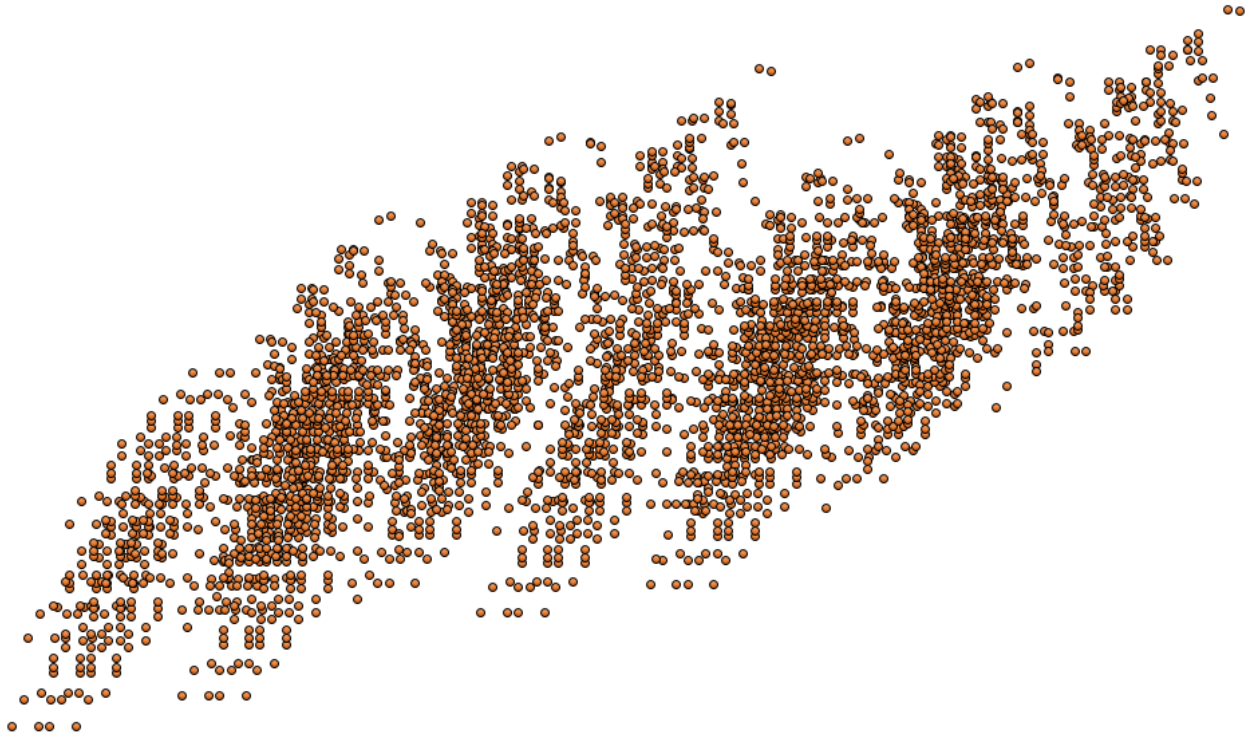




CHALMERS
UNIVERSITY OF TECHNOLOGY



Optimal GenSet

Model Creation For Optimization

Master's Thesis in Product Development

RASMUS ERIKSSON

NELLIE LEXANDER

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
www.chalmers.se

MASTER'S THESIS 2022

Optimal GenSet

Model Creation For Optimization

RASMUS ERIKSSON

NELLIE LEXANDER



CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Industrial and Materials Science
Division of Product Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022

Optimal GenSet
Model Creation For Optimization
RASMUS ERIKSSON
NELLIE LEXANDER

© RASMUS ERIKSSON, 2022.
© NELLIE LEXANDER, 2022.

Supervisor: Roger Leirvik, Volvo Penta
Supervisor: Björn Wessman, Volvo Penta
Examiner: Erik Hulthén, Chalmers University of Technology

Master's Thesis 2022
Department of Industrial and Materials Science
Division of Product Development
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Possible combinations of technologies plotted in a graph of increase in efficiency vs cost.

Typeset in L^AT_EX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2022

Optimal GenSet
Model Creation For Optimization
RASMUS ERIKSSON
NELLIE LEXANDER
Department of Industrial and Materials Science
Chalmers University of Technology

Abstract

This project is carried out in collaboration between Volvo Penta and Chalmers University of Technology. This is a master's thesis and the report outlines the overall work carried out by two Product Development students at Chalmers University of Technology. Volvo Penta is a company within the Volvo Group and manufactures products within the marine-and-industry segment. A generator set (GenSet) with a diesel engine, which the project focuses on, is necessary for a wide range of applications, for instance at hospitals or in mines. The reliability of the power source is of great importance whether it is for a constant supply or a back-up generator supplying energy to vital functions in the society.

This project was initialized since one of the most challenging problems right now is the increase in global warming, which emissions from diesel engines contribute to. Volvo Group has its own targets that are within the line of the Paris Agreement, where Volvo Group has committed to the Science Based Targets initiative. Volvo Penta has set a target to absolute reduce greenhouse gases by 37.5% by 2034 and the overall goal for Volvo Group is to have net-zero greenhouse gas emissions by 2040. By constructing a model and methodology that enables Volvo Penta to find the most promising improvements for a GenSet engine, with the cost taken into account, this project can help Volvo Penta to lower the CO_2 emissions.

The report showed the workflow for concept selection by constructing a model and methodology. The course of action followed: technology research, screening technologies by using an elimination matrix, methodology research, model creation that combines technologies for improving the efficiency of the engine by using Matlab and Simulink, sensitivity analysis and multi-criteria decision-making matrix, to finally have three concepts. The final concepts were visualized.

By using the created model, the three most promising combinations of technologies could be selected. The first one included turbo compound, continuously varying transmission, cylinder deactivation and thermal barrier coating. The second one contained turbo compound, continuously varying transmission, dynamic skip fire and thermal barrier coating. The third one consisted of turbo compound, continuously varying transmission, cylinder deactivation, thermal barrier coating and variable compression ratio. The increased efficiency respectively were 29.4%, 29.6% and 29.5%. The cost for the additional technologies was approximately between 66300-68300 SEK.

Keywords: GenSet, Diesel Engine, Volvo Penta, Optimization, Concept Selection.

Acknowledgements

This report was written as a master's thesis at Chalmers University of Technology in the spring of 2022. The project group consisted of two students from the master program Product Development. The project has been in cooperation with AB Volvo Penta and was initiated by Björn Wessman, Innovation & Emerging Technology Manager at AB Volvo Penta. Together with this project's manager, Andreas Samson, Manager of Industrial MDEP and Testing at AB Volvo Penta, and this project's supervisor, Roger Leirvik, Project Manager of Verification at AB Volvo Penta, we have been able to complete this report. We would like to thank them for their contribution with the knowledge necessary for the project implementation and their support throughout the entire project.

We would like to thank our examiner at Chalmers University of Technology, Erik Hulthén, Associate Professor in Product Development, we are grateful for your time and advice.

Finally, we want to direct a big thanks to Iñigo Alonso Fernandez, Ph.D. student at Chalmers University of Technology for your time and discussion about the possible methods to use. Thanks to Product Developer Per Liljeros at Volvo Penta and Patrik Landberg, Senior CAE Engineer at Volvo Penta, for discussing technologies. Thanks to Francesco Galuppo, Senior CAE Engineer at Volvo Penta for guidance in Simulink. Thanks to Elias Sonnsjö Lönegren, consultant at Volvo Penta, and Rebecca Henrysson, consultant at Volvo Penta for guidance in Matlab.

We appreciate everyone's time, willingness to help and encouragement. Without your help, the work would not have been feasible.

Rasmus Eriksson, Gothenburg, June 2022
Nellie Lexander, Gothenburg, June 2022

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BDC	Bottom Dead Centre
CDA	Cylinder Deactivation
CI	Compression Ignition
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CR	Compression Ratio
CVT	Continuously Varying Transmission
DEF	Diesel Exhaust Fluid
DSF	Dynamic Skip Fire
DWI	Direct Water Injection
EGR	Exhaust Gas Recirculation
EMF	Emulsified Fuel
EPA	Environmental Protection Agency
GenSet	Generator Set
HC	Hydrocarbon
H_2O	Water
LIVC	Late Intake Valve Closing
MCDM	Multi-Criteria Decision-Making
N_2	Dinitrogen
NO_x	Nitrogen Oxides
O_2	Oxygen
ORC	Organic Rankine Cycle
PM	Particulates matter
PN	Particle Number
RL	Rotational Liner
SBTi	Science Based Targets initiative
SCR	Selective Catalyst Reduction
SI	Spark Ignition
SST	Single Speed Transmission
TBC	Thermal Barrier Coating
TC	Turbo Compound
TDC	Top Dead Centre
TRL	Technology Readiness Level
VCR	Variable Compression Ratio
_x VVA	Variable Valve Actuation



Contents

List of Acronyms	ix
List of Figures	xvii
List of Tables	xix
1 Introduction	1
1.1 Background	1
1.2 About Volvo Penta	2
1.3 Goal To Achieve Within The Company	2
1.4 Stakeholders	2
1.5 Aim	3
1.5.1 Goal	3
1.5.2 Research Questions	3
1.5.3 Objectives	4
1.6 Limitations	4
1.7 Information About The Current Engine	4
2 Theory	7
2.1 GenSet	7
2.2 Diesel Engines	8
2.2.1 Components	8
2.2.2 Combustion Theory	11
2.2.3 Emissions	12
2.3 Regulations	13
2.4 ISO 8178	14
2.5 Optimization Technologies	14
2.5.1 Direct Water Injection	14
2.5.2 Continuously Varying Transmission	15
2.5.3 Single Speed Transmission	16
2.5.4 Variable Compression Ratio	16
2.5.5 Variable Valve Actuation	17
2.5.6 Turbo Compound	18
2.5.7 Emulsified Fuel	18
2.5.8 Organic Rankine Cycle	19
2.5.9 Cylinder Deactivation	19
2.5.10 Dynamic Skip Fire	20

2.5.11	Thermal Barrier Coating	20
2.5.12	Rotational Liner Engine	21
2.6	Programs Used In This Project	21
2.6.1	Matlab	21
2.6.2	Simulink	22
2.6.3	App Designer	22
2.6.4	Excel	22
3	Methodology And Results	23
3.1	General Research	23
3.1.1	Research About Technologies	23
3.1.2	Selection Of Technologies	24
3.1.3	The 12 Chosen Technologies	25
3.1.4	Estimation Of Technology Information	25
3.1.5	Research About Already Existing Methods	27
3.2	Model And Methodology Creation	28
3.2.1	Cost For The Technologies	28
3.2.2	Trustworthiness	29
3.2.3	Implementation Ability	31
3.2.4	Technology Readiness Level	33
3.2.5	Efficiency In D2 Cycle	34
3.2.6	Ranking Of Technologies	35
3.2.7	Sensitivity Analysis	36
3.2.8	Design Structure Matrix	39
3.2.9	Matlab And Simulink	40
3.2.10	Graphical User Interface	43
3.3	Concept Selection	46
3.4	Final Concepts	50
3.4.1	Concept Nr.20	51
3.4.2	Concept Nr.21	52
3.4.3	Concept Nr.22	53
4	Sustainability And Ethics	55
5	Discussion	57
5.1	Motivations and Discussion of Results	57
5.2	Final Discussion	61
6	Conclusion	65
6.1	Conclusion of Research Questions	65
6.2	Final Conclusion	66
	Bibliography	67
	Appendix A Efficiency, Temperature And NO_x Data For Continuously Varying Transmission	I
A.1	Efficiency	I

A.2 Exhaust Gas Temperature And NO_x Emissions	I
Appendix B Efficiency, Temperature And NO_x Data For Single Speed Transmission	III
B.1 Efficiency	III
B.2 Exhaust Gas Temperature And NO_x emissions	III
Appendix C Efficiency, Temperature And NO_x Data For Turbo Compound	V
C.1 Efficiency	V
C.2 Exhaust Gas Temperature And NO_x Emissions	V
Appendix D Efficiency For Organic Rankine Cycle	VII
D.1 Efficiency	VII
Appendix E Data Sheets For The 12 Chosen Technologies	IX
E.1 Direct Water Injection	IX
E.2 Continuously Varying Transmission	X
E.3 Single Speed Transmission	XI
E.4 Variable Compression Ratio	XII
E.5 Variable Valve Actuation	XIII
E.6 Turbo Compound	XIV
E.7 Emulsified Fuel	XV
E.8 Organic Rankine Cycle	XVI
E.9 Cylinder Deactivation	XVII
E.10 Dynamic Skip Fire	XVIII
E.11 Thermal Barrier Coating	XIX
E.12 Rotational Liner	XX
Appendix F Temperature And NO_x Data For Selective Catalyst Reduction	XXI
F.1 Exhaust Gas Temperature	XXI
F.2 NO_x Emissions	XXI
Appendix G Results From Sensitivity Analysis On Multi-Criteria Decision-Making Matrix	XXIII
G.1 Scenario 1	XXIII
G.2 Scenario 2	XXIV

List of Figures

3.1	Timeplan for the individual deadlines	23
3.2	Changes in ranking position for different scenarios	38
3.3	Visualization of the ranking position for different scenarios	39
3.4	The structure of the simulink model	40
3.5	On/Off switch. Either the input transports directly to the output or into the next box	41
3.6	On/Off switches depending on load case.	42
3.7	Inputs are multiplied with a factor for the specific technology and load case. The new value is then transported to the output of the technology	42
3.8	Start view of the app	43
3.9	Results from manually simulation is visualized in this tab and comparative input numbers are stated	44
3.10	The graph visualizing the increase in efficiency versus cost for all the different combinations	45
3.11	Parameter changes can be done in the app	46
3.12	Cost vs increase in efficiency for all combinations	47
3.13	Efficiency vs cost for the possible combinations	47
3.14	Increase in efficiency vs cost for the selected combinations	48
3.15	The relation of increase in efficiency and cost	48
3.16	Components and their position for Concept Nr.20	51
3.17	Components and their position for Concept Nr.21	53
3.18	Components and their position for Concept Nr.22	54

List of Tables

1.1	Current engine data [9]	5
2.1	Weighting factors in D2 cycle ISO 8178 [29]	14
3.1	Elimination matrix of the 12 selected technologies	25
3.2	Description of the methods and motivations if used or not	28
3.3	The cost for the technologies	29
3.4	Trustworthiness weighting	31
3.5	Implementation ability weighting	33
3.6	Technology readiness level for each technology	34
3.7	Weighted efficiency D2 cycle for the different load cases	35
3.8	Ranking of the technologies with regard to efficiency, cost, TRL level and implementation ability	36
3.9	Ranking result for scenario: original, 2 & 3	37
3.10	The ranking result for the different scenarios	38
3.11	Design structure matrix	40
3.12	The level of performance for different criteria	49
3.13	The influence from the number of technologies the combination have .	49
3.14	MCDM matrix for the 40 selected combinations	50
3.15	Data for Concept Nr.20	52
3.16	Data for Concept Nr.21	53
3.17	Data for Concept Nr.22	54
A.1	Improvements of efficiency for CVT at different load cases	I
A.2	Exhaust gas temperature and NO_x emissions for different load cases for the CVT technology	I
B.1	Mapping of the brake specific fuel consumption for different engine speeds for the SST technology	III
B.2	Exhaust gas temperature and NO_x emissions for different load cases for the SST technology	III
C.1	Correlation between inflow exhaust gas temperature and efficiency for the TC technology	V
C.2	Exhaust gas temperature and NO_x emissions for different load cases for the TC technology	V

D.1	Correlation between inflow exhaust gas temperature an efficiency for the ORC technology	VII
E.1	Data sheet for Direct Water Injection	IX
E.2	Data sheet for Continuously Varying Transmission	X
E.3	Data sheet for Single Speed Transmission	XI
E.4	Data sheet for Variable Compression Ratio	XII
E.5	Data sheet for Variable Valve Actuation	XIII
E.6	Data sheet for Turbo Compound	XIV
E.7	Data sheet for Emulsified Fuel	XV
E.8	Data sheet for Organic Rankine Cycle	XVI
E.9	Data sheet for Cylinder Deactivation	XVII
E.10	Data sheet for Dynamic Skip Fire	XVIII
E.11	Data sheet for Thermal Barrier Coating	XIX
E.12	Data sheet for Rotational Liner	XX
F.1	Correlation between in-and-outflow exhaust gas temperature for the SCR	XXI
F.2	Correlation between inflow exhaust gas temperature and the NO_x emissions from the SCR	XXI
G.1	Ranking result for scenario 1	XXIII
G.2	Ranking result for scenario 2	XXIV

1

Introduction

Making a product as efficient as possible with as low impact on the environment is an important aspect to consider when developing a product. By using a sustainable mindset together with product development, already existing products can be improved. Furthermore, by taking this product development process one step further and developing a standardized methodology for improving a product, the development time for achieving a sustainable outcome might be shorter and engineers at companies do not risk to do the same work multiple times.

1.1 Background

One of the most challenging problems today is the increase in global warming. This problem is the cause of various reasons from different places around the world including the use of combustion engines. For some of the areas where combustion engines are used, a replacement to more sustainable alternatives are in progress, for instance, electrification within the transport sector. There are still areas where combustion engines are the most promising or the only option. It is within this segment essential to optimize the efficiency of the combustion engine to get as low impact on the global warming as possible. A product within this segment is power generators, which is a device that converts chemical energy into electrical energy, that for instance is used when electricity is needed without having the access to a power grid [1].

Volvo Penta is one of the leading developers and manufacturers of diesel engines used in power generators. The capacity of the different models of the engines ranges from 75kW to 800kW [2]. Volvo Penta has set a goal to increase the efficiency of the diesel engines as much as possible to contribute to the goal to decrease the overall CO_2 emissions by 37.5% by 2034 [3]. Procedures that must be considered are to improve the efficiency of the engine by finding new technical solutions. However, the process of selecting improvements when developing concepts is challenging based on the complexity of the various technologies and the lack of consistency in the decision making. Volvo Penta has therefore expressed the need for a model for the company to find the most promising improvements concerning efficiency and cost, and also a methodology of mapping the attributes of the technologies. This model and methodology could result in a more effective way of selecting and developing concepts and improving the consistency in decision making.

1.2 About Volvo Penta

The mechanical workshop Sköfde Gjuteri Mekaniska Verkstad was founded in 1868. In 1919, the company changed its name and was instead called Pentaverken AB after the decision in 1907 to construct the first Swedish engine for marine use. When Volvo created their first passenger car in 1927 an engine from Pentaverken AB was used and the company became an established car engine manufacturer. In 1935, Volvo bought Pentaverken AB and the company instead became Volvo Pentaverken [4].

Volvo Penta is now a company within the Volvo group and is developing products within the marine-and industry segment. The central part is diesel engines manufactured in Vara and Skövde and petrol engines manufactured in Tennessee, USA, mainly for the American market. The headquarter is situated in Gothenburg, where also the majority of the development takes place [5].

The reliability of the power source is necessary whether it is for a constant supply or a backup generator supplying energy to vital functions in society. Volvo Penta is providing customers with engines that have reliable efficiency and unmatched load acceptance [6].

1.3 Goal To Achieve Within The Company

Volvo Group's target are within the line of the Paris agreement where Volvo has committed to the Science Based Targets initiative (SBTi). Different goals are set depending on the products and industry segments. Volvo Penta has a target that commits to absolute reduction of greenhouse gases with 37.5% by 2034. The overall goal for Volvo Group is to have net-zero greenhouse gas emissions by 2040, 10 years before the same target set by SBTi [3].

1.4 Stakeholders

To understand and formulate the aim of a project, it is crucial to investigate the different stakeholders that the project concerns. For this project, the stakeholders are Volvo Penta, the employees at Volvo Penta, customers of Volvo Penta, suppliers to Volvo Penta and the society [7].

Volvo Penta

Volvo Penta has a goal to reduce the greenhouse gases that are emitted from their products. By using different technologies that enable the reduction of carbon dioxide emissions, this can be achieved. If technologies should be used in combination, the technologies would operate differently compared to being used individually. By having a model to generate the most suitable combinations to a specific efficiency increase and at as low cost as possible, this project will help Volvo Penta reach their

goal.

Employees at Volvo Penta

Having a methodology to follow when technologies should be chosen will simplify the work for the engineers and the same job does not have to be done several times. The model and methodology should be created in a way that technologies easily can be added and be developed further.

Customers

Increasing the efficiency of the engine is positive for the customer in terms of lower operating costs when the fuel consumption is lower.

Suppliers

Volvo Penta does not collaborate with specific suppliers for these kinds of technologies studied in this report. If some of the technologies are not developed in-house, it will be necessary to find relevant suppliers.

Society

Everyone should contribute to minimize the emissions emitted in society. If Volvo Penta reaches their goal, it would benefit society and the environment.

1.5 Aim

This project aims to help Volvo Penta lower the CO_2 emissions by 37.5% that are emitted from diesel engines in GenSets during the use phase.

1.5.1 Goal

The Goal is to construct a methodology that enables Volvo Penta to find the most promising improvements at a conceptual level, for a GenSet engine to lower the CO_2 emission with the cost taken into account.

1.5.2 Research Questions

- Which existing technologies could potentially increase the efficiency of the engine?
- What kind of structured models/methods are the most suitable to improve the efficiency of the engine in a cost-efficient way?
- What kind of correlations and parameters are the most interesting to investigate in the comparison between combinations of technologies?
- Which combinations of technologies are the most promising?
- How can the model and methodology be verified?

1.5.3 Objectives

- Find information about the technologies to an extent so that a selection of the most relevant technologies can be made.
- Find information about current established product development methods and tools.
- Create a suitable model to generate the most promising technology combinations based on the correlation between the technologies.
- Create a methodology that can select the most promising combinations based on different requirements.
- Choose a test method for verifying the created model and methodology and executing the verification.

1.6 Limitations

- The report is only covering implementations and technologies related to the diesel engine.
- The report is using average data.
- The investigated technologies are verified technologies.
- The report is only studying one alternative engine model.
- Diesel is remaining as fuel.
- The study is only investigating technologies that reduce the emissions of CO_2 .
- Only emissions emitted in the use phase is being accounted for.
- The report is only covering calculations of the 1500 rpm engine that results in electricity distribution of 50Hz that is used in Europe.
- The study is using the operating conditions from the D2 driving cycle and other load cases are not taken into account.
- The study is only estimating the purchase price for the technologies.

1.7 Information About The Current Engine

One diesel engine model is studied in this report and is called D13-EU STAGE V. Below in Table 1.1 are specifications for this engine model [8].

Table 1.1: Current engine data [9]

Specifications/Engine Models	D13	Explanation
General Information		
Displacement litres	12.8	Displacement litres is the total volume of all the cylinders.
Emission Levels	EU Stage V	The emission levels are what kind of regulations the engine models comply with.
Number of Cylinders	6	
Method of Operation	4-stroke	
Compression Ratio	16.8:1	The compression ratio is the ratio between the volume of the cylinder, including the combustion chamber, when the piston is at the bottom to the volume of the space when the piston is at the top.
Measurements		
Length [mm]	1426	
Width [mm]	923	
Height [mm]	1200	
Bore [mm]	131	Bore is the diameter of the circular opening.
Stroke [mm]	158	Stroke is the depth of the circular opening.
Weight (engine only) [kg]	1267	
Power		
Prime Power at 1500 rpm [kW]	359	Prime power is measured for a continuous operation when electrical power is supplied at a variable load for unlimited hours.
Standby Power at 1500 rpm [kW]	393	Standby power is it when electrical power is supplied at a variable load in areas with well established electrical network and only used in case of normal utility power failure.
Torque at Prime Power at 1500 rpm [Nm]	2285	
Torque at Standby Power at 1500 rpm [Nm]	2502	
Fuel Consumption		
25% (at 1500 rpm) [g/kWh]	213	The fuel consumption measured at a capacity of 25%, 50%, 75% and 100%.
50% (at 1500 rpm) [g/kWh]	197	
75% (at 1500 rpm) [g/kWh]	196	
100% (at 1500 rpm) [g/kWh]	200	
Technologies for Reduction of PM and NOx		
SCR	Yes	SCR is selective catalyst reduction and is an after treatment to reduce NOx emissions.
DPF+ DOC	Yes	DPF+ DOC is a diesel particulate filter to reduce particles of matter.
EGR	Yes	EGR is an exhaust gas recirculation system that reduces NOx emissions
Airless Urea Injection	Yes	Urea is a fluid added into the SCR system.
Emissions of Interest		
CO2 Emissions (at 1500 rpm) [g/kWh]	628	

2

Theory

To get an understanding of this project, the theory chapter starts with an explanation of what a GenSets is, and what components it consists of. The chapter then continues with a description of diesel engines and their component systems. Combustion theory is then explained and different kinds of emissions from diesel engines are discussed. Regulations that have to be followed to minimize the emissions are then presented. Finally, the ISO standard used to compare technologies is explained and the relevant technologies for this study are presented.

2.1 GenSet

A GenSet is equipment consisting of an engine and an alternator. The engine converts chemical energy from the fuel into mechanical energy. The alternator has two main parts, the rotor and the stator. The mechanical energy makes the rotor in the alternator spin through a magnetic field between the rotor. The stator creates a voltage on the stator, called electromagnetic induction. If the voltage on the stator is connected to a load, electrical current starts to flow and the generator starts producing electricity. From this process, mechanical energy is converted into electrical energy [10].

Even though the main parts of a GenSet are the engine and the alternator, a GenSet consists of more components described below.

