools and fixtures. For different types of cost and examples see Table 1.

However, according to Ulrich and Eppinger [7] no cost is ever completely fixed. For example if the production is increased multiple times new investments will be needed, e.g. for tool investment. In Ulrich and Eppinger [7] only fixed and variable cost are used in structuring the costs.

Table 1. Example to the different types of costs presented by Pahl and Beitz [6]

Different types of cost		Example
Direct cost	Fixed cost	<i>Tool investment</i>
	Variable cost	<i>Material cost</i>
Indirect cost	Fixed cost	<i>Management salaries</i>
	Variable cost	-

One driving force behind part commonalization is that the product cost is reduced when volumes are increased, due to for example learning effects in assembly, better equipment and supplier discounts, which should be taken into account when calculating the direct costs, Blackenfelt [8]. Blackenfelt also claims that German design literature often describes these effects by the formula of Bronner. Equation (2) describes the decline of the direct cost of units due to larger production volumes. The exponent (λ) describes the size of the decline and has to be estimated for each specific case.

3.3. Two methods of calculating the product cost

Blackenfelt [8] calculate the total product cost by dividing the cost into direct and indirect costs. While Fujita et al [5] calculate the total product cost by dividing the cost into a few different areas that easily can be related to the product development process and product life cycle.

3.3.1. Product portfolio cost calculation by Blackenfelt [8]

Estimations of following parameters are used in the model:

DC = Direct cost

IC = Indirect cost

v = Nof units at two levels

λ = exponent describing the decline (normally 0.322, means a price red. to 80% when double volume)

x = characteristic variable

a, b, p = constants

Blackenfelt [8] presents equation (2), based on a formula by A. Bronner. Bronner tried with his formula to describe the effects of learning, better equipment and supplier discounts to the product cost, when increasing production volume. Blackenfelt [8] combined Bronners formula and the direct cost, (3), to calculate the direct cost at a new production volume.

$$(2) \quad DC_2 = DC_1 \left(\frac{v_2}{v_1} \right)^{-\lambda} \quad [\text{cost}]$$

$$(3) \quad DC = a + b \cdot x^p \quad [\text{cost}]$$

Blackenfelt [8] describe that the indirect cost can be divided into two parts, IC_1 and IC_2 , one part that is easy to estimate and one that is difficult. IC_1 is the more simple part and can be related to the volume and thereby related to the DC according to Blackenfelt [8], the relation is expressed with a coefficient c . IC_2 is related to the kind number and yearly cost for maintaining the products. It

is calculated by the yearly cost for maintaining a part (' d ') multiplied by the number of different parts (' n ').

$$(4) \quad IC_1 = c \cdot DC_2 \quad [\text{cost}]$$

$$(5) \quad IC_2 = d \cdot n \quad [\text{cost}]$$

The total cost (TC) for all products is then calculated with equation (6) by Blackenfelt.

$$(6) \quad TC = \sum^{\text{parts}} IC_2 + \sum^{\text{parts}} (1 + c) \cdot DC_2 \cdot v_p \quad [\text{cost}]$$

3.3.2. Product portfolio cost calculation by Fujita [5]

Fujita et al [5] present a procedure for optimizing the product variety design by expected total profit.

In their model they present a few cost criteria. Here will the three most important criteria for the cost estimation of HyCC components, according the author, be presented. The three criteria are design and development cost, facility cost, and production cost. The different costs are calculated for each cost criteria and product kind. The result is then superposed (addition) to calculate the total portfolio cost.

Design and development cost

Fujita [5] assumes that "design and development cost is proportional to the weight of each module and that cost savings for similar design is also proportional to the difference of corresponding weight".

The design and development cost is presented by C_D in equations (7)-(8). In equation (8) $\alpha_{D,j}$, $\beta_{D,j}$ and $\gamma_{D,j}$ are coefficients dependent on the products kind. C_D^i is the cost per product consisting of a range of more or less similar variants. i is product index and j is module index.

$$(7) \quad C_D^i = \sum_{j=1}^m C_{D,j}^i \quad [\text{cost/product}]$$

$$(8) \quad C_{D,j}^i = \begin{cases} \alpha_{D,j} \cdot W_j^i & \text{(Independent design)} \\ \left(\beta_{D,j} \cdot \frac{W_j^i - W_j^1}{W_j^1} + \gamma_{D,j} \right) \cdot C_{D,j}^1 & \text{(Similar design)} \\ 0 & \text{(Same design)} \end{cases} \quad [\text{cost/variant}]$$

Facility cost

Fujita et al [5] assumes that estimation of facility cost is similar to the design and development cost. But instead of proportional to the weight it can be assumed to be proportional to the dimension of the product. The formulas presented in their work for calculating the facility cost are (9)-(10). The coefficients $\alpha_{F,j}$, $\beta_{F,j}$ and $\gamma_{F,j}$ are depending on the product kind. C_F^i is the cost per

product consisting of a range of more or less similar variants. i is product index and j is module index. Example of facility cost is e.g. rent of factory.

$$(9) \quad C_F^i = \sum_{j=1}^m C_{F,j}^i \quad [\text{cost/product}]$$

$$(10) \quad C_{F,j}^i = \begin{cases} \alpha_{F,j} \cdot x_j^i & \text{(Independent design)} \\ \left(\beta_{F,j} \cdot \frac{x_j^i - x_j^1}{x_j^1} + \gamma_{F,j} \right) \cdot C_{F,j}^1 & \text{(Similar design)} \\ 0 & \text{(Same design)} \end{cases} \quad [\text{cost/variant}]$$

Production cost

The third cost criterion is the production cost. It consists of material cost and processing cost (e.g. labor cost). Fujita et al [5] (similar to Blackenfelt [8]) says that with increased production volume the production efficiency is increased, and refers to the learning curve. The effects on the processing pace can be described with the learning curve itself.

Fujita [5] calculates the production cost of a single product production. The cost of the l -th unit in the production flow can be calculated by equation (11), where r is the learning curve ratio (typically $r = 0.75 \sim 0.85$). Fujita [5] claims that equation (11) can be applicable for independent and same design.

$$(11) \quad c_p(l) = c_p(1) \cdot l^{\frac{\ln r}{\ln 2}} \quad [\text{cost/unit}]$$

The material part of the production cost is expressed with equation (12) and calculates the cost of each product based on the material cost and weight of each module in the product.

$$(12) \quad c_m^i = \sum_{j=1}^m v_j \cdot W_j^i \quad [\text{cost/unit}]$$

The production cost of the l -th unit of product i (13). This equation is expressed for calculating the cost per unit in a full range of different products. Equation (11) must then be modified for each product kind.

$$(13) \quad c_p^i(l^i) = c_m^i + c_p^i(l^i) \quad [\text{cost/unit}]$$

Fujita et al. [5] does not present a way to calculate the cost per unit in their model. Their approach is towards estimating a profit. Equation (14) is an idea for calculating the total cost per unit presented by the author. At this point (14) is not used in the report.

$$(14) \quad c^i = \left(\frac{C_D^i + C_F^i}{N_i} \right) + c_p^i \quad [\text{cost/unit}]$$

3.4. Differences between Blackenfelt and Fujita

The biggest difference between Blackenfelt and Fujita is that the method of Blackenfelt is dividing cost items by their relation to the product volume and Fujita divides the cost items by different product and company related areas. The method of Blackenfelt is preferable if the important cost items of the product/process are identified and their relations to different product/process parameters are known. In Fujita et al.'s model different cost items can be estimated/calculated based on product and module specific parameters. This model requires knowledge about how to specify the coefficients in the model.

The benefit of scale is included in both models, in Fujita in the 'Production cost' and in Blackenfelt in the direct cost. The factor λ used by Blackenfelt is equal to the ' $\ln(r)/\ln(2)$ ' in the model by Fujita, even if Blackenfelt does not give this formula to λ . A part in Fujita's model that could be questioned is the estimation the production cost of one product ($c_p(1)$) used in equation (11). It could be questioned if $c_p(1)$ can be related to an accurate cost.

4. METHODOLOGY

This chapter describes the procedure to solve the problem of generating a cost efficient ESS portfolio used in this project.

4.1. Product portfolio derivation

An ESS portfolio is generated by selecting one ESS for each VCE model (see Table 4, ch. 4.3) from a selection of developed ESSs (see Figure 14, ch. A2.1). Because there are 11 different machine models regarded (Table 4, ch. 4.3) and 18 different ESSs (Figure 14, ch. A2.1) there is a possibility of creating 11^{18} unique portfolio proposals. It will not be possible to evaluate the complete portfolio selection so a cost effective portfolio will have to be selected from a sample of the complete portfolio selection. To generate this portfolio sample selection an optimization algorithm was used. The algorithm chosen was an Evolutionary Algorithm (EA). The optimization process is further described in section 10.1 and in the “Example Problem Four” in chapter 8.

When evaluating a portfolio proposal the ESS attributes must fulfil the machine requirements, described in section 9.1, according to section 1.5 “Purpose”. The life cycle cost of all satisfactory portfolios will then be estimated and the portfolios will be ranked by this particular cost. At the end a portfolio should be selected from the top of this ranking list.

The procedure to test the requirements fulfilment is described in chapter 5 “Example Problem One” and chapter 6 “Example Problem Two” is similar to the method presented in the literature survey in section 2.2 “Method for handling variants”. The requirement fulfilment will only be expressed binary, fulfil or not.

The cost model is one of the most complex parts of the optimal portfolio derivation. It is a life cycle cost estimation of the portfolio. The model include the investment cost (component cost); the cost of power losses; and a possible wear cost into consideration and is described in equation (15). The cost model used and its components are presented in section 4.2 and are influenced by a cost model described by Blackenfelt [8].

The results ended up at deriving optimal portfolios for different scenarios. Because of the difficulty in predicting future prerequisites, different scenarios provides an opportunity to observe the influence of uncertain parameters for the result, see more about the scenarios in section 10.1.1.

4.2. Cost model

Equation (15) presents how the unit cost is built up. It is based on estimated cost items related to each type of ESS. The cost items in (15) are based on the cost items direct- and indirect costs described by Blackenfelt [8]. The ‘direct cost’ item is then divided into a material- and a labor-part by the author. The two last cost parameters, loss cost and wear cost introduced in “HYCC Milestone - Gross set of ESS regulations” [10] are also included in the equation and will be described in the following sections.

$$(15) \quad Cost_{estimated}^{ESS(i),CM(j)} = \underbrace{Cost_{Indirect}^{ESS(i)} + Cost_{Direct,material}^{ESS(i)} + Cost_{Direct,labor}^{ESS(i)}}_{Investment\ cost} + Cost_{loss}^{ESS(i),CM(j)} + Cost_{wear}^{ESS(i),CM(j)} \quad [cost/unit]$$

The relation between the cost parameters and the production volume is presented in Table 2 (below) and the equations behind the different cost items can be found in Appendix A10, equation (31)-(34) and (38)-(49).

The cost of a complete hybrid ESS portfolio is then calculated in equation (18) by summarizing the total cost of each ESS variant, calculated by equation (16)-(17). More equations are presented in Appendix A10.

$$(16) \quad Cost_{\text{component}}^{\text{ESS}(i)} (N_{\text{tot}}^{\text{ESS}(i)}) = Cost_{\text{Indirect}}^{\text{ESS}(i)} (N_{\text{tot}}^{\text{ESS}(i)}) + Cost_{\text{Direct,material}}^{\text{ESS}(i)} + Cost_{\text{Direct,labor}}^{\text{ESS}(i)} (N_{\text{tot}}^{\text{ESS}(i)}) \quad [\text{cost/unit}]$$

$$(17) \quad Cost_{\text{Total}}^{\text{ESS}(i)} = Cost_{\text{component}}^{\text{ESS}(i)} \cdot N_{\text{tot}}^{\text{ESS}(i)} \quad [\text{cost}]$$

$$(18) \quad Cost_{\text{portfolio}} = \sum_i Cost_{\text{Total}}^{\text{ESS}(i)} + Cost_{\text{loss total}} \quad [\text{cost}]$$

The $Cost_{\text{estimated}}^{\text{ESS}(i),\text{CM}(j)}$ in (15) can be used to calculate the unit cost at any future production volume.

Table 2. The cost parameters relation to the production volume

Cost parameter	Relation to production volume
$Cost_{\text{Indirect}}$	Decrease when production volume increases [cost/unit] (author's hypothesis)
$Cost_{\text{Direct,material}}$	Constant when production volume changes [cost/unit] (author's hypothesis)
$Cost_{\text{Direct,labor}}$	Change with production volume [cost/unit] (literature survey)
$Cost_{\text{loss}}$	Cost of energy losses in the ESS due to inner resistance, the cost is individual for each ESS and is not influenced by production volume.
$Cost_{\text{wear}}$	Cost for replacing worn ESS. The size of the cost, if it exist, depends on the life length of the machine. The wear cost is depending on the production volume.

4.2.1. Wear cost

Wear cost represent the additional cost to replace a worn or damaged ESS. If no replacement is needed, the $Cost_{\text{wear}}^{\text{ESS}(i),\text{CM}(j)}$ equals zero. There wear cost only exist if the ESS will be replaced during the machine life length. The cost is based on the parameters in equation (19), the complete relation can be found in equation (42). The interest in equation (19) and (42) was set to 10%, $Cost_{\text{Gross set ESS regulation}}^{\text{ESS}(i)}$ is equal to the parameter "Invest cost" in Figure 13 ch. A2.1, and $t_{\text{life length}}^{\text{CM}(j)}$ can be found in Table 3 below.

How to calculate the $\Delta\text{State of health}^{\text{ESS}(i),\text{CM}(j)}$ is explained with an example problem in 7 "Problem three – ESS degradation example".

$$(19) \quad Cost_{\text{wear}}^{\text{ESS}(i),\text{CM}(j)} = f\left(Cost_{\text{Gross set ESS regulation}}^{\text{ESS}(i)}, \Delta\text{State of health}^{\text{ESS}(i),\text{CM}(j)}, \text{interest}, t_{\text{life length}}^{\text{CM}(j)}\right) \quad [\text{cost}]$$

Table 3. Machine usage data used in this report. The figures marked blue under “Annual usage” and “Machine life length” are equal to the data in ‘Gross set ESS regulation’ [10], the other numbers are re-evaluated.

Machines	Annual usage [h]	Machine life length [years]
EC210	2000	7,5
EC240	3000	5
EC290	3000	5
EC360	4000	5
EC460	4000	5
L150	2080	10
L180	2340	10
L220	2390	10
L350	2470	10
G940 Micro Grad 600V	180	10
DD112 Micro Comp 600V	300	15
DD112 Series Comp 600V	300	15

4.2.2. Cost of power losses

There exist power losses in the energy storage system. These losses are created by inner resistance in the battery or super capacitor cells. The summarized power loss of each cell here represents the total power loss of the complete ESS. The cost of these power losses can be calculated by estimating the amount of diesel corresponding to the power losses. The power losses cause energy losses during the machines duty cycles. The energy lost during the machines life length can be related to a quantified amount of diesel, and the cost of that amount of diesel corresponds to the cost of the power losses during the machine life length. The equations used to calculate the cost from the power losses can be found in Appendix A10 equations (43)-(49).

The power losses of the ESSs are calculated for the machine it is developed for, in TESSS [11]. Because of this the loss cost of an ESS is only received for one of all machines, this is the case for all ESSs. From these few estimated loss costs the loss cost of one ESS in another machine can be estimated by calculating the relation between two different machines power characteristics (proportional relationship between two machines using the same ESS, see equation (45)). The loss cost is originally calculated by an equation similar to (48), but in this report it is just a matter of proportionally transform known loss costs between two different machines. How the loss cost is created can be seen in (20).

(20) inner resistance → power loss → energy loss → lost diesel → additional cost

4.3. Production volume

Table 4 describes the yearly production volume of the different machines, estimated by the author. The numbers in *italic* presents the yearly amount of hybrids for the different (estimated), for both a mild and an aggressive volume scenario that is going to be used later. The production life length is estimated to 8 years with the yearly production volume used in Table 4 below.

