Impact of different energy types of military vehicles on the supply chain

A MILP model for an optimal military Vehicle Energy Supply Chain

Master Thesis

M.W. van Maldegem

Delft University of Technology

Impact of different energy types of military vehicles on the supply chain

A MILP model for an optimal military Vehicle Energy Supply Chain

by

M.W. van Maldegem

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Friday May 24, 2024 at 15:00.

Rapport number:	2024.MME.8923	
Student number:	4579836	
Project duration:	September 4, 2023 – May 24, 2024	
Thesis committee:	dr. ir. H. Polinder,	TU Delft, supervisor
	dr. F. Schulte,	TU Delft
	dr. A. Coraddu,	TU Delft
	D.M. Nagtegaal,	COMMIT

Cover: CV90 by Dutch military[1]

TU Delft

Preface

This thesis marks the culmination of my time as a student. I thoroughly enjoyed my experience as a student here in Delft and the opportunities it afforded me. I am particularly pleased that I was able to merge my passion for defense with technology in my graduation assignment, a combination that has been a constant throughout my student days.

First and foremost, I would like to express my gratitude to my supervisors, Henk Polinder and Frederik Schulte, for their guidance and insightful feedback, which greatly assisted me in completing this thesis. Additionally, I extend my thanks to the supervisors from COMMIT, Mark Nagtegaal and Rick van der Gouw, for their valuable input from the COMMIT perspective and for their collaborative approach.

Special appreciation goes to my girlfriend and parents, who patiently listened to numerous stories about the military supply chain and supported me throughout, even assisting me in rectifying linguistic errors.

At the end, I would like to express my gratitude to all the military units who generously shared their knowledge and user data with me, despite their busy schedules, regarding the military supply chain. I extend my heartfelt thanks to 130 Bevocie, 230 Bevocie, Brandstofbedrijf Defensie, 44e Paininf, and Kenniscentrum Logistiek. Without their invaluable contributions, acquiring the depth of knowledge necessary would have been impossible.

M.W. van Maldegem
Delft, May 2024

Abstract

The Dutch Ministry of Defence (NLMoD) has stated the goal of reducing dependency on fossil fuels by at least 20% by the year 2030 and at least 70% by the year 2050 compared to the year 2010. Research in the NLMoD explores the possibility of changing diesel-fuelled vehicles and weapon platforms to alternative forms of energy such as electric or sustainable fuels. In these projects, the focus is on (part of) the vehicle or energy source itself, but the impact on the Military Supply Chain (MSC) is missing.

This research has developed a Mixed Integer Linear Programming model that can be used to gain insight into the impact of the energy type of tactical vehicles and weapon platforms on the MSC and therefore is able to see what energy type has the lowest impact on that MSC. The impact on the MSC is measured by minimizing the refuel time, number of supply trips, and CO2 equivalent emissions. The model can provide insight into what the minimal requirements of potential energy carriers and conversion devices should be in order to have a similar or better impact on the current diesel MSC. The model is based on the current supply chain of the NLMoD and is expanded with the use of APUs for vehicles, energy generation at Nodes, the use of small supply trucks as energy buffers, compatible supply material, and longer self-sufficient times. Combinations of these are looked at in different policies.

Results show the trend that energy types with lower CO2 equivalent emissions have higher refuel time and number of supply trips. An exception to this is HVO and HVO-electric series hybrid, which also have the least impact on the MSC. Energy types such as hydrogen and electric require huge improvements in energy density, fill speed, and FTW efficiency to come close to the results of current diesel.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Abbreviation	English Definition	Dutch Definition
AoO	Area of Operation	
APU	Auxiliary Power Unit	
BVE	Fuel Consumption Unit	Brandstofverbruikseenheid
COMMIT	Materiel and IT Command	Commando Materieel en IT
CVV	Compensation Fuel Consumption	Compensatie verplaatsingsverbruik
DOS	Day of Supply	
FSC	Forward Supply Centre	
FTW	Fuel To Wheel	
GBV	Standardized Fuel Consumption	Gestandaardiseerd Brandstof Verbruik
HVO	Hydrotreated Vegetable Oil	
ICE	Internal Combustion Engine	
IF	Intensity Factor	
KPI	Key Performance Indicator	
MILP	Mixed-Integer Linear Programming	
MINLP	Mixed-Integer Nonlinear Programming	
MSC	Military Supply Chain	
(NL)MoD	(Netherlands) Ministry of Defence	
SC	Supply Centre	
TAS	Temporarily Additional Supply	
VESC model	Vehicle Energy Supply Chain model	
WLS	Swap Body, name for supply truck Scania WLS 165 kN	Wissellaadsysteem
WTW	Well To Wheel	

Definitions

Definition	Explanation
Auxiliary Power Unit	Is a device that provides energy for functions in the vehicle or weapon platform other than propulsion.
Pull-supply	A method of supply in which the supplier generates the flow of goods based on actual use by the customer, after a request from the user.
Push-supply	A method of supply in which the supplier generates the flow of goods at the customer based on expected use, without a request from the user.
Independent Load Carrier Concept	Concept whereby the truck and load carrier can be physically separated and the truck can therefore transport different load carriers.
Day of Supply	The stock that equals the standard or combat daily consumption.
Standardized Fuel Consumption (GBV)	Fuel consumption of units in normal conditions. Differs per vehicle/platform and is given in L/day given for 100km/day.
Fuel Consumption Unit (BVE)	The sum of GBV's of all users in the unit or formation. Given in L/day.
Compensation Fuel Consumption (CVV)	Energy consumption for whole units calculated for movement, combat and stand-by time.