- A control panel that regulates all the components.
- A fuel system that consists of fuel tanks that supply fuel to the engine.
- A voltage regulator that controls the amount of voltage produced and transforms it from alternating current into direct current.
- A housing that holds the components together reduces vibrations and grounding the equipment.
- A battery to start the GenSet.
- A manual or automatic transfer switch keeps the flow of electricity consistent and prevents dangerous disruptions.
- A lubrication system and a baffle box or enclosure that reduces noise, prevents corrosion and creates airflow to the engine to enable cooling of the GenSet and exhaust transportation out from the GenSet [11].

GenSets can be found in different sizes and can use different fuels. The fuels can be diesel, gasoline, biodiesel, natural gas, propane and solar.[11].

GenSets are used in industry, developing areas or places that are not supplied with electricity from the power grid. These are places where outages are frequent, such as locations prone to extreme weather conditions or where outages can be dangerous, for example, in a mine or a hospital. GenSets can in other words be used as either the primary source or a supplementary power source [10]. GenSets do not have a specific application in a single industry but are used for the same purpose in various industries. GenSets prevents lost business and lost productivity. Besides healthcare facilities as mentioned, the equipment can be used at emergency departments and news stations during, for example, critical situations, military operations or to get contact with remote islands [13]. GenSets can also be used to keep refrigerated loads cold during transportation, at offshore operations, and at festivals where the peak demand is usually high [14].

2.2 Diesel Engines

The German engineer Dr. Rudolf Diesel invented the diesel engine at the end of the 19th century. Diesel engines use Compression Ignition (CI) that turns the energy in diesel into rotary mechanical energy. It is the most efficient power source known among internal combustion engines. Diesel engines are fuel-efficient and contribute to lower greenhouse gas emissions compared to other combustion engines. The engines are also more durable and reliable than other engines and require less maintenance [15]. The cost of the fuel per kilowatt produced is 30-50% lower than for other engines. Diesel engines also have a longer life compared to spark ignition engines [16]. The negative aspects of diesel engines are the high cost and high amounts of NO_x and Particulates Matter being emitted [15].

Diesel engines are widely used in society for example in construction equipment, automobiles, marine, mining, hospitals, forestry, telecommunications, subway, agricultural and industrial applications. [16].

2.2.1 Components

A diesel engine consists of different systems and the main systems are called fuel system, lubrication system, air intake system, exhaust system, cooling system and electrical system. Within these systems there are components included and in this sub-chapter describes how these components are connected and what they are used for. In a diesel engine, components are used to minimize the exhaust emissions, which will also be presented [17].

Fuel System

1. Fuel tank
2. Water separator
3. Feed pump
4. Filter

5. Injection pump
6. Injection nozzle
7. Cylinder

The fuel is transported from the fuel tank, where the fuel is stored, through the water separator, which prevents fuel of poor quality to damage the engine. From the water separator, the fuel is transported to the feed pump that is pumping the fuel further in the engine, through a filter into the injection pump that transports the fuel up to the injection nozzle that then finally doses the fuel into the cylinder. To open the nozzle, the fuel has to be pressurized. The injection nozzle breaks the fuel into particles and this occurs at a pressure between 10MPa-28MPa [17].

Lubrication System

1. Oil sump
2. Oil pump
3. Strainer
4. Filter
5. Main gallery
6. Main bearings + camshaft + timing gears + valve tappets
7. Sump + cylinder walls + crankpin + piston pin + piston ring

The pump pumps oil under pressured feed to lubricate the engine to reduce friction and prevent wear. The oil also removes heat from the pistons and separates the piston rings and the cylinders. The filters clean the oil from contaminants [17].

When the engine is not in use, the oil is stored in the oil sump, where the oil pump takes the oil from. The oil must be within a temperature range so the viscosity of the oil does not get too high and therefore is an oil cooler used. The oil is led through a strainer, a filter and then into the main gallery. From the main gallery, the oil flows to the main bearings, the camshaft, timing gears and valve tappets. The oil left after lubricating the main bearings either flows back to the sump or splashes on the cylinder walls. The oil remaining from the cylinder walls goes to the crankpin, to the piston pin and finally to the piston ring [17].

Air Intake System

1. Air cleaner
2. Turbocharger
3. Intake manifold
4. Inlet port
5. Inlet valve
6. Cylinder bore

The air cleaner consists of a filter to prevent dust from entering the cylinder bore. The air from the air filter is compressed in the turbocharger to generate a higher efficiency in the cylinder bore and it is the exhaust gas that drives the turbocharger. The intake manifold leads the air from the turbocharger to the inlet port. From

the inlet port the air is transported into the inlet valve, where the valve allows air into the cylinder bore. The camshaft controls the opening and closing of the valve components.

Exhaust System

1. Cylinder bore
2. Exhaust valve
3. Exhaust port
4. Exhaust manifold
5. Turbocharger
6. Muffler

The exhaust system moves the exhaust gas from the cylinder bore through the exhaust valve out through the exhaust port into the exhaust manifold. The exhaust then passes through the turbocharger to make it spin and compress the air from the air intake system. The exhaust is then transported out of the system, through a muffler to cool down the exhaust gases, reduce the pressure of the gases and therefore also reduce the noise from the engine. [17].

Cooling System

A cooling system is used to maintain an optimal temperature to make the engine as efficient as possible, to protect the components and make the life of the engine longer. The cooling system is also used to maintain an optimal temperature of the oil in the lubrication system. Cooling can be done either by air cooling or water cooling. The cooling system consists of a radiator used to cool the liquid and a pump pushing the liquid around inside the engine. The liquid is usually a mixture of distilled water, glycol and additives that prevent corrosion. [17].

Electrical System

The electrical system consists of a starter motor, an alternator and a battery. The task of the alternator is to charge the batteries. The battery gives power to the starter motor, enabling the flywheel to rotate, which then allows the crankshaft to rotate. This is the motion that enables the pistons in the cylinders to move. The pistons suck air and fuel into the combustion chamber and the engine can start. When the speed of the engine is at a required speed, the starter motor stops rotating and the flywheel stops since it is not needed anymore [17].

Minimize Exhaust Emissions System

Emissions are emitted from diesel engines, and to reduce these, different systems are included among the other components in the diesel engine. Three methods used in almost all diesel engines are Exhaust Gas Recirculation (EGR), particle filter and Selective Catalyst Reducer (SCR) [18].

Exhaust Gas Recirculation has been described briefly in the exhaust system above, where the exhaust gas is recirculated into the turbocharger to make it spin. The EGR valve consists of a funnel with a filter mounted where the engine ends and

the exhaust system begins. The valve opens when the exhaust is sent back in for combustion once again. By reheating the soot, the NO_x is reduced, since the oxygen concentration in the combustion chamber is now lower than before the combustion [18].

When exhaust gases leave the engine, they are transported through a particle filter where most of the Particulates Matter are filtered. When the exhaust exits the filter, the exhaust are transported into a Selective Catalyst Reducer. Diesel exhaust fluid (DEF), stored in a urea tank in connection to the SCR, is added and the DEF consists of purified water and urea. The urea reacts with the NO_x emissions leaving the combustion chamber and creates harmless emissions. When the exhaust leaves the SCR and is released into the air, the NO_x and Particulates Matter are reduced with 98-99% [19].

2.2.2 Combustion Theory

The basic principle of a diesel engine is that it converts chemical energy in terms of fuel into mechanical energy by combustion. This engine is called a compression ignition engine since this engine only requires heat generated from air compression. There are two types of diesel engines, two-stroke-and four-stroke engines. This chapter is describing the process of a 4-stroke engine. Four-stroke means that the piston changes direction four times to complete a combustion cycle, which is two turns for the crankshaft [20].

The first phase is called intake stroke, this starts when the piston is in the top dead centre (TDC). The inlet valve opens as the piston moves down towards the bottom dead centre (BDC). This creates air suction and will continue until the piston reaches the BDC [20].

The second phase is called compression stroke and the piston goes from BDC to TDC. This is done while both the valves are closed and air compression occurs. When the piston is close to the TDC, the fuel is injected by a nozzle as the crank angle for this time is around 25 degrees [21]. The fuel mixes and absorbs the heat of the surrounded compressed air to a temperature close to the ignition temperature. As the piston moves towards the TDC, some of the mixed air and fuel start to ignite. This can be defined as the start of the combustion, as the process from fuel injection to this point is mentioned as ignition delay. This local ignition influences the rapid vaporization and increases the overall compression to the ignition temperature. This results in the combustion of all the unburned fuel as the piston reaches the TDC and starts to move down to BDC. At this point, the crankshaft has rotated 360 degrees and the second phase of the combustion cycle is completed [22].

The third phase is called power stroke and begins when the piston is in the TDC and starts to move towards BDC. This is done when the valves are closed and the high gas pressure from combustion pulls the piston down. The pressure remains

constant in this state as the piston is moving [20].

The fourth and last phase is called the exhaust stroke and includes a movement of the piston from the BDC to the TDC. The exhaust valve is now open and the piston pulls the burned gas out of the chamber as it becomes exhaust gas. The four-stroke cycle is complete, and the crankshaft has rotated 720 degrees [20].

2.2.3 Emissions

The diesel engine is a combustion engine that converts chemical energy to thermal energy and then to mechanical energy. In theory, the combustion should only generate H_2O and CO_2 , but this is not the case due to various reasons, such as ignition timing, combustion temperature and air-fuel ratio. This results in various harmful substances in terms of pollution. This is harmful for both for the human health and the environment. This type of pollution represents 1% of the exhaust gas and consists of carbon monoxide (CO), hydrocarbon (HC), Particulates Matter and nitrogen oxides (NO_x). The rest of the emissions consists of approximately 12% carbon dioxide (CO_2), 67% dinitrogen (N_2), 11% water (H_2O) and 9% oxygen (O_2). Carbon dioxide has an impact on the global warming, since CO_2 is one of the most critical greenhouse gases [23].

Carbon monoxide is a result of an incomplete combustion process where the air-fuel mixture is too rich. This means that not all the carbon in the diesel will convert to CO_2 but will instead create CO. The concentration of CO in the exhausted gas is always minimal, nevertheless, the substance is a harmful gas and could by inhalation result in slow reflexes, mental illness and impaired concentration. CO is also indirectly contributing to climate change in terms of tropospheric greenhouse gas as ozone [24].

Hydrocarbons are a result of unburned fuels. The principal reason is insufficient combustion temperature. The substance often occurs when the engine is operating at light loads. Another reason for unburned fuel is often related to injector needle bounce, a speed change in the engine's excessive nozzle cavity volumes. The emissions of HC occur mainly from the exhaust pipe but also the crankcase, the fuel system and atmospheric venting vapors in the fuel distribution process. The substance harms human health. It could potentially lead to respiratory tract irritation and increase the risk of cancer. The substance is one of the gases that impacts the most when it comes to the formation of ground-level ozone [23].

Particulates Matter are related to sulfates and water or burned fuel, burned lube oil, ash from fuel oil or cylinder lube oil. The formation of Particulate Matter results from various factors such as fuel quality, lubrication oil quality, combustion temperature, consumption of exhaust gas cooling or the expansion process. The size of the particles is often around 15-40nm in diameter. Three types of categories cover the different types of Particulates Matter and they are soot, inorganic fraction and soluble fraction. The Particulates Matter in the exhaust gas from a diesel engine

consists of approximately 50% soot, called the black smoke. Soluble fraction is the cause of low exhaust temperature, which consists of unburned fuel and a compound of combustion and lubrication oil. It could contribute to the soiling of buildings but also pollution of water, air and soil. Particulates Matter also contributes to worse human health since inhaling could cause asthma, lung cancer and premature death [23].

Nitrogen oxide gas is caused by a high combustion temperature, the oxygen concentration level or resident time. At high temperatures, over 1600°C, the nitrogen reacts with the oxygen and forms NO_x . NO_x is representing both nitrogen oxide (NO) and nitrogen dioxide (NO_2). NO_x predominantly consists of NO. NO_x is considered a toxic gas, where NO_2 has a toxicity by a factor of five compared to NO. NO_x has an impact on human health in terms of lung diseases. Except for the bad impact on human health, NO_x contribute to acidification and smog formation. It is a terrestrial substance that stays in the ground and disturbs the aquatic ecosystem. [23].

2.3 Regulations

Standards and regulations are developed to ensure that vehicle emissions are being limited. These standards and regulations also applies for non-road compression ignition engines and power generators. There are currently two leading agencies that have presented the strictest regulations. The Environmental Protection Agency (EPA) has provided multiple emission standards over the years and the presently proposed regulations are called Tier final 4 and was introduced between 2013-2015 [25]. The second leading agency, European Commission has provided several emission standards where the current standard is called Stage 5 and the standard was applied between 2019-2020 [26].

Tier final 4 and Stage 5 provide requirements to control the harmful substances emitted from a compression-ignition engine. The regulated substances are nitrogen oxides (NO_x), hydrocarbons (HC), particle number (PN), Particulates Matter and carbon oxide (CO). The mentioned regulations require a change in the region after exhaust treatment, where technologies such as diesel particle filter, SCR and EGR need to be implemented to fulfill the requirements [27].

At the end of November 2021, a potential new regulation was presented by the California Air Resources Board. The suggestion is called Tier 5 and is estimated to be in commercial service between 2028-2030. The suggested Tier 5 aims to make the regulation of the substances presented in Stage 5 and Tier final 4 more strict. The early proposal of restrictions includes an after treatment that absorbs NO_x up to 90% and particulates matter up to 75%. In addition, the regulation will include non-road compression-ignition engines and for the first time propose limitations for the carbon dioxide emissions. However, the only announced goal for reduction of carbon dioxides is the SBTi target, which includes that Volvo Penta will reduce the absolute greenhouse gas emissions by 37.5% by 2034 [28].

2.4 ISO 8178

The ISO 8178 is an international standard for exhaust emissions created only for off-road engine applications. The cycle used in this project is type D2 and is performed at a constant speed, but at a rated speed, which means that it is the speed of the engine when it produces its maximum power. The torque changes between 100%, 75%, 50%, 25% and 10%. The weighting factors for each load are presented in Table 2.1 and represents the most common loads for this kind of engine [29].

Table 2.1: Weighting factors in D2 cycle ISO 8178 [29]

D2 Cycle ISO 8178	
Torque	Weighting Factor
100%	0,05
75%	0,25
50%	0,3
25%	0,3
10%	0,1

2.5 Optimization Technologies

This subchapter presents the twelve interesting and relevant technologies for this project.

2.5.1 Direct Water Injection

By combining the needle for fuel in the injection nozzle with a needle for water, this technology injects water through the nozzle directly into the combustion chamber. The water is injected before the fuel to cool down the combustion chamber, which creates the time to evaporate before the fuel is injected and the combustion starts. The water is injected after filtration at a pressure of 200-400 bar. This is controlled by a pressure regulating valve to enable the correct pressure and a water pump is therefore also needed to be implemented [30].

The main benefit of this technology is that the temperature in the combustion chamber gets lower before the fuel is injected. Turbocharged engines are pushing their limits both in performance and fuel efficiency. When the water is added it lowers the temperature and allows for a higher compression ratio without the risk of a knock [31].

Another benefit is that Direct Water Injection (DWI) enhances the fuel efficiency at a fixed water to fuel ratio suitable for the specific engine. The water injection duration is of great importance for the technology to improve efficiency and has to be ideal for the specific engine. When the water evaporates in the combustion cham-

ber it reduces the temperature and pressure. This results in a negative compression stroke's work. The steam adds to the working fluid and gives a positive stroke's work. At tests done on a common rail diesel engine retrofitted from a two-cylinder mechanical pump diesel engine, it was seen that the thermal efficiency could be increased by up to 4.08% [32].

When using Direct Water Injection the combustion temperature will decrease because of the ignition delay and therefore will the NO_x concentration also decrease. The cylinder temperature decreases by approximately 6.5%. The maximum cylinder pressure is also decreasing due to the lower combustion temperature. The change is approximately 4.5%. The effective power increases for all the speed cases by a maximum of 3.7%. The torque will increase by 3.5% over all the speed conditions. NO_x reduction is around 55% lower for all the engine speeds [33].

Bosch is a supplier of direct water injection for gasoline engines and is supposed to be a supplier for diesel engines as well [31]. The cost for this technology is approximated to 7000 SEK [34].

2.5.2 Continuously Varying Transmission

In the GenSet used today, the alternator is directly connected to the engine. The engine is required to have the same rotational speed at all loads. This means that the current engine is not running at an optimal speed in terms of efficiency as the optimal rotational speed is 1200-1300 rpm for different load cases. This also means that the capacity of the engine, in other words, the maximum torque, is dependent on the maximum load required from the GenSet even if the GenSet is running on a maximum load of one percent of its use time. Because of the constant rotational speed limitation, the engine is running on lower efficiency and can potentially be oversized. The solution to this problem is a transmission box. It could either be a single speed transmission (SST), which can be read about below in subchapter 2.5.3, or a Continuously Varying Transmission (CVT). The later technology changes gearing with a wide range of ratio depending on the load [35].

Mazaro has come up with a technology that is called drilled free curve-CVT. This transmission can change gearing up to the ratio of 10:1 [36]. The basic function of the transmission consists of a ring wheel connected to the input shaft, a sun wheel connected to the output shaft, and three planet wheels transmitting the torque between the sun-and ring wheel. Since both the sun-and ring wheel are conically shaped, the relative gearing ratio could be changed depending on where the planet wheels are positioned on the wheels. The function of changing the gearing ratio occurs when the distance between the sun-and ring wheels changes and the planet wheel transmits rotational movement at different positions of the sun-and ring wheels. By changing the contact position, the diameter of the ring-and sun wheels are different and contributes to different gearing ratio [37]. The internal efficiency is 94.6% [38]. It is stated that approximately 30% smaller engines can be used for the same demand if this transmission is implemented. This is an approximation and is depending on

the purpose of the GenSet and the driving cycle [39].

For Continuously Varying Transmission, the efficiency can increase by up to 22.8% in brake specific fuel consumption, see Appendix A.1. The exhaust temperature increases for all the load cases and can increase by up to 29.5%. For the two highest load cases the NO_x concentration will decrease by up to 11.3%, but for the lower load cases the NO_x concentration will increase by up to 14.4%, see Appendix A.2. Mazaro is a possible supplier for Continuously Varying Transmission and the model that Mazaro currently provides, which is capable for GenSets, is called SVT. An approximate price for this technology is 29000 SEK [40].

2.5.3 Single Speed Transmission

The Single Speed Transmission (SST) can change the engine speed from 1500 rpm down to a more optimal level, for instance, 1300 rpm. The engine is still changing the torque to regulate the different loads, but the overall efficiency is higher. This technology can although only be used for GenSets with a maximum load of 75% since it can not give the same maximum power as a GenSet with 1500 rpm. The cost for a Single Speed Transmission is approximately 5000 SEK [41].

If using a Single Speed Transmission, the efficiency is increasing by up to 19% in brake specific fuel consumption, see Appendix B.1. The exhaust temperature for Single Speed Transmission gets higher for all the load cases and is increasing by up to 10.8%. For all the load cases, except for 25%, the NO_x concentration decrease by up to 54.8% but for the 25% load case is the NO_x concentration increasing by up to 9.3%, see Appendix B.2.

2.5.4 Variable Compression Ratio

One vital parameter for high thermal efficiency in diesel engines is compression ratio (CR). For the internal combustion engines, the ratio is fixed, and the performance of the engine is a result of trade-offs between different parameters. Since the diesel engine is a compression ignition engine, the ratio must be adopted for different loads, speeds and ambient conditions as cold starts to self-ignite. This means that the limitation of the CR affects the operational efficiency [42]. Standard CR is between a ratio of 14:1 to 25:1, and the fixed CR results from a trade-off between part load and full load conditions. A high CR improves efficiency when the engines operate at low load conditions but will have peak pressure limitations. It will also increase the frictional losses and increase the temperature gradient due to heat transferred into the combustion chamber. A low CR contributes to a decrease in frictional losses but is also decreasing the maximum torque. A low CR will have problems at cold start conditions and might have to use a glow plug for more beneficial conditions [43].

Variable Compression Ratio (VCR) adjusts the CR depending on the speed and load conditions. This type of method is an upcoming area primarily for spark igni-

tion engines where the potential for an increase in efficiency is higher, nevertheless, there is a potential to increase the efficiency of diesel engines for a varying load. By increasing CR at low load and start-up conditions, a more stable and efficient operating condition is achieved [43].

The technical solution to achieve VCR varies and most of the solution is only in the theoretical stage. The primary function is thought to be able to change the combustion chamber volume. The solution to this is to change the effective rod length, change the distance between the rotational axis of the crankshaft and the cylinder head and change the distance between the top of the piston and the piston pin axis [44].

The company FEV provides a VCR solution for both spark ignition (SI) engines and CI engines. This solution changes the distance between the piston pin and the rotational crankshaft axis. This is done by an eccentric bearing rotating around an offset axis related to the center axis of the bearing. This result in a change of the TDC and BDC for the piston [45]. The technology provides a more flexible way of using dual-fuel, adaptive to the engine layout and can improve the brake specific fuel consumption by up to 4.59% [46].

With an increase in compression ratio, the exhaust heat decreases due to more efficient combustion. A general decrease in exhaust temperature of 4% is measured when the ratio changes from 16:1 to 18:1 [42]. The peak combustion pressure is increasing with VCR and a stable improvement over different load cases has shown an increase by 6-7%. This could enable downsizing [47]. FEV is a suitable supplier for this technology and an approximate cost is 2000 SEK [46].

2.5.5 Variable Valve Actuation

One way to reduce fuel consumption and improve the after-treatment condition is to implement Variable Valve Actuation (VVA). One benefit of this type of technology is the decrease of NO_x emissions without an increase in fuel consumption. The technology can increase the efficiency by up to 3.2% [50]. Eaton has provided a technology within the area of VVA and estimates that it is lowering both the fuel consumption and NO_x pollution [48].

Late intake valve closing (LIVC) is one of Eaton's recently developed VVA technology. This technology has a delay of the closing of the intake process. This result in a lower compression ratio relative to the expansion ratio. This process increases the thermal efficiency which increases the exhaust temperature by 40 degrees Celsius, which contributes to a more efficient after treatment, in terms of SCR utilization. The overall impact of this technology is a reduction of CO_2 with up to 1-2% [49].

A decrease in NO_x at different load cases occurs using an EGR. At part load the NO_x reduction is measured to 64%, at high engine loads a reduction of 67% but at

low loads is the NO_x emissions close to unchanged [51]. Eaton is a possible supplier and the approximate cost for the technology is around 7000 SEK [52].

2.5.6 Turbo Compound

One way to increase the efficiency of the diesel engine is to utilize the thermal energy wasted in the combustion. Using the heat from the exhaust gases to generate mechanical or electrical heat increases the engine's thermal efficiency. One way of doing this is by adding a Turbo Compound (TC) to the exhaust flow. It is comparable to a turbo compressor but instead of using the energy to compress air, the energy is transferred to the output of the GenSet. There are different ways of transferring the energy. Some engine manufacturers connect the turbo to the output shaft, converting thermal energy into mechanical energy. Another way to transfer the energy is to let the turbine generate electricity by using a generator [53]. Turbo Compound has advantages such as increasing the thermal efficiency, increasing the power density of the engine and is resulting in a downsizing of the engine [54].

Volvo Trucks is providing a D13TC engine with turbo compound that has a maximum increased in fuel efficiency by 16.7%, which is interpreted as a maximum efficiency increase of 19.5% for GenSet engines, see Appendix C.1. The thermal efficiency increase is varying depending on the amount of energy, in terms of the heat that the exhaust gases consist of. Depending on the load and speed conditions, different thermal efficiencies are delivered. Volvo Trucks D13TC's optimal operation condition is 1000-1100 rpm, which means that the thermal efficiency increase is not assumed to be the same for the D13 GenSet engine [55].

Turbo Compound decreases the exhaust gas temperature between 16.0-38.2% and reduces the NO_x emissions by up to 67.8%, see Appendix C.2. Volvo Group already has the technology available at the company and the technology has an estimated cost of 30000 SEK.

2.5.7 Emulsified Fuel

One way to increase the efficiency of a diesel engine, but at the same time lower exhaust gas emissions, is to use Emulsified Fuel (EMF). Increasing the concentration of water in the emulsion results in an increase in ignition delay since the water will absorb the heat by vaporizing and reduce the chemical reaction in the combustion chamber. The fuel is consisting of diesel and an emulsion. The emulsion consists of a certain percentage of water; the rest is a surface-active agent that reduces the surface tension and enables substances to blend, usually immiscible [56].

In a study where the emulsion consists of 30% water, the maximum increase in efficiency is confirmed to be 8.7% at 100% load. In the same study, the NO_x emissions was reduced by up to 79% due to the ignition delay. Furthermore, due to the evaporation of water, the cylinder temperature is decreasing, which results in a decrease in exhaust gas temperature by 15% at 1500 rpm at 100% load [56]. The

cost for the technology is approximately 7000 SEK based on an estimation that similar equipment is used for DWI.

2.5.8 Organic Rankine Cycle

There are several ways of utilizing the thermal energy loss from internal combustion. One way of doing this is called Organic Rankine Cycle (ORC). This cycle is a closed system that uses energy losses from exhaust gases to boil organic fluid. The system consists of three parts, an evaporator, an expander and a condenser. This technology is commonly used in large plants such as geothermal reservoirs, turbines, combustion engines and solid biomass combustion, where the thermal losses consist of a high amount of energy compared to one single GenSet [57]. The cycle consists of a three-step process, where the first step is to pressurize the liquid in the vaporizer by using the energy from the exhaust gas. In the second step, the vapor is transferred to the expander, where the thermal energy is converted into mechanical energy. This results in a pressure drop, that in the third step condensate in the condenser by cooling down the liquid [58]. The technology is directly influenced by the exhaust gas temperature, which means that with an increase in temperature, there is an increase in delivered power from the ORC technology. The thermal efficiency is approximately 19% at 75% load, which corresponds to an exhaust gas temperature of 196°C [57].