Table 4. Yearly production volume of different VCE machines

	 EC210	 EC240	 EC290	 EC360	 EC460	 L150	 L180	 L220	 L350	 G940	 DD112	sum
Yearly production volume total	confidential	-	-	-	-	-	-	-	-	-	-	-
Hybrid fraction = 10%	-	-	-	-	-	-	-	-	-	-	-	-
Hybrid fraction = 50%	-	-	-	-	-	-	-	-	-	-	-	-

5. EXAMPLE PROBLEM ONE – ESS IN HYBRID CAR

Example problem one is a very simplified example of the real problem. It is the first step towards solving the complete problem.

5.1. Problem definition

The simple problem consists of creating a cost efficient ESS component portfolio for a company producing two different cars, a conventional and a hybrid car. The company has four different ESSs to choose from when putting together a complete component portfolio. The ESS attributes and the car requirements are stated in Table 5 and Table 6. The two attributes/requirements that were compared are power and energy.

Table 5. The four ESSs and their attributes

	Attributes		
	Power [kW]	Energy [MJ]	Cost [€/unit] (low nof units)
ESS 1	1	0,1	2000
ESS 2	30	0,5	6000
ESS 3	100	20	20000
ESS 4	150	100	30000

Table 6. The 2 cars and their requirements

	Requirements		Sales
	Power [kW]	Energy [MJ]	NOF units/year
CAR1 (conventional)	2	0,1	100000
CAR2 (hybrid)	50	1	50000

The problem to solve is how to select the component portfolio with lowest cost and fulfilled requirements.

5.2. Problem solution

The first task is to examine which ESS that is compatible with each car.

5.2.1. Create a component portfolio

In Matlab the attributes of each ESS are compared to the corresponding requirement of the car. One binary matrix was created for each attribute (see Table 7 and Table 8 below). From Table 7 it can be concluded that the power of ESS1 will not satisfy either CAR1 or CAR2.

Table 7. Compatibility of the ESSs in the cars when the power attributes are regarded

	ESS1	ESS2	ESS3	ESS4
CAR1 (conventional)	0	1	1	1
CAR2 (hybrid)	0	0	1	1

Table 8. Compatibility of the ESSs in the cars when the energy attributes are regarded

	ESS1	ESS2	ESS3	ESS4
CAR1 (conventional)	1	1	1	1
CAR2 (hybrid)	0	0	1	1

The next step was to create a matrix regarding the compatibility of all attributes at ones. This was done by simply combining the matrices using an AND operation. The result can be observed in Table 9.

Table 9. Example of the “master” compatibility matrix where all attributes are regarded

	ESS1	ESS2	ESS3	ESS4
CAR1 (conventional)	0	1	1	1
CAR2 (hybrid)	0	0	1	1

From the result in Table 9 six different portfolios can be created, see Table 10. There are in this case 6 different ways of equipping the cars with ESSs, satisfying the requirements in Table 6, but which is the most cost efficient?

Table 10. The possible component portfolios

	Possible portfolios					
CAR1 (conventional)	ESS2	ESS2		ESS3	ESS4	
CAR2 (hybrid)	ESS3	ESS4	ESS3	ESS4	ESS3	ESS4

5.2.2. Cost estimation of each component portfolio

The final step of the example is to calculate the total cost of each component portfolio. From the result the most cost efficient component portfolio can be selected. The cost estimation is based on a cost function with the in-parameters: ‘number of units/year’ and ‘cost/unit’ at low production volume. The cost function is expressed based on the cost/unit variable see Figure 3. From the cost function a new cost $c^i(N_{ESS}^i)$ [cost/unit] of each ESS system can be calculated. The total cost of one particular ESS type in a complete portfolio, $Cost_{ESS}^i$ [cost], can be calculated by Equation (22).

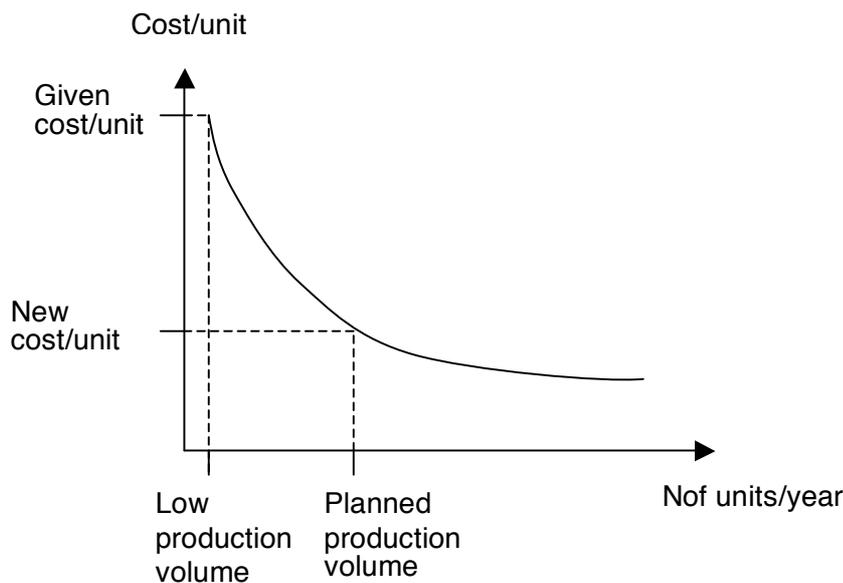


Figure 3. Estimated cost variation for a ESS unit based on numbers of units yearly produced

Parameter explanation:

- N_{ESS}^i = Number of ESS_i produced per year
 $c^i(N_{ESS}^i)$ = Cost per unit when N units produced
 N_{Car}^j = Number of Car_i produced per year
 $Cost_{InitialUnitCost}$ = Cost per unit at low production volumes
 C_{Base} = Constant cost for ESS base
 λ = Exponential describing the influence of mass production on cost compare to equation (2)

Based on the calculations, from the estimations made, Matlab was set to give a vector with the total cost of each portfolio (see Table 11). The total cost was calculated with the equations (21)-(25). Figure 4 shows an example describing the portfolio design variable P used in (24)-(25). Equation (23) is based on equation (2) by Blackenfelt but modified for the particular problem.

$$(21) \quad Cost_{Portfolio} = \sum_{i=1}^4 Cost_{ESS}^i$$

$$(22) \quad Cost_{ESS}^i = N_{ESS}^i \cdot c^i(N_{ESS}^i)$$

$$(23) \quad c^i(N_{ESS}^i) = \frac{Cost_{InitialUnitCost}}{N_{low\ peoduction}} \cdot \left(\frac{N_{ESS}^i}{N_{low\ peoduction}} \right)^{-\lambda} + C_{Base} \quad N_{low\ peoduction} = 1000 \text{ units}$$

$$(24) \quad N_{ESS}^i = (P(1) == i) \cdot N_{Car}^1 + (P(2) == i) \cdot N_{Car}^2$$

$$(25) \quad P = (ESS_{Car1}, ESS_{Car2}) \quad ESS_{Car,i} \in [1, \dots, 4]$$

Ex: $P = (2 \ 3) \Rightarrow \begin{cases} N_{ESS}^1 = 0 \\ N_{ESS}^2 = N_{Car}^1 \\ N_{ESS}^3 = N_{Car}^2 \\ N_{ESS}^4 = 0 \end{cases}$

Figure 4. Example of parameter $P()$, describing the nof ESS for an example portfolio.

5.3. Matlab program for generating component portfolios

In Figure 5 a flow chart of the Matlab program for generating all component portfolios in the example problem are shown.

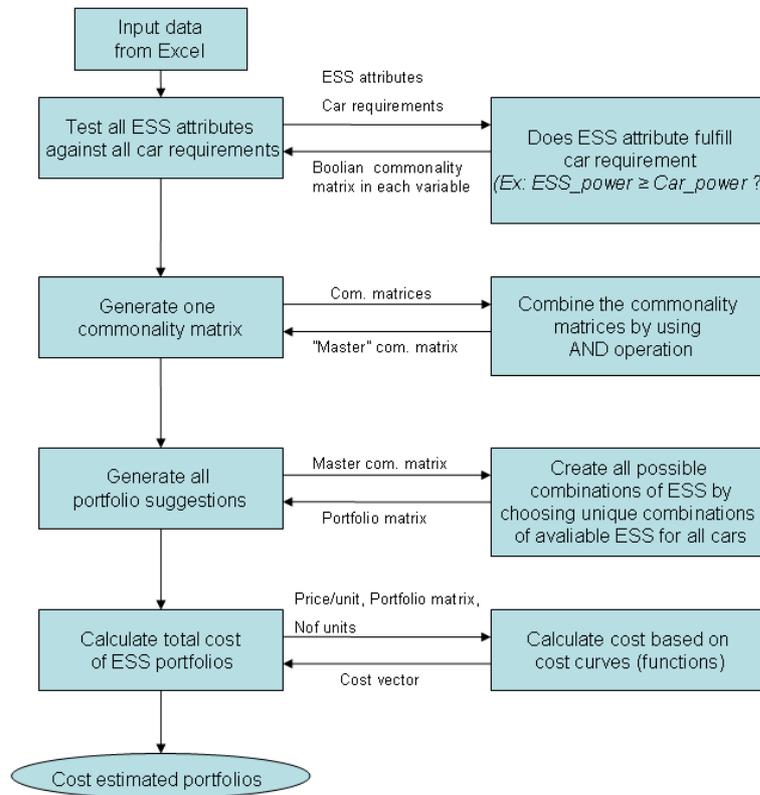


Figure 5. The structure of the Matlab program

5.4. Result

Table 11 and Table 12 present the result of example one with two different cost estimations based on different influences of mass production (different λ). The estimated cost of each portfolio can be observed for every proposed portfolio. The cost figure itself is not that interesting here. It is more interesting to see the relation between the costs of the different proposals. Remember that all proposals fulfill the car requirements.

Table 11. The result of example one: The estimated cost for each portfolio proposal ($\lambda = -0,322$ in (23))

rank	Portfolio cost (MEuro)	Average unit cost (Euro)	Portfolio proposal	
			Car1	Car2
1	430	2867	2	3
2	580	3867	2	4
3	610	4067	3	3
4	900	6000	3	4
5	910	6067	4	4
6	980	6533	4	3

Under these cost conditions ($\lambda = -0,322$ in equation(23)) the total portfolio cost can be cut by more than half by choosing the right portfolio, compare portfolio costs in Table 11. The basic/constant cost C_{Base} is set to 100.

Lambda (λ) equal to -0,322 corresponds to an 80% reduction of labor effort per produced unit when the production volume is doubled. This reduction in labor effort can be related to an equivalent reduction of labor cost.

It should be considered that the result here is totally depending on the cost expression and in this example not based on a fully realistic expression; equation (23).

In Table 12 the results of example one based on a cost estimation where $\lambda = -1$ in equation (23). The difference from the result in Table 11 is that a larger part of the product cost is variable. The benefits of mass production will then be a greater, compare rank 1 in Table 11 and Table 12. The result is that it is more beneficial to increase volumes and reduce variation of the ESSs, when λ decrease.

Table 12. The result of example one, with increases influence of the benefits of mass production ($\lambda = -1$ in (23))

rank	Portfolio cost (MEuro)	Average unit cost (Euro)	Portfolio proposal	
			Car1	Car2
1	35	233	3	3
2	41	273	2	3
3	45	300	4	4
4	51	340	2	4
5	65	433	3	4
6	65	433	4	3

5.5. Adaptation to real ESS component portfolio problem

From the example problem above the foundation for solving the main problem, defined in chapter 1 “Introduction”, is built. With a starting point in the Matlab program created for the simple problem adjustments will make this existing program adaptable to the real problem.

6. EXAMPLE PROBLEM TWO – ESS IN HYBRID CAR

This part describes the second example problem.

6.1. Evolution of Example Problem One

Example problem two is based on example problem one but further developed. The problem has been extended to now contain three different cars (Table 14) and the number of ESS has been varied between 4 and 18. One purpose with the larger number of ESS variants is to see how the solution time is affected by large number of parameters, but here will only the result from simulations with 4 unique ESSs be presented. More differences are:

1. Loading data form an excel file similar to a TESSS top list
2. One more car is added to handle more data
3. One more requirement (mass) is added
4. Introduction of a new model for cost calculation (described in section 4.2)

The procedure on how to solve the problem has also slightly been changed; the idea is still the same though. The first example problem was solved by generating all possible ESS portfolios and then calculate the cost of each of them (see program structure, Figure 5 ch. 5.3). The second example problem is solved by:

1. Generate all ESS portfolio combinations there is, even non-satisfactory.
2. Test the ESS attributes against the car requirements in each proposed portfolio, if fulfilled the cost of the particular portfolio is calculated (see program structure, Figure 22 ch. A9).
3. The cost calculation is based on a more scientific model than in example problem one.

The four ESSs and the three cars resulted in 12 feasible portfolios. The result can be observed in Table 15. The four ESSs are the same as the ones used in example one (see Table 13). The cost between problem one and two are not comparable, since it calculates the cost of the complete portfolio.

To perform the cost calculation the cost model in section 4.2 is fed with the cost parameters in Table 13. The different cost parameters are based on the author's hypothesis. The parameter 'Price' in Table 13 is equal to the parameter $Cost_{Gross\ set\ ESS\ regulation}^{ESS(i)}$ in the cost model in section 4.2.

Abbreviation:

DC1 mtrl	= Material based direct cost
DC2 labor	= Labor based direct cost
IC	= Indirect cost
X	= Nof units produced to receive the price 'Price' per unit.
n	= Nof units needed of a certain type of ESS

Table 13. ESS data for example two

	Attributes			Cost parameters				
	Power [kW]	Energy [MJ]	Mass [kg]	Price [€] p.u.	DC1 mtrl	DC2 labor	IC	X
ESS1	1	0,1	100	2000	8000	2500	2 000	1 000
ESS2	30	0,5	150	6000	7000	1500	2 000	1 000
ESS3	100	20	300	20000	14000	3000	2 000	1 000
ESS4	150	100	200	30000	10000	10000	10 000	1 000

Table 14 presents the car requirements.

Table 14. The car requirements

	Requirements			Sales
	Power [kW]	Energy [MJ]	Mass [kg]	NOF units/year
CAR1 (conventional)	2	0,1	160	100000
CAR2 (hybrid)	50	1	250	50000
CAR3 (hybrid2)	50	15	300	40000

Table 15. The result of example 2. Four different ESSs and three cars resulted in 12 feasible portfolio combinations.

Rank	Cost	Portfolio proposal		
		Car1	Car2	Car3
1	2116327214	2	3	3
2	2342786900	2	3	4
3	2387995480	2	4	3
4	2545235088	2	4	4
5	3310822850	3	3	3
6	3542813651	3	3	4
7	3589999035	3	4	3
8	3767417815	3	4	4
9	3809706940	4	3	3
10	3972265917	4	3	4
11	4011214616	4	4	3
12	4150939024	4	4	4

From the result it can be observed that with this way of calculating the cost it is not beneficial to use full component commonality when equipping the vehicles with ESSs.

7. EXAMPLE PROBLEM THREE – ESS DEGRADATION

One of the most complex requirements to take into consideration is the degradation of the ESS cells, caused by the energy flow in the system, when implementing an ESS developed for one machine in another machine. The machines have different power profiles and thereby different energy flows in the ESS. The size of the energy flow affects the life length of the ESS cells. Implementing an ESS developed for one vehicle into another vehicle can therefore strongly limit the life length of the ESS.

In this example there are two different machines Veh1 and Veh2 with different energy flows; Table 16. There are also two different ESSs developed for Veh1 with belonging values of the degradation for that ESS/machine combination, Table 17.

The degradation of the cells when implemented in Veh1 is specified by simulations (TESSS [11]). The objective of this example is to explain how to calculate the life length of the ESS cells when implemented in a new vehicle, here Veh2. The objective of this example is to investigate the possibility of implement

7.1. Energy flow

The degradation of the cells is measured by the parameter Δ State of Health (dSoH). The degradation is related to the energy flow, equation (26), in the ESS system and thereby related to the power profile of the machine.