ORC is an established technology at a large scale at power plants, but there are ongoing pilot projects and research on implementing this technology on single light-and-heavy diesel engines. A study from a master's thesis at Chalmers University of Technology was working on the Volvo D13 engine to simulate the impact of implementing an ORC. The result can be interpreted as an efficiency increase between 3-12%, see Appendix D, depending on the exhaust gas temperature [57].

Different pilot projects have shown an efficiency increase, where an ORC system is implemented in a diesel engine. The efficiency improvements are estimated to be 5% [59]. Volvo Buses presented a project where they are implementing an ORC system in a D13 engine on a city bus. It resulted in efficiency improvements with up to 6% using typical driving cycle for city buses [60].

Borg Warner is one of the suppliers that enables this technology to be implemented in a diesel engine [61]. The estimated cost for all the components is 80000 SEK, which includes fluid pump, condenser, evaporator, superheater, recuperator, turbine expander, alternator piping, generator electrical conditioning and a control system [62].

2.5.9 Cylinder Deactivation

A technology relevant for part load conditions is the Cylinder Deactivation (CDA), whose primary function is to deactivate or close both the injection intake valve and exhaust valve for some cylinders. This is done at low load conditions when the

engine does not require all the cylinders and can increase the exhaust temperature and improve the after-treatment conditions. By deactivating some of the cylinders, the still operating cylinders will decrease the air-fuel ratio so that an increase in temperature at low load conditions occurs [63].

Cylinder Deactivation is resulting in a reduction of CO_2 with up to 9% [64]. This technology is also reducing the NO_x concentration by up to 8% and the average exhaust gas temperature increase is around 9% [65]. Jacob's or Eaton are possible suppliers for this technology and the approximate price is 4500 SEK [66].

2.5.10 Dynamic Skip Fire

A problem when the engine operates on low or part loads is that the efficiency decreases. One solution to improve the performance at low load conditions is implementing a Dynamic Skip Fire (DSF). This is a Cylinder Deactivation technology that deactivates or fires one of the cylinders with the help of a software based on algorithms depending on the load cases. This enables the engine to operate on the demanded torque at an optimal efficiency [67].

Tula has provided a DSF technology implemented in a Cummins X15 HD diesel engine. This implementation resulted in a 74% reduction of NO_x emissions and a CO_2 reduction by 5%. The test results are based on driving cycles for vehicles and trucks. This has an impact on the result since the efficiency is highly correlated to the load conditions of the engine [68].

Using the D2 cycle instead of a driving cycle results in an approximate increase of efficiency with up to 15% at low load conditions and a decrease of concentration of NO_x with approximately 29%. The exhaust gas temperature increases by approximately 9% at 25% load. As mentioned earlier, Tula is a suitable supplier for this technology and an approximate price is 6375 SEK [67].

2.5.11 Thermal Barrier Coating

Heat losses regarding the combustion process are an area where the potential for improvement is high. Several problems cause heat losses such as friction, water cooling and heat transfer in terms of exhaust gases. One way of improving the thermal losses by heat transfer is to implement Thermal Barrier Coating (TBC). Thermal Barrier Coating means that the parts from the combustion chamber are coated with a material with low thermal conductivity to minimize the heat transfer from the combustion chamber. The coating material is often of ceramic structure and is applied to the components by a plasma spraying process. The purpose of the TBC is to reduce the heat transfer from the hot gas to the combustion chamber parts. There is a high variety of coating materials where the selection of material significantly impacts the result depending on the application. A study was conducted on a single-cylinder four-stroke engine. Three different materials, with two different thicknesses of layers was tested. The result shows a decrease in brake specific fuel

consumption by 14.96%. The 13% higher cylinder pressure resulted in a 12.35% higher torque, increasing power by 14.92%. Since this study is conducted based on a single-cylinder, similar result for a larger engine is not guaranteed [69].

Toyota is the first and only automotive company that has implemented the TBC technology in their engine. A report from the R&D department at Toyota presented a decrease in fuel consumption by 5.1% in a 4-cylinder diesel engine. This is done by a Thermo-Swing Wall Insulation Technology [70].

By looking at the D2 cycle used for comparison in this project, Thermal Barrier Coating increases efficiency up to 20.3% at low loads. The exhaust gases for the thermal coating are around 40°C higher during the whole cycle for loads at 10%. For loads between 25-50%, the increase in temperature after the combustion is about 20% higher [71]. The price for the TBC is around 1500 SEK for six pistons and 1300 SEK for the combustion chamber including exhaust ports and valve heads [72].

2.5.12 Rotational Liner Engine

One common cause of energy losses in internal combustion is friction. The friction between the contact region of the piston and cylinder is increasing proportionally to the pressure in the combustion chamber. One way of reducing the friction is to apply rotational piston liners. The technology is called Rotational Liner (RL) and minimizes the piston ring friction by having a rotational movement on the piston relative to the cylinder. A few studies have verified that this type of movement in a combustion engine decreases friction. In 2019 a study was conducted where the technology was tested in a four-stroke single-cylinder Cummins 4BT engine. The result shows a fuel saving by 3.5% at maximum load and up to 10% fuel saving at lower loads. When the engine was idle, the fuel consumption decreased around 25%. This study shows that there is a possibility that this technology can improve the internal combustion efficiency, but the technology is in an early development state [73].

No information is found on the change in temperatures of the technology and neither about changes in NO_x concentration, therefore it is assumed that the changes are negligible. Rotating Sleeve Engine Technologies Inc is a possible supplier for this technology and an approximate cost is 29000 SEK [74].

2.6 Programs Used In This Project

Interesting programs for creating models are established by MathWorks, including Matlab, Simulink and App Designer. In addition, Excel is a helpful tool when analyzing the results.

2.6.1 Matlab

Matlab is a programming language and a numeric computing environment developed by MathWorks. Matlab did first appear for commercial use in 1979. The program is

designed to be used for analyzing data, developing algorithms and creating models [75].

2.6.2 Simulink

Simulink is a graphical programming tool, built up with blocks, and is used when dynamic systems are being modelled, simulated and analyzed. Simulink is connected to Matlab scripts and can either be run directly from the model or the background through a script [76].

2.6.3 App Designer

The App Designer is a tool to create a graphical user interface by building the interface with visual components like push buttons. By integrating the Matlab script and Simulink simulations within the components, the app's behavior is programmed and used independently [77].

2.6.4 Excel

Excel is a tool created by Microsoft in 1987. Excel is built up of spreadsheets arranged in rows and columns, can be used for calculations, and has integrated graphical tools. In addition, it is a tool for organizing and presenting data in an understandable way [78].

3

Methodology And Results

This chapter presents the methodology this project followed together with the results that were received by following the steps in the methodology. The working process is visualized below in Figure 3.1.

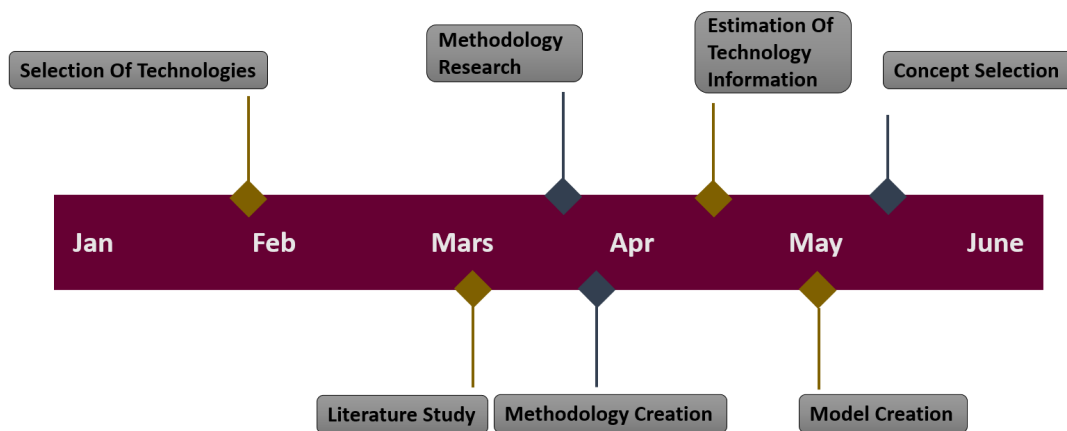


Figure 3.1: Timeplan for the individual deadlines

3.1 General Research

The method to find the information needed for this project was performed by conducting a literature study. The sources of information used were mainly from the internet but also books. Literature on the internet was obtained from online databases, for instance, Google Scholar and Chalmers Library. From these databases most of the articles were found on portals where they gather technical papers in one place. These portals are SAE International, DieselNet, SpringerLink, ResearchGate, SAGE journals and ScienceDirect. Information was also obtained from webpages, for example, Volvo Penta's webpage or possible suppliers' webpages.

3.1.1 Research About Technologies

Researching possible technologies started with finding names of parameters that were possible to change in an engine and technologies that will enhance the performance. When a list of parameters and technologies was created, the process to screen the parameters and technologies started. It was decided that parameters

were not of interest to change in this project since it was assumed that the parameter values already were optimized. A deeper investigation of the technologies was performed and it was realized that many of the technologies were implemented outside of the engine, for example, in the fan. These technologies are therefore out of scope. Another example of excluded technologies were if the technologies were only valuable in vehicle applications during starts and stops. The process of screening the technologies was an iterative process where investigations about the technologies were performed more profoundly and more detailedly every time. Finally, the technologies were screened in an elimination matrix shown below in Table 3.1.

3.1.2 Selection Of Technologies

The twelve technologies were selected based on multiple criteria corresponding to the main goal. The selection process was conducted through an elimination matrix, where the technologies needed to be approved for all the different criteria, see Table 3.1. Four criteria needed to be approved for and can be read about below. If a technology pass the criteria the box was filled in with green. If a technology did not pass the criteria, the box was filled in with red, and the following criteria were not necessary to analyze since the technology was now screened out.

- *Are able to decrease the CO_2 emissions.*
This criteria exclude all the technologies that did not directly have an impact on the efficiency or did not decrease the CO_2 emissions. This means that technologies that, for example, improve the after-treatment system, and as a result of that could impact the efficiency, were considered out of scope.
- *Are able to be implemented in a diesel GenSet.*
The technologies that met the criteria did not have to be demonstrated or validated in a GenSet if tests had been carried out in a relevant environment, where it indicated that the technology could be applied to a GenSet.
- *Provide a solution that is not possible to accomplish with the current engine parts.*
This criteria means that changes in terms of tuning the engine or parameter changes were excluded.
- *Shows improvements in relevant operating conditions.*
This criterion excludes all technologies that do not impact the efficiency when the GenSet operates in the D2 driving cycle. For instance, technologies that only improved the performance under cold start conditions or increased the maximum engine power were excluded since these are not relevant performance parameters for this project.

Table 3.1: Elimination matrix of the 12 selected technologies

Technologies	Are able to decrease the CO2 emissions	Are able to be implement in a diesel GenSet	Provide a solution that is not possible to accomplish with the current engine parts	Shows improvements in relevant operating conditions (D2 cycle)
Direct water injection				
Continuously varying transmission				
Single speed transmission				
Air power assist engine				
Electric boosting				
Miller cycle				
Intake temperature management				
Variable compression ratio				
Cylinder deactivation				
Variable valve actuation				
Multiple fuel injections				
Turbo Compounding				
Organic Rankine Cycle				
Thermalelectric generator				
Emulsified fuel				
Thermal barrier coating				
Low Viscosity engine Oil				
Dynamic skip fire				
Rotational liner				
Reduced piston cool				
Injection timing				
Glowplug				
Ducted fuel injection				
Mild-hybrid turbo				
Fast idle				
Wet scrubber				
Electric catalyst heating				
Thermochemical recuperation				
Thermoacoustic conversion				
Heat exchangers				

3.1.3 The 12 Chosen Technologies

The Twelve technologies that were found interesting and could increase the efficiency of the engines, can be read further about in the theory chapter and summarized information sheets can be seen in the tables in Appendix E.1 - Appendix E.12. The collected information is presented in the tables and also specifications of how the studies were performed.

3.1.4 Estimation Of Technology Information

Under the process of conducting literature research for the technologies, there was a limitation of relevant information for four of the technologies, CVT, SST, TC and ORC. By using internal test data from Volvo Penta and insufficient data from the literature study, estimations and calculations could be made to provide relevant information for all the technologies. This chapter also includes the process of estimating how the SCR technology is operating in different exhaust gas temperatures.

An estimation of the performance of the Continuously Varying Transmission technology was performed based on the current data from a D13 GenSet engine. 200 data points from different engine speeds, efficiency, NO_x emissions, exhaust heat and power were interpolated to correspond to the relevant load cases for the D2 cycle. The efficiency was interpolated for the five different load cases at the engine speed from 1800 rpm to 600 rpm with a step size of 100 rpm. Since the technology has an efficiency of approximately 97%, the power output will have an energy loss

of 3%. This meant that to be able to compare the efficiency for different load cases, the requested power output needed to be set to 3% higher to deliver the same energy output as the current engine, see Appendix A.1. The estimation shows that by using a transmission box, the efficiency could increase by 2.9-22.8% depending on the load case. Since the Continuously Varying Transmission technology enables the engine to run at different engine speeds, NO_x emissions and exhaust heat will differ relative to the current engine, see Appendix A.2.

An estimation based on the current engine data was performed to understand how well the Single Speed Transmission was performing and what engine speed was the most suitable. An interpolation was conducted in the same procedure as for the Continuously Varying Transmission estimation for engine speeds was made from 1400-900 rpm with a step size of 100 rpm. The Single Speed Transmission was assumed to have a similar efficiency as the Continuously Varying Transmission. To compare different speed conditions, the power output needed to be set to 3% higher than the current engine operating conditions. The selection of the most suitable engine speeds was performed with respect to the weighting factors of the D2 cycle. This is presented as the sum column, see Appendix B.1, where the efficiency for the different load cases was multiplied by the corresponding weighting factor. They are then summarized for all the cases to one number that describes the total efficiency. This enabled the selection of the most suitable engine speed to be the overall best choice, which was 1300 rpm. The exhaust heat and the NO_x emission were set to correspond to the selected engine speed conditions for 1300 rpm, see Appendix B.2.

The Turbo Compound technology performance was estimated based on current engine data for two D13 diesel engines, where one was using a Turbo Compound. 200 data points were interpolated to illustrate the correlation between the in-and-out flow of the exhaust temperature and the efficiency improvements, see Appendix C.1. The correlation was demonstrated by a ten-step temperature interval, where the size of the interval was based on the changes in efficiency. The NO_x emissions and the outflow exhaust gas temperature is presented for the different load cases as percentage change relative to the input data, see Appendix C.2.

The ORC technology was estimated based on five data points collected from a study where the implementation of Organic Rankine Cycle in a D13 diesel engine was investigated [57]. The study presented that the Organic Rankine Cycle technology contributed with additional energy supply for the different load cases. This additional energy was assumed to represent the efficiency increase for the technology. An interpolation was conducted based on the five load cases to establish the relation between in-and outflow of the exhaust gas temperature, NO_x emission and increase in efficiency. The relation between the increase in efficiency and inflow exhaust gas temperature is presented in intervals where the size of the interval is depending on the changes in efficiency, see Appendix D. The changes of NO_x emission was assumed to be negligible and the change in the outflow of exhaust gas temperature was estimated to be 90% lower than the inflow temperature [57].

The data from the SCR technology was estimated based on test data from a D13 diesel engine. Data from 200 data points were interpolated to understand the relation between the exhaust temperature and the performance of the SCR in terms of extracting the NO_x particles from the exhaust gas. Both the outflow of the exhaust gas and the rate of reduction of NO_x were directly influenced by the inflow exhaust gas temperature. The outflow temperature is presented based on the inflow temperature between 150-340°C, see Appendix F.1. For the outflow temperature, the relation is presented by temperature intervals down to 150°C. With temperatures under 150°C, the technology will not operate in an acceptable environment and the extrusion of NO_x will not be enough. With lower temperatures under 150°C, the correlation of NO_x extraction and temperature was linearly correlated, see Appendix F.2.

3.1.5 Research About Already Existing Methods

Research of already existing development tools and methods was performed to understand what kind of methods that could be useful. Methods searched for were in the category of methods in ranking different concepts individually and getting a value for the specific concept instead of comparing concepts against each other based on criteria from a requirements list. The chosen methods suitable for this project were concept scoring matrix, indicators for technology, Multi-Criteria Decision-Making (MCDM) matrix, design structure matrix, sensitivity analysis and change propagation. The concept scoring method is included in the MCDM matrix and the indicators for technology were the multi-criteria in the matrix. Change propagation is the factor that resulted in implementation ability, which is one of the indicators for technology in the MCDM matrix. Different methods are therefore used in combination to utilize the methods more efficiently. A list of all the methods found and motivations if used or not can be seen in Table 3.2.

Table 3.2: Description of the methods and motivations if used or not

Method	Used in Project? [Yes/No]	Description and Motivation if Used or Not
Concept Screening Matrix	No	Did not want to screen out concepts
Concept Scoring Matrix	Yes	Wants the concepts to get scores to be able to rank them
Morphological Matrix	No	This method is used to generate concepts by combining solutions to certain criteria, the concepts are already generated at this stage
Analytical Hierarchy	No	A method to organize and analyze complex decisions, which was decided not needed in this project
Elimination Matrix	No	A method where concepts gets screened out because they do not pass criteria. This method is used in an earlier stage, the research stage, but is not used in the model and methodology creation
Indicators for Technology	Yes	Indicators are used to describe each technology in terms of technology readiness level and implementation ability
Combined Compromise Solution	No	A method where the criteria values is normalized into equations and from these get weighting to be able to compare the concepts against each other. In this project is the criteria not stated as specific numbers
Multi-Criteria Decision-Making Matrix	Yes	The method evaluates conflicting criteria, which is useful and necessary in this project
Design Structure Matrix	Yes	Visualizes which technologies that can not be combined, which is necessary information in this report to notice
Technology Management Tools: Generalization, Integration and Configuration	No	A method that describes how to implement different kinds of tools and methods with each other. Is an interesting subject, but was not necessary in this work to study further
House of Quality / Quality Function Deployment	No	In this method is sub-solutions to a specific problem ranked from percentage of importance rating and how well the sub-solution reach requirements. In this project, it was not needed to find the best sub-solution to a specific problem, concepts was already generated
Sensitivity Analysis	Yes	This method studies how uncertain the output from a model is, this method will be used to check the created model
Enhanced Functions Means Model	No	Alternative designs can be created through reverse engineering. In this project is the possible solutions already found
Value Model	No	This model has been used to understand the goal better, to include the company, the customer and the environment but is not used in this stage, the model and methodology creation stage
Change Propagation	Yes	This method analyzes if there is a change needed to a product, are other components then affected by this change and needs a reconstruction? This has been useful in this project to understand the implementation ability
Value-Driven Design	No	The method encourages design optimization by eliminating the performance requirements constraints. This was not used in this project since this is not this type of development
Parallel-Coordinate Plots	No	The method is used for plotting large amounts of data by plotting parallel lines in the background to highlight additional information than in an ordinary x and y axis plot. This was not needed in the project since it was only necessary to plot two parameters at a time
Delphi Method	No	This method is performed by giving some experts questions and then giving the experts a summarized version of the answers. By giving the experts the same questions again it is found that the answers will converge against the most correct answer. This method was not useful in this project because it was not necessary to have exact numbers since the focus was on the methodology creation and experts within each technology could not be found

3.2 Model And Methodology Creation

To create the model, a methodology has been constructed and followed. The methodology consists of finding criteria and defining them and based on the criteria being able to perform a MCDM matrix. On the matrix, it was suitable to perform a sensitivity analysis. A design structure matrix was helpful to realize which technologies that could not be combined and then the model was created in Matlab, Simulink and App Designer.

3.2.1 Cost For The Technologies

The cost for each technology is presented in Table 3.3 and is based on the literature study in the theory chapter. These costs will be used as a criteria in the methodology. The reason the cost was selected as a criteria was based on the goal stating that the efficiency should increase with the cost taken into account. The cost is one of the most important factors when it comes to significant attributes for all stakeholders. With improvements for a low cost, there is a possibility of either delivering better profit margin or lowering the sales prices. The costs will be graded from one to five in the compilation of the technologies ranking, and the span for each grade

is presented below.

1. = 64000-80000 SEK
2. = 48000-64000 SEK
3. = 32000-48000 SEK
4. = 16000-32000 SEK
5. = < 16000 SEK

Table 3.3: The cost for the technologies

Technologies	Cost [SEK]
Direct Water Injection	7000
Continuously Varying Transmission	29000
Single Speed Transmission	5000
Variable Compression Ratio	2000
Variable Valve Actuation	7000
Turbo Compounding	30000
Emulsified Fuel	7000
Organic Rankine Cycle	80000
Cylinder Deactivation	4500
Dynamic Skip Fire	6375
Thermal Barrier Coating	2800
Rotational Liner Engine	29000

3.2.2 Trustworthiness

Trustworthiness is a factor that is important for this creation of the methodology since the data found about the different technologies has been of varying levels of trustworthiness. The trustworthiness can get a grade between one to five, where the five represents the best grading, see list below. The grade decision is based on an overall impression and the information the research on the technologies provided. A compilation of the grading can be seen in Table 3.4. The grading of the trustworthiness will not be used in the comparison of the technologies, they will be used as a validation at the end of the project and as a help to understand how trustworthy the results are.

1. = There was lack of vital data and unreliable assumptions were necessary
2. = The data was not representing the relevant environment but showed the overall performance of the technology with room for assumptions
3. = The data was representing similar operating conditions, but assumptions were made
4. = The data was presented with relevant operating conditions and with information that indicated high reliability
5. = The data was presented with relevant operating conditions and with information that could not be misinterpreted

3. Methodology And Results

Direct Water Injection was given a two in trustworthiness, which is based on the information found about the efficiency does not clearly describe what kind of load cases are being used. Therefore was an assumption that the efficiency was constant for all the different load cases. This assumption was also based on another study with other load cases where this assumption is pointed out to be reliable.

Continuously Varying Transmission was graded a four in trustworthiness because the information is based on test data for a D13 engine. The technology did not get a five since the efficiency was based on recalculations from test data of how a CVT is supposed to behave. Single Speed Transmission also got a four based on the same assumptions, since the calculations were conducted similarly.

Variable Compression Ratio got a grading of five since the data used was from Volvo and simulations have been executed with this specific technology purchased from FEV.

Variable Valve Actuation got a three in trustworthiness based on the relevance of the test that was executed. The speed was changing instead of the torque when the load was changing. For more reliable information, the speed should be the same for all the load cases.

Turbo Compound got a grading of four since it was a technology available at Volvo, but was not tested in a GenSet. The numbers from an engine with a Turbo Compound have been compared with a GenSet engine. This technology got a four based on the same motivation as the Continuously Varying Transmission.

Emulsified Fuel got a grade of two in trustworthiness since the test from which the information was gathered did not provide sufficient relevant data. The test was carried out at different load cases where the engine speed was changed instead of the torque to deliver different loads. Another reason for the low grading is that information was only available for the load cases 100% and 75%. After these loads, it was assumed, by looking at a graph during the research phase, that the difference gets stabilized and the same efficiency is set for the three other load cases.

Organic Rankine Cycle got the highest grade since the conducted simulation used relevant operating conditions, that corresponded to the current engine. The information also came from a master's thesis performed at Volvo Penta that described how to find improvements for each load case.

Cylinder Deactivation got a two in trustworthiness because the information was taken from a test where the test cycle had an average load of 25% and the cycles were transient.

Dynamic Skip Fire got a rating of four since the test data used was based on a test with a test cycle where the average load was 25%. This data was analytical and values for all the different load cases at various speeds could be found in the diagram.

Thermal Barrier Coating got a three in trustworthiness because the data was missing information about the highest and lowest load cases and the engine did not cohere with the requested environment.

Rotational Liner got a rating of one in trustworthiness since the data for all the load cases were missing and the data presented in this report were assumed based on what was described in the text about the technology.

Table 3.4: Trustworthiness weighting

Technologies	Trustworthiness
Direct Water Injection	2
Continuously Varying Transmission	4
Single Speed Transmission	4
Variable Compression Ratio	5
Variable Valve Actuation	3
Turbo Compounding	4
Emulsified Fuel	2
Organic Rankine Cycle	5
Cylinder Deactivation	2
Dynamic Skip Fire	4
Thermal Barrier Coating	3
Rotational Liner Engine	1

3.2.3 Implementation Ability

Implementation ability is one of the factors for comparing the technologies against each other. It is a difference between the ability to implement a technology almost directly with minor adjustments and the need to reconstruct parts that gets affected by the new components. This was a result of using the method change propagation. The implementation ability for each technology can be seen in Table 3.5 and comments for each decision in the text below. The grade decision was based on an overall impression and the information the literature study provided.

1. = Required internal development of the technology and redesign occurred.
2. = Purchase from a supplier was required and redesign occurred.
3. = Purchase from a supplier was required and minor redesign might occurred.
4. = Purchase from a supplier was required and could be implemented directly without redesign or complexity.
5. = Could be implemented directly without redesign or complexity. The technology was already available within the company.

3. Methodology And Results

Direct Water Injection got a grade of three since this technology required a minor engine block redesign to enable the technology's connection. Software changes was also required.

Continuously Varying Transmission got a grade of two in implementation ability since space had to be made for the technology and it was assumed that this technology required a reprogramming of the control scheme.

The Single Speed Transmission got a grade of three because space had to be made for the technology and the speed was required to be reprogrammed.

Variable Compression Ratio got a four in implementation ability since the technology only required a change for some parts and no extensive changes. The connecting rod had to be exchanged for a new one and the new connecting rod was including the Variable Compression Ratio technology and there was no need for any additional software. Volvo already had a contact created with a possible supplier called FEV.

Variable Valve Actuation got a grade of three because the technology only required changing from the old valves to new valves, including the technology Variable Valve Actuation. An additional software for this technology was needed. Volvo had a contact with a possible supplier, Eaton.

Turbo Compound got a five in implementation ability since this technology was existing at Volvo and the information about the redesign that was required was also already available.

Emulsified Fuel got a three because the technology required minor redesign of the involving parts. Moreover, the implementation has to be performed by adding additional components.

Organic Rankine Cycle got a three in grade since the technology required redesign at the attachment of the exhaust system. The technology required some extra space but the parts did not have fixed places where they needed to be placed and could therefore be placed where space was available.

Cylinder Deactivation got a grade of three in implementation ability since the old valves had to be changed into new ones. Possible suppliers for this technology was either Jacobs or Eaton and Volvo had contact with Eaton already. An additional software had to be implemented.

Dynamic Skip Fire got a four in implementation ability because the valves had to be changed in the same manner as for Cylinder Deactivation. In this technology was although the software included and was based on algorithms.

Thermal Barrier Coating got a four since the same components could be used without reconstructions, but had to be sent to a supplier for coating. The pistons and

the combustion chamber including the exhaust port and valves was supposed to be coated in this case.

Rotational Liner got the grade of one since redesign of nearby parts had to be re-designed and a new camshaft, a new crankshaft, new pistons and new cylinders that includes the rotational liner function had to be implemented.

Table 3.5: Implementation ability weighting

Technologies	Implementation ability
Direct Water Injection	3
Continuously Varying Transmission	2
Single Speed Transmission	3
Variable Compression Ratio	4
Variable Valve Actuation	3
Turbo Compounding	5
Emulsified Fuel	3
Organic Rankine Cycle	3
Cylinder Deactivation	3
Dynamic Skip Fire	4
Thermal Barrier Coating	4
Rotational Liner Engine	1

3.2.4 Technology Readiness Level

Technology Readiness Level (TRL) analysis was a method to understand the maturity level of a particular technology. Each level had specific requirements and to reach a certain level in the TRL table the technology had to comply with all the requirements for the specific level. The ten requirements used in this project came from Volvo Penta. When doing the TRL it was important to implement the technology for a specific purpose. In this case, it was in a GenSet engine at Volvo. A TRL was used in this project since the information about the maturity of the technology was of great importance. Information about different TRL levels was required since technologies needs different amounts of work before launch. The TRL analysis conducted for this project did not include all necessary steps and procedures for a fully executed TRL analysis. For this project, the analysis included an estimation of the TRL based on the knowledge from the literature study.

In Table 3.6, the different TRL requirements was stated in the left column. Each technology was presented in green at which TRL level the technology was placed, regarding diesel engines in GenSets at Volvo Penta. In the green boxes, it was also stated what the decisions are based on. To implement the technology readiness level, seen in Table 3.6, in the MCDM matrix, where all factors are weighted together, the TRL levels were divided by two before being implemented. This was done because

3. Methodology And Results

the other factors were weighted from one to five and therefore this factor should also have the same magnitude.

Table 3.6: Technology readiness level for each technology

TRL/Technology	Definition	Direct Water Injection	Continuously Varying Transmission	Single Speed Transmission	Variable Compression Ratio	Variable Valve Actuation	Turbo Compounding
TRL1	Have basic principles been identified that could potentially form the basis of a new or improved technology?	Yes	Yes	Yes	Yes	Yes	Yes
TRL2	Has key elements of the technology been identified and expected benefits formulated?	Yes Research of the technology has been made and benefits has been noted	Yes	Yes An analytical verification has been executed.	Yes	Yes Research of the technology has been made and benefits has been noted	Yes
TRL3	Has analytical and experimental proof-of-concept been demonstrated?		Yes An analytical verification and a 1D simulated verification has been executed.		Yes Has been simulated in a relevant environment		Yes
TRL4	Has a prototype of the key elements of the technology been demonstrated in a laboratory environment?						Yes
TRL5	Has a representative system prototype of the technology been demonstrated in a relevant environment (product/process)?						Yes
TRL6	Has a representative system prototype of the technology been demonstrated in the targeted environment (product/process)?						Yes Verification in a representative engine has been executed
TRL7	Has a system prototype, in a near final form, been successfully operated under expected conditions?						
TRL8	Has an identical unit of the technology been successfully qualified under operational conditions (field tests)?						
TRL9	Has an identical unit of the technology been successfully launched/operated on market in an identical configuration?						
TRL10	Is the technology commercially available in a GenSet at Volvo Penta?						

TRL/Technology	Definition	Emulsified Fuel	Organic Rankine Cycle	Cylinder Deactivation	Dynamic Skip Fire	Thermal Barrier Coating	Rotational Liner Engine
TRL1	Have basic principles been identified that could potentially form the basis of a new or improved technology?	Yes	Yes	Yes	Yes	Yes	Yes
TRL2	Has key elements of the technology been identified and expected benefits formulated?	Yes Research of the technology has been made and benefits has been noted	Yes	Yes Research of the technology has been made and benefits has been noted	Yes Research of the technology has been made and benefits has been noted	Yes Research of the technology has been made and benefits has been noted	Yes Research of the technology has been made and benefits has been noted
TRL3	Has analytical and experimental proof-of-concept been demonstrated?		Yes Has been verified in a 1D simulation				

3.2.5 Efficiency In D2 Cycle

In the twelve tables, Appendix F.1 - Appendix F.12, the different efficiency improvements for the technologies could be seen. To compare the technologies against each other, the efficiencies at the different load cases were multiplied with the weighting specific to the D2 cycle. In Table 2.1 the weighting for the D2 cycle can be seen. In the right column of Table 3.7, the sum of the overall efficiency increase for each technology is presented.

Table 3.7: Weighted efficiency D2 cycle for the different load cases

Technologies/Load	100%	75%	50%	25%	10%	Sum
Weighted Efficiency D2 Cycle	0,05	0,25	0,3	0,3	0,1	
Direct Water Injection	0,204	1,02	1,224	1,224	0,408	4,1
Continuously Varying Transmission	0,15	0,5	0,9	1,8	2,3	5,7
Single Speed Transmission	0	0,5	0,6	0,6	1,9	3,6
Variable Compression Ratio	0	0,395	1,377	0	0,352	2,1
Variable Valve Actuation	0,05	0,8	0,9	0,9	0,3	3,0
Turbo Compounding	0,85	1,25	0,6	0,6	0,3	3,6
Emulsified Fuel	0,435	1,825	1,5	1,5	0,05	5,3
Organic Rankine Cycle	0,39	1,9	1,29	2,88	0,6	7,1
Cylinder Deactivation	0	0	0	1,8	0,9	2,7
Dynamic Skip Fire	0	0	0	1,5	1,5	3,0
Thermal Barrier Coating	0,265	1,325	3	2,34	2,03	9,0
Rotational Liner Engine	0,175	1,75	2,4	2,7	1	8,0

3.2.6 Ranking Of Technologies

The Multi-Criteria Decision-Making matrix was chosen because the method evaluates conflicting criteria, which in this project were the efficiency, the cost, the technology readiness level and the implementation ability. These factors were also a part of the method that was studying indicators of technology, where these indicators resulted in the conflicting criteria in the Multi-Criteria Decision-Making matrix. There was no obvious solution of which technology combinations were the most optimal, and it was therefore necessary to use this method to differentiate between the concepts. By using the concept scoring method, the technologies could get a value and be compared against each other based on that value. Each criterion was weighted from one to five based of how important the criterion was. The numbers for each respective technology were then multiplied with the weighting of the criteria and the different values for each technology were summarized. When all the technologies had a total value, a ranking of the technologies was done with respect to the criteria.

The four factors: increased efficiency, cost, TRL and implementation ability were weighted with the respect to importance in this study. The increased efficiency got the highest weighting, a five, since increasing the efficiency was assumed to be the most important aspect concerning the scope. The cost got a three since it was important to consider the price because the customers would not buy the product if it were too costly. Although, the cost was not of as high importance as the efficiency. The TRL level got a four since it was important to know at what stage the technology was at. Development takes a long time, is costly and technology with a high TRL level was therefore advantageous since it could start to be used faster. It is assumed to be more important than the cost, since both cost and longer development time are variables that get impacted when studying TRL. A higher TRL

3. Methodology And Results

level is therefore advantageous. Implementation ability also got a three because it was more advantageous the less redesign that had to be done. It was assumed to be less important than the TRL level, since the implementation ability will not directly present how costly or how long the implementation would take. The results from Table 3.3, Table 3.5, Table 3.6 and Table 3.7 was put in Table 3.8 and multiplied with the weighting of importance for each factor. The sum and ranking can be seen at the bottom of the table.

The ranking process showed that the most promising technology to implement would be the TBC technology. Since this was a technology with a high increase of efficiency, it was given the highest ranking in that specific criteria. The sum of TBC was significantly better compared to the other technologies. The trustworthiness of this technology was given a grade of three, indicating that the information needs to be verified to conclude that this was the most optimal technology selection.

Table 3.8: Ranking of the technologies with regard to efficiency, cost, TRL level and implementation ability

Technologies							
Criteria	Weight	Direct Water Injection	Continuously Varying Transmission	Single Speed Transmission	Variable Compression Ratio	Variable Valve Actuation	Turbo Compounding
Increased Efficiency [%]	5	2	2,8	1,8	1,1	1,5	1,8
Cost [SEK]	3	5	4	5	5	5	4
TRL	4	1	1,5	1	1,5	1	3
Implementation Ability	3	3	2	3	4	3	5
Sum		38	38	37	38,5	35,5	48
Ranking		6	6	7	5	8	2
Criteria	Emulsified Fuel	Organic Rankine Cycle	Cylinder Deactivation	Dynamic Skip Fire	Thermal Barrier Coating	Rotational Liner Engine	
Increased Efficiency	2,7	3,5	1,4	1,5	4,5	4	
Cost	5	1	5	5	5	4	
TRL	1	1,5	1	1	1	1	
Implementation Ability	3	3	3	4	4	1	
Sum	41,5	35,5	35	38,5	53,5	39	
Ranking	3	8	9	5	1	4	

3.2.7 Sensitivity Analysis

When developing a Multi-Criteria Decision-Making matrix, the weighting of the criteria is one of the significant factors for the ranking outcome. A sensitivity analysis was performed to understand how well defined the weighted criteria were and how robust the selection model was. The analysis was performed to answer two critical questions, *How much impact did the choice of the weighting for the different criteria have on the ranking results?* and *How much impact did the individual criteria have on the ranking result?*. To be able to answer these questions, two different analytical analyzes were conducted.

The first scenario was performed by defining all the criteria with equal weighting, see Appendix G.1. The second scenario was conducted by reordering the hierarchy

of the criteria, with the highest weighting criteria to the lowest value and the criteria with the lowest weighting to the highest value and so on, see Appendix G.2. By changing the weighted values, an understanding of how much impact it had on the individual technologies were discovered, see Table 3.9. The three scenarios, including the original case, were visualized in a graph where the ranking position for each technology was presented for each scenario, see Figure 3.2. It could be interpreted that most technologies changed one ranking position, but two technologies stood out. The RL went from position four to eleven between the original and the equal weighted scenarios and the CDA changed position from twelve to eight from the original to the equal weighted scenario. There was also an identification of more minor position changes for the technologies on the more advantageous half of the scoreboard compared to the other half. This is because there were more minor differences between the sum values for the higher scored technologies. This could have resulted in more extensive changes in the ranking result. Although the analysis showed that the selection model was trustworthy.

Table 3.9: Ranking result for scenario: original, 2 & 3

Ranking position from the different scenarios						
weight scenario	Direct Water Injection	Continuously Varying Transmission	Single Speed Transmission	Variable Compression Ratio	Variable Valve Actuation	Turbo Compounding
1	5	5	9	5	10	2
2	6	8	7	3	8	2
3	6	10	7	3	7	1
weight scenario	Emulsified Fuel	Organic Rankine Cycle	Cylinder Deactivation	Dynamic Skip Fire	Thermal Barrier Coating	Rotational Liner Engine
1	3	10	12	5	1	4
2	3	12	8	3	1	11
3	5	12	7	3	2	11

3. Methodology And Results

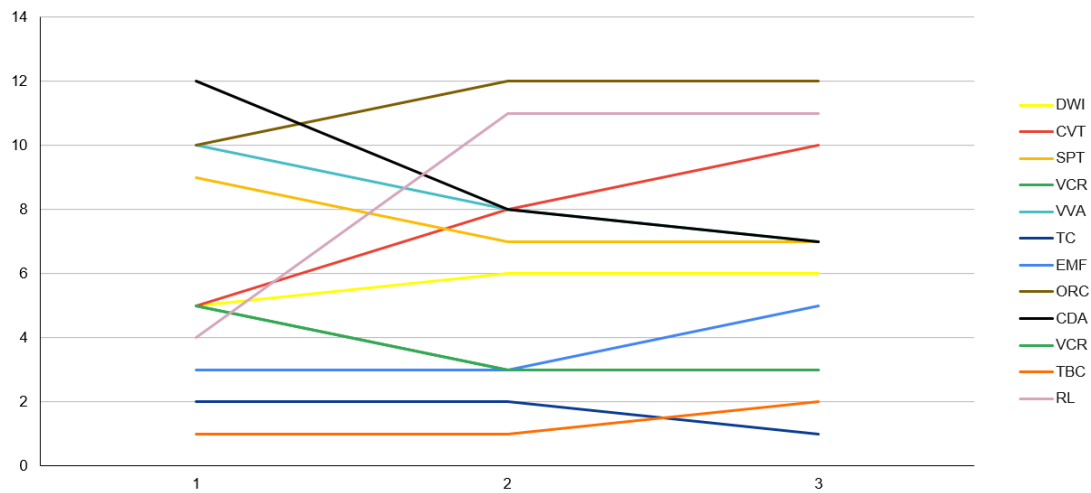


Figure 3.2: Changes in ranking position for different scenarios

The second analysis was performed by creating four different scenarios where one of the criteria was excluded. This analysis developed an understanding of how great of an impact the individual criteria had on the different technologies, see Table 3.10. To visualize the result from the analysis, a graph is shown with the five different scenarios on the x-axis where the first scenario is the original and the ranking position for each scenario is shown on the y-axis, see Figure 3.3. The excluded criteria were ordered as followed: cost, efficiency, TRL, and implementation ability. It could have been interpreted that most changes in position occurred when the TRL criteria were excluded.

Table 3.10: The ranking result for the different scenarios

Criteria	Direct Water Injection	Continuously Varying Transmission	Single Speed Transmission	Variable Compression Ratio	Variable Valve Actuation	Turbo Compounding
Original	5	5	9	5	10	2
Without Cost	7	5	10	7	11	2
Without Efficiency	5	10	5	2	5	1
Without TRL	5	7	7	7	10	3
Without Implementation Ability	6	3	7	8	8	3
Criteria	Emulsified Fuel	Organic Rankine Cycle	Cylinder Deactivation	Dynamic Skip Fire	Thermal Barrier Coating	Rotational Liner Engine
Original	3	10	12	5	1	4
Without Cost	5	3	12	7	1	4
Without Efficiency	5	12	5	3	3	11
Without TRL	2	12	10	5	1	3
Without Implementation Ability	3	8	12	8	1	2

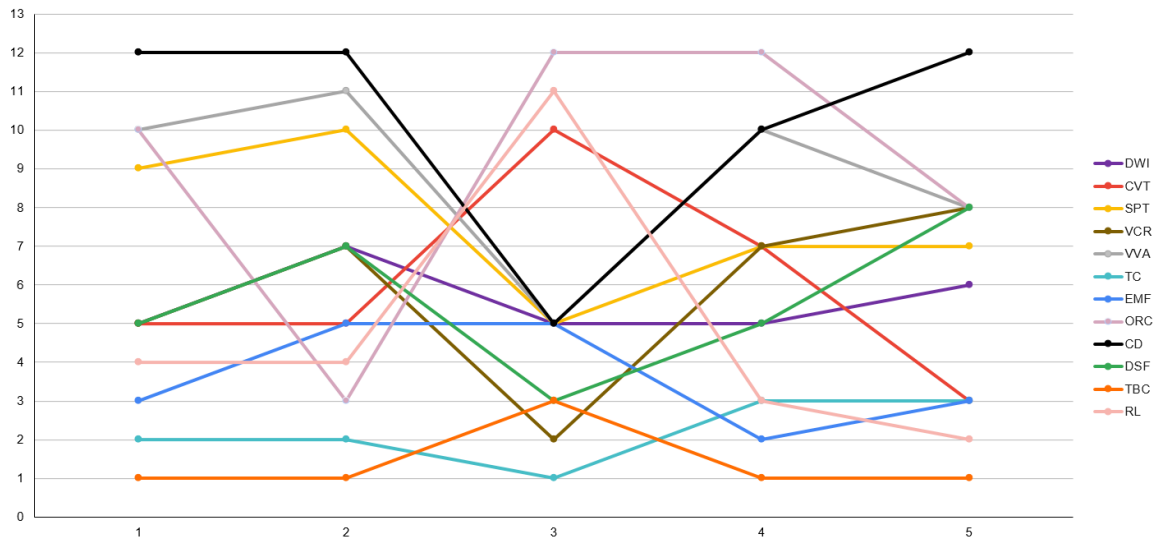


Figure 3.3: Visualization of the ranking position for different scenarios

3.2.8 Design Structure Matrix

A Design Structure Matrix was a square matrix containing the technologies on the first row and the first column. The matrix represented relationships between the technologies. This method visualized which technologies that could be combined and which technologies that could not operate at the same time. An "X" in the matrix described that a linkage between the technologies was found and an empty box described that no linkage was found and therefore could the technologies not be combined. This method was used to understand which combinations that did not work together and could be removed from the total list of combinations that the methodology for this project generated.

Before starting the methodology creation, this matrix was performed, see Table 3.11. Combinations of Continuously Varying Transmission and Single Speed Transmission were not a working combination. This was because these two were the same type of technology, only different types of transmissions. Neither were Direct Water Injection and Emulsified Fuel working together since these technologies were connected at the same place at the engine. It was contradictory to cool down the combustion chamber with DWI and then use Emulsified Fuel afterwards. Turbo Compound and Organic Rankine Cycle were neither working together since both of them were a solution for waste heat recovery. These technologies were optimal when the input temperature was high and resulted in higher engine efficiency and lower exhaust gas temperature. If one of these technologies was used, it was unnecessary to use the other one since the temperature input was too low. The last combination that was not working together was Cylinder Deactivation and Dynamic Skip Fire since these were almost the same technology except that Dynamic Skip Fire has an additional software.

Table 3.11: Design structure matrix

Technologies	Direct Water Injection	Continuously Varying Transmission	Single Speed Transmission	Variable Compression Ratio	Variable Valve Actuation	Turbo Compounding	Emulsified Fuel	Organic Rankine Cycle	Cylinder Deactivation	Dynamic Skip Fire	Thermal Barrier Coating	Rotational Liner Engine
Direct Water Injection		X	X	X	X	X		X	X	X	X	X
Continuously Varying Transmission	X			X	X	X	X	X	X	X	X	X
Single Speed Transmission	X			X	X	X	X	X	X	X	X	X
Variable Compression Ratio	X	X	X		X	X	X	X	X	X	X	X
Variable Valve Actuation	X	X	X	X		X	X	X	X	X	X	X
Turbo Compounding	X	X	X	X	X		X		X	X	X	X
Emulsified Fuel		X	X	X	X	X		X	X	X	X	X
Organic Rankine Cycle	X	X	X	X	X		X		X	X	X	X
Cylinder Deactivation	X	X	X	X	X	X	X	X			X	X
Dynamic Skip Fire	X	X	X	X	X	X	X	X			X	X
Thermal Barrier Coating	X	X	X	X	X	X	X	X	X	X		X
Rotational Liner Engine	X	X	X	X	X	X	X	X	X	X	X	

3.2.9 Matlab And Simulink

Matlab and Simulink were the tools used for the creation of the model. Simulink was chosen because it could create a graphical model and simulate a dynamic system, which was the type of tool needed in this project.

The model creation in Matlab and Simulink started with the decision of having the structure of each technology connected in a series, as seen in Figure 3.4. All the information must pass through each technology and depending on if the technology was activated or not, the technology should give the respective data.

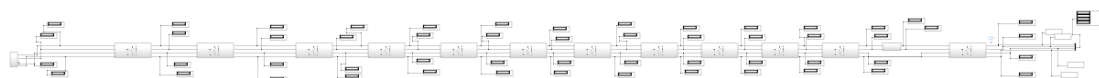


Figure 3.4: The structure of the simulink model

Furthest to the left in the model is the input values, which are the parameter values taken from the D13 engine as it is today, without any additional technologies. These values are the input in the first technology studied in this project.

Ten of the technologies were structured and created with the same structure, except the waste heat recovery technologies Turbo Compound and Organic Rankine Cycle which were created differently. The ten technologies that were created similarly to each other were constructed in a way that if the on/off switch were set to off, the input values would be transported directly to become the output values for the technology, this can be seen in Figure 3.5. If the on/off switch instead was set to on, the input values would be transported into another box within the technology, this new box can be seen in Figure 3.6. At this stage, it was included more on/off switches where the load was decided. If 100% load were being used, the on/off switch would have been activated and set to on, while the other on/off switches were set to off. When the load was decided, the inputs moved on to the next box, which can be seen in Figure 3.7. In the last box, the input parameters were multiplied with the respective factor that increased the parameter, decreased the parameter, or had the same value as before, if the technology did not change that specific parameter. The output from these boxes was the output from the entire technology and also the input to the next technology.

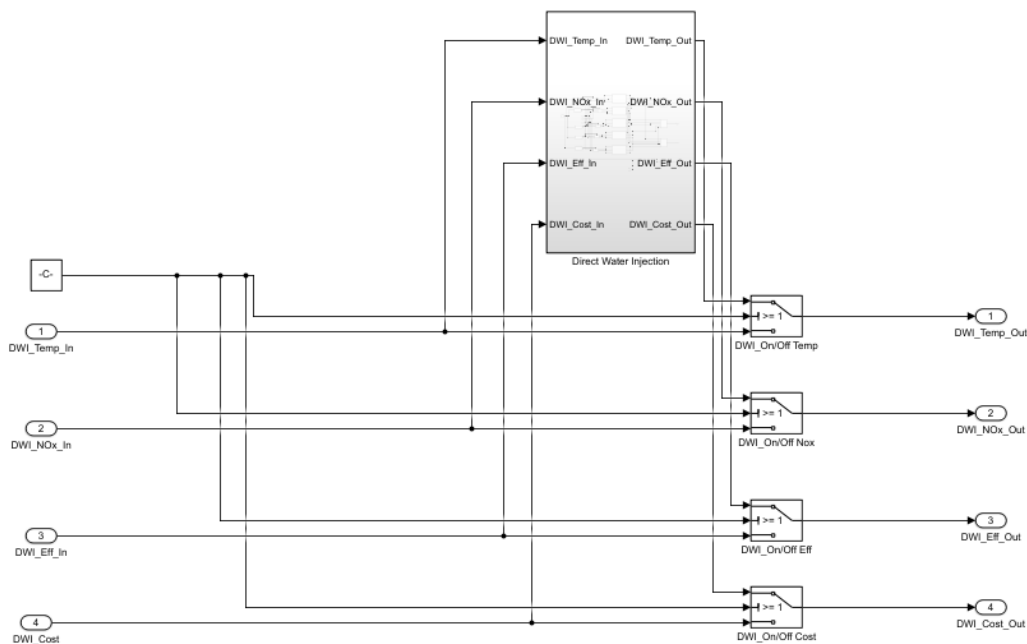


Figure 3.5: On/Off switch. Either the input transports directly to the output or into the next box

3. Methodology And Results

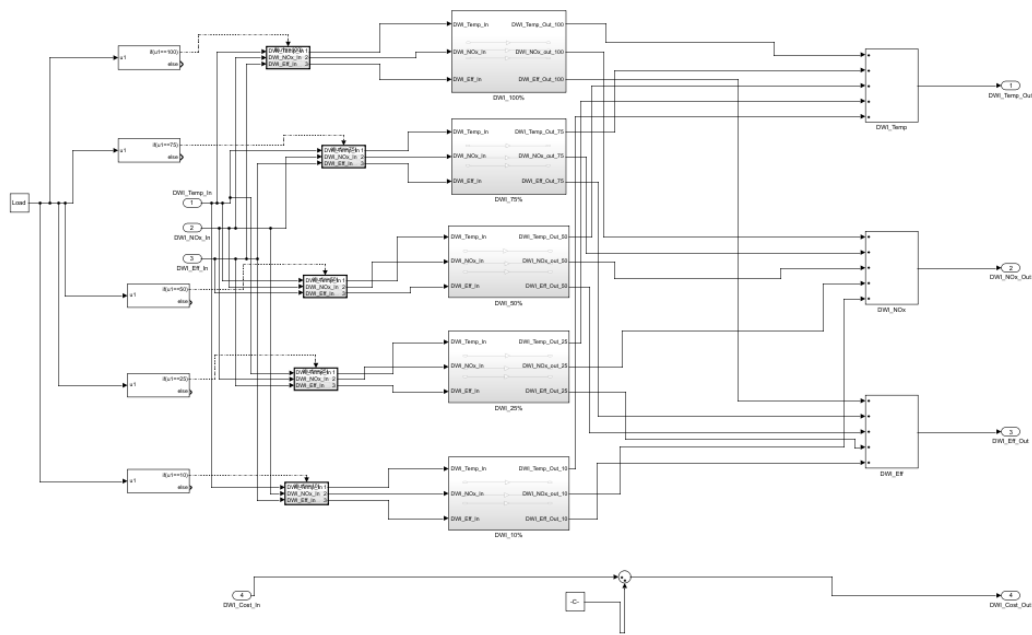


Figure 3.6: On/Off switches depending on load case.