Table 16. The energy flow in both vehicles during a life time use

	Veh1	Veh2
Eflow	10 (mild) [TJ]	100 (heavy) [TJ]

Table 17. Degradation of ESS when implemented in Vehicle 1

	dSoH	
	Veh1	Veh2
ESS 1	0,3	-
ESS 2	0,01	-

To calculate the dSoH of an ESS in a new vehicle equation (27) can be used.

Abbreviation:

$dSoH = \Delta$ State of Health

$dSoH_B(ESS_N) =$ Degradation of ESS_N when implemented in a new vehicle

$dSoH_A(ESS_N) =$ Degradation of ESS_N from simulation (TESSS result)

$eflow() =$ The energy flow in the machine during its life time [J]

$$(26) \quad eflow = \int_{t=0}^{\text{lifetime}} |P_{\text{ESS}}| \cdot dt \quad [\text{J}]$$

$$(27) \quad dSoH_B(ESS_N) = \frac{eflow(B)}{eflow(A)} \cdot dSoH_A(ESS_N) \quad [\text{no unit}]$$

In Table 18 the result of implementing the ESSs in Veh2, when regarding the energy flow, can be observed. The new energy flow was received by using equation (27). Equation (27) is created on the assumption that there is a linear relationship between energy flow and degradation. It is also assumed that the relation between the energy flow and degradation is the same between different vehicles.

Table 18. Table over the degradation of the different ESS in the two machines

	dSoH	
	Veh1	Veh2
ESS 1	0,3	3
ESS 2	0,01	0,1

If the value of dSoH is larger than 1 ($dSoH > 1$) the ESS will be damaged by the high energy flow. One of the cells in Table 18 is crossed with a bar. This is not a feasible implementation of ESS 1 because there is a high risk of damaging the ESS unit. But implement ESS 2 in Veh2 is a feasible combination.

8. EXAMPLE PROBLEM FOUR – PORTFOLIO OPTIMIZATION

This chapter describes the process of finding a cost efficient ESS component portfolio by using an optimization approach. The optimization method used is an evolutionary algorithm (EA) based one.

The EA algorithm randomly generates a number of populations to start with. The populations are each solution proposals. Each population is then evaluated by a goal function with the purpose to find the best solution to the problem. The goal function expresses the problem to be solved, and the best portfolio (population in EA) will generate the best result from the goal function. A new population will then be generated based on the prior one. A low number of the best populations will remain unchanged but the rest of the populations can be manipulated before next evaluation. The populations to manipulate are selected randomly. After the manipulation the process of evaluating populations will be iterated. The iteration process will run for a chosen number of generations. The solution to the optimization process can, after all generations, be the best population or a top-list of the best populations to pick a solution from.

In this chapter an example problem will be solved using an EA and the result will be compared to the global result of the problem. Optimization methods are often utilized for problems too large to generate all possible solutions to. To find the global result will be too time-consuming if even possible. The solution to an optimization method is called local result. The purpose of the optimization method is to generate a local result as close as possible to the global result without regarding the full range of results.

8.1. The problem

This problem consist of 4 machines that each will be equipped by one of 7 ESSs. Table 19 shows the compatibility between the ESSs and the vehicles. This problem, similar to Problem one and two, is to find the most cost efficient ESS component portfolio. The design of this problem will generate $6 \times 5 \times 5 \times 4 = 600$ possible portfolio combinations.

The problem is causal, meaning that the result of selecting an ESS for a vehicle depends on the ESS selection for the other vehicles.

Table 19. Present the compatibility between ESSs and vehicles

ESS	Cost [€]	Type	Veh 1	Veh 2	Veh 3	Veh 4
ESS 1	3391	Super Capacitor,1	1	1	0	0
ESS 2	3212	Super Capacitor,2	1	1	0	0
ESS 3	1859	Super Capacitor,3	1	1	1	1
ESS 4	1754	Battery,1	0	0	1	1
ESS 5	6493	Battery,2	1	0	1	1
ESS 6	6512	Passive Comb,1	1	1	1	0
ESS 7	8000	Passive Comb,2	1	1	1	1

8.2. Global result

The global result of the problem is received by calculating the portfolio cost of each 600 portfolios. The most cost efficient result is shown in Table 20. The results from the 600 portfolios are also presented in a histogram in Figure 6, to be compared with the result of the optimization later.

Table 20. The portfolio with lowest cost

Cost	Veh 1	Veh 2	Veh 3	Veh 4
3563152	ESS 3	ESS 3	ESS 3	ESS 3

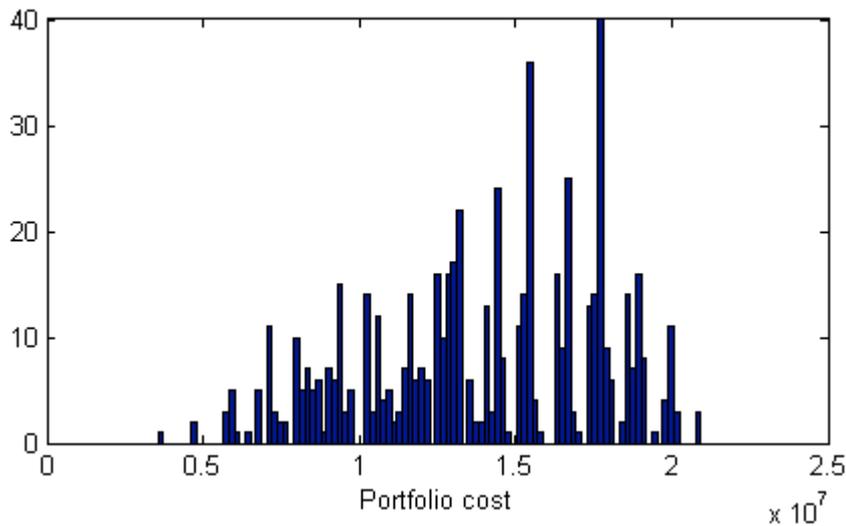


Figure 6. Histogram containing all 600 solutions.

8.3. Local result

Table 21 presents the result from 3 different optimization runs with different nof generations (iteration) and nof populations (portfolios). If the populations are too few, the process might not find a solution good enough because there are not enough variants or options to choose from. In Table 21 it can be observed that the run with most populations finds the global solution but the other runs does not even for this small problem.

To evaluate the exactness of the optimizations runs the results can be compared to a histogram of all optimization results, see Figure 6. As can be seen, by comparing portfolio cost, all 3 local result are good estimations of the global result when compared to all possible results.

Table 21. Optimization result from 3 different optimization processes

Cost	Portfolio				Population size	Generations
	Veh1	Veh2	Veh3	Veh4		
3563200	ESS 3	ESS 3	ESS 3	ESS 3	100	20
5942600	ESS 3	ESS 3	ESS 5	ESS 3	10	20
4776200	ESS 3	ESS 3	ESS 3	ESS 4	10	40

9. ESS PRODUCT DATA

This chapter presents the data from the ESSs proposed by TESSS and also the requirements the vehicles put on the ESS attributes. This is the data that is going to be analyzed in the optimization problem.

9.1. Requirements

To be able to implement an ESS in a VCE machine the attributes of the ESS must fulfil the requirement of the machine. In the analysis presented in this report the requirements are regarded as fulfilled or not. This binary approach to evaluating the fulfilment of the requirement is not considering additional value to the customer when an attribute exceeds the requirement.

In the process of evaluating the ESS six different requirements are regarded, the requirements are:

Charge power

The charge power presents the amount of power possible to charge the ESS with.

$$C1. \quad \text{Charge power(ESS)} \geq \text{Charge power(Vehicle)}$$

Discharge power

The discharge power describes the possible power level that the ESS can deliver to the vehicle at any time. If the discharge power is too low the ESS will not be able to support the power consuming equipment in the vehicle in the right way.

$$C2. \quad \text{Discharge power(ESS)} \geq \text{Discharge power(Vehicle)}$$

Energy capacity

The energy capacity describes the amount of energy possible to store in the ESS. The size of the energy capacity will decide the engine of time.

$$C3. \quad \text{Energy capacity(ESS)} \geq \text{Energy capacity(Vehicle)}$$

Mass

The mass requirement sets the limit of the maximum weight of the ESS to load the vehicle with.

$$C4. \quad \text{Weight(ESS)} \leq \text{Max extra weight allowed}$$

Volume

The volume requirement tests if the ESS will fit in the vehicle. This requirement can be complex to evaluate because of the three dimensions in the value. Even if a thorough package analysis has been performed the volume requirement is at the moment disregarding the multiple dimensions and simply compare volume in litres.

$$C5. \quad \text{Litre(ESS)} \leq \text{Litre(Vehicle)}$$

Degradation

The degradation of the ESS is the most complex parameter. The parameter is named Δ State of health (dSoH) and measures the gradual degradation. The requirement refers to dSoH at the end of the predefined vehicle lifetime. The value of dSoH must then be <1 , a higher value will lead to damage of the cells and the ESS will have to be replaced before the machine life length is over.

$$C6. \quad \Delta \text{ State of health(ESS)} \leq 1$$

In the calculations a safety factor was used saying that $dSoH \leq 0,9$.

9.2. Input data

The input data, needed to perform the ESS portfolio composition and evaluation, are of two types. There are the requirements/attributes and the cost related data.

The requirement and attribute data is needed to compose portfolios and evaluate ESS utilization in different machines, as discussed earlier.

The cost related data is needed to evaluate the portfolio proposals, to find the most beneficial portfolio. The cost related data needed is

- Predicted sales volume
- Estimated cost items to calculate the product cost (investment, manufacturing etc)
- Learning ratio (λ)

9.2.1. Estimate the cost items

Here follows the cost items, in the cost model, quantified by values received from Jonas Hellgren and guessed by the author.

Direct cost (material): (DC_{mtrl})

DC_{mtrl} is assumed to be constant per unit through the complete interval of potential production volumes. The material cost was set to 10% (super capacitors) and 25% (batteries) of the complete product cost according to estimations made by Jonas Hellgren.

Direct cost (labor): (DC_{labor})

The labor cost was estimated to 40% of the complete product cost for super capacitors and 35% for batteries. In [13] the labor cost of battery cells is estimated to 12-15%. Another estimation received from Jonas Hellgren, Vtec, is that 50% of the total ESS cost can be represented by assembly cost if the components are purchased from vendors.

Indirect cost (IC)

The complete IC is regarded as constant in the production, because the IC has reduced influence on each unit when the production volume increases. This is a simplification; new investments will eventually be required when the production volume reaches certain limits.

The cost item figures in this report can be compared to a cost analysis of Lithium-Ion cells performed by [13] on the behalf of the United States Department of Energy. The initiative was the promising but expensive usage of Li-Ion batteries in electric- and hybrid electrical vehicles. The paper present different areas where cost reduction can be expected, these are due to: material

substitution, economies of scale in production, design improvements, and development of new materials.

In this project, which observes specific ESSs, the most promising factors to take into consideration will be economies of scale and perhaps also design improvements. Design improvements can be achieved if the number of ESS variants is reduced and the design work focused on few variants.

In [13] the cost items are estimated based on observations in a lithium cell production plant in Georgia, producing 30 million small cells per year. Initial investment cost for the plant was 25 million dollars (1996). The manufacturing cost of each cell, approximately 2 dollars, is based on three main components: material, labor, and overhead. The material cost was estimated to 75-80%, labor to 12-15%, and overhead to 8% of the manufacturing cost.

If these figures are implemented in the model with direct and indirect costs the result will be:

$$\text{Indirect cost} = \text{investment} + \text{overhead} = (25 \text{ million} + 2 \cdot 30 \text{ million} \cdot 8\%) / (25 + 2 \cdot 30 \text{ million}) = 35\%$$

$$\text{Direct cost material} = 2 \cdot 30 \text{ million} \cdot 75\% / (25 + 2 \cdot 30 \text{ million}) = 55\%$$

$$\text{Direct cost labor} = 2 \cdot 30 \text{ million} \cdot 15\% / (25 + 2 \cdot 30 \text{ million}) = 10\%$$

These figures give some ideas about the size of the different cost items, but it should be regarded that the plant observations are about 10 years old.

Cost parameters for all different ESSs can be found in Table 22. The cost values of the combinatorial ESSs, in Table 22, are based on a weighted average of the two combined ESSs. The values are estimated at a production of 1000 units.

In Figure 7 graphs for each ESS type (super capacitor & combinatorial) and cost scenario are presented, showing the unit cost at different production volumes. The graphs show an ESS representative for its particular type.

Table 22. Describes the fraction of the complete product cost that each cost item of all ESS fill. These values are used in Scenario 1,3,5, and 7.

Type of ESS		IC	DCmtrl	DClabor
Supplier A1	1	0,5	0,1	0,4
Supplier A2	2	0,5	0,1	0,4
Supplier B1	3	0,5	0,1	0,4
Supplier B2	4	0,5	0,1	0,4
Supplier C	5	0,5	0,1	0,4
Supplier D	6	0,4	0,25	0,35
Supplier E	7	0,4	0,25	0,35
Supplier A1 + Supplier D	8	0,45	0,175	0,375
Supplier A1 + Supplier E	9	0,3	0,466667	0,233333
Supplier B2 + Supplier D	10	0,45	0,175	0,375
Supplier E		0,2	0,65	0,15

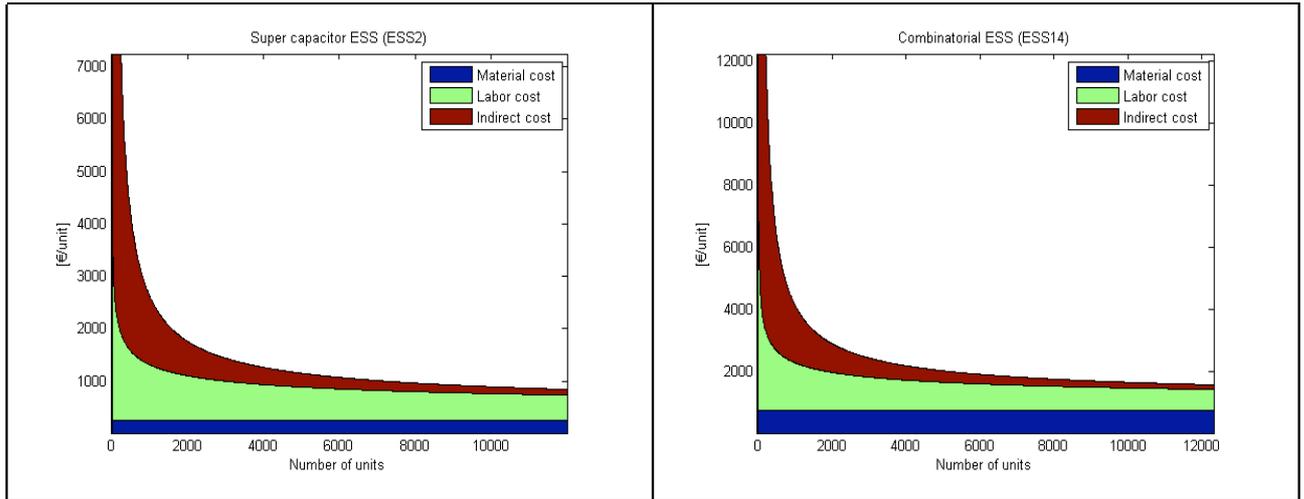


Figure 7. Cost graphs for each ESS type and cost scenario

10. RESULTS

This chapter presents the results from the portfolio derivation process.

10.1. Optimization process

To evaluate all possible portfolios would not be possible because of the large amount of combinations (10^{12} satisfactory portfolios). Instead an optimization process is used to generate and evaluate a limited number of portfolio proposals.

The individuals (portfolio proposals) in the population are evaluated by a goal function (equation (28)) based on the variable $Cost_{portfolio}$ (calculated by equation (37)). The constraints C1. - C6. regarded in (28), binary describes the portfolio fulfillment of the machine requirements. The portfolio is generated from a combination of ESSs (ESSs in Figure 14 ch. A2.1).

$$(28) \quad \text{Best portfolio} = \min (Cost_{portfolio}) \quad \text{with respect to constraints C1. - C6.}$$

To observe how different parameters affect the optimization result, different scenarios with varying values of a few chosen parameters were created. The scenarios in the optimization processes are represented in Table 23.

The optimization process searches for the best portfolio according to equation (28). Figure 8 shows the Fitness of the best (cheapest) portfolio so far in the optimization process with a curve. As can be observed the best solution is gradually, with each iteration, becoming more and more beneficial throughout the process. In this optimization process 60 iterations (generations), each containing 100000 individuals (portfolio proposals), was used.

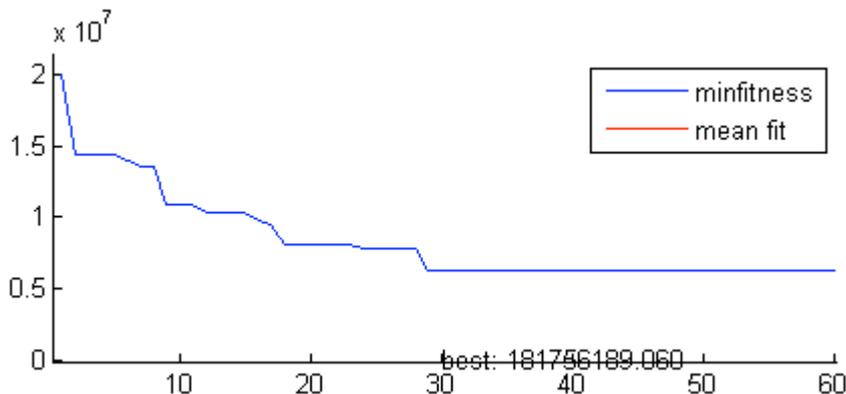


Figure 8. The fitness curve of the best portfolio in each optimization iteration

In Figure 9 the mean fitness of all proposed portfolios in each iteration can be observed in relation to the fitness of the best portfolio (minfitness). The mean fitness curve does not converge to the best fitness curve which means that optimization process repeatedly generate new different portfolios throughout the process. Similar graphs (Figure 8 & Figure 9) were received for all scenarios.

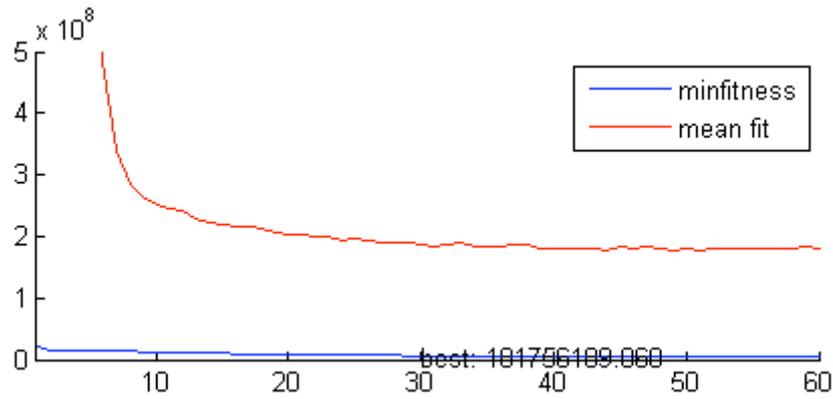


Figure 9. Best fitness (minfitness) and mean-fitness of the populations in the optimizations process

10.1.1. Optimization scenarios

The two parameters to vary are ESS selection and produced volume of each machine type.

The type is expressed in three scenarios:

- All ESS types
- Exclude low farad single string super capacitor ESSs from EC360,460;L150,180,220,350, due to low energy capacity.
- Only ESSs containing battery cells

The three 'ESS type' scenarios regard the energy capacity with different importance. An energy capacity requirement analysis has already been performed for all ESS, but two of the scenarios regard higher, though not specified, energy needs for the machines.

The other parameter, production volume, is based on estimated fractions describing the degree of hybrids of all machines. Sales number from Toyota [14] was used as inspiration with the purpose to reflect the market. It should be regarded that Toyota has long experience of hybrids in comparison to Volvo and the figures might not be as high as for Toyota. On the other hand, increased environmental concern and an increased maturity of hybrid products on the market might raise the interest of all hybrid products. Toyota produced 17% hybrids of all their cars in Feb 2009 according to [14].

The two values here were chosen to be 10% and 50%, above and below Toyota. The values will be affected by e.g. diesel price, financial climate, emission regulation etc.

The complete set-up for each scenario can be observed in Table 23.

Table 23. Optimization scenarios

Scenario	Type	Nof (N)
1	All ESSs (SC, Battery, and PassComb)	10%
2	Exclude low farad single string SC from EC360,460; L150-350	10%
3	Only battery based ESSs (Battery and PassComb)	10%
4	All ESSs (SC, Battery, and PassComb)	50%
5	Exclude low farad single string SC from EC360,460; L150-350	50%
6	Only battery based ESSs (Battery and PassComb)	50%

10.2. Optimization result

The optimization process chooses the best portfolio according to the goal function, (28). The most satisfactory portfolio of each scenario is presented in Table 24, a larger part of the optimization result can be observed in Table 29 ch. A3. From the optimization it can be concluded that a super capacitor based ESS (ESS2) is the most satisfactory choice according to the goal function, independent of production volume (Scenario1-2,4-5).

In Table 29 ch. A3 some additional interesting portfolio proposals are presented. For example Scenario1 number 23, where a SC based ESS (ESS2) is used in the complete portfolio except for the grader where a pure battery based ESS (ESS11) is selected. This is an interesting selection due to the graders low power requirements.

Another interesting portfolio is the one presented in Scenario 2 number 50, where one SC based ESS variant (ESS2) is used in all machines except the largest excavator and largest wheel loader. In these two machines a larger ESS of same kind (ESS1) is used. This portfolio setup could be a candidate for the “best” portfolio if additional customer value would have been evaluated.

For Scenario 3 and 6 where only battery based ESSs are regarded there is a difference between the proposals at different production volumes. It can be seen that for low volume it is more important to reduce the number of variants, using only one type of ESS (ESS14) at 10% fraction of hybrid machines while using two ESS variants (ESS13 and ESS11) at 50% hybrid fraction. For the 10% hybrid fraction even the second most cost effective portfolio is a single variant one. Even here some additional interesting portfolio proposals are presented in Table 29 ch. A3.

Included in Table 29 ch. A3 is also the estimated cost of each portfolio. It can be seen that the cost of a combinatorial ESSs (super capacitor + battery) is twice as expensive as a super capacitor based one. But at the same time the battery based ESS has about 20 times higher energy capacity, while the power performance is reduced about 15-40% for the combinatorial ESS in Scenario 3 and increased by about 20-35% for the combinatorial ESS in Scenario 6.

Table 24. Scenario result, ESS with same color code represents equal ESSs

	1	2	3	4	5	6	Scenario
 EC210 E: 590kJ Pc:440kW Pdc:440kW	⇋	⇋	E: 9,8MJ Pc:268kW Pdc:347kW	⇋	⇋	E: 10,2MJ Pc:519kW Pdc:598kW	
 EC240	⇋	⇋		⇋	⇋		
 EC290	⇋	⇋		⇋	⇋		
 EC360	⇋	⇋		⇋	⇋		
 EC460	⇋	⇋		⇋	⇋		
 L150	⇋	⇋		⇋	⇋		
 L180	⇋	⇋		⇋	⇋		
 L220	⇋	⇋		⇋	⇋		
 L350	⇋	⇋		⇋	⇋		
 G940	⇋	⇋		⇋	⇋	E: 9,05MJ Pc:25kW Pdc:100kW	
 DD112	⇋	⇋		⇋	⇋		
	Supplier A1(supper capacitor), double string, 232 cells/string						
	Passive combination Supplier A1 (super capacitor) + Supplier D (battery), super capacitor: 350F, single string, 258 cells, battery: single string, 275 cells						
	Passive combination Supplier A1 (super capacitor) + Supplier D (battery), super capacitor: 350F, double string, 258 cells/string, battery: single string, 275 cells						
	Supplier (battery), single string, 262 cells						

10.3. ESS portfolio proposal

This section presents the list of ESSs that the portfolios are conducted from and the different portfolio proposals that were conducted from the optimization process.

10.3.1. ESS lists

The spreadsheet in Figure 13 ch. A2.1 presents the first step towards a result. The spreadsheet contains the top 3 ESSs from the top lists of ESSs for each VCE machine given in section A2.1.

The spreadsheet also shows the compatibility between each ESS and all machines. The fulfillment of the machine requirements are presented binary.

In the spreadsheet there is some ESS kinds that are similar but the cost of them differ greatly. The ESSs from the original top lists are tailored for each machine but is most often based on different configurations of similar components. The difference is just the number and/or arrangement of cells. The cost differs because the loss- and wear cost can differ greatly for similar ESSs in different machines, the 'invest cost' is then similar.

As mentioned before, the "cost loss" in Figure 13 has been individualized for each ESS/machine combination by scaling according to the power consumption between different machines, described in section 4.2.2.

The optimization process was performed also without individual loss costs, showing completely different result, yet still single variant solutions. The difference was that a single string SC based ESS was replaced by a dual string SC based ESS when the cost loss was individualized. This was a result of too low loss cost for the single string super capacitor ESS.

10.3.2. Portfolio proposals

The scenarios in the optimization process each generated the best portfolio of the scenarios; these are presented in Table 24. Some additional interesting portfolio proposals are presented in Table 25; some of these portfolios were not considered as the best ones but are still interesting because they contribute to increased portfolio diversity. In the table the average unit cost at different production volumes is also included, with the purpose to show cost differences between different ESS technologies and volumes.

In Table 25 two additional portfolios are added, portfolios that are not conducted from the optimization process but still cost calculated in the same procedure. One is a portfolio of a single Li-Ion battery. This portfolio creates additional technology diversity. The second additional portfolio is created randomly and consists of many different ESS variants. It gives some indication on the cost difference between high and low variety portfolios given by this cost model.

Table 26 presents an evaluation with pros and cons of the proposals given in Table 25.

In Table 29 ch. A3 even more portfolio results from the optimization process are presented.

In chapter A4 diagrams of the cost items for the different ESS presented in the Table 24 and Table 25 can be observed.

Figure 10 shows two diagrams presenting the average life cycle cost of an ESS unit in each portfolio. The life cycle cost of the unit is also put in relation to the component cost (investment cost) of the ESS unit to enable comparison. This analysis has been carried out for both of the production volume scenarios. It is in Figure 10 also possible to easy compare the costs of different

portfolios and thereby ESS types. It can be noticed that since the investment cost decrease with larger production volume, the gap between life cycle cost and component cost increase with increased production volume since the loss cost is independent of production volume. It can also be noticed that the cost difference is large between portfolios of different ESS kind but similar between portfolios of similar kind but with different cell arrangements.

Table 25. Interesting additional ESS portfolios from the optimization result, also containing an extra portfolio of Li-Ion batteries only.

*The benefit of economy of scale might be too large, making the loss cost a larger fraction of the complete unit cost

												avg €/unit 10% hybrid	avg €/unit 50% hybrid	inv. cost 10% hybrid	inv. cost 50% hybrid	
	EC210	EC240	EC290	EC360	EC460	L150	L180	L220	L350	G940	DD112					
1	Supplier A1 s.c. dual string	⚡	⚡	⚡	⚡	⚡	⚡	⚡	⚡	⚡	⚡	1124	846	844*	566*	
2	⚡	⚡	⚡	⚡	⚡	⚡	⚡	⚡	⚡	Supplier D batt.		1282	908	1000*	625*	
3	⚡	⚡	⚡	⚡	Supplier A1 s.c. dual string	⚡	⚡	⚡	⚡	⚡	⚡	1305	905	1030*	630*	
4	Supp. D+ Supp. A1 sing. string											2209	1810	1561*	1262*	
5	Supp. D+ Supp. A1 dual string											2328	1850	1857*	1380*	
6	Supp. D+ Supp. A1 dual string											2430	1827	2110*	1507*	
7												2501	1846	2184*	1529*	
8	Supplier F batt. sing. string											5503	4587	4481*	3565*	
X	Random ESS	Random ESS	Random ESS	Random ESS	Random ESS	Random ESS	Random ESS	Random ESS	Random ESS	Random ESS	Random ESS	6271	3484			
	⚡	Supplier A1, dual string 232 cells/string						Supplier A1, dual sting 223 cells/sting + Supplier D, single string 275 cells/sting								
	⚡	Supplier A1, dual string 264 cells/string						Supplier A1, dual sting 258 cells/sting + Supplier D, single string 275 cells/sting								
		Supplier D, sting 262 cells/string						Supplier F, single string 170 cells								
		Supplier A1, single sting 258 cells/sting + Supplier D, single string 275 cells/sting														

Table 26. Pros and cons of the portfolios in Table 25

	Pros	Cons
1	(+) Cheapest of all ESSs (+) High power capacity (+) Long life (wear resistant) (+) Low mass and volume	(-) Low energy storage capability (-) Short engine shut off
2	(+) High energy capability for grader and compactor with low power reqs, batt already used in other Volvo hybrid solutions (+) Longer engine off time (+) Low power ESS for low power machines	(-) Different variants (-) Add. logistics (-) Add. knowledge (-) Add. dev work
3	(+) Interesting if other parameters than cost would influence customer value (+) Same type of ESS with different cell configuration	(-) Different variants (-) Add. logistics (-) Add. knowledge (-) Add. dev work
4	(+) High energy capability (+) One ESS variant	(-) Double cost compared to SC (-) Large volume, double volume compared to SC (-) Low power capability, short engine off time
5	(+) High energy capability (+) High power capability because of combination (+) One ESS variant	(-) Double cost (-) Large volume, double volume compared to SC
6	(+) High energy (+) Low power ESS for low power machines	(-) High cost (-) Different variants (-) More knowledge needed (-) Add. dev. work (-) Large volume for [13], double volume compared to SC
7	(+) High energy (+) high power for machines that require high power (+) Low power for machines that does not require high power	(-) Large volume, double volume compared to SC (-) Different variants (-) Expensive (-) Add. dev. work
8	(+) Very low weight (+) Relatively high energy capacity (+) Low volume	(-) Very expensive (5 times s.c. cost, 2 times combinatorial ESS) (-) Relatively low energy capacity (-) High loss cost

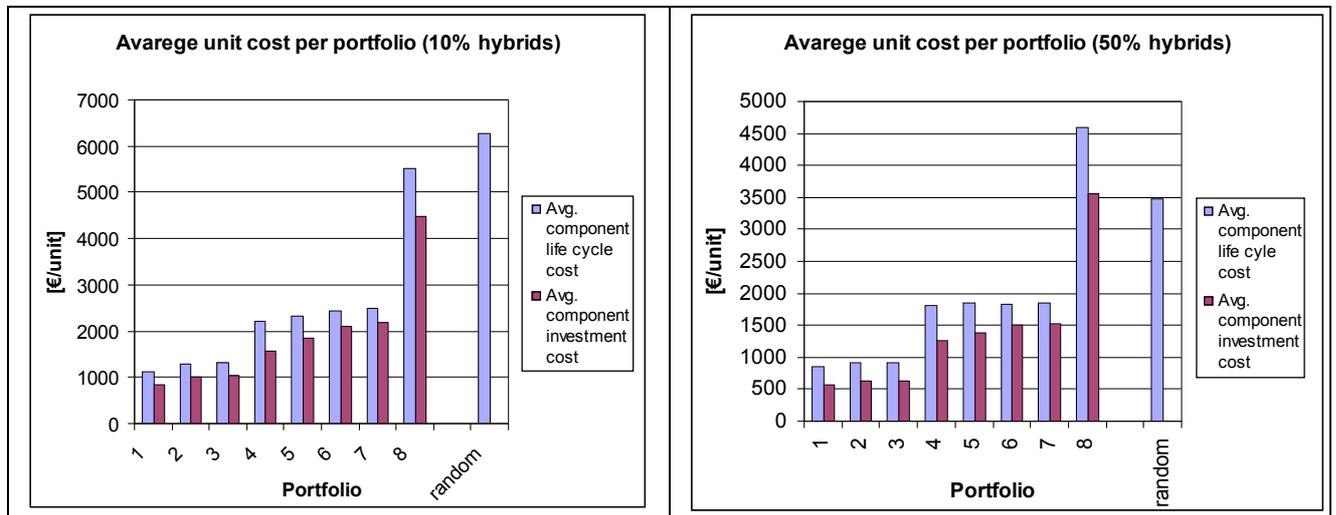


Figure 10. The average complete life cycle cost of an ESS unit in relation to the investment cost of the same unit for each portfolio

11. DISCUSSION

The goal of the optimization process is to find the most cost efficient portfolio, the function expressing this goal regards low cost as the highest value to the customer. After observing and evaluating the result it was realized that it would have been very interesting to also measure the performance as a more graded value and included such a parameter in the goal function. Especially since the problem ended up at not being as complex as first imagined (most ESSs were possible to implement in almost all machines). Though it might be difficult to state how such additional performance should be valued correctly. This will require good knowledge about the customers.