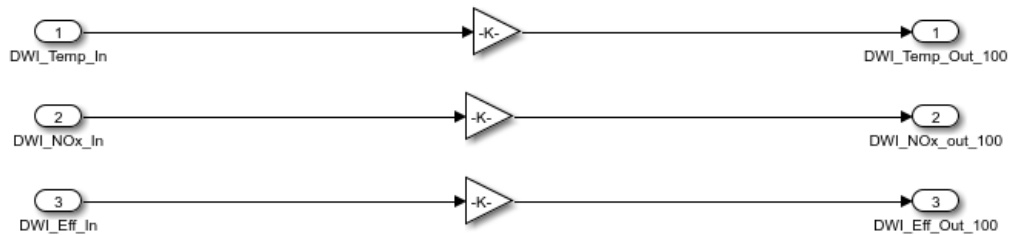


Figure 3.7: Inputs are multiplied with a factor for the specific technology and load case. The new value is then transported to the output of the technology

Turbo Compound and Organic Rankine Cycle had on/off switches to determine whether the technology should be active or not and for choosing the different load cases. Instead of changing parameters by multiplying with a factor, these technologies increased the efficiency depending on the temperature input. A function was used inside these boxes and based on different temperature ranges different improvement factors for the efficiency were being used, see Appendix C.1 and Appendix D.

The SCR was also included in the model since it reduced the NO_x emissions and the temperature of the exhaust gases. The SCR should be placed before the waste heat recovery technologies. Still, since the information Turbo Compound was based on already had SCR included, the SCR was placed behind the Turbo Compound and before the Organic Rankine Cycle. The SCR lowered the NO_x emissions based on the temperature and would result in an output of a lower temperature and a lower amount of NO_x emissions. The SCR did not change the efficiency of the engine and

it did not have an additional cost since an SCR already was included in the D13 engine.

The Simulink model was created with variables of all the different parameters. The variables were defined in a Matlab script with headlines for each technology to enable manageable changes if parameter values were found not to be accurate.

3.2.10 Graphical User Interface

A graphical user interface was created in Matlab's App Designer to simplify the usage of the model. When the app is started, the first viewing window is the simulation window. The starting view of the app can be seen in Figure 3.8. The first step is to choose which load case that should be simulated. For running the simulation, there are two possible options, either running the simulation manually or running the simulation automatically. If the simulation should be run manually, technologies included in the evaluation must be chosen before the "simulate" button is pushed. When the button is pressed, the program will calculate the new parameters. Suppose the results tab is pressed and the results from the manual simulation are chosen. In that case, the efficiency, the amount of NO_x emissions, the new temperature output and the cost for the additional technologies will be shown which is visualized in Figure 3.9. By using the manual simulation tab, specific combinations can be tried and results and answers can be received after a few seconds.

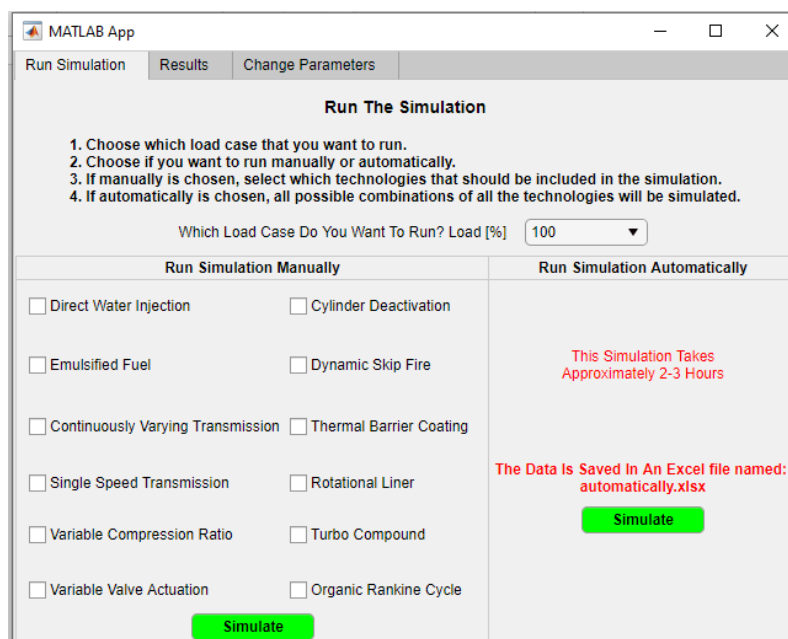


Figure 3.8: Start view of the app

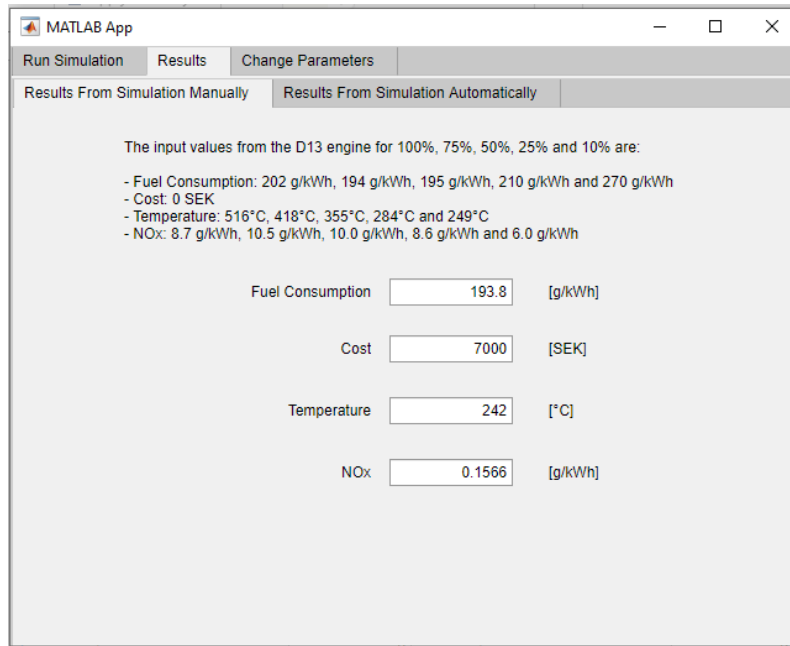


Figure 3.9: Results from manually simulation is visualized in this tab and comparative input numbers are stated

By running the simulation automatically, all possible combinations of all the technologies will be evaluated and the results will be saved in an excel file for the user to continue to analyze afterwards. This simulation takes approximately two to three hours depending on the capacity of the computer. Suppose the results tab is pressed after the simulation is done and instead the results from the simulation automatically are chosen. In that case, a graph is visualizing the cost on the x-axis and increased efficiency on the y-axis. For all the different combinations, this graph is shown below in Figure 3.10.

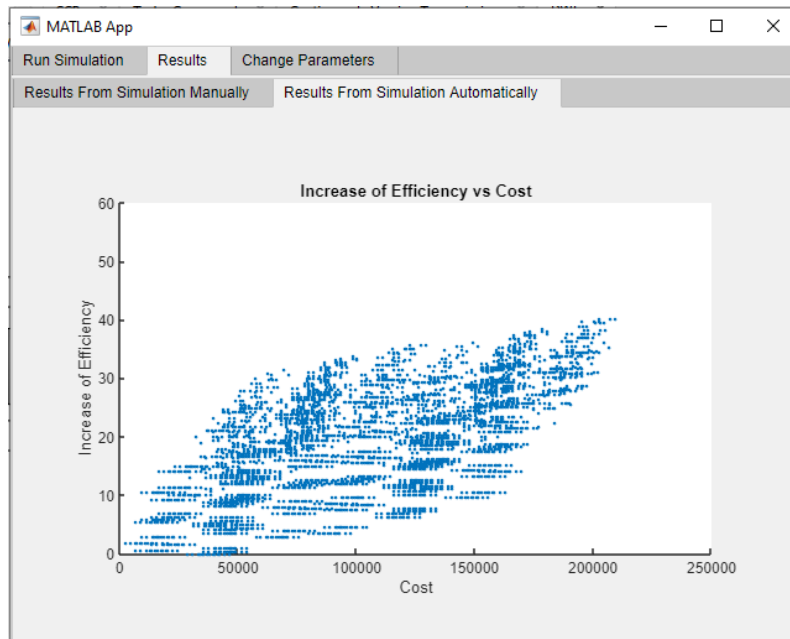


Figure 3.10: The graph visualizing the increase in efficiency versus cost for all the different combinations

The third tab in the app is called change parameters and is only necessary to use if new information is found about the parameter values and has to be updated. The ten first technologies are designed in the same way, and the factors that can be changed are efficiency, temperature and NO_x for each load case and also the cost of the technology. For the last two technologies, it is possible to change the efficiency for the different temperature spans and also the cost for both technologies. An example of how the graphical user interface for the possibility of parameter value changes is seen below in Figure 3.11.

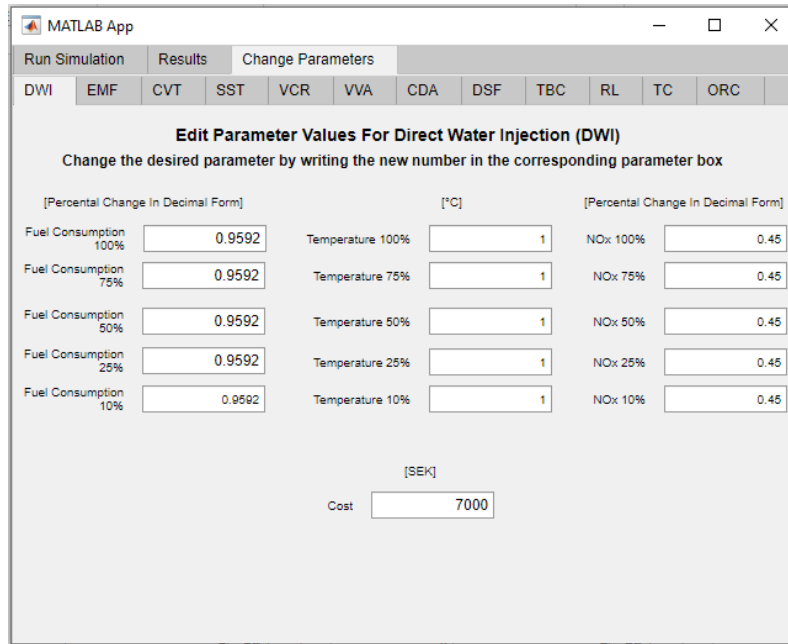


Figure 3.11: Parameter changes can be done in the app

3.3 Concept Selection

The first step in the concept selection procedure was a screening process of the inappropriate combinations. This was executed since the generic combination model generated all possible combinations from the twelve technologies. A graph was plotted that presented the increase in efficiency in relation to the summarized cost, see Figure 3.12. By using all the data points from the Matlab model, several combinations were shown that were not possible to implement. By excluding these combination based on the design structure matrix, see Figure 3.11, a more realistic visualization was presented, see Figure 3.13. This figure also excluded all the combinations that included the SST technology. The reason was based on that all the technologies needed to be able to perform under all conditions of the D2 cycle. Since the SST technology performance was limited to operating from 10-75% in load, the technology was inappropriate to include in this selection process. The figure also excluded combinations with duplicates in terms of cost, therefore only the combinations with the highest increase in efficiency for every cost were presented. Based on this graph, with all acceptable combinations, the most promising concepts were selected. This was executed by selecting the combinations that were on the top edge of the data points, the green ones.

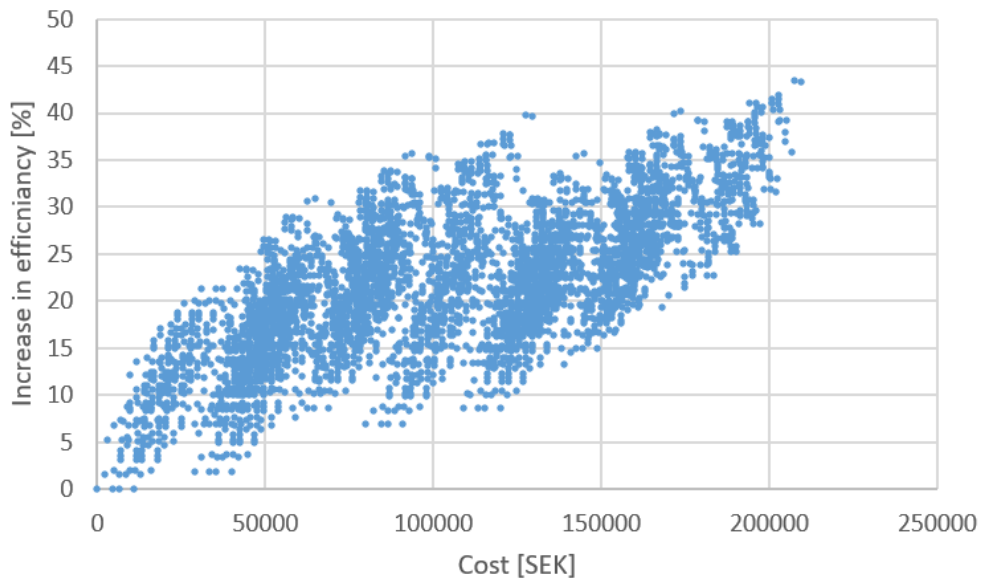


Figure 3.12: Cost vs increase in efficiency for all combinations

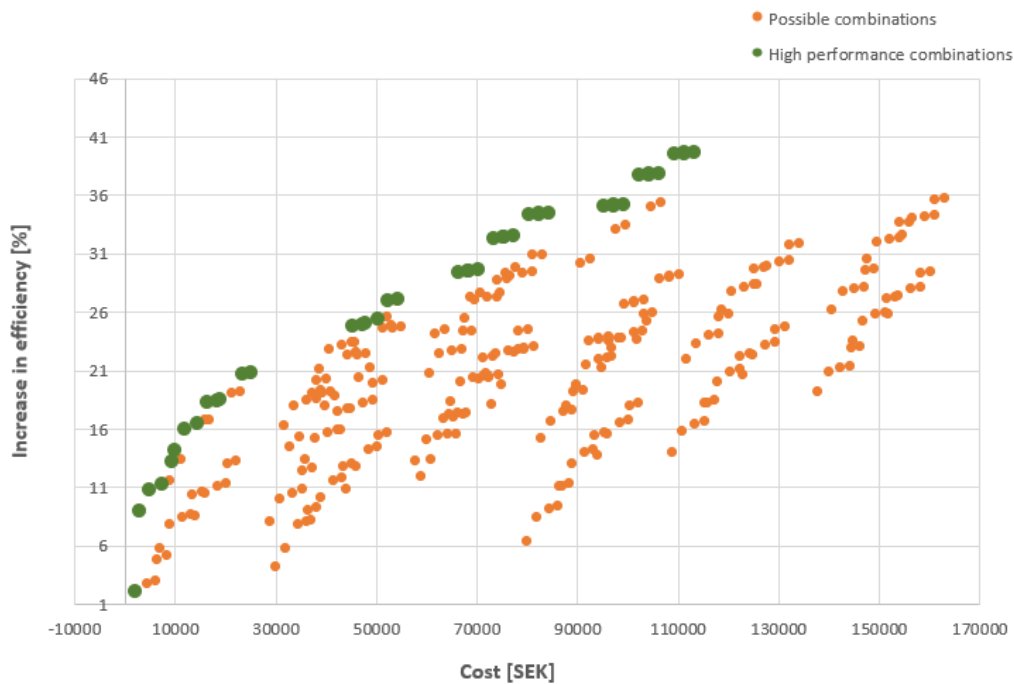


Figure 3.13: Efficiency vs cost for the possible combinations

The selected combinations were visualized in a graph where it could be shown that the relation between an increase in efficiency and cost was not linearly, see 3.14. It seems that the increase in efficiency was steeper for the lower costs and the steepness decreases with higher values for the cost. To understand the relations better, a visualization between the ratio of increase in efficiency and cost and the cost itself was plotted, see Figure 3.15. This visualization showed that there was an exponential

3. Methodology And Results

relation which demonstrated that the cost to increase the efficiency was increasing exponentially.

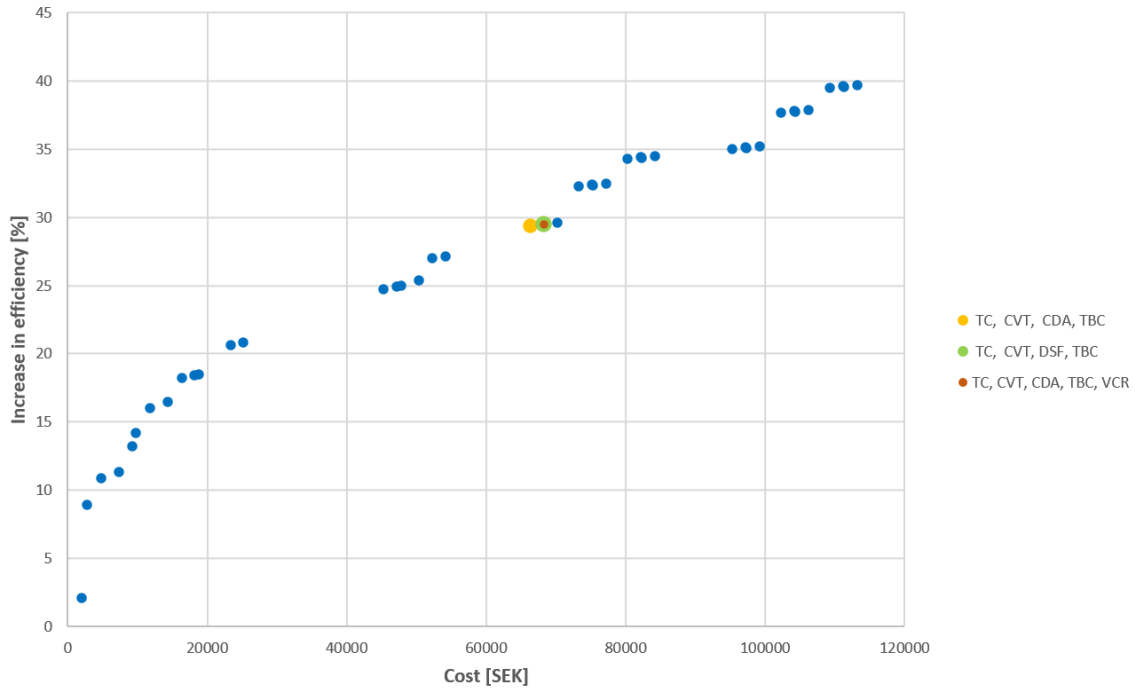


Figure 3.14: Increase in efficiency vs cost for the selected combinations

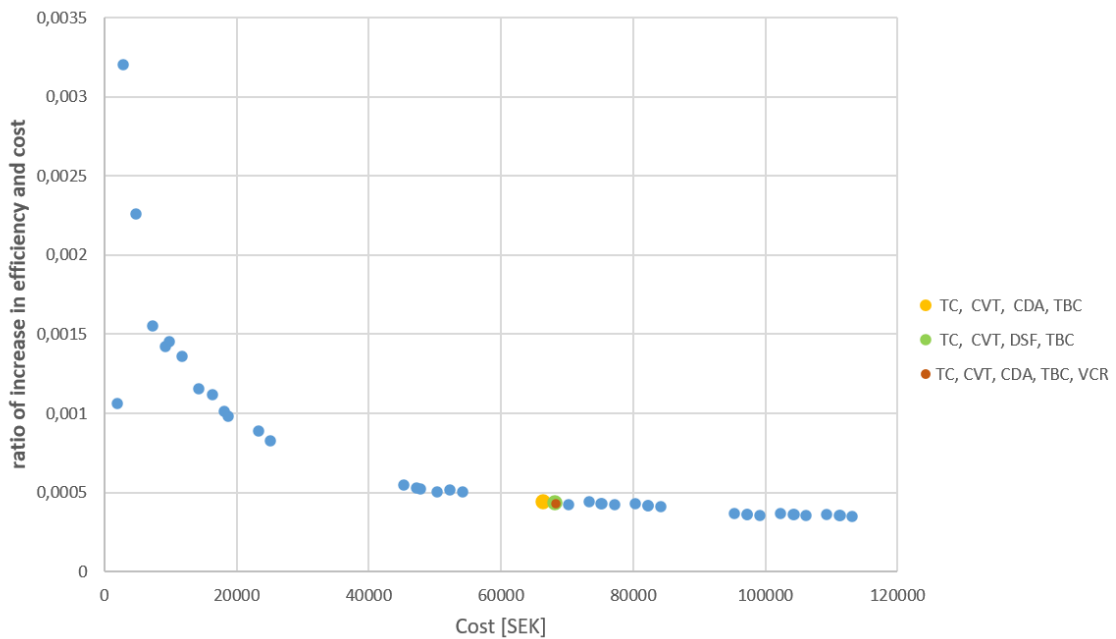


Figure 3.15: The relation of increase in efficiency and cost

The previously applied ranking method was performed to select the most promising

combinations out of the 40 selected from the screening process. One new criterion was added, in terms of NO_x emissions and this criterion could be investigated through the Matlab model. The criterion was added since some technologies impacted the exhaust gas temperature. The temperature change could lead to a change in the performance of the SCR component, which could result in an change in NO_x reduction. The scale of the ranking for all the parameters was changed to 1-10, to distinguish the performance of the technologies even more. The level of performance, which is the ranked value for the different criteria, was changed since the performance of a combination of technologies differs from the performance of a single technology, see 3.12. The level of performance for the criteria increase efficiency, cost and NO_x emissions were defined based on the lowest and the highest value from the 40 selected combinations. The TRL criteria were defined using the average value from the TRL assessment for all the technologies. Since the highest level of TRL for the twelve technologies was five, a suitable way to convert the performance level to a scale of ten was by multiplying the TRL value by two. The implementation ability criteria was defined by using the average value for all the included technologies and adding a supplement value based on how many technologies were included in the combination, see Table 3.13. By considering the number of technologies in the implementation criteria, a more realistic evaluation was created of how well the ability was to implement the technology combinations.

Table 3.12: The level of performance for different criteria

Criteria	Level of Performance									
	1	2	3	4	5	6	7	8	9	10
Increased Efficiency	<6	6–10	10–14	14–18	18–22	22–26	26–30	30–34	34–38	>38
Cost SEK	>104000	92000–104000	80000–92000	68000–80000	56000–58000	44000–56000	32000–44000	20000–32000	8000–20000	<8000
TRL		<1		2		3		4		>5
Implementation Ability		1		2		3		4		5
Implementation Ability (Corrected)	IA+NOT	IA+NOT	IA+NOT	IA+NOT	IA+NOT	IA+NOT	IA+NOT	IA+NOT	IA+NOT	IA+NOT
NOx Emission	>0,1	0,09–0,1	0,08–0,09	0,07–0,08	0,06–0,07	0,05–0,06	0,04–0,05	0,03–0,04	0,02–0,03	<0,02

Table 3.13: The influence from the number of technologies the combination have

Criteria	Number of technologies						
	2	3	4	5	6	7	>8
Influence on Implementation ability (Corrected)	2,25	1,5	0,75	0	-0,75	-1,5	-2,25

The Multi-Criteria Decision-Making matrix was utilized for the 40 combinations to make a well-founded selection based on the criteria, see Table 3.14. It could be seen that the three combinations with the highest score were combinations with similar technologies. All three concepts included the same three technologies and were using TC, CVT and TBC, where all of the mentioned technologies had top scores individually from the Multi-Criteria Decision-Making matrix, see Table 3.8. The technologies that separated the combinations were CDA, VCR and DSF.