In the cost model, the costs calculated can be a bit unrealistic at high production volumes (see Figure 7 ch. 9.2.1). In the cost model the 'Indirect cost' is limited by a maximum value per unit. A limit could be good even at high production volume, at the moment no such minimum indirect cost exists. This makes the indirect cost per unit converge to zero at very large production volumes.

12. CONCLUSION

The background to the problem, as explained in section 1.3 “Problem description”, is that a selection of Volvo Construction Equipment hybrid machines are going to be equipped with ESSs. The ESSs are independently developed for each machine, creating a large ESS component portfolio. This goal is to find possible options to share the ESS between the different VCE machines, with the prioritization to save cost while maintaining the usability of the system.

One of the most interesting results from the work is received from the optimization result. The different scenarios all shows that the benefit of reducing the number of different product variants is inversely proportional to the number of units (production volume). When the expected production volume increases the importance of variant reduction has lower significance for a low cost. It also shows that a portfolio consisting of one expensive single variant ESS is of lesser interest compared to a mixed variant portfolio when the production volume increase, according to the optimization result (Table 24 ch. 10.2).

Positive effects of a variant reduced ESS portfolio:

The most obvious positive effect and one of the major driving forces behind finding a product portfolio is the possible cost savings of producing large quantities of few variants rather than producing a variety of products at relatively low quantities.

Another positive effect is that the detailed design and development work would benefit from an ESS portfolio with few variants. The detail design work can be focused on one or a few ESS variants and that would shorten the complete development process, especially the detailed design phase, possibly enabling an earlier product launch or a more mature product at market entry.

Negative effects of a variant reduced ESS portfolio:

Even if the result pointed at reducing the number of different ESS variants in the portfolio. The downside of using few ESS variants is the compromise with performance. The ESS will, in that case, not be developed to optimally fulfill the machine requirements. The result will therefore be suboptimal from a performance point of view.

Another aspect is that smaller machines will be added additional investment cost when seeking cost savings by variant reduction, and thereby choosing more powerful ESSs in the portfolio to satisfy larger machines. Another negative effect of exceeding the requirements is that the ESS also might be bulkier and heavier than needed for some machines. At the same time a larger ESS will decrease the power loss and related costs for small machines.

Using one ESS variant for all machines can for some ESS variants limit the ESS performance upwards. This limit can result in unnecessary high cost losses for more powerful machines e.g. EC460, L350. This is why some of the additional results are added in Table 29, results that could have been very interesting if the performance exceeding machine requirements would have been regarded in the evaluation and would have affected customer value.

Critical assumptions:

The result of this report is based on a lot of different parameters, a lot of them are estimated and the uncertainty of them is not specified. Because of the many uncertain values, the result should be used as guidelines rather than true values.

The parameters that contain large uncertainties are the decomposition of the unit costs into different cost items (Table 22 ch. 9.2.1), the future production volume is off course another uncertain parameter (Table 4 ch. 4.3).

It can also be discussed if the cost model expresses the change of the different cost items in the right way when the production volumes change.

Portfolio proposals:

Table 25 ch. 10.3.2 contains a portfolio of randomly selected portfolios; this is supposed to show the cost of a portfolio of individually selected ESSs for each machine variant. The cost of this individualized portfolio is substantially higher than most of the portfolios presented in the same table and is a motivator for selecting few ESS variants in the portfolio.

As it looks for now a portfolio of Supplier A1 super capacitors with two cell strings and about 232-264 cells per string is the most cost effective choice. The benefit of the Supplier A1 super capacitors is high power capacity, low weight, and long life length to a low cost. A neglected attribute in this ESS is low energy capacity that will limit the engine off time for the machine.

If more energy is needed a combinatorial system of Supplier A1 super capacitors with one or two strings of 223-258 cells per string in combination with a Supplier D battery of 275 cells in one string is a good option. The combined ESS of Supplier A1 and Supplier D cells provides high power and high energy capacity. The power capacity of the combined ESS can be adjusted by using one or two super capacitor strings.

Using a combinatorial ESS will provide about 20 times higher energy capacity compared with a pure super capacitor ESS, to a cost that is about twice as high (Table 25 ch. 10.3.2). Doubled cost is the price to pay for longer engine off time.

The result presented in Figure 10 ch. 10.3.2 indicates that the big question concerning cost lies in choosing the ESS type rather than selecting the number of cells and cell arrangement.

13. RECOMMENDATION

Preferably further work on the subject would be to reduce uncertainty in cost related data and also to improve on the precision of the cost model used to estimate future product cost. A recommendation is also to look at the possibility of including customer satisfaction received by additional product performance and the benefit it could possibly bring to the analysis result.

An improved cost estimating method could also serve as a product portfolio analyzing tool in other products areas where the product fulfillment is mainly based on technical requirements.

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A1. ESS TECHNOLOGY

The material presented in this chapter is originally from the document “Tool for Energy Storage System Synthesis” by Haimin Zhang 2008, a previous master thesis report at Volvo Technology. The purpose of this chapter is to give a deeper understanding the characteristics of the different types of ESS presented in this thesis and also support the understanding of pros and cons of different portfolio proposals in the result.

A1.1. Electric energy storage systems

When dealing with an ESS, it is vital to understand that the system is constituted of cells. This is schematically described in Figure 11. For super capacitors and batteries, the voltage off one cell is typically 1-3 Volt. The voltage of the ESS must be adapted to a suitable operating voltage range of the load. Therefore an appropriate number of cells must be connected in series. Several cells are connected in parallel if the current loads are high. Power electronics, excluded in the figure, might be necessary to balance voltage of individual cells. Power electronics can also be used to step up (or down) the voltage between the load and the ESS.

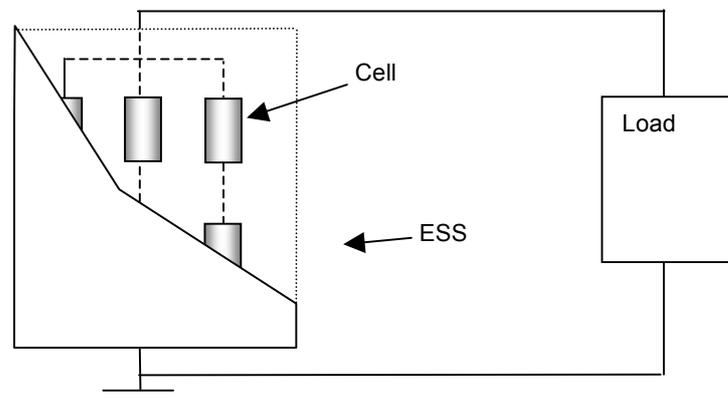


Figure 11. Overview of ESS. This ESS system has two cells in series (strings) and three in parallel.

Batteries started to be a source of electricity in the 19th century. The oldest form of rechargeable battery, still in modern usage, is the "wet cell" lead-acid battery. Its low cost makes its use very common. However, alternative technologies are becoming stronger and stronger candidates. Today (2008), NiMH batteries is the dominating ESS technology in HEVs. However, Li-Ion batteries and super capacitors are potential candidates. Figure 12 shows how specific power and energy varies between some ESS technologies. Another important aspect is lifetime. Super capacitors, for example, have an almost infinite lifetime. Table 27 presents advantages and disadvantages for different ESS technologies.

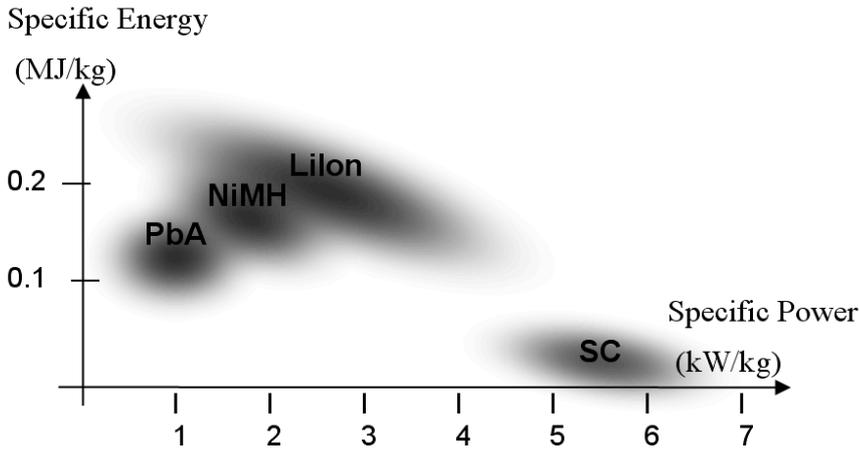


Figure 12. Specific power and energy for different ESS technologies.

Table 27. Advantages and disadvantages with different ESS technologies.

ESS technology	Advantages	Disadvantages
Lead acid batteries	+ Low investment cost + Proven technology	- Low specific power, especially at charging - Short lifetime
NiMH batteries	+ Proven for HEV	- Low specific energy compared to Li-ion batteries
Li-ion batteries	+ High specific energy	- Safety problems, especially related to overheating
Super capacitors	+ Very high specific power and long lifetime + Performance is not degraded at low/high temperature	- Wide voltage range and low energy density - High investment cost
Combined ESS	+ Extended lifetime and improved specific power compared to a traditional battery	- Added complexity

A2. ESS SELECTION

Figure 13 presents the ESSs to evaluate for different ESS portfolio proposals. The ESSs are taken from the top lists from each machine; see Table 28 for an example of the top list from EC210. A lot of the ESSs in this summarized top list are similar. To make the optimization process shorter, similar ESSs were combined and a lower number of ESSs were possible to present in Figure 14. This procedure reduced the number of unique ESSs from 33 to 18 ones.

A2.1. Top candidates for each machine – from TESSS

ESS top list results from simulations in TESSS performed by Fredrik Larsson, VTEC,

Table 28. Top3 ESSs for EC210

Id	Cost	Architecture	Battery Type Name	SC Type Name	Energy Capacity	Mass - ESS	Nof batt cells par	Nof batt cells ser	Nof SC cells par	Nof SC cells ser	UESS - Avg	dSoHSim - Battery	dSoHVehLifeTime - Battery	Power Capacity Charge	Power Capacity Discharge	Volun - ESS
1	3 056	SingleSC			671 045	125	0	0	2	263	617	5,49E-008	2,97E-003	502 117	502 117	0,1
2	4 842	SingleSC			638 779	125	0	0	2	292	583	5,49E-008	2,97E-003	103 238	103 238	0,1
3	6 886	PassComb			9 792 205	258	1	274	1	253	603	7,31E-006	3,95E-001	267 775	346 564	0,2

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	
	Type of ESS	Type	No batt cell s	No batt cell s	No SC cell s	No SC cell s	Cost	Invest cost	IC (factor)	DCmtrl (factor)	Delabor (factor)	Cost loss	Year cost	EC210	EC240	EC290	EC360	EC460	L150	L180	L220	L350	G940	DD112	
1																									
2	1 SingleSC, Supplier A1	1	0	0	2	264	3391,26	2910,46	0,5	0,1	0,4	480,8	0	1	1	1	1	1	1	1	1	1	1	1	
3	2 SingleSC, Supplier A1	1	0	0	2	232	3213,83	2631,68	0,5	0,1	0,4	582,16	0	1	1	1	1	1	1	1	1	1	1	1	
4	3 SingleSC, Supplier A1	1	0	0	1	285	1859,99	1851,95	0,5	0,1	0,4	8,04	0	1	1	1	1	1	1	1	1	1	1	1	
5	4 SingleSC, Supplier A1	1	0	0	1	258	1754,37	1734,34	0,5	0,1	0,4	20,03	0	1	1	1	1	1	1	1	1	1	1	1	
6	5 SingleSC, Supplier A2	2	0	0	1	232	6493,97	5319,71	0,5	0,1	0,4	1174,26	0	1	1	1	1	1	1	1	1	1	1	1	
7	6 SingleSC, Supplier B1	3	0	0	2	295	5512,82	3180,53	0,5	0,1	0,4	2332,29	0	1	1	1	1	1	1	1	1	1	1	1	
8	7 SingleSC, Supplier B1	3	0	0	2	258	5191,58	2858,19	0,5	0,1	0,4	2333,39	0	1	1	1	1	1	1	1	1	1	1	1	
9	8 SingleSC, Supplier B1	3	0	0	1	283	2066,16	1843,24	0,5	0,1	0,4	222,92	0	0	0	0	0	0	0	0	0	0	0	0	
10	9 SingleSC, Supplier B2	4	0	0	1	310	8509,24	6588,6	0,5	0,1	0,4	1920,64	0	1	1	1	1	1	1	1	1	1	1	1	
11	10 SingleSC, Supplier C	5	0	0	2	269	1834,32	1708,25	0,5	0,1	0,4	126,07	0	0	0	0	0	0	0	0	0	0	0	0	
12	11 SingleBatt, Supplier D	6	1	262	0	0	5092,59	3074,97	0,4	0,25	0,35	28,34	1989	0	0	0	0	0	0	0	0	0	0	0	
13	12 SingleBatt, Supplier E	7	1	420	0	0	10659,53	9697,8	0,4	0,25	0,35	961,73	0	1	1	1	1	1	1	1	1	1	1	1	
14	13 PassComb, Supplier D, Supplier A1	8	1	275	2	258	5637,72	5219,01	0,45	0,175	0,375	418,7	0	1	1	1	1	1	1	1	1	1	1	1	
15	14 PassComb, Supplier D, Supplier A1	8	1	275	1	258	6885,95	4162,41	0,45	0,175	0,375	555,84	2168	1	1	1	1	1	1	1	1	1	1	1	
16	15 PassComb, Supplier D, Supplier A1	8	1	275	2	223	7868,6	4881,58	0,45	0,175	0,375	979,35	2008	1	1	1	1	1	1	1	1	1	1	1	
17	16 PassComb, Supplier F, Supplier A1	9	1	178	1	252	9680,27	8442,46	0,3	0,466667	0,233333	1237,81	0	1	1	1	1	1	1	1	1	1	1	1	
18	17 PassComb, Supplier F, Supplier A1	9	1	178	2	252	10654,04	9381,51	0,3	0,466667	0,233333	1272,53	0	1	1	1	1	1	1	1	1	1	1	1	
19	18 PassComb, Supplier D, Supplier B2	10	1	257	1	244	7947,67	6948,01	0,45	0,175	0,375	999,65	0	1	1	1	1	1	1	1	1	1	1	0	
20																									
21	19 SingleBatt, Supplier F	11	1	170	0	0	12191,82	10183,2	0,4	0,25	0,35	2008,62	0	1	1	1	1	1	1	1	1	1	1	1	

Figure 14. Short list of ESSs (reduced number of ESS variants)

A3. OPTIMIZATION RESULT

The numbers representing ESSs in Table 29 and Table 30 refers to the ESS numbers in Figure 14.

Table 29. Optimization result, scenario1 to 6
populations=100000, generations=60, time=ca20min

Rank	Fitness	Cost	EC210	EC240	EC290	EC360	EC460	L150	L180	L220	L350	Micro Grad 600V G940	Micro Comp 600V DD112	HEV fraction
Scenario1														
														10%
1	13577269	13577269	2	2	2	2	2	2	2	2	2	2	2	
2	14566856	14566856	2	2	2	2	2	2	2	2	2	10	2	
3	14579513	14579513	2	2	2	2	2	2	2	2	2	4	2	
9	14666087	14666087	2	2	2	2	2	2	2	2	2	10	10	
13	14794721	14794721	2	2	2	2	2	2	2	2	2	8	8	
23	15151794	15151794	2	2	2	2	2	2	2	2	2	11	2	
Scenario2														
														10%
1	13577269	13577269	2	2	2	2	2	2	2	2	2	2	2	
2	14566856	14566856	2	2	2	2	2	2	2	2	2	10	2	
3	14579513	14579513	2	2	2	2	2	2	2	2	2	4	2	
9	14666087	14666087	2	2	2	2	2	2	2	2	2	10	10	
14	15151794	15151794	2	2	2	2	2	2	2	2	2	11	2	
48	15752462	15752462	2	2	2	2	2	2	2	2	2	6	6	
50	15759003	15759003	2	2	2	2	1	2	2	2	1	2	2	
Scenario3														
														10%
1	27214539	27214539	14	14	14	14	14	14	14	14	14	14	14	
2	28118791	28118791	15	15	15	15	15	15	15	15	15	15	15	
3	28689489	28689489	14	14	14	14	14	14	14	14	14	11	14	
5	28878893	28878893	14	14	14	14	14	14	14	14	14	11	11	
6	29352119	29352119	13	13	13	13	13	13	13	13	13	11	11	
Scenario4														
														50%
1	51095002	51095002	2	2	2	2	2	2	2	2	2	2	2	
2	52331455	52331455	2	2	2	2	2	2	2	2	2	10	2	
3	52336470	52336470	2	2	2	2	2	2	2	2	2	4	2	
10	52640630	52640630	2	2	2	2	2	2	2	2	2	10	10	
16	53523395	53523395	2	2	2	2	2	2	2	2	2	11	2	
67	54840873	54840873	2	2	2	2	2	2	2	2	2	11	11	
Scenario5														
														50%
1	51095002	51095002	2	2	2	2	2	2	2	2	2	2	2	
2	52331455	52331455	2	2	2	2	2	2	2	2	2	10	2	
3	52336470	52336470	2	2	2	2	2	2	2	2	2	4	2	
16	53523395	53523395	2	2	2	2	2	2	2	2	2	11	2	

46	54641270	54641270	2	2	2	2	1	2	2	2	1	2	2
59	54840873	54840873	2	2	2	2	2	2	2	2	2	11	11

Scenario6

50%

1	110328411	1,1E+08	13	13	13	13	13	13	13	13	13	11	11
2	111488760	1,11E+08	14	14	14	14	14	14	14	14	14	14	14
3	111510769	1,12E+08	13	13	13	13	13	13	13	13	13	14	14
4	111759996	1,12E+08	15	15	15	15	15	15	15	15	15	15	15
12	113469994	1,13E+08	14	14	14	14	14	14	14	14	14	11	14
21	114109043	1,14E+08	14	14	14	14	14	14	14	14	14	11	11

Table 30. Ranking (by cost) of interesting ESS portfolios

Rank	EC210	EC240	EC290	EC360	EC460	L150	L180	L220	L350	Micro Grad 600V G940	Micro Comp 600V DD112	Average cost per unit [€/unit]	
												10% hybrid fraction	50% hybrid fraction
1	2	2	2	2	2	2	2	2	2	2	2	1124	846
2	2	2	2	2	2	2	2	2	2	11	11	1282	908
3	2	2	2	2	1	2	2	2	1	2	2	1305	905
4	14	14	14	14	14	14	14	14	14	14	14	2209	1810
5	15	15	15	15	15	15	15	15	15	15	15	2328	1850
6	13	13	13	13	13	13	13	13	13	11	11	2430	1827
7	13	13	13	13	13	13	13	13	13	14	14	2501	1846
8	19	19	19	19	19	19	19	19	19	19	19	5503	4587
random	-	-	-	-	-	-	-	-	-	-	-	6271	3484

[1] Supplier A1 s.c. double string 264 cells/string, Energy= 674kJ, Powercharge= 504 kW, Powerdischarge=504kW, invcost=2910€, costloss=289€, volume=105L, mass= 126kg

[2] Supplier A1 s.c. double string 232 cells/string, Energy=592kJ, Powercharge= 443kW, Powerdischarge= 443kW, invcost=2637€, costloss=331€, volume=94L, mass=113kg

[11] Supplier D batt. single string 262 cells/string, Energy=9055kJ, Powercharge= 25kW, Powerdischarge= 100kW, invcost=3075€, costloss=77€, volume=165L, mass=181kg

[13] Supplier D batt. single string 275 cells/string + Supplier A1 s.c. double string 258 cells/string, Energy=10162kJ, Powercharge=519 kW, Powerdischarge= 598kW, invcost=5219€, costloss=374€, volume=275L, mass=311kg

[14] Supplier D batt. single string 275 cells/string + Supplier A1 s.c. single string 258 cells/string, Energy=9792kJ, Powercharge=268 kW, Powerdischarge=347 kW, invcost=4162€, costloss=781€, volume=232L, mass=258kg

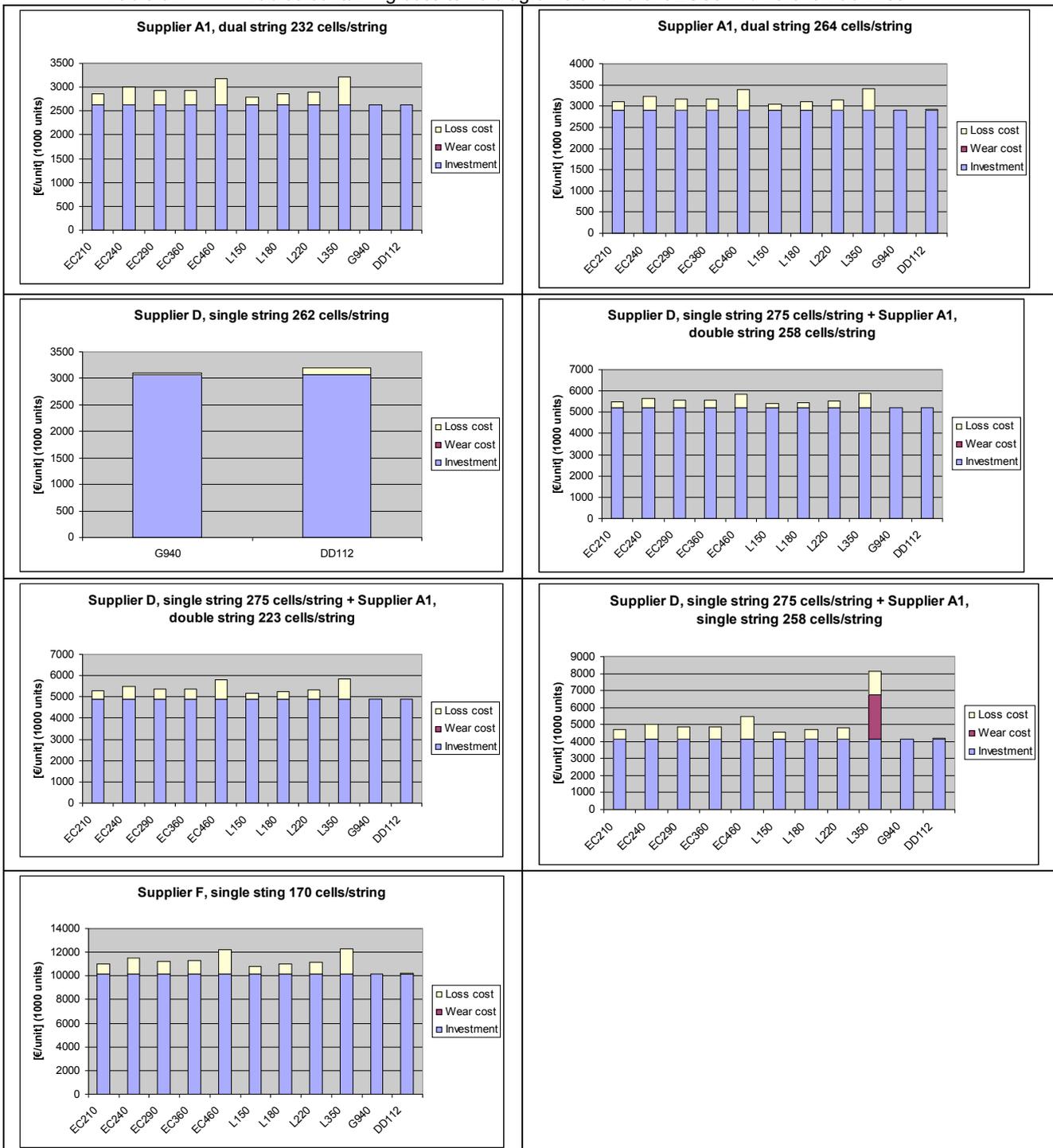
[15] Supplier D batt. single string 275 cells/string + Supplier A1 s.c. double string 223 cells/string, Energy=9762kJ, Powercharge= 451kW, Powerdischarge= 528kW, invcost=4882€, costloss=556€, volume=259L, mass=292kg

[19] Supplier F batt. single string 170 cells/string, Energy=3719kJ, Powercharge= 84kW, Powerdischarge= 141kW, invcost=10183€, costloss=2009€, volume=110L, mass=97kg

A4. COST ITEM DIAGRAMS

This chapter presents diagrams of cost items of different ESSs in different machines. The diagrams show 'investment-', 'loss-' and 'wear cost'. The costs are calculated at a production volume of 1000 units. When increasing the number of units the loss- and wear cost will be a larger fraction of the complete unit cost.

Table 31. Tables containing cost items diagrams of different ESSs in different machines



A5. PACKAGE ANALYSIS (SPACE OPTIMISATION)

This part presents the result of the common space research for ESSs in the VCE vehicles.

In the search for a hybrid component portfolio with commonality between the hybridized VCE products an available equal sized geometry in the vehicles is necessary. An exploration on the available space in each hybrid VCE vehicle performed by Magnus Larsson, VTEC, [12] served as an input in the search for a common geometry.

A5.1. Possible Placements on the vehicles

There are different spaces available on each vehicle for placing the ESS. On most vehicles there are even a few options on where to place the ESS.

A5.1.1. Excavator

For the Excavator the possible places are; inside the tool box, behind the cabin and in the counterweight body (See Figure 17 in chapter A6 for detailed pictures).

There are two possible alternatives for putting it behind the cabin. Both alternatives interfere with the current design of the excavator and design changes will be required (see Figure 17 in chapter A6). Placing the ESS in the toolbox also require some redesign according to ESS Sizing for Hybrid VCE Vehicles [12]. The counterweight body is probably the future placement but there is a patent present concerning that placement according to [12]. (See Figure 17 in chapter A6 for detail picture)

A5.1.2. Wheel loader

According to [12] the placement of the ESS for a prototype is on one of the rear wheel fenders (See Figure 18 in chapter A6 for detail picture). For a long-term solution the ESS should be placed inside the vehicle, which requires re-organization of several components. The placement on the fender does not heavily interfere with the current design.

A5.1.3. Grader

For the grader there are two possible locations. One is in between the engine and the wheels on the outside of the vehicle. This location gives two spaces one on each side of the machine. In one of these two spaces are today low voltage batteries situated. It is not known if the batteries would be unnecessary if a battery based ESS solution is selected.

The second placement is on the roof of the cab. The roof placement does not heavily interfere with the complete design for what is known. The roof might have to be strengthened dependent of the weight of the ESS but it has to be further investigated if this placement is selected. The cost of the re-design should be considered in the total cost of the ESS. (See Figure 19 in chapter A6 for detail pictures)

A5.1.4. Compactor

On the Compactor there are three different options to put the ESS: under the cabin floor, on the roof and under the seat. Under the cabin floor there are spaces, for the operator to store things,

which could be used. To place the ESS under the seat would need a redesign of that space according to the [12].

The roof placement of the ESS should not heavily interfere with current design but should be examined thoroughly. Strengthening redesign of the roof might be needed and the cost of that could affect the placement decision.

(See Figure 20 in chapter A6 for detail pictures)

A summary of the possible places to put the ESS and the pros and cons for each placement can be found in Table 32.

Table 32. Pros and cons for ESS placement options in each machine

Machine	Placement	Advantage	Disadvantage
Excavator EC210-460	Tool box	Large volume Little re-design work	Deletes toolbox use
	Behind cabin 1	Integrated	Re-design work Small volume
	Behind cabin 2	Integrated	Re-design work Affect operator sight
	Counterweight	Integrated	Patent exist Re-design
Wheel loader L150-L350	On rear wheel fender	Large volume No re-design	
Grader G940	Beside engine	Little re-design	Long volume
	On the roof	Large volume	Flat Strengthening roof
Compactor DD112	Under cabin platform		Small volume
	On the roof	Large volume	Flat Strengthening roof
	Under the seat		Re-design work Small volume

The additional cost of a possible re-design for placing the ESS is recommended to explore. This cost could affect the selection of placement.

A5.2. Variant reduction in Matlab

The input data are measurements from the available space in each VCE model received from [12]. The data was presented in a vector describing length, width and height.

The idea is to arrange the elements in the data vector based on the size of the measured geometries.

Only width and length elements were arranged by size, because there is a possibility of rotating the ESS (battery) but not to flip it see Figure 15. When the elements in each vector are arranged by size a common geometry can be found by choosing the smallest value in each dimension from a group of product geometries, see example in Table 33.

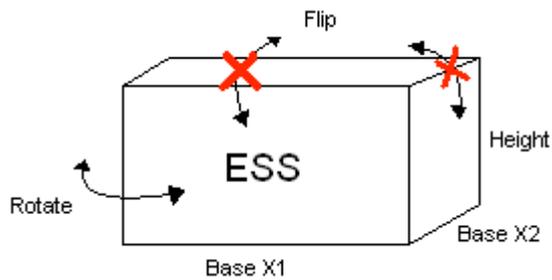


Figure 15. Options to transform the ESS in the vehicle

Table 33. Example of the difference in result between base dimensions arranged by size and not

	Width	Length	Height		Base1	Base2	Height	
Machine 1	10	20	30	→	Machine 1	10	20	30
Machine 2	15	10	40		Machine 2	10	15	40
Common	10	10	30		Common	10	15	30

Table 33 presents the common geometry between two vehicles for two cases, one where the base dimensions are not arranged by size and one where they are. For the one where the dimensions are arranged the common geometry is larger.

The same action was performed on the all possible placements in all hybrid VCE vehicles. This was done in Matlab. A flow chart to describe the program is presented in Figure 16.

The results of the arrangement and combined machines can be seen in Table 34. For the excavators different geometries for all engine sizes (EC210, EC240, etc) were reduced to a single geometry. We think this is appropriate according to modular thinking because the complexity in the design will also be reduced. The same procedure was used on the wheel loaders.