Table 3.14: MCDM matrix for the 40 selected combinations

Technologies	Concepts Nr.	Increased Efficiency [%]	Cost [SEK]	TRL	Implementation Ability (Corrected)	NOx Emission	Sum	Ranking
Weight		0,3	0,2	0,15	0,2	0,15	1	
VCR	1	1	10	9,0	10,0	1	5,8	40
TBC	2	2	10	6,0	10,0	1	5,7	41
VCR, TBC	3	3	10	7,5	10,0	1	6,2	34
CDA, TBC	4	3	10	6,0	9,3	1	5,8	39
VCR, CDA, TBC	5	3	9	7,0	8,6	1	5,6	43
EMF, TBC	6	4	9	6,0	9,3	3	6,2	32
EMF, VCR, TBC	7	4	9	7,0	8,6	3	6,2	31
EMF, CDA, TBC	8	4	9	6,0	7,9	3	5,9	38
EMF, VCR, CDA, TBC	9	5	9	6,8	7,8	3	6,3	30
EMF, VCR, DSF, TBC	10	5	9	6,8	7,8	5	6,6	24
EMF, VCR, VVA, TBC	11	5	9	6,8	7,8	9	7,2	7
EMF, VCR, VVA, CDA, TBC	12	5	8	6,6	6,8	9	6,8	17
EMF, VCR, VVA, DSF, TBC	13	5	8	6,6	6,8	9	6,8	17
EMF, VCR, CDA, TBC, RL	14	6	6	6,6	6,0	3	5,6	42
EMF, VCR, DSF, TBC, RL	15	6	6	6,6	6,0	5	5,9	37
EMF, VCR, VVA, TBC, RL	16	6	6	6,6	6,0	9	6,5	27
EMF, VVA, CDA, TBC, RL	17	6	6	6,0	5,6	9	6,4	29
EMF, VCR, VVA, CDA, TBC, RL	18	7	6	6,5	5,3	9	6,7	20
EMF, VCR, VVA, DSF, TBC, RL	19	7	6	6,5	5,3	9	6,7	20
TC, CVT, CDA, TBC	20	7	5	9,8	7,8	10	7,6	1
TC, CVT, DSF, TBC	21	7	5	9,8	7,8	10	7,6	1
TC, CVT, VCR, CDA, TBC	22	7	5	9,6	7,2	10	7,5	3
TC, CVT, VCR, DSF, TBC	23	7	4	9,6	7,2	10	7,3	5
DWI, TC, CVT, CDA, TBC	24	8	4	9,0	6,8	5	6,7	23
DWI, TC, CVT, DSF, TBC	25	8	4	9,0	6,8	7	7,0	14
DWI, TC, CVT, VCR, CDA, TBC	26	8	4	9,0	6,3	5	6,6	26
DWI, TC, CVT, VCR, DSF, TBC	27	8	4	9,0	6,3	7	6,9	15
DWI, TC, CVT, VVA, CDA, TBC	28	9	4	8,5	5,9	9	7,3	4
DWI, TC, CVT, VVA, DSF, TBC	29	9	3	8,5	5,9	10	7,3	6
DWI, TC, CVT, VCR, VVA, CDA, TBC	30	9	3	8,6	5,4	9	7,0	13
DWI, TC, CVT, VCR, VVA, DSF, TBC	31	9	3	8,6	5,4	10	7,2	8
TC, CVT, CDA, TBC, RL	32	9	2	9,0	6,0	10	7,2	9
TC, CVT, DSF, TBC, RL	33	9	2	9,0	6,0	10	7,2	9
TC, CVT, VCR, CDA, TBC, RL	34	9	2	9,0	5,6	10	7,1	11
TC, CVT, VCR, DSF, TBC, RL	35	9	2	9,0	5,6	10	7,1	11
DWI, TC, CVT, CDA, TBC, RL	36	9	2	8,5	5,3	5	6,2	35
DWI, TC, CVT, DSF, TBC, RL	37	9	2	8,5	5,3	7	6,5	28
DWI, TC, CVT, VCR, CDA, TBC, RL	38	9	2	8,6	4,8	5	6,1	36
DWI, TC, CVT, VCR, DSF, TBC, RL	39	9	1	8,6	4,8	7	6,2	33
DWI, TC, CVT, VVA, CDA, TBC, RL	40	10	1	8,1	4,5	9	6,7	22
DWI, TC, CVT, VVA, DSF, TBC, RL	41	10	1	8,1	4,5	10	6,8	16
DWI, TC, CVT, VCR, VVA, CDA, TBC, RL	42	10	1	8,3	4,0	9	6,6	25
DWI, TC, CVT, VCR, VVA, DSF, TBC, RL	43	10	1	8,3	4,0	10	6,7	19

3.4 Final Concepts

The three selected concepts were visualized in the Figures below, see Figure 3.16, Figure 3.17 and Figure 3.18. There were evident similarities between the concepts as three technologies were involved in all the selected concepts. The first technology that all the concepts had in common was Continuously Varying Transmission, where a transmission box was implemented between the output shaft of the engine and the alternator. The engine would then be able to change the engine speed depending on the load and would always operate at optimal conditions. This implementation would have required reconstructions of the GenSet since there was no space for an implementation of a CVT in the current GenSet.

The next technology that all the concepts had in common was Turbo Compound. This technology would be able to use the energy losses from the exhaust gas and would have utilized it for either electrical energy or mechanical energy. The TC technology would be implemented between the EGR system and the SCR. The implementation possibilities of this technology were relatively high since the technology

and the implementation has already been performed in a D13 engine at Volvo Trucks.

The last technology that the concepts had in common was Thermal Barrier Coating. This implementation reduced the thermal losses in the combustion chamber by changing the thermal conductivity on the surface of the combustion chamber parts: pistons, cylinders, exhaust port valves and heads. The coating layer would have a negligible thickness, resulting in no reconstructions of the various parts.

3.4.1 Concept Nr.20

The first selected concept, Concept Nr.20, used CVT, TC, TBC and cylinder Deactivation, see Figure 3.16 and Table 3.15. This last technology was both utilized in the first and third concepts. The contribution from the technology was mainly at low loads where some of the cylinders was being deactivated to increase the thermal conditions in the combustion process. This technology was developed to be implemented on current diesel engines and could therefore be implemented at a GenSet without reconstructions. This concept was one of two that was ranked as number one in the MCDM matrix, see Table 3.14. The reliability of this concept in terms of trustworthy data was questionable. CDA was graded with the value of two, which corresponded to low trustworthiness. The other technologies were given values from three to four, which showed higher reliability. This concept had a higher level of improvements at lower operation loads and was therefore a more suitable choice for GenSets mostly running at 10-25% in load.

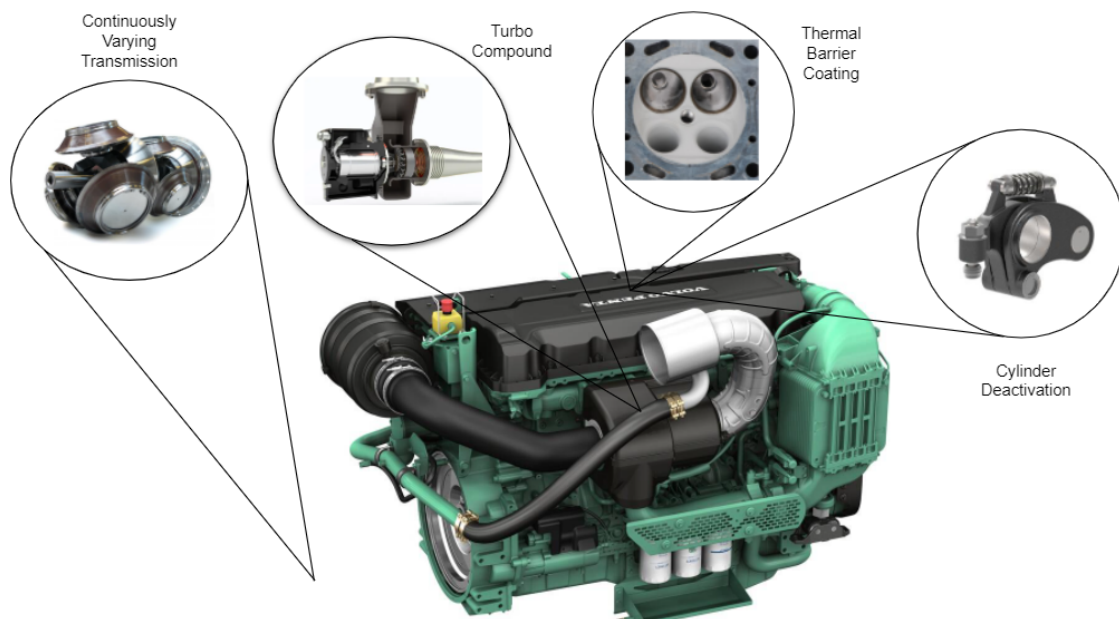


Figure 3.16: Components and their position for Concept Nr.20

Table 3.15: Data for Concept Nr.20

Concept Nr.20	
Turbo Compound	
Continuously Varying Transmission	
Cylinder Deactivation	
Thermal Barrier Coating	
Increased Efficiency [%]	29,4
Cost [SEK]	66300
TRL	6, 3, 2, 2
Implementation Ability	7,05
Implementation Ability (Corrected)	7,75
NOx Emission [g/kWh]	0,14

3.4.2 Concept Nr.21

The second concept, Concept Nr.21, was including CVT, TC, TBC and Dynamic Skip Fire, see Figure 3.17 and Table 3.16. This technology was also a Cylinder Deactivation technology with a more advanced operation procedure. The technology used an algorithm that dynamically activated and deactivated different cylinders depending on the load. This technology was developed to be implemented on various diesel engines, so it was no need to reconstruct the engine. The trustworthiness of this concept was relatively high based on that three out of four concepts were given a grade of four which corresponded to a high reliability. This concept had its benefits at lower loads similar to the first concept. Compared to the first concept, this concept was more adaptable to various load changes in terms of transient driving conditions.

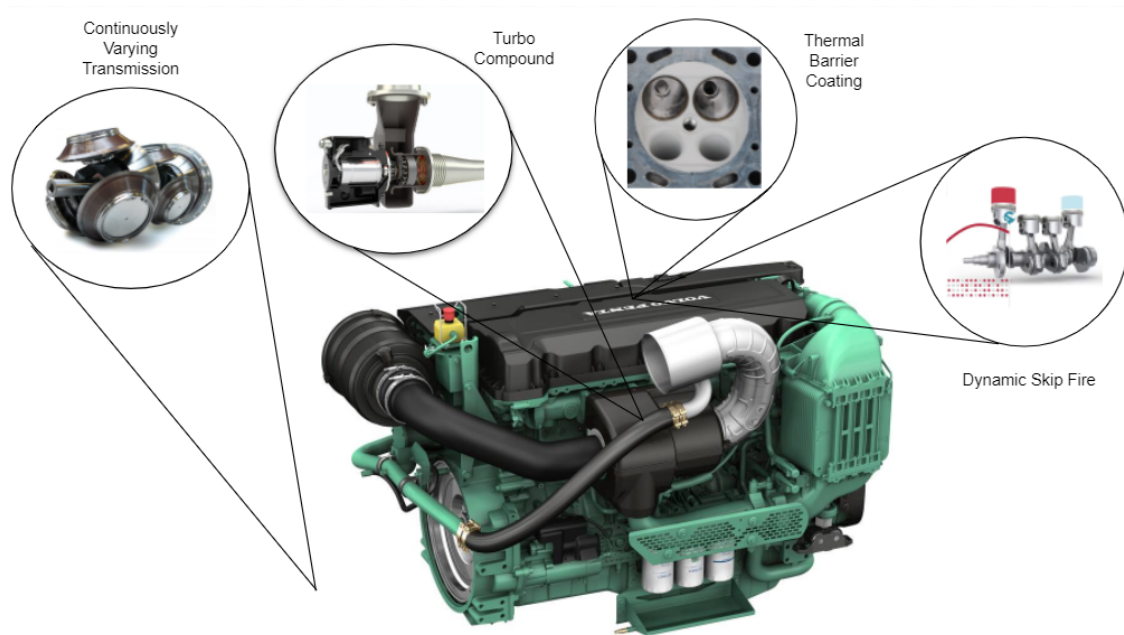


Figure 3.17: Components and their position for Concept Nr.21

Table 3.16: Data for Concept Nr.21

Concept Nr.21	
Turbo Compound	
Continuously Varying Transmission	
Dynamic Skip Fire	
Thermal Barrier Coating	
Increased Efficiency [%]	29,6
Cost [SEK]	68175
TRL	6, 3, 2, 2
Implementation Ability	7,05
Implementation Ability (Corrected)	7,75
NOx Emission [g/kWh]	0,11

3.4.3 Concept Nr.22

The third and last selected concept, Concept Nr.22, consisted of CVT, TC, TBC, CDA, and Variable Compression Ratio, see Figure 3.18 and Table 3.17. The VCR was changing the operating conditions in the combustion process. This enabled the engine to run at a more beneficial combustion condition without being influenced by external complications, such as cold start conditions or which type of fuel the engine was using. This technology was replacing the existing connecting rod and possibly small reconstructions were necessary to achieve optimal combustion conditions. This concept had the same trustworthiness as Concept Nr.20 since the performance of the CDA technology was not based on reliable information. This concept was beneficial if the GenSet was placed in environments with varying weather conditions.

3. Methodology And Results

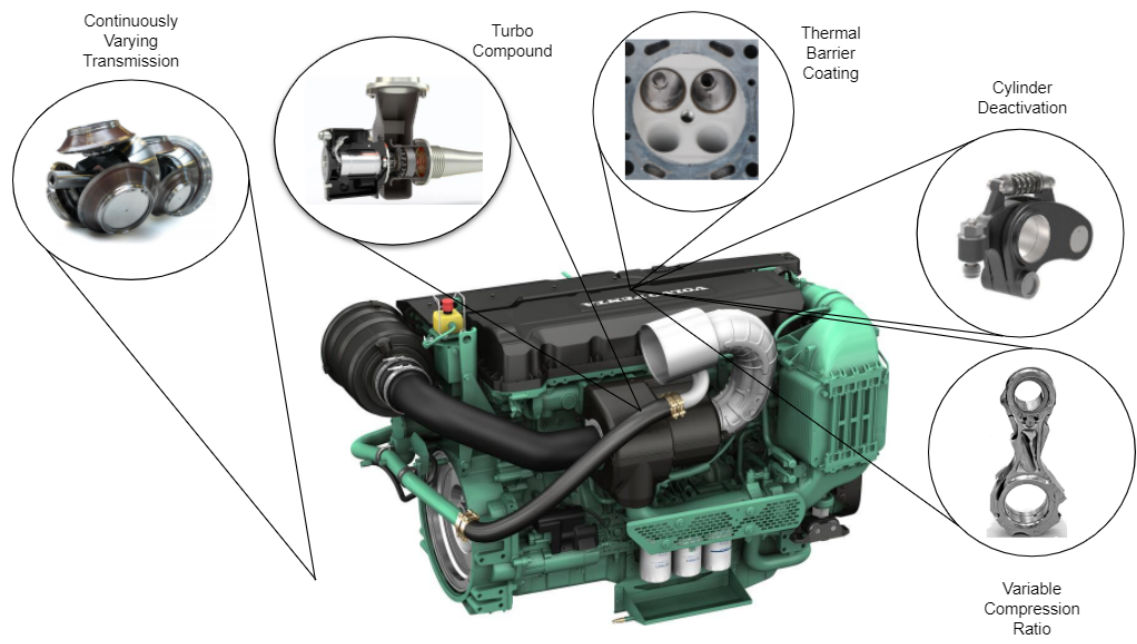


Figure 3.18: Components and their position for Concept Nr.22

Table 3.17: Data for Concept Nr.22

Concept Nr.22	
Turbo Compound	
Continuously Varying Transmission	
Cylinder Deactivation	
Thermal Barrier Coating	
Variable Compression Ratio	
Increased Efficiency [%]	29,5
Cost [SEK]	68300
TRL	6, 3, 2, 2, 3
Implementation Ability	7,2
Implementation Ability (Corrected)	7,2
NOx Emission [g/kWh]	0,11

4

Sustainability And Ethics

The sustainability and ethics perspective are necessary to consider in this project since diesel emits emissions into the air, which have to decrease. Global warming is an important topic to discuss since diesel engines contribute to global warming and engines is therefore an ethical aspect of this project. The development of CI engines with more sustainable fuels is in progress. To improve the efficiency of CI engines is necessary since there is yet no other promising solution that can be utilized instead of diesel engines for various applications. Since there is no better solution yet for these kinds of applications that a GenSet is used for, it is a good alternative to do this kind of research and improvements to the engine and improve the performance as much as possible with the technology available today.

None of the regulations that has to be followed, as it is today, are directed toward carbon dioxide emission. Approximately 12% of the emissions are carbon dioxide which results in global warming but no laws say that it must be reduced from the emissions. A prediction is that carbon dioxide will be included in the new regulations updates. These are mostly predictions in line with the Paris agreements, but to take a responsible choice, Volvo Penta has committed to the Science Based Target initiative and has decided to lower the emissions of carbon dioxide by 37.5% by 2034.

An ethical aspect to consider is that besides from the 12% emissions of carbon dioxide, 1% of the emissions consists of harmful emissions in terms of carbon monoxide, hydrocarbon, particulates matter and nitrogen oxides. Carbon monoxide is a result of an incomplete combustion and could by inhalation result in slow reflexes, mental illness and impaired concentration. Hydrocarbons are a result of unburned fuels and harms human health. It could potentially lead to respiratory tract irritation and increase the risk of cancer. The formation of Particulates Matter is a result of various factors such as fuel quality, lubrication oil quality, combustion temperature, consumption of exhaust gas cooling or the expansion process. It also contributes to worse human health since inhaling could cause asthma, lung cancer and premature death. Nitrogen oxide gas is caused by a high combustion temperature, the level of concentration of oxygen or resident time and has an impact on human health in terms of lung diseases. A discussion to have is therefore necessary. Is it ethically correct to continue to develop and use diesel engines even though the emissions harm human health? There is not an easy answer to this question. Since there are yet no other alternatives solutions for replacing the combustion engine in this area, this can result in positive consequences. By developing and optimizing the efficiency for all load cases at a correct temperature of diesel engines, incomplete combustion and

unburned fuel can be minimized. By minimizing these factors, less harmful emissions will be emitted.

An aspect not studied in this report is the environmental aspect to produce the technologies suggested to use. In this report, the use phase is only studied and no further studies have been done on the product's life cycle, for instance, what kind of materials are being used, how the technologies are manufactured or where the technologies are produced. Another aspect not studied in this report is the other emissions emitted from diesel. In this report, the emissions CO_2 and NO_x are studied and the other emissions were put as out of scope since the main goal was to lower the CO_2 emission for the upcoming regulations and since the focus was put on getting the model to work. The ethical aspect of the limitations can be questioned, but the delimitation is necessary.

Although that it is contradictory to put more time on diesel engines when they have a negative impact on the environment, it is positive that companies try to make the best out of the situation, in terms of global warming, and try to lower the emissions as much as possible during this time that no other solutions can be used for some applications.

5

Discussion

The first part of this chapter discusses decisions made during the project and the consequences that could be drawn from these. Specific conclusions that gave interesting results are also discussed in the first part. In the second part is the aim and goal discussed, knowledge gathered during the project is described, and possible further development is explained to finalize by stating the most interesting outcomes from this project.

5.1 Motivations and Discussion of Results

There are limitations in this project that had to be decided for this project to be feasible in 20 weeks. The first limitation is *The report only covers implementations and technologies related to the diesel engine*. It is chosen because Volvo Penta is almost only selling their gasoline engines to the United States of America and therefore it is more interesting to study diesel engines in this project. The second limitation *The report is using average data* is decided upon since it is too time consuming to gather the exact data from each technology. The third limitation *The investigated technologies are verified technologies* is chosen because the time before the launch of upcoming technologies is too long and therefore it is more interesting with verified technologies. The fourth limitation *The report is only studying one alternative engine model* is chosen because otherwise would all the calculations have to be done several times. The technologies are although working similarly with other engine models as well. The fifth limitation *Diesel remain as fuel* is chosen because some technologies found in the research stage could be used with other kinds of fuels. This is interesting, but to compare the technologies against each other would be difficult and therefore diesel remained as fuel. The sixth limitation *The study is only investigating technologies that reduce the emissions of carbon dioxide*, is chosen because the aim of the project is only focusing on the reduction of CO_2 . The seventh limitation *Only CO_2 emissions emitted in the use phase is accounted for* is chosen because, in the SBTi, where Volvo Penta is committing to the target, the whole product life cycle is included. By limiting this project to only investigating the engine's impact in the use phase, more effort is put into the performance of the different technologies. This limitation is though something that should be included in a continued work, since the impact from the life cycle is of high relevance when it comes to lowering the overall CO_2 emissions. In that case, including concepts on different fuel alternatives and suppliers are necessary to investigate. The eighth limitation *The report only covers calculations of the 1500 rpm that results in 50Hz*

that is used in Europe is an assumption that the difference between the 50Hz and 60Hz is negligible. Calculations and the development of the model for both options are more time consuming to create, but also unnecessarily complicated. The ninth limitation *The study is using the operating condition from the D2 driving cycle and other load cases are not taken into account* means that the operating conditions are five different steady-state load cases, where different load cases are operating under a specific time that corresponds to how the overall GenSet is used to operate in. This means that operating conditions such as cold start, acceleration or transient driving cycles are not included in this project. The estimation would have been too complicated and it would have been more difficult than necessary to compare the current engine to the different concepts.

In the graph in Figure 3.14 are the chosen technology combinations visualized. It is seen that a balance is found between increasing the efficiency and the cost for the combination. In the graph it is also visualized that the pareto frontier is steeper in the beginning and at a cost of approximately 110000 SEK and higher, the pareto frontier is not as steep anymore. This can be evaluated in terms that the combinations of technologies have an area where they perform better compared to the cost. This depends primarily on the number of technologies implemented in the combination and the complexity of the implementation ability that gets higher when the number of technologies in the combination increases.

The cycle that is being used for calculating the efficiency of each technology is called the D2 cycle. This cycle is being used since it is created for non-road engine applications and the tests are performed at a steady state, at a constant speed. The cycle analyzes the efficiency at different loads, 100%, 75%, 50%, 25% and 10%. Another cycle can be chosen, but this is the cycle used most frequently at Volvo Penta and is why it is selected in this project. One of the technologies, Single Speed Transmission, is deselected from the results in this report since the technology is not handling a load at 100% and therefore can not be used in the D2 cycle. The technology is still in the report since it is an interesting alternative. This technology can be included if another cycle is used or if it is known that a specific product should not be using a load of 100% for a specific application.

The technologies chosen are based on criteria, limitations and guidance from Volvo Penta, as mentioned earlier in the report. There is a possibility that certain technologies are being missed that would enhance the results even further but the technologies chosen are carefully selected with no rush and therefore are the results considered trustworthy. The values for efficiency, temperature, NO_x and the cost for the technologies are not as reliable since they are difficult to find specific values on. Almost every supplier for all of the technologies are contacted, but none of them answered, so assumptions are made. Each assumption are being described in the report. Since the most important aspect of the report is to create a model that worked, the focus is put on that. Instead, the model is built so that the parameter values for each technology can easily be changed when more reliable numbers are found.

The chosen computer programs that is being used to create the model, are Matlab, Simulink and App Designer. The model is probably possible to build in Excel, but the reason not to do it is that it would have been difficult to create a model in Excel that is easy for other people to use. In Matlab, it is easier to structure the parameters and then code for the actions without seeing all the numbers on the sheets, which can easily get confusing. By using Matlab it is also possible to visualize the whole model in Simulink for further understanding and App Designer for a graphical user interface to simplify it even further for people to use the model in the future.

In the process of estimating the technology information that is missing after the technology research is conducted, the calculations are based on interpolated test data from the current D13 engine. The data used for the TC technology is based on the current D13 diesel engine with an existing TC technology. The reliability of the data is questioned since it is assumed that the brake specific fuel consumption for the new engine is a result of the TC technology. The engine with the implemented TC technology is a newer version. This could mean that other improvements have also been implemented or that the engine is more optimized in terms of efficiency. This means that an overestimation of the performance of the TC technology could have been done.

The process of selecting the specific weighting values for the criteria are conducted based on experience and subjective assessments. In a fully conducted requirement specifications list, needs must be established based on the relevant stakeholders. In this specific situation, a limited list of the numbers of criteria are necessary, since the complexity of the Matlab model is directly influenced by the criteria. To increase the reliability and the quality of the decision-making of the three concepts, a more elaborated selection of criteria and weighting can be performed.

The sensitivity analysis is performed with the purpose to get an understanding of how robust the MCDM model is. This can be done in many ways and can be executed with more scenarios than the current sensitivity model is performed with. The reason for the limited extent of the analysis is that the result does not impact the decision model's structure. So, there is no need for a more in-depth analysis when the purpose is to understand the influence of the different criteria. An analysis is performed on the MCDM matrix where an evaluation is conducted on the individual technologies. This is in a more or less early stage in the selection phase. This analysis can also be conducted on the MCDM matrix for the different combinations and can increase the reliability of the decisions made. For this particular project, the analysis is not prioritized but can still be a useful process to perform if more time is available.

When creating the model in Matlab and Simulink the technologies are put beside each other in a series and the outputs from one technology are the input in the next one. It can be discussed if this is a correct way of structuring the model since other factors can affect the technologies. A decision within this project is to not look at too many factors but instead get the model to work, and an assumption taken

is that the additional factors do not affect the result too much. Another aspect to mention about the model is that inside the technology boxes are the parameter values, in most cases, multiplied with each other and then transported as an output. In some cases, this may not be the most correct way of doing it since other factors can affect the multiplication and losses must be included. Although not enough information is available about these questions in the research about the technologies and because of the time limitation, it is decided to not put too much energy into trying to contact the suppliers for more information. Instead, the model is created to be modified easily, if new changes appear.

All the graphs and figures throughout this report are results based on the D2 cycle and therefore include the five different loads. If the model in Matlab, Simulink and App Designer is being used for this specific purpose, to study the D2 cycle, the model can maybe be perceived as a bit complicated. To receive the values for each load it has to be simulated for each load and then weighted with help of the D2 cycle. The model is constructed in this specific way since the D2 cycle is not used in all cases at Volvo, and by structuring the model like this, there is a possibility to choose how the results should be studied and there is no restriction to only studying the D2 cycle.

By looking at the figure, see Figure 3.13, it is noticeable that the relation between increased efficiency and cost is changing depending on the cost. The pareto frontier can be the most suitable approximation of the best performed combinations relative to its cost. It can be interpreted that the relation is an upgoing trend until the cost reaches 110000 SEK, the curve then flattens out. This is why combinations after 110000 SEK are later excluded from the decision-making model. There is no need of evaluating combinations that delivers the same efficiency for higher costs. If the choice of including the whole pareto frontier is made, a more well-grounded decision can be achieved. None of the excluded combinations from the pareto frontier can be selected as the most promising concept but to increase the reliability of the final decision, it can be more beneficial to include the whole pareto frontier curve.