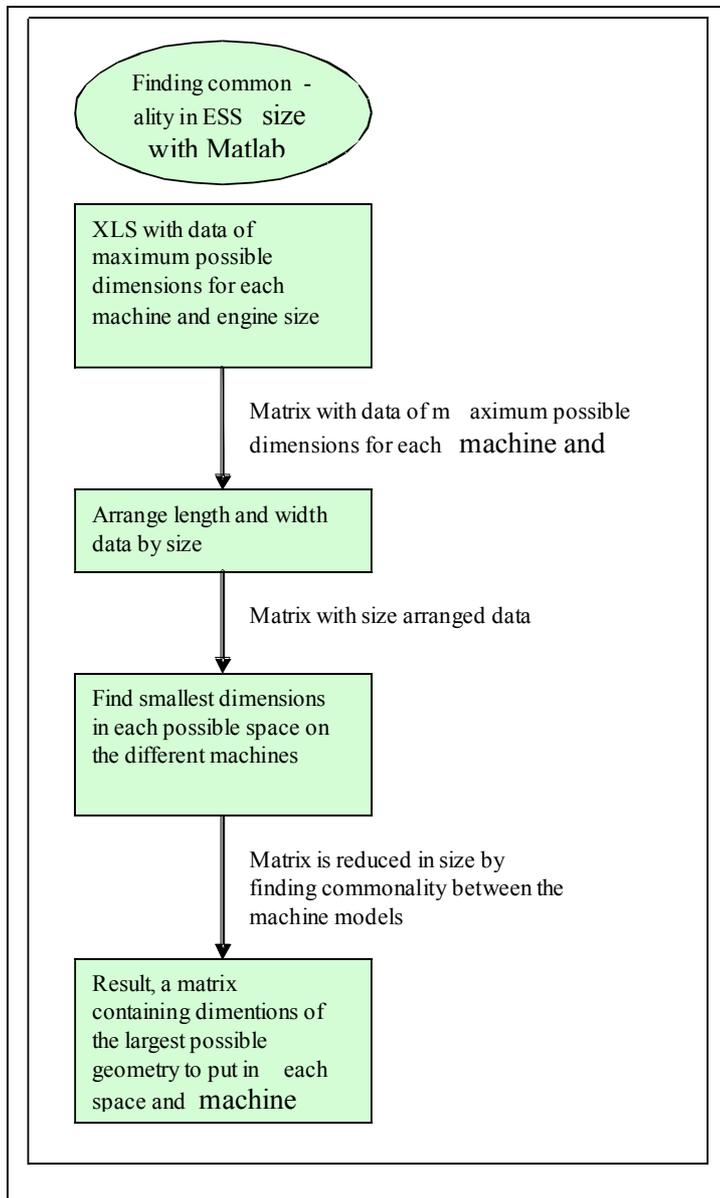


Figure 16. Matlab program for finding commonality in ESS size among the VCE vehicles

For the excavator and the wheel loader the smallest vehicle happened to set the limiting dimensions in this case. The excavator vehicle size is different for different engines (at least for EW180 and EW210).

It can be observed in the common geometry results in Table 34 that the toolbox in the excavator, by far, delivers the largest geometry on the excavators with more than twice as big volume as the second largest placement option.

From these Matlab results it was possible to combine the different geometries into 2 geometries that cover all geometry requirements of hybrid VCE machines. One geometry for all products is probably not fruitful with the geometries available at the moment because it would be too small (25x60x35). Instead 7 concepts (see Table 36 in chapter A7 for more info) based on, in each case, two shared geometries were established. The concept generation was performed by hand after the number of variants was reduced in the Matlab simulation. More information about the concepts can be found in chapter A7.

Table 34. Common geometries within each product and placement on/in that product

Machine	Placement	Base1 (cm)	Base2 (cm)	Height (cm)	Volume (L)
Excavator EC210-460	Tool box	64	80	56	287
	Behind cabin 1	45	82	20	74
	Behind cabin 2	45	82	35	129
	Counterweight body	30	70	60	126
Wheel loader L150-L350	On rear wheel fender	60	75	40	180
Grader G940	Beside engine	25	140	38	133
	On the roof	150	240	15	540
Compactor DD112	Under cabin platform	40	45	28	50
	On the roof	150	150	15	338
	Under the seat	50	60	35	105

A5.3. Size commonality result

The concept that was finally chosen during the meeting 30/9 was concept 6. The shared geometries within this concept consist of the two geometries 64x80x56 (Geometry 3) and 25x60x35 (Geometry 5) see Table 35 or Table 36 in chapter A7.

The geometries Geometry 1 and Geometry 3 are similar (Table 36 in chapter A7). Both Geometry 1 and Geometry 3 are supposed to be used on the excavators and the wheel loaders. The difference between them is that only the dimensions on the wheel loader limit Geometry 1, but the dimensions on the wheel loader are possible to increase. For Geometry 3 the wheel loader dimensions are increased, making the excavator dimensions limiting instead.

For the Grader and the Compactor the place to put the ESS is beside the engine and under the seat these two places gave the most practical (cubic) geometry to work with. For both machines a placing on the roof is possible. A placement on the roof without increasing the height would give a very flat geometry. This roof placement could still be an option though because the now offered 53 liter is probably too small for containing an ESS.

Table 35. Chosen geometries and placements for the ESS on the hybrid VCE machines

Machine	Placement	Base1 (cm)	Base2 (cm)	Height (cm)	Volume (L)
Excavator EC210-460	Tool box	64	80	56	287
Wheel loader L150-350	On rear wheel fender	64	80	56	287
Grader G940	Beside engine	25	60	35	53
Compactor DD112	Under the seat	25	60	35	53

A6. OPTIONS OF PLACING THE ESS ON THE MACHINES

The pictures are taken from the report ESS Sizing for Hybrid VCE Vehicles [12].

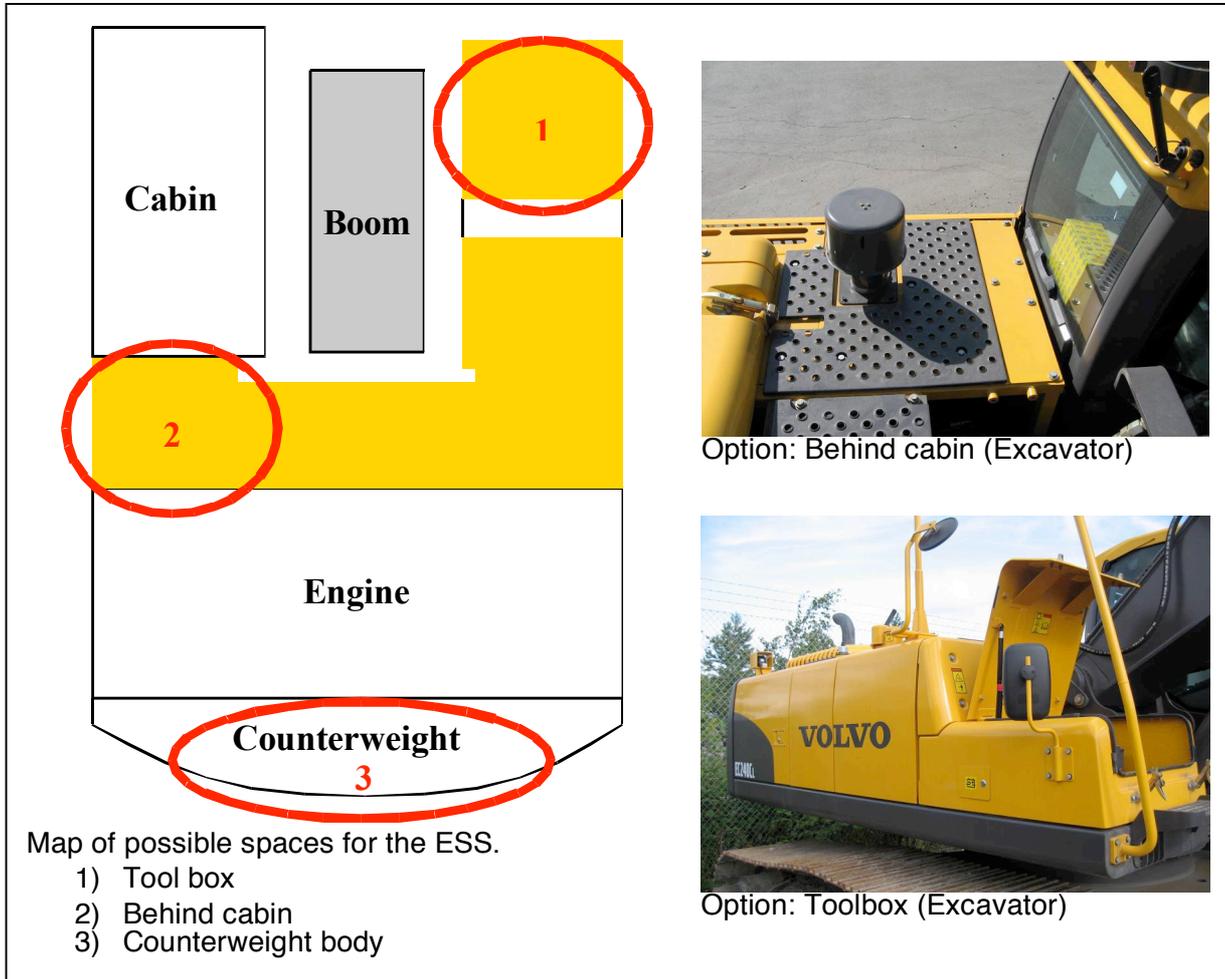


Figure 17. Detailed pictures of the possible locations of ESS in the excavators.



Figure 18. Detailed picture of the possible location of ESS on the wheel loader.



Figure 19. Detailed pictures of the possible locations of the ESS on the grader.

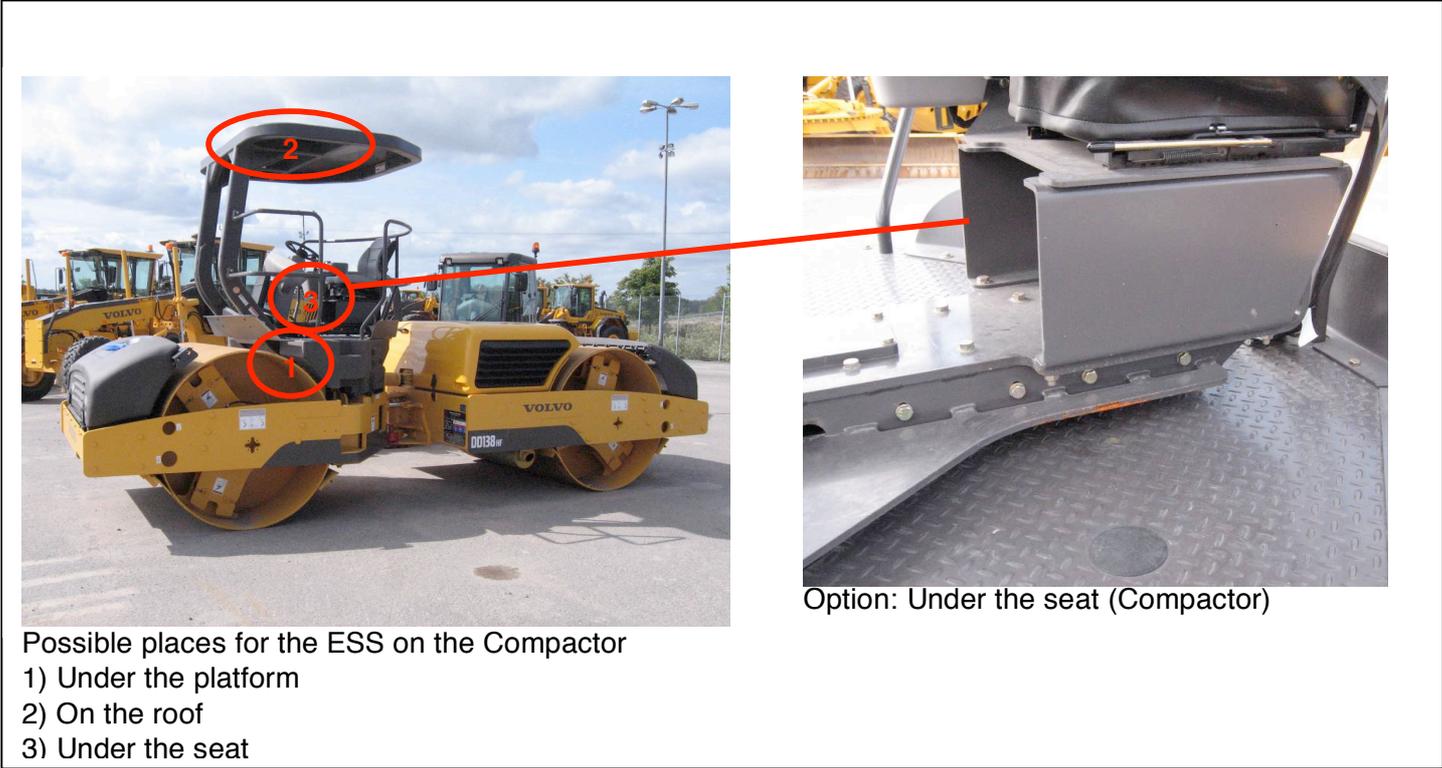


Figure 20. Detailed pictures of the possible locations of the ESS on the compactor.

A7. RESULT FROM PACKAGE ANALYSIS

Table 36. The result from the packaging analysis presented in an excel sheet. Concepts 1-7 are possible solutions to the problem of finding a shared geometry among the vehicles.

	Model	L (cm)	W (cm)	H (cm)	Volume (L)	Concept 1	Volume (L)	Volume efficiency
Excavator 1 tool box	EC210	80	64	56	287	Geometry 1	180	63%
These are maximum values	EC240	90	80	56	403	Geometry 1	180	45%
	EC290	90	80	56	403	Geometry 1	180	45%
	EC360	98	80	61	478	Geometry 1	180	38%
	EC460	98	80	61	478	Geometry 1	180	38%
Excavator 2 behind cabin 1	EC210	45	82	20	74			
Length and width are max values	EC240	45	82	20	74			
	EC290	45	82	20	74			
	EC360	61	92	20	112			
	EC460	89	92	20	164			
Excavator 3 behind cabin 2	EC210	45	82	35	129			
Length and width are max values	EC240	45	82	35	129			
	EC290	45	82	35	129			
	EC360	61	92	35	196			
	EC460	89	92	35	287			
Excavator 4 counterweight	EC210	30	70	60	126			
Height are probably max values	EC240	30	70	60	126			
Length and width are corresponding:	EC290	40	70	60	168			
If L is decreased by 1, W can be increased by a	EC360	50	80	65	260			
	EC460	60	80	70	336			
Wheel loader 1	L150	75	60	40	180	Geometry 1	180	100%
Not critical. Values may be adjusted.	L180	80	77	45	277	Geometry 1	180	65%
	L220	90	88	45	356	Geometry 1	180	51%
	L250	110	88	50	484	Geometry 1	180	37%
	L350	140	100	50	700	Geometry 1	180	26%
Grader 1 beside engine max values. Two eq	G940	140	25	38	133	Geometry 2	43	32%
Grader 2 on roof	G940	240	150	15	540			
Compactor 1 undercabin platform. Max val	DD112	40	45	28	50	Geometry 2	43	85%
Compactor 2 on the roof	DD112	150	150	15	338			
Compactor 3 under the seat	DD112	50	60	35	105			

Red values may not be exceeded

Green values can be exceeded

A8. PROGRAM STRUCTURE: COST CALCULATION

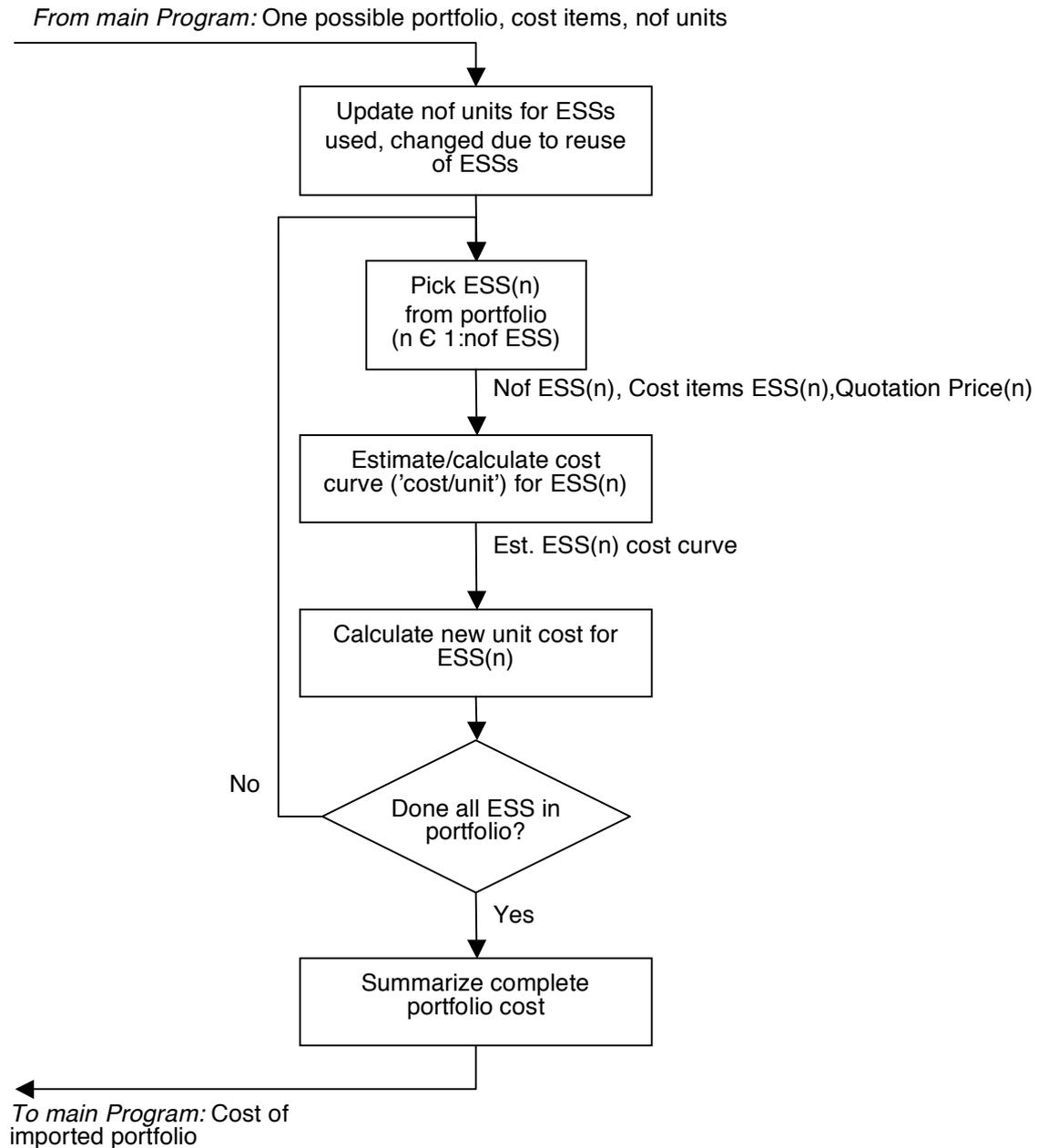


Figure 21. Matlab program structure for calculating the portfolio cost

A9. PROGRAM STRUCTURE: PROBLEM TWO

In the program, for solving “problem two”, is described in the flow chart in Figure 22. The program can be divided into three large steps, described in the bullet list in chapter 6. In the end a matrix with all portfolios and cost of each portfolio is presented. The portfolios in the matrix are then sorted by cost to easily obtain the most cost efficient ESS portfolio. All the information for the ESSs are planned to be imported from an Excel file.

More requirements and vehicles could be regarded by making small changes in the Matlab code. More ESS alternatives can be added without changes made to the program code.

The biggest problem in the solution still lies in the accuracy in the cost estimation and how to quantify the cost items.

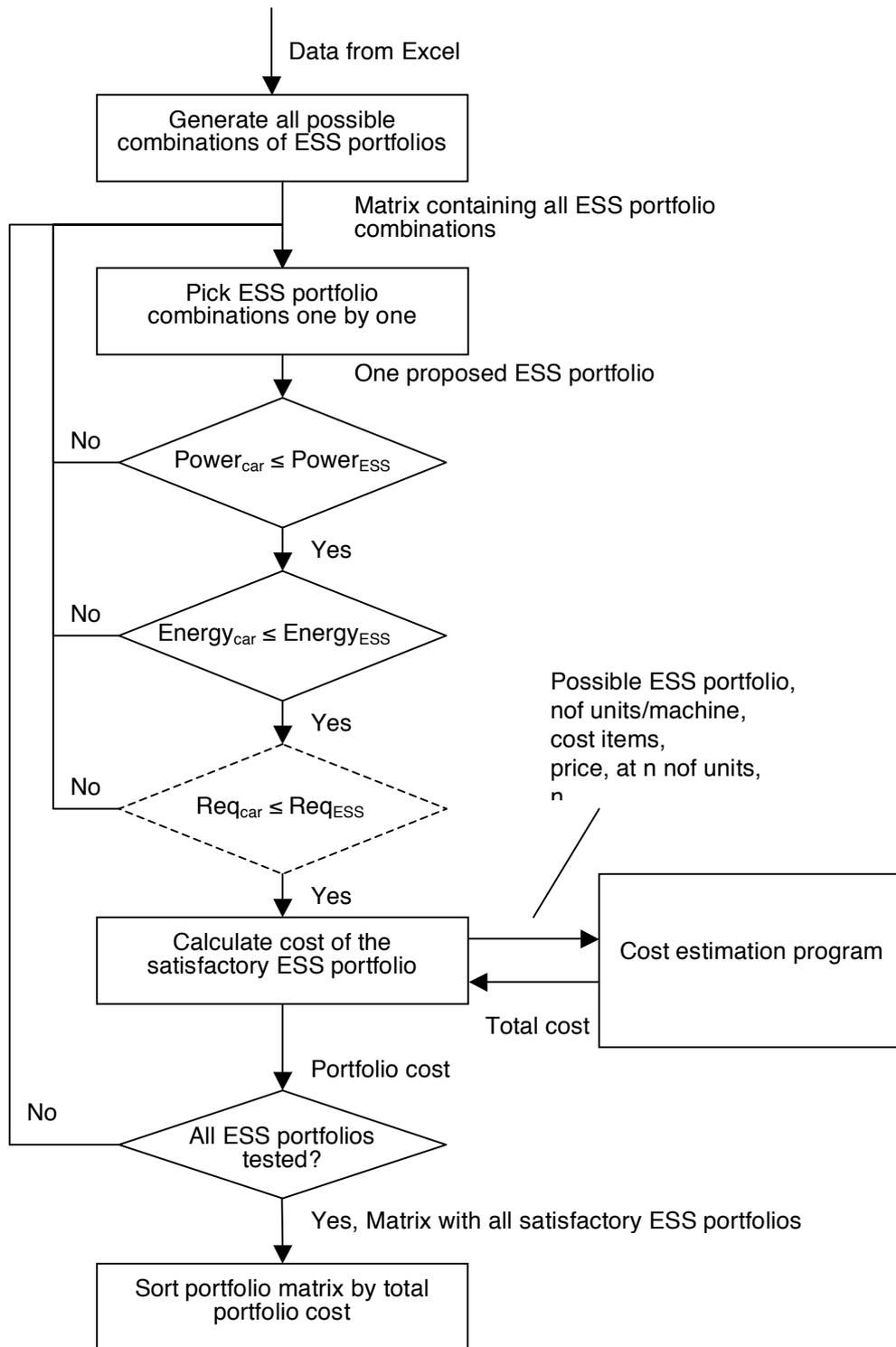


Figure 22. Flow chart of solution of advanced example problem

A10. COST MODEL EQUATIONS

Cost model

Parameter	Explanation
$N_{Units}^{ESS(i)}$	Number of units of variant ESS(i) needed to fill the portfolio
$N_{wear}^{ESS(i),CM(j)}$	Number of units of ESS(i) in Machine(j) that will have to be replaced due to wear
N_{REF}	Number of units used in cost estimations in [10]
$Cost_{"Gross set ESS regulation"}^{ESS(i)}$	Component cost of ESS(i) estimated at N_{REF} units in [10]
<i>Learning</i>	Learning rate is set to 0,8 (80%). This mean that a doubling in production volume will decrease the labor time per unit (cost) with 80%.

Number of units

Calculating the total number of ESS units of each ESS type.

$$(29) \quad N_{tot}^{ESS(i)} = N_{Units}^{ESS(i)} + \sum N_{wear}^{ESS(i),CM(j)}$$

Number of ESSs in mind when setting the investment cost in [10].

$$(30) \quad N_{REF} = 1000 \quad [units]$$

ESS unit cost

Integrating the cost of replacement ESSs in the general investment cost of each ESS type by using an average value.

The factors; $k_{Indirect}^{ESS(i)}$, $k_{Direct,material}^{ESS(i)}$, $k_{Direct,labor}^{ESS(i)}$ refers to Table 22.

$$(31) \quad Cost_{Indirect}^{ESS(i)}(N_{REF}) = Cost_{investment}^{ESS(i)}(N_{REF}) \cdot k_{Indirect}^{ESS(i)} \quad [cost/unit]$$

$$(32) \quad Cost_{Direct,material}^{ESS(i)}(N_{REF}) = Cost_{investment}^{ESS(i)}(N_{REF}) \cdot k_{Direct,material}^{ESS(i)} \quad [cost/unit]$$

$$(33) \quad Cost_{Direct,labor}^{ESS(i)}(N_{REF}) = Cost_{investment}^{ESS(i)}(N_{REF}) \cdot k_{Direct,labor}^{ESS(i)} \quad [cost/unit]$$

A new investment (component) cost is calculated if a wear cost exists. The wear cost is included in the investment cost because the wear cost is also influenced by the production volume, see Table 2. $Cost_{"Gross set ESS regulation"}^{ESS(i)}$ is the cost per unit estimated at a production volume of 1000 units (N_{REF}) in [10].

$$(34) \quad Cost_{investment}^{ESS(i)} = \frac{Cost_{"Gross set ESS regulation"}^{ESS(i)} \cdot N_{Units}^{ESS(i)} + \sum_j Cost_{wear}^{ESS(i),CM(j)} \cdot N_{wear}^{ESS(i),CM(j)}}{N_{Units}^{ESS(i)} + \sum_j N_{wear}^{ESS(i),CM(j)}} \quad [cost/unit]$$

Calculating the “new” cost per component (unit) from the cost parameters.

$$(35) \quad Cost_{\text{component}}^{\text{ESS}(i)} (N_{\text{tot}}^{\text{ESS}(i)}) = Cost_{\text{Indirect}}^{\text{ESS}(i)} (N_{\text{tot}}^{\text{ESS}(i)}) + Cost_{\text{Direct,material}}^{\text{ESS}(i)} + Cost_{\text{Direct,labor}}^{\text{ESS}(i)} (N_{\text{tot}}^{\text{ESS}(i)}) \quad [\text{cost/unit}]$$

The cost of all ESS units of variant i, excluding the cost of power losses.

$$(36) \quad Cost_{\text{tot}}^{\text{ESS}(i)} = Cost_{\text{component}}^{\text{ESS}(i)} \cdot N_{\text{tot}}^{\text{ESS}(i)} \quad [\text{cost}]$$

The cost of the complete ESS portfolio

$$(37) \quad Cost_{\text{portfolio}} = \sum_i Cost_{\text{tot}}^{\text{ESS}(i)} + Cost_{\text{loss total}} \quad [\text{cost}]$$

Labor cost

Calculating the labor cost per unit at a new production volume. Equations (38) & (39) are based on a combination of equation (2) by Blackenfelt and (11) by Fujita. A disadvantage with the labor cost model in (39) is that the labor cost converges to 0 when the production volume turns towards infinity. There is no limit for the lowest labor cost possible.

$$(38) \quad Cost_{\text{Initial,Direct,labor}} = \frac{Cost_{\text{Direct,labor}} (N_{\text{REF}})}{N_{\text{REF}}^{\frac{\ln(\text{learning})/\ln(2)}{2}}}$$

The new labor cost:

$$(39) \quad Cost_{\text{Direct,labor}} (N_{\text{tot}}^{\text{ESS}(i)}) = Cost_{\text{Initial,Direct,labor}} \cdot N_{\text{tot}}^{\text{ESS}(i)} \frac{\ln(\text{learning})/\ln(2)}{2} \quad [\text{cost/unit}]$$

Indirect cost

The total indirect cost is the same for different production volumes, though there is a maximum value of the indirect cost per unit introduced (41).

$$(40) \quad Cost_{\text{Indirect}}^{\text{ESS}(i)} = \frac{Cost_{\text{Indirect}}^{\text{ESS}(i)} (N_{\text{REF}})}{N_{\text{tot}}^{\text{ESS}(i)}} N_{\text{REF}} \quad [\text{cost/unit}]$$

$$(41) \quad Cost_{\text{Indirect}}^{\text{ESS}(i)} \leq 10^5 \quad [€]$$

Wear cost:

$$(42) \quad Cost_{\text{wear}}^{\text{ESS}(i),\text{CM}(j)} = Cost_{\text{“Gross set ESS regulation”}}^{\text{ESS}(i)} \cdot (1 + \text{interest})^{-\frac{\text{life length CM}(j)}{2}} \cdot \text{floor}(\Delta \text{State of health}^{\text{ESS}(i),\text{CM}(j)}) \quad [\text{cost/unit}]$$

Loss cost:

Total power loss in an ESS unit is calculated by equation (43)-(44)

$$(43) \quad P_{\text{tot loss}} = R_{\text{cell}} \left(\frac{P_{\text{tot}}}{U_{\text{ESS}} \cdot N_{\text{cell strings}}} \right)^2 \cdot N_{\text{cells}} \quad [W]$$

$$(44) \quad \frac{P_{\text{tot loss}}}{P_{\text{tot}}^2} \approx R_{\text{cell}} \cdot \underbrace{\frac{N_{\text{cells}}}{(U_{\text{ESS}} \cdot N_{\text{cell strings}})^2}}_{\text{Constant for equal ESS}}$$

Relation between power losses for an ESS in a machine and the power losses for the same ESS in the machine it is simulated/developed for:

$$(45) \quad \frac{P_{\text{tot loss}}^{\text{ESS}(i),\text{CM}(j)}}{(P_{\text{tot}}^{\text{CM}(j)})^2} = \frac{P_{\text{tot loss}}^{\text{ESS}(i),\text{CM}(\text{REF})}}{(P_{\text{tot}}^{\text{CM}(\text{REF})})^2}$$

$$(46) \quad (45) \rightarrow P_{\text{tot loss}}^{\text{ESS}(i),\text{CM}(j)} \propto (P_{\text{tot}}^{\text{CM}(j)})^2$$

Loss cost relation between two machines with the same ESS, in which the loss cost is known for one of the machines. $t^{\text{CM}(j)}$ is the time, in hours, that the machine is used during its life time.

$$(47) \quad \text{Cost}_{\text{loss}}^{\text{ESS}(i),\text{CM}(j)} = \text{Cost}_{\text{loss}}^{\text{ESS}(i),\text{CM}(\text{REF})} \frac{(P_{\text{tot}}^{\text{CM}(j)})^2 \cdot t^{\text{CM}(j)}}{(P_{\text{tot}}^{\text{CM}(\text{REF})})^2 \cdot t^{\text{CM}(\text{REF})}} \quad [\text{cost/unit}]$$

E_{diesel} express the energy content per liter diesel. $\text{Price}_{\text{diesel}}$ express the diesel price per liter.

$$(48) \quad \text{Cost}_{\text{loss}}^{\text{ESS}(i),\text{CM}(\text{REF})} = \frac{P_{\text{tot loss}}^{\text{ESS}(i),\text{CM}(j)} \cdot t_{\text{life length}}^{\text{CM}(j)} \cdot \text{Price}_{\text{diesel}}}{E_{\text{diesel}}} \quad [\text{cost/unit}]$$

$$(49) \quad \text{Cost}_{\text{loss total}} = \sum_j \text{Cost}_{\text{loss}}^{\text{ESS}(i),\text{CM}(j)} \cdot N_{\text{Units}}^{\text{CM}(j)} \quad [\text{cost}]$$