The correlation between the ratio of increased efficiency, cost and cost for itself, see Figure 3.15 shows how much efficiency can increase in relation to the cost. The relation can be interpreted as logarithmic or exponential. This information is highly valuable since there is a need of knowing how much every percentage of increase in efficiency is worth. The information can be utilized when a trade-off between how the company values efficiency and what the actual cost for it is. The outcome of the most promising combination can be different from the three current selected ones.

By looking at the graph, see Figure 3.15 it is noticeable that the three selected concepts have a relatively low efficiency ratio relative to cost. That is a good example of how the MCDM matrix has provided additional information and contributed to a more well-grounded decision. If the criteria for the decision only is high efficiency for low cost, the mentioned graph would be a good tool for selecting concepts. In this case, the decision is based on multi-criteria and even if both cost and increase in efficiency are weighted as the most important criteria, other aspects influenced

and created a more reliable decision.

The different criteria in the MCDM matrix includes cost and efficiency increase. The cost is weighted to 0.2 and the increase in efficiency to 0.3. This means that these two criteria are highly important and essential for the decision. Despite this, concepts with a high efficiency and cost increase can get a high ranking either way, see Table 3.14. An aspect that can be useful to implement as criteria are the ratio between cost and increase in efficiency. It is possible that it can create a decision model that priorities concepts that give more efficiency for the money since the three current selected concepts do not have the highest rate. One of the disadvantages or potential challenges with such criteria is that some of the attributes can be double counted, for instance the increases in efficiency. So, if the ratio criteria can be implemented, both the cost and increase in efficiency criteria would need to be changed in the weighting aspects or excluded from the decision model.

The selection of the concepts is based on the ranking process. The top three are assumed to be the most promising, see Table 3.14. The differences in the sum for the highest scored concept are relatively low as the sum differs from 7.6 to 7.2 between the ten best scored concepts. Even if the three selected concepts has the highest score, the performance of the ten best concepts are similar. CVT, TBC and TC are included in the top five scored concepts and the difference between them is one technology. One way of interpreting this information is that depending on the segment the GenSet will operate in, it is suitable to select concepts from the top five since there are some differences in terms of how well they perform at different loads and operating environments.

The trustworthiness is based on different criteria and the perspective given from the research stage. The trustworthiness for the different concepts varies, but it is evident that the concepts have questionable trustworthiness that must be considered before implementation. When a concept is chosen it is suitable to research further and contact suppliers to receive information of higher trustworthiness. It is to prefer to receive the exact numbers from a supplier, then finding the data from experiments performed by people outside of that company to compare. This approach is effective and cost efficient. Otherwise, an alternative is to receive a model and simulate it or buying one product and trying it.

5.2 Final Discussion

The aim of this project is to help Volvo Penta to lower the CO_2 emissions, that are emitted from diesel engines in GenSets during the use phases. This is achieved by constructing a methodology that enables Volvo Penta to find the most promising improvements, at a conceptual level, for a GenSet engine, to lower the CO_2 emission with cost taken into account. The goal is to present a model of combining technologies to find the most promising improvements. By only studying the chosen concepts, they increase the efficiency by up to 29.6% and since the aim is

to help Volvo Penta to increase the efficiency with the cost taken into account, the goal is achieved. By studying the model, it is also evident that the model can find combinations that increase the efficiency by more than 37.5%, but then to a higher price. A limitation stated early in this project is to only study the engine of the GenSet. At the same time, there are still possibilities to improve the efficiency by investigating other components of the GenSet. The final concepts that this project results in increase the efficiency by 29.4%, 29.5% and 29.6% which is a step toward increasing the efficiency by 37.5% by 2034 and if looking at other components in the GenSet there are promising possibilities to find the remaining percent.

In the process of executing this project, the understanding of the subject has been improved. Several aspects can be improved based on what has been realized after the project was conducted. The distribution of time in the different phases of this project could have been carried out differently. Almost eight weeks of technology research and selection were conducted as the project started. This was more time-consuming than necessary since the goal of the project did not require the information and the data to be that reliable. This would have lead to more time spent on the selected concepts, where more focus on the explanation and further development on the specific concept could have been possible. Another aspect that would have been changed if the project should have been conducted again is the creation of the criteria. The criteria themselves are suitable and provide good results, but more effort could have been spent on how the criteria were established. Instead, it could have been conducted as a study or a focus group where the stakeholders were allowed to express their needs and interpret them into useful criteria.

Improvements and further development of the current work are needed. A next step to improve the combination model is to define more attributes that the different technologies influence each other with. In the current model, exhaust gas heat is a variable that has a dynamic impact on several technologies. This is something that can be more investigated. By theoretically understanding the different technologies and their impact on a deeper level, more information and data can be implemented in the combination model. This results in a more dynamic approximation of the combinations and a more realistic simulation of the technologies. Another aspect to extend or develop even further is the segment where the technologies impact, for example excluding some of the limitations or adding more parameters to the model. In the current model, only technologies that improve the efficiency under the D2 cycle are investigated. If instead various external conditions are taken to account as cold start conditions or to increase the maximum power of the engine, excluded technologies are being investigated and the selection process is even more reliable.

This project are creating several interesting outcomes. Established possible technologies that can improve the efficiency, a methodology to select concepts but also a model to generate a dynamic synergy effect and combinations of technologies are being presented. Combining solutions, generating multiple outcomes and trying to understand how different solutions or alternatives correlate with each other can be implemented in various areas. There are several upcoming challenges where the

decision making process of which technology or concept that is the most promising will be useful at Volvo Penta. Presenting a large number of combinations and presenting the most promising combinations by using a pareto frontier is useful in many different areas. This is a suitable way of excluding or screening alternative solutions in not just product development areas, but for any decision-making process with a trade-off between criteria.

6

Conclusion

To complete the goal, several research questions needed to be answered. In this chapter, the answers to the research questions are summarized in the first subchapter to then finalize this report by writing the conclusion of the goal.

6.1 Conclusion of Research Questions

Which existing technologies could potentially increase the efficiency of the engine?
By performing a literature study, twelve promising technologies, that are suitable for this project, are studied. These technologies can potentially increase the efficiency of the engine individually but also in combination with each other. The selection of these twelve technologies is based on several requirements that are necessary to accomplish. The selected technologies are, DWI, CVT, SST, VCR, CDA, VVA, TC, ORC, EMF TBC, DSF and RL. These technologies are possible to implement in the current engine and can improve the performance of the engine in the relevant operation condition, which in this case is the D2 cycle.

What kind of structured models/methods are the most suitable to select to achieve improvements for the efficiency of the engine in a cost-efficient way?

By conducting methodology research, several suitable methods to select the most promising concept are defined. A simulation model is created to convey the data and information needed to perform the selection procedure and evaluate the different concepts. The selection methodology consists of six established concept selection tools, MCDM matrix, TRL assessment, DSM, sensitivity analysis, indicators for technology and change propagation. This set of tools enables the selection of the concepts based on various criteria. It concludes which combinations of technologies that are not suitable to combine. Further, it creates an understanding of how well established the specific technologies are in relation to Volvo Penta and concludes how robust the selection process is for different data changes.

What kind of correlations and parameters are the most interesting to investigate in the comparison between combinations of technologies? By executing the technology research, correlations that impact the different technologies are defined. The research provides information that states that the temperature of the exhaust gases is affected by most of the technologies. The exhaust gas temperature impacts the performance of both TC and ORC. The increase in efficiency is another attribute

that the different technologies correlate with. An independent relation in terms of increase in efficiency is concluded between ten of the technologies.

Which combinations of technologies are the most promising? A verification of the model is executed by using the model to define all possible combinations and the performance for every single combination. The model generates over 4000 combinations and by using the developed selection process, three combinations are selected to be the most promising concepts. Concepts Nr.20, Concept Nr.21 and Concept Nr.22 are the final ones.

How can the model and methodology be verified?

The model is verified by implementing the twelve selected technologies and evaluating if the performance is realistic. To verify the methodology, implementation of both the individual-and-combination of technologies are performed. The outcome of the selection process is evaluated and concluded that the most promising technology and combination of technologies are selected. To further verify if it provides a reliable choice, a sensitivity analysis is conducted on the individual technology selection process. This confirms the robustness of the decision. It is concluded that the concept selection that is based on the model and the methodology, is well-founded and it seems that these three concepts are the most promising.

6.2 Final Conclusion

The Goal is to construct a methodology that enables Volvo Penta to find the most promising improvements, at a conceptual level, for a GenSet engine to lower the CO_2 emission with cost taken into account.

The goal is completed. By using the developed methodology and model it was possible to select three concept suggestions with a performance to increase the efficiency of a GenSet engine by 29.4, 29.5 and 29.6%. The increase in efficiency results in a CO_2 emission decrease, which corresponds to the goal. If this project is studied from another perspective by looking at its aim, it is evident that the project has fulfilled its purpose, but more development must be done until 2034. The aim is to help Volvo Penta to lower the CO_2 emissions by 37.5% that are emitted from diesel engines in GenSets during the use phase. As stated above, the goal is fulfilled, this project has helped Volvo Penta to lower the CO_2 emissions. The project has although not resulted in a decrease of CO_2 emissions by 37.5% and more development has to be executed before 2034. This methodology and model is although considered having the capacity to be developed further with more parameter values and more technologies.

Bibliography

- [1] World Power Products. (2022). Current & Future Market Trends In Diesel Generators [Online]. <https://www.wpowerproducts.com/news/diesel-generator-market-trends/> (Retrieved: 2022-01-28).
- [2] Volvo Penta. (2022). Marine Genset Engine range [Online]. <https://www.volvopenta.com/marine/products/marine-genset/marine-genset-engine-range//all> (Retrieved: 2022-01-28).
- [3] Volvo. (2022). Climate Strategy [Online]. <https://www.volvogroup.com/en/sustainability/climate-goals-strategy.html> (Retrieved: 2022-01-28).
- [4] Volvo Penta. (2022). A History of Innovation [Online]. <https://www.volvopenta.com/about-us/history/> (Retrieved: 2022-01-28).
- [5] Volvo. (2022). Looking back – stories from the archive [Online]. <https://www.volvogroup.com/en/about-us/history-and-r-d-milestones/stories-from-the-archive.html> (Retrieved: 2022-01-28).
- [6] Volvo Penta. (2022). The Heart That Never Stops [Online]. <https://www.volvopenta.com/industrial/power-generation/> (Retrieved: 2022-01-28).
- [7] SCA. We have to act in harmony with the society in which we operate in order to remain relevant now and in the future. [Online]. <https://www.sca.com/en/about-us/sustainability/stakeholder-dialogue/> (Retrieved: 2022-01-31).
- [8] Volvo Penta. (2022). Off-Road Engine Range [Online]. <https://www.volvopenta.com/industrial/off-road/off-road-engine-range//all> (Retrieved: 2022-02-03).
- [9] VOLVO PENTA SALES SUPPORT TOOL, 2022 [online]. Unpublished for the general public. (Retrieved: 2022-02-03).

- [10] APR ENERGY. (2018). What is a genset & what is it used for? [Online]. <https://www.aprenergy.com/what-is-a-genset-used-for/> (Retrieved: 2022-02-05).
- [11] BIG RENTZ. (2022). What Is a Genset? [Online]. <https://www.bigrentz.com/blog/what-genset> (Retrieved: 2022-02-05).
- [12] DIESEL GENERATOR DIRECT. (2018). What is a Genset? [Online]. <https://dieselgeneratordirect.uk/genset.html> (Retrieved: 2022-02-05).
- [13] Klinge Corporation. (2020). What is a Genset? [Online]. <https://klingecorp.com/blog/what-is-a-genset/> (Retrieved: 2022-02-05).
- [14] Bredenoord. (2020). What is a genset and how does it work? [Online]. <https://www.bredenoord.com/en/knowledge/what-is-a-genset/> (Retrieved: 2022-02-05).
- [15] H. Jääskeläinen, M.K. Khair, "Diesel Engines", *DieselNet*. [Online]. Nov, 2021. https://dieselnet.com/tech/diesel_engines.php (Retrieved : 2022 – 02 – 07).
- [16] GENERATOR SOURCE. (2022). Why Should I Choose a Diesel Powered Engine or Generator? [Online]. https://www.generatorsource.com/why_choose_diesel.aspx (Retrieved : 2022 – 02 – 07).
- [17] School of PE. (2018). Diesel Engine Components and Their Functional Applications. [Online]. <https://www.schoolofpe.com/blog/2018/02/diesel-engine-components-and-their-functional-applications.html> (Retrieved: 2022-02-07).
- [18] autobutler. (2019). EGR-ventilen: Vad är det? [Online]. <https://www.autobutler.se/wiki/egr-ventilen-vad-ar-det> (Retrieved: 2022-02-07).
- [19] Diesel Technology Forum. ABOUT CLEAN DIESEL WHAT IS SCR? [Online]. <https://www.dieselforum.org/about-clean-diesel/what-is-scr> (Retrieved: 2022-02-07).
- [20] EXTRUDESIGN.COM. (2018). What is a 4 stroke Diesel engine? [Online]. <https://extrudesign.com/4-stroke-diesel-engine/> (Retrieved: 2022-02-09).
- [21] K. von Mitzlatf, "3. Essential theory on internal combustion engines", *Energies for Biogas*, 1988, pp. 133.

-
- [22] H. Jääskeläinen, M.K. Khair, "Combustion in Diesel Engines", *DieselNet*. [Online]. May, 2020. https://dieselnet.com/tech/diesel_ombustion.php (Retrieved : 2022 – 02 – 09).
- [23] I. A. Resitoglu, K. Altinisik, A. Keskin, "The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems", *SpringerLink*. [Online]. June, 2014. <https://link.springer.com/article/10.1007/s10098-014-0793-9Fig1> (Retrieved: 2022-02-10).
- [24] California Air Resources Board. (2022). Carbon Monoxide & Health [Online]. <https://ww2.arb.ca.gov/resources/carbon-monoxide-and-health> (Retrieved: 2022-02-10).
- [25] DieselNet. (2022). Emission Standards [Online]. <https://dieselnet.com/standards/us/nonroad.php> (Retrieved: 2022-02-11).
- [26] DieselNet. (2021). Emission Standards [Online]. <https://dieselnet.com/standards/eu/nonroad.php> (Retrieved: 2022-02-11).
- [27] GENESAL ENERGY. (2022). DO YOU KNOW WHAT STAGE V EMISSION STANDARDS ARE? We'll explain! [Online]. <https://genesalenergy.com/en/communication/articles/stage-v-emission-standards/> (Retrieved: 2022-02-11).
- [28] California Air Resources Board. (2022). Potential Amendments to the Diesel Engine Off-Road Emission Standards: Tier 5 Criteria Pollutants and CO2 Standards. [Online]. <https://ww2.arb.ca.gov/our-work/programs/tier5/about> (Retrieved: 2022-02-11).
- [29] DieselNet. (2001). Emission Test Cycles, ISO 8178 [Online]. <https://dieselnet.com/standards/cycles/iso8178.php> (Retrieved: 2022-02-14).
- [30] WÄRTSILÄ. (2022). Direct Water Injection (DWI) [Online]. [https://www.wartsila.com/encyclopedia/term/direct-water-injection-\(dwi\)](https://www.wartsila.com/encyclopedia/term/direct-water-injection-(dwi)) (Retrieved: 2022-02-16).
- [31] NEW ATLAS. (2016). Bosch WaterBoost injection opens door to better power and economy [Online]. <https://newatlas.com/bosch-water-injection/45205/> (Retrieved: 2022-02-16).

- [32] Zhang et al, "Effect of direct water injection during compression stroke on thermal efficiency optimization of common rail diesel engine", *Energy Procedia*, vol.142, pp. 1251-1258, December. 2017, <https://doi.org/10.1016/j.egypro.2017.12.514>.
- [33] V. Ayhan, Y.M Ece, "New application to reduce NOx emissions of diesel engines: Electronically controlled direct water injection at compression stroke", *Applied Energy*, vol.260, pp. February. 2020, <https://doi.org/10.1016/j.apenergy.2019.114328>.
- [34] MAPerformance. (2022). [Online]. <https://www.maperformance.com/products/aem-v2-water-methanol-injection-kit-multi-input-5-gallon-tank-30-3351> (Retrieved: 2022-02-16).
- [35] T.E. Diyu, C. Malaysia, "Building a Fuel Efficient Electrical Generator Using Continuously Varying Transmission," *taufeeq* [Online]. 2011. http://taufeeq.com/articles/pdf/CVT_genset_taufeeq_elahi_diju.pdf (Retrieved: 2022-02-17).
- [36] MAZARO. Optimal use of the engine or E-motor [Online]. <https://www.mazaro.eu/en/benefits/energy-emission-reduction> (Retrieved: 2022-02-17).
- [37] A METHOD FOR CONTROLLING A CONTINUOUSLY VARIABLE TRANSMISSION AND A TRANSMISSION EQUIPPED WITH A CONTROL SYSTEM FOR IMPLEMENTING SAID METHOD, by F. De Maziere, L. Present. (2021, October 7). WO2021197568A1 [Online]. <https://worldwide.espacenet.com/patent/search/family/070224338/publication/WO2021197568A1?q=ia%20%3D%20%22mazar%22%20AND%20ta%20%3D%20%22CVT%22>
- [38] MAZARO. (2019). Single stage Variable Transmission: spec SVT230 [Online]. <https://www.mazaro.eu/sites/default/files/2019-10/spec-svt230-for-electric-lcv.pdf> (Retrieved: 2022-02-17).
- [39] MAZARO. Electric vehicles [Online]. <https://www.mazaro.eu/en/applicationsindustrialdrives> (Retrieved: 2022-02-17).
- [40] AAMCO Transmissions Inc. (2019). EVERYTHING YOU NEED TO KNOW ABOUT CVT TRANSMISSIONS [Online]. <https://aamcoutah.com/all-about-cvt/> (Retrieved: 2022-02-17).
- [41] RS Components. (2022). Motovario Worm Gearbox, 10:01 Gear Ratio, 270 Nm Maximum Torque [Online]. <https://se.rs-online.com>. (Retrieved: 2022-02-17).

-
- [42] R.B. Pesic, S.T. Milojevic, S.P. Veinovic, "BENEFITS AND CHALLENGES OF VARIABLE COMPRESSION RATIO AT DIESEL ENGINES", *THERMAL SCIENCE*. [Online]. Vol. 14, No. 4, pp. 1063-1073, 2010. <https://thermalscience.vinca.rs/pdfs/2010-4/TSCI10041063P.pdf> (Retrieved: 2022-02-18).
- [43] D. Khan, M. Zafer Gul, "Zero-dimensional modelling of a four-cylinder turbocharged diesel engine with variable compression ratio and its effects on emissions", *SpringerLink*. [Online]. September, 2019. <https://link.springer.com/article/10.1007/s42452-019-1185-x> (Retrieved: 2022-02-18).
- [44] R.B. Pesic, S.T. Milojevic, S.P. Veinovic, "BENEFITS AND CHALLENGES OF VARIABLE COMPRESSION RATIO AT DIESEL ENGINES", *THERMAL SCIENCE*, vol.14, nr.4, pp. 1063-1073, January. 2010, <https://doaj.org/article/11d4e977d0904c19a9f7d0129969b4da>.
- [45] FEV. (2022). Why VCR? [Online]. <https://vcr.fev.com/solution>. (Retrieved: 2022-02-18).
- [46] Tech. Specialist Presentation 2021, Introduction - Variable compression connecting rod (VCR), unpublished.
- [47] D.T. Hountalas, T.C. Zannis and G.C. Mavropoulos, "Potential Benefits in Heavy Duty Diesel Engine Performance and Emissions from the Use of Variable Compression Ratio", *SAE International*, April. 2006, <https://doi.org/10.4271/2006-01-0081>.
- [48] businesswire. (2021). Eaton Introduces Variable Valve Actuation Technologies to Help Commercial Truck Makers Meet Upcoming China Emissions Regulations [Online]. <https://www.businesswire.com/news/home/20211202005043/en/Eaton-Introduces-Variable-Valve-Actuation-Technologies-to-Help-Commercial-Truck-Makers-Meet-Upcoming-China-Emissions-Regulations>. (Retrieved: 2022-02-21).
- [49] EATON. (2022). LIVC - Late Intake Valve Closing [Online]. https://www.eaton.com/us/en-us/catalog/engine-valvetrain/diesel-vva.html?utm_source=China+VVA+Press+Releaseutm_medium=China+VVA+Press+Releaseutm_campaign=China+VVA+Press+Releaseutm_id=China+VVA+Press+Release. (Retrieved: 2022-02-21).
- [50] D. Afshari, A. Afra, "Effect of Variable Valve Timing to Reduce Specific Fuel Consumption in HD Diesel Engine", *ResearchGate*, October. 2016, <http://dx.doi.org/10.4172/2168-9873.1000238>.

- [51] W. Guan, V.B. Pedrozo, H. Zhao, Z. Ban, T. Lin, "Variable valve actuation-based combustion control strategies for efficiency improvement and emissions control in a heavy-duty diesel engine", *SAGE journals*, April. 2019, <https://doi.org/10.1177%2F1468087419846031>.
- [52] repairpal. (2022). Variable Valve Timing Actuator Replacement Cost [Online]. <https://repairpal.com/estimator/variable-valve-timing-actuator-replacement-cost>. (Retrieved: 2022-02-21).
- [53] H. Jääskeläinen, W.A. Majewski, "Turbocompounding", *DieselNet*. [Online]. May, 2020. https://dieselnet.com/tech/engine_whr_turbocompound.php (Retrieved: 2022-02-21).
- [54] HANDWIKI. (2021). Engineering:Electric turbo compound [Online]. https://handwiki.org/wiki/Engineering:Electric_turbo_compound. (Retrieved: 2022-02-21).
- [55] S. Brooks, "EXCLUSIVE: VOLVO TESTS TURBO-COMPOUND ENGINE DOWN UNDER", *ATN*. [Online]. December, 2019. <https://www.fullyloaded.com.au/truck-reviews/1911/exclusive-volvo-tests-turbo-compound-engine-down-under> (Retrieved: 2022-02-21).
- [56] O. Badrana, S. Emeish, M. Abu-Zaid, T. Abu-Rahma, M. Al-Hasan, M. Al-Ragheb, "Impact of Emulsified Water/Diesel Mixture on Engine Performance and Environment", *IASKS*, vol.3, nr.1, pp.1-7, 2011, <https://iasks.org/articles/ijtee-v03-i1-pp-1-7.pdf>.
- [57] A.G. Bharadwaj, W. Al Haji, "Waste Heat Recovery in Diesel Engines using the Organic Rankine Cycle: Potential of Heat Recovery in the Volvo D13 Engine for Marine and Standby Power Generation Applications," MSc thesis, Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg, Sweden 2020, [Online] <https://odr.chalmers.se/bitstream/20.500.12380/300716/1/Master-%20A.%20G.%20Bharadwaj%2C%20W.%20A1%20Haji.pdf>.
- [58] A.T Hoang, "Waste heat recovery from diesel engines based on Organic Rankine Cycle", *ScienceDirect*, vol.231, pp.138-166, December. 2018, <https://doi.org/10.1016/j.apenergy.2018.09.022>.
- [59] S. Swami, "Heavy Duty Roots Expander Heat Energy Recovery (HD-REHER)", *U.S. Department of Energy Office of Scientific and Technical Information*, October. 2015, <https://doi.org/10.2172/1337562>.
- [60] T. Howell, J. Gibble, C. Tun, "Development of an ORC system to improve HD truck fuel efficiency", *VOLVO - DEER 2011 CONFERENCE*, 2011, https://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2011/

wednesday/presentations/deer11_howell.pdf.

- [61] *Explore our Technologies ORC (Organic Rankine Cycle) Waste Heat Recovery System*, BorgWarner, <https://cdn.borgwarner.com/docs/default-source/default-document-library/orc-product-sheet.pdf?sfvrsn=96bccf3c13>, (Retrieved : 2022 - 02 - 22).
- [62] T. Park, H. Teng, G.L. Hunter, B. van der Velde, J. Klaver, "A Rankine Cycle System for Recovering Waste Heat from HD Diesel Engines - Experimental Results", *SAE International*, April. 2011, <https://doi.org/10.4271/2011-01-1337>.
- [63] EATON. (2022). CDA - Cylinder Deactivation [Online]. https://www.eaton.com/us/en-us/catalog/engine-valvetrain/diesel-vva.html?utm_source=China+VVA+Press+Releaseutm_medium=China+VVA+Press+Releaseutm_campaign=China+VVA+Press+Releaseutm_id=China+VVA+Press+Release. (Retrieved: 2022-02-22).
- [64] T. Park, H. Teng, G.L. Hunter, B. van der Velde, J. Klaver, "A Rankine Cycle System for Recovering Waste Heat from HD Diesel Engines - Experimental Results", *SAE International*, December. 2011, <https://doi.org/10.4271/2011-01-1337>.
- [65] A. Matheaus, J. Singh, L. Sanchez, D. Evans, R. Janak, "Evaluation of Cylinder Deactivation on a Class 8 Truck over Light Load Cycles", *SAE International*, April. 2020, <https://doi.org/10.4271/2020-01-0800>.
- [66] N. Lutsey, D. Meszler, A. Isenstadt, J. German, J. Miller, "EFFICIENCY TECHNOLOGY AND COST ASSESSMENT FOR U.S. 2025-2030 LIGHT-DUTY VEHICLES", *International Council on Clean Transportation*, March. 2017, https://theicct.org/sites/default/files/publications/US-LDV-tech-potential_ICCT_white-paper_22032017.pdf.
- [67] M. Scassa, T. Körfer, K. Chen, J. Fuerst, M. Younkings, M. Nencioni, S. George, "Smart Cylinder Deactivation Strategies to Improve Fuel Economy and Pollutant Emissions for Diesel-Powered Applications", *SAE International*, September. 2019, <https://doi.org/10.4271/2019-24-0055>.
- [68] businesswire. (2021). Cummins and Tula Study of Diesel Dynamic Skip Fire (dDSF™) Shows 74% Reduction in NOx Emissions [Online]. <https://www.businesswire.com/news/home/20210413005025/en/Cummins-and-Tula-Study-of-Diesel-Dynamic-Skip-Fire-dDSF%E2%84%A2-Shows-74-Reduction-in-NOx-Emissions>. (Retrieved: 2022-02-23).

- [69] E. Vural, S. Özel, S. Özer, "Coating of diesel engine with new generation ceramic material to improve combustion and performance", *ResearchGate*, January. 2021, <http://dx.doi.org/10.2298/TSCI200601011V>.
- [70] A. Kawaguchi et al, "Thermo-Swing Wall Insulation Technology; - A Novel Heat Loss Reduction Approach on Engine Combustion Chamber -", *SAE International*, October. 2017, <https://doi.org/10.4271/2016-01-2333>.
- [71] S.K. Rupangudi, C.S. Ramesh, K. Veerabhadhrappa, R. Rohit V, "Study of Effect of Coating of Piston on the Performance of a Diesel Engine", *SAE International*, April. 2014, <https://doi.org/10.4271/2014-01-1021>.
- [72] MOTORTREND. (2008). All About Engine Coatings - Are They Worth It? [Online]. <https://www.motortrend.com/how-to/hrdp-0612-engine-coatings/>. (Retrieved: 2022-02-24).
- [73] D. Dardalis, M. Hall, R. Matthews, A. Basu, T. Ozel, "The Rotating Liner Engine (RLE) Diesel Prototype: Preliminary Testing", *SAE International*, January. 2019, <https://doi.org/10.4271/2019-01-0084>.
- [74] D. Dardalis, R. Matthews, A.O. Lebeck, "Design Details of the Compression Ignition Rotating Liner Engine. Reducing Piston Assembly Friction and Ring/-Liner Wear in Heavy-Duty Diesel Engines", *SAE International*, September. 2012, <https://doi.org/10.4271/2012-01-1963>.
- [75] MathWorks. (2022). Designed for the way you think and the work you do. [Online]. <https://se.mathworks.com/products/matlab.html>. (Retrieved: 2022-05-10).
- [76] MathWorks. (2022). Design. Simulate. Deploy. [Online]. <https://se.mathworks.com/products/simulink.html>. (Retrieved: 2022-05-10).
- [77] MathWorks. (2022). App Designer Create desktop and web apps in MATLAB <https://se.mathworks.com/products/matlab/app-designer.html>. (Retrieved: 2022-05-10).
- [78] Microsoft. (2022). Microsoft Excel <https://www.microsoft.com/sv-se/microsoft-365/excel>. (Retrieved: 2022-05-10).

A

Efficiency, Temperature And NO_x Data For Continuously Varying Transmission

A.1 Efficiency

Table A.1: Improvements of efficiency for CVT at different load cases

Load [%]	Power [kW]	Required power due to losses [kW]	Increase in efficiency [BSFC], CVT	Enigne speed [rpm]
100%	407	419	2,9	1600
75%	305	315	1,8	1300
50%	204	210	2,9	1100
25%	102	105	6,5	1000
10%	41	42	22,8	700

A.2 Exhaust Gas Temperature And NO_x Emissions

Table A.2: Exhaust gas temperature and NO_x emissions for different load cases for the CVT technology

100% Load	1500 rpm	1600 rpm	Improvements [%]
Exhaust temp [°C]	516,2	537,9	4,0
NOX concentration [g/kW]	9,1	8,039572312	11,3
75% Load		1300 rpm	
Exhaust temp [°C]	416,9	449,3	7,2
NOX concentration [g/kW]	10,6	9,5	11,0
50% Load		1100 rpm	
Exhaust temp [°C]	356,0	462,8	23,1
NOX concentration [g/kW]	9,4	10,8	-14,4
25% Load		1000 rpm	
Exhaust temp [°C]	284,0	402,9	29,5
NOX concentration [g/kW]	8,8	9,5	-7,4
10% Load		700 rpm	
Exhaust temp [°C]	244,2	313,1	22,0
NOX concentration [g/kW]	10,2	9,3	9,1

A. Efficiency, Temperature And NO_x Data For Continuously Varying Transmission

B

Efficiency, Temperature And NO_x Data For Single Speed Transmission

B.1 Efficiency

Table B.1: Mapping of the brake specific fuel consumption for different engine speeds for the SST technology

Load [%]	Weighting	1400 rpm	1300 rpm	1200 rpm	1100 rpm	1000 rpm	900 rpm
100%	0,05	2	2	5	2	8	9
75%	0,25	2	2	0	0	0	0
50%	0,3	2	1	2	3	1	-1
25%	0,3	2	4	5	6	6	6
10%	0,1	22	19	23	21	22	22
Sum		4	4	5	5	4	4

B.2 Exhaust Gas Temperature And NO_x emissions

Table B.2: Exhaust gas temperature and NO_x emissions for different load cases for the SST technology

100% Load	1500 rpm	1600 rpm	Improvements [%]
Exhaust temp [°C]	516,2	537,9	4,0
NOX concentration [g/kW]	9,1	8,039572312	11,3
75% Load	1300 rpm		
Exhaust temp [°C]	416,9	449,3	7,2
NOX concentration [g/kW]	10,6	9,5	11,0
50% Load	1100 rpm		
Exhaust temp [°C]	356,0	462,8	23,1
NOX concentration [g/kW]	9,4	10,8	-14,4
25% Load	1000 rpm		
Exhaust temp [°C]	284,0	402,9	29,5
NOX concentration [g/kW]	8,8	9,5	-7,4
10% Load	700 rpm		
Exhaust temp [°C]	244,2	313,1	22,0
NOX concentration [g/kW]	10,2	9,3	9,1

C

Efficiency, Temperature And NO_x Data For Turbo Compound

C.1 Efficiency

Table C.1: Correlation between inflow exhaust gas temperature and efficiency for the TC technology

Temperature in [°C]	Increase in efficiency [%]
>560	19,5
560-540	18,5
540-520	17,5
500-480	16
480-450	13
450-400	10
400-350	6
350-300	3
300-200	1,6
200-150	2,5
150-100	2,3
<100	1,5

C.2 Exhaust Gas Temperature And NO_x Emissions

Table C.2: Exhaust gas temperature and NO_x emissions for different load cases for the TC technology

100% Load	TC Outflow	TC Inflow	Reference	Improvements [%]	Decrease in temperature for TC [5]
Exhaust temp [°C]	428,3	671,6		36,2	36,2
NOX concentration [g/kW]		3,7	8,7	57,7	
75% Load					
Exhaust temp [°C]	345,3	559,0		38,2	38,2
NOX concentration [g/kW]		3,4	10,5	67,8	
50% Load					
Exhaust temp [°C]	286,0	457,6		37,5	37,5
NOX concentration [g/kW]		3,2	10,0	67,6	
25% Load					
Exhaust temp [°C]	236,0	333,8		29,3	29,3
NOX concentration [g/kW]		3,8	8,6	56,0	
10% Load					
Exhaust temp [°C]	234,5	279,3		16,0	16,0
NOX concentration [g/kW]		4,6	6,0	22,9	

D

Efficiency For Organic Rankine Cycle

D.1 Efficiency

Table D.1: Correlation between inflow exhaust gas temperature an efficiency for the ORC technology

Temperature in [°C]	Increase in efficiency [%]
>400-350	10
350-275	12
275-250	5
250-225	3
<225	4

E

Data Sheets For The 12 Chosen Technologies

E.1 Direct Water Injection

Table E.1: Data sheet for Direct Water Injection

Data/Technology	Direct Water Injection
Engine	
Model type	Common rail diesel engine retrofitted from a two cylinder mechanical pump diesel engine
Number of cylinders	2
Compression ratio	17:1
Displacement volume [liter]	0,81
Bore [mm]	95
Stroke [mm]	255
Changes	
Added component(s)	Bosch diesel injector, air booster, gas-liquid booster, high pressure water rail, rail pressure gauge , rail temperature controller, direct water injector
Variable	Lower temperature in combustion chamber
Added cost [SEK]	7000
Case	
Speed [rpm]	1000
Pressure [MPa]	0,9296
Torque [Nm]	1680,248001
Water injection temperature [°C]	15
Water injection pressure [MPa]	35
Water injection timing at maximum efficiency	-180°CA BTDC
Diesel injection timing at maximum efficiency	8°CA BTDC
Water injection duration at maximum efficiency [ms]	0,4
Diesel injection duration at maximum efficiency [ms]	0,85
Increased efficiency 100% [%]	4,08 (BSFC)
Increased efficiency 75% [%]	4,08 (BSFC)
Increased efficiency 50% [%]	4,08 (BSFC)
Increased efficiency 25% [%]	4,08 (BSFC)
Increased efficiency 10% [%]	4,08 (BSFC)
Supplier(s)	
Name of supplier(s)	Bosch has for gasoline engines
Specifications	
Temperature change 100%	0
Temperature change 75%	0
Temperature change 50%	0
Temperature change 25%	0
Temperature change 10%	0
NOx change 100%	55% lower
NOx change 75%	55% lower
NOx change 50%	55% lower
NOx change 25%	55% lower
NOx change 10%	55% lower

E.2 Continuously Varying Transmission

Table E.2: Data sheet for Continuously Varying Transmission

Data/Technology	Continuously Varying Transmission
Engine	
Model type	D13
Maximum energy output [kW]	407
Maximum rpm	2100
Changes	
Added component(s)	Transmission box
Variable	Enigne speed, rpm
Cost [SEK]	29000
Case	
Increased efficiency 100% [%]	2,9 (BSFC)
Increased efficiency 75% [%]	1,8 (BSFC)
Increased efficiency 50% [%]	2,9 (BSFC)
Increased efficiency 25% [%]	6,5 (BSFC)
Increased efficiency 10% [%]	22,8 (BSFC)
Supplier(s)	
Name of supplier(s)	Mazaro
Specifications	
Temperature change 100%	4 % higher
Temperature change 75%	7,2% higher
Temperature change 50%	23% higher
Temperature change 25%	29,5% higher
Temperature change 10%	22% higher
NOx change 100%	11,3% lower
NOx change 75%	14,4% lower
NOx change 50%	14% lower
NOx change 25%	7,4% lower
NOx change 10%	9,1% lower

E.3 Single Speed Transmission

Table E.3: Data sheet for Single Speed Transmission

Data/Technology	Single Speed Transmission
Engine	
Model type	D13 eSCR
Maximum energy output	407
Maximum rpm	2100
Changes	
Added component(s)	Single speed gearbox
Variable	Enigne speed, rpm
Cost [SEK]	5000
Case	
Engine speed [rpm]	1300
Output speed [rpm]	1500
Increased efficiency 100% [%]	Can not provide maximum power at this load
Increased efficiency 75% [%]	2 (BSFC)
Increased efficiency 50% [%]	1 (BSFC)
Increased efficiency 25% [%]	4 (BSFC)
Increased efficiency 10% [%]	19 (BSFC)
Supplier(s)	
Name of supplier(s)	-
Specifications	
Temperature change 100%	2,9% higher
Temperature change 75%	7,2% higher
Temperature change 50%	10,8% higher
Temperature change 25%	10,6% higher
Temperature change 10%	3% higher
NOx change 100%	54,8% lower
NOx change 75%	11% lower
NOx change 50%	1% lower
NOx change 25%	9,3% lower
NOx change 10%	29,7% lower

E.4 Variable Compression Ratio

Table E.4: Data sheet for Variable Compression Ratio

Data/Technology	Variable Compression Ratio
Engine	
Model type	D16
Changes	
Added component(s)	A new connecting rod
Variable	Compression ratio adjusted to get a more efficient engine.
Cost [SEK]	2000
Case	
Engine speed [rpm]	1500
Pressure [MPa]	3
Increased efficiency 100% [%]	0 (BSFC)
Increased efficiency 75% [%]	1,58
Increased efficiency 50% [%]	4,59
Increased efficiency 25% [%]	0,00
Increased efficiency 10% [%]	3,52
Supplier(s)	
Name of supplier(s)	FEV
Specifications	
Temperature change 100%	4% lower
Temperature change 75%	4% lower
Temperature change 50%	4% lower
Temperature change 25%	4% lower
Temperature change 10%	4% lower
NOx change 100%	0
NOx change 75%	0
NOx change 50%	0
NOx change 25%	0
NOx change 10%	0

E.5 Variable Valve Actuation

Table E.5: Data sheet for Variable Valve Actuation

Data/Technology	Variable Valve Actuation
Engine	
Model type	A one-dimensional model of OM457
Number of cylinders	6
Compression ratio	17,5:1
Displacement volume [liter]	12
Maximum energy output [kW]	257 at 2000 rpm
Bore [mm]	128
Stroke [mm]	155
Maximum torque [Nm]	1598 at 1200 rpm
Changes	
Added component(s)	New valves + software
Variable	Lowers the compression ratio to increase thermal efficiency
Cost [SEK]	7000
Case	
Engine speed [rpm]	800-2000
Torque [Nm]	400-1600
Increased efficiency 100% [%]	1,0
Increased efficiency 75% [%]	3,2
Increased efficiency 50% [%]	3
Increased efficiency 25% [%]	3
Increased efficiency 10% [%]	3
Supplier(s)	
Name of supplier(s)	Eaton
Specifications	
Temperature change 100%	0
Temperature change 75%	0
Temperature change 50%	0
Temperature change 25%	0
Temperature change 10%	0
NOx change 100%	67% lower
NOx change 75%	66% lower
NOx change 50%	64% lower
NOx change 25%	20% lower
NOx change 10%	0

E.6 Turbo Compound

Table E.6: Data sheet for Turbo Compound

Data/Technology	Turbo Compound
Engine	
Model type	D13 GTT_TC
Changes	
Added component(s)	Turbo Compound
Variable	Uses exhaust gases to generate more electricity
Cost [SEK]	30000
Case	
Engine speed [rpm]	1500
Torque [Nm]	557-2232
Increased efficiency 1-100°C [%]	1.0
Increased efficiency 101-150°C [%]	1.5
Increased efficiency 151-200°C [%]	2.3
Increased efficiency 201-300°C [%]	2.5
Increased efficiency 301-350°C [%]	1.6
Increased efficiency 351-400°C [%]	3.0
Increased efficiency 401-450°C [%]	6.0
Increased efficiency 451-480°C [%]	10.0
Increased efficiency 481-500°C [%]	13.0
Increased efficiency 501-520°C [%]	16.0
Increased efficiency 521-540°C [%]	17.5
Increased efficiency 541-560°C [%]	18.5
Increased efficiency >560°C [%]	19.5
Supplier(s)	
Name of supplier(s)	Volvo
Specifications	
Temperature change 100%	36,2% lower
Temperature change 75%	38,2% lower
Temperature change 50%	37,5% lower
Temperature change 25%	29,3% lower
Temperature change 10%	16% lower
NOx change 100%	57,7% lower
NOx change 75%	67,8% lower
NOx change 50%	67,6% lower
NOx change 25%	56% lower
NOx change 10%	22,9% lower

E.7 Emulsified Fuel

Table E.7: Data sheet for Emulsified Fuel

Data/Technology	Emulsified Fuel
Engine	
Model type	LISTER 8-1 diesel engine
Number of cylinders	1
Compression ratio	17:1
Displacement volume [liter]	1,43
Maximum energy output [kW]	6
Bore [mm]	114,3
Stroke [mm]	139,7
Maximum speed [rpm]	1850
Changes	
Added component(s)	Water + Emulsion + Injector
Variable	Delays the ignition
Cost [SEK]	7000
Case	
Engine speed [rpm]	1000-1500
Torque [Nm]	27,1-29,2
Increased efficiency 100% [%]	8,7 (Brake Thermal Efficiency)
Increased efficiency 75% [%]	7,3 (Brake Thermal Efficiency)
Increased efficiency 50% [%]	5 (Brake Thermal Efficiency)
Increased efficiency 25% [%]	5 (Brake Thermal Efficiency)
Increased efficiency 10% [%]	5 (Brake Thermal Efficiency)
Supplier(s)	
Name of supplier(s)	Bosch
Specifications	
Temperature change 100%	15% lower
Temperature change 75%	15% lower
Temperature change 50%	15% lower
Temperature change 25%	15% lower
Temperature change 10%	15% lower
NOx change 100%	79% lower
NOx change 75%	79% lower
NOx change 50%	79% lower
NOx change 25%	79% lower
NOx change 10%	79% lower

E.8 Organic Rankine Cycle

Table E.8: Data sheet for Organic Rankine Cycle

Data/Technology	Organic Rankine Cycle
Engine	
Model type	D13
Changes	
Added component(s)	Fluid pump, condenser, evaporator, superheater, recuperator, turbine expander, alternator, piping, flywheel motor/generator, electrical conditioning, control system
Variable	Uses waste heat to generate more electrical power
Cost [SEK]	80000 (estimated cost based on 10000 units)
Case	
Increased efficiency 1-100°C [%]	4.0
Increased efficiency 101-150°C [%]	4.4
Increased efficiency 151-200°C [%]	5.3
Increased efficiency 201-225°C [%]	6.0
Increased efficiency 226-250°C [%]	6.9
Increased efficiency 251-275°C [%]	9.5
Increased efficiency 276-350°C [%]	11.6
Increased efficiency 351-400°C [%]	10.0
Increased efficiency >400°C [%]	9.7
Supplier(s)	
Name of supplier(s)	BorgWarner
Specifications	
Temperature change 100%	91% lower
Temperature change 75%	91% lower
Temperature change 50%	91% lower
Temperature change 25%	91% lower
Temperature change 10%	91% lower
NOx change 100%	0
NOx change 75%	0
NOx change 50%	0
NOx change 25%	0
NOx change 10%	0

E.9 Cylinder Deactivation

Table E.9: Data sheet for Cylinder Deactivation

Data/Technology	Cylinder Deactivation
Engine	
Model type	13L class 8 engine
Number of cylinders	6
Displacement volume [liter]	13
Changes	
Added component(s)	New cylinder heads + software
Variable	Makes engine more efficient by deactivating cylinders at lower loads
Cost [SEK]	4500
Case	
Increased efficiency 100% [%]	0
Increased efficiency 75% [%]	0
Increased efficiency 50% [%]	0
Increased efficiency 25% [%]	6 (CO2 reduction)
Increased efficiency 10% [%]	9 (CO2 reduction)
Supplier(s)	
Name of supplier(s)	Jacob's or Eaton
Specifications	
Temperature change 100%	9% higher
Temperature change 75%	9% higher
Temperature change 50%	9% higher
Temperature change 25%	9% higher
Temperature change 10%	9% higher
NOx change 100%	9% lower
NOx change 75%	9% lower
NOx change 50%	9% lower
NOx change 25%	9% lower
NOx change 10%	9% lower

E.10 Dynamic Skip Fire

Table E.10: Data sheet for Dynamic Skip Fire

Data/Technology	Dynamic Skip Fire
Engine	
Model type	MD I-6 Diesel engine
Number of cylinders	6
Compression ratio	17,6
Displacement volume [liter]	7,7
Changes	
Added component(s)	New pistons + software for controlling the deactivations
Variable	Changes the number of active pistons
Cost [SEK]	6375
Case	
Engine speed [rpm]	1500
Pressure [MPa]	0,5-2
Torque [Nm]	80-318
Increased efficiency 100% [%]	0
Increased efficiency 75% [%]	0
Increased efficiency 50% [%]	0
Increased efficiency 25% [%]	5 (BSFC)
Increased efficiency 10% [%]	15 (BSFC)
Supplier(s)	
Name of supplier(s)	Tula
Specifications	
Temperature change 100%	9% higher
Temperature change 75%	9% higher
Temperature change 50%	9% higher
Temperature change 25%	9% higher
Temperature change 10%	9% higher
NOx change 100%	29% lower
NOx change 75%	29% lower
NOx change 50%	29% lower
NOx change 25%	29% lower
NOx change 10%	29% lower

E.11 Thermal Barrier Coating

Table E.11: Data sheet for Thermal Barrier Coating

Data/Technology	Thermal Barrier Coating
Engine	
Model type	Kirloskar TV1 engine
Number of cylinders	1
Compression ratio	17,5:1
Maximum energy output [kW]	3,7
Bore [mm]	80
Stroke [mm]	110
Changes	
Added component(s)	ZrO ₂ /Al ₂ O ₃ with a coating thickness of 150 microns
Variable	Reduces thermal losses
Cost [SEK]	1500 (for the pistons), 1300 (combustion chamber including exhaust port and valve heads)
Case	
Engine speed [rpm]	1500
Increased efficiency 100% [%]	5,3
Increased efficiency 75% [%]	5,3
Increased efficiency 50% [%]	10,0
Increased efficiency 25% [%]	7,8
Increased efficiency 10% [%]	20,3
Supplier(s)	
Name of supplier(s)	Toyota has implemented this
Specifications	
Temperature change 100%	7% higher
Temperature change 75%	8% higher
Temperature change 50%	20% higher
Temperature change 25%	20% higher
Temperature change 10%	8% higher
NOx change 100%	0
NOx change 75%	0
NOx change 50%	0
NOx change 25%	0
NOx change 10%	0

E.12 Rotational Liner

Table E.12: Data sheet for Rotational Liner

Data/Technology	Rotational Liner
Engine	
Model type	3.9L Cummins B-Series engine
Number of cylinders	4
Compression ratio	17,5:1
Displacement volume [liter]	3,9
Maximum energy output [kW]	78
Bore [mm]	102
Stroke [mm]	119
Maximum speed [rpm]	2300
Maximum torque [Nm]	360
Changes	
Added component(s)	New camshaft, new crankshaft, new pistons and cylinders that includes the rotational liner function
Variable	Reduced friction for reduced fuel consumption
Cost [SEK]	29000
Case	
Rotational speed of RLE [rpm]	300
Increased efficiency 100% [%]	3,5 (fuel economy)
Increased efficiency 75% [%]	7 (fuel economy)
Increased efficiency 50% [%]	8 (fuel economy)
Increased efficiency 25% [%]	9 (fuel economy)
Increased efficiency 10% [%]	10 (fuel economy)
Supplier(s)	
Name of supplier(s)	Rotating Sleeve Engine Technologies Inc
Specifications	
Temperature change 100%	0
Temperature change 75%	0
Temperature change 50%	0
Temperature change 25%	0
Temperature change 10%	0
NOx change 100%	0
NOx change 75%	0
NOx change 50%	0
NOx change 25%	0
NOx change 10%	0

F

Temperature And NO_x Data For Selective Catalyst Reduction

F.1 Exhaust Gas Temperature

Table F.1: Correlation between in-and-outflow exhaust gas temperature for the SCR

Temperature in [°C]	Temperature out [°C]
>340	242
340-260	225
<260	135

F.2 NO_x Emissions

Table F.2: Correlation between inflow exhaust gas temperature and the NO_x emissions from the SCR

Temperature in [°C]	NOx concentration reduction [%]
>250	96
250-150	60
<150	$(-0,0021*t+1,1287)*100$

G

Results From Sensitivity Analysis On Multi-Criteria Decision-Making Matrix

G.1 Scenario 1

Table G.1: Ranking result for scenario 1

Weight scenario with equal weight							
Criteria	Weight	Direct Water Injection	Continuously Varying Transmission	Single Speed Transmission	Variable Compression Ratio	Variable Valve Actuation	Turbo Compounding
Increased Efficiency	0,25	2	2,8	1,8	1,1	1,5	1,8
Cost	0,25	5	4	5	5	5	4
TRL	0,25	1	1,5	1	1,5	1	3
Implementation Ability	0,25	3	2	3	4	3	5
Sum		2,8	2,6	2,7	2,9	2,6	3,5
Ranking		6	8	7	3	8	2
Criteria	Weight	Emulsified Fuel	Organic Rankine Cycle	Cylinder Deactivation	Dynamic Skip Fire	Thermal Barrier Coating	Rotational Liner Engine
Increased Efficiency	0,25	2,7	3,5	1,4	1,5	4,5	4
Cost	0,25	5	1	5	5	5	4
TRL	0,25	1	1,5	1	1	1	1
Implementation Ability	0,25	3	3	3	4	4	1
Sum		2,9	2,3	2,6	2,9	3,6	2,5
Ranking		3	12	8	3	1	11

G.2 Scenario 2

Table G.2: Ranking result for scenario 2

Weight scenario with opposite weight							
Criteria	Weight	Direct Water Injection	Continuously Varying Transmission	Single Speed Transmission	Variable Compression Ratio	Variable Valve Actuation	Turbo Compounding
Increased Efficiency	0,15	2	2,8	1,8	1,1	1,5	1,8
Cost	0,3	5	4	5	5	5	4
TRL	0,25	1	1,5	1	1,5	1	3
Implementation Ability	0,3	3	2	3	4	3	5
Sum		3,0	2,6	2,9	3,2	2,9	3,7
Ranking		6	10	7	3	7	1
Criteria	Weight	Emulsified Fuel	Organic Rankine Cycle	Cylinder Deactivation	Dynamic Skip Fire	Thermal Barrier Coating	Rotational Liner Engine
Increased Efficiency	0,15	2,7	3,5	1,4	1,5	4,5	4
Cost	0,3	5	1	5	5	5	4
TRL	0,25	1	1,5	1	1	1	1
Implementation Ability	0,3	3	3	3	4	4	1
Sum		3,1	2,1	2,9	3,2	3,6	2,4
Ranking		5	12	7	3	2	11

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



CHALMERS
UNIVERSITY OF TECHNOLOGY