1 Introduction

Military units consume a lot of energy, which is used for living facilities, communication, logistics, vehicles and weapon platforms. Currently, almost all vehicles and weapon platforms use fossil fuels such as diesel as primary fuel. In the *Roadmap Energy Transition* [2], the Dutch Ministry of Defence (NLMoD) has stated the goal of reducing dependency on fossil fuels by at least 20% by the year 2030 and at least 70% by the year 2050 compared to the year 2010. A three-step strategy called 'Trias Energetica' is used, which starts with reducing the required energy. Step two is to transition to renewable energy. Step three involves utilizing fossil fuels efficiently and cleanly, in the case their use is inevitable. One side note is that the reduced dependency of fossil fuels should not lead to deterioration of the operational task performance. Research in the NLMoD explores the possibility of changing diesel-fuelled vehicles and weapon platforms to alternative forms of energy such as electric or sustainable fuels. These alternatives could even lead to tactical advantages such as lower heat image and noise reduction by use of electric drive and safer operation by decreasing supply movements. This new trend of alternatives to fossil fuels, such as electric vehicles and weapon platforms, require a thorough examination of the energy generation and supply required for supplying those systems. For this research, alternative energy types are options that deviate from the current standard, which is 100% diesel, and are less depended on fossil fuels, compared to diesel.

1.1. Problem definition

The Materiel and IT Command (COMMIT), located within the NLMoD, is responsible for ensuring that military personnel have modern, robust, and safe materiel to work with. The department of Ground-based Weapon Platforms, especially the section Energy, focuses on research on alternative energy types for their vehicles instead of the current fossil fuels used. Multiple projects and studies have been conducted or are currently looked into, such as fully electric vehicles, hybrid vehicles, potential use for hydrogen or nuclear energy in vehicles, pneumatic motors and many more projects. In these projects, the focus is on (part of) the vehicle or energy source itself, but the impact on the Military Supply Chain (MSC) is missing. COMMIT currently lacks insight in the quantitative impact of the alternative energy types on the MSC.

Logistics is one of the most important, or maybe the most important part of the military. As once Lt. Gen. Fredrick Franks (USA, 7th Corps Commander) said during the military operation Desert Storm: *"Forget logistics, you lose"* [3]. The military uses a one-fuel policy, which means that all combat vehicles have the ability to use the same fuel in order to simplify the MSC. Currently, Dutch military vehicles and weapon platforms use diesel as fuel for propulsion and to generate electricity for their communications and sensors. Diesel has the special characteristics: it has a high energy density, world wide availability, uniform quality and competitive pricing because it is commonly used on the civil market [4]. The MSC is fully developed for the distribution of diesel, and tactical performance is tailored to this MSC. A change of fuel type could lead to major changes in the MSC and therefore it is crucial to understand the impact of possible new energy types on the this.

The war in Ukraine is forcing the NLMoD to reconsider their MSC and adjust to the new threat of conventional war. The NLMoD is accustomed to peacekeeping missions and not to warfighting anymore after the cold war ended. The MSC for peacekeeping missions and warfighting is, in basic principles, similar but differs in execution in some parts. The most important difference is that for warfighting the MSC has longer distances, must be mobile all the time and is more critical compared to peacekeeping missions.

COMMIT does not currently have a quantitative way to determine the impact of an energy type on the MSC. The impact on the MSC has all to do with the energy density of the energy carrier, efficiency of the conversion device, the time of refuelling and the complexity of maintenance of components, as well as how labour-intensive it is. At the moment, the impact of the energy type is estimated based on experience and various research in sub-areas. A complete overview is lacking. This research is done in order to create a scientific tool that provides COMMIT with an overview of the impact of energy types for specific warfighting scenarios, which could help later on in decision making.

1.2. Goals and scope

The main goal of this research is to develop a model which can be used to gain insight into the impact of the energy type of tactical vehicles and weapon platforms on the MSC and therefore be able to see what energy type has the lowest impact on that MSC. The model can provide insight in what the minimal requirements of potential energy carriers and conversion devices should be in order to have a similar or better impact to the current diesel MSC. This main goal can be split into several smaller goals, which are:

- To be able to combine and extract the different projects and research data as well as operational data to find how the total supply system is linked together;
- To introduces various enhancements to the MSC aimed at mitigating the impact of the different energy types;
- To develop a model that shows the performance of the MSC based on the energy type and MSC enhancements during warfighting situations;
- To give a well-argued advice on which energy type has the lowest impact on the MSC;
- To provide insight into what the minimal technical requirements should be for alternative energy carriers and conversion devices to have the same impact on the MSC as the current diesel has.

This research will focus on army units which operate outside their home base while carrying out NLMoD's main task 1, which is protecting one's own territory and that of allies. One has to think of warfighting in deployments, (major) exercises or other activities that require the use of substantial military force for a longer period, which would require refuelling. The MSC is chosen with one boundary the suppliers for the supply centre and at the other end the user in the field. The supply/generation of the energy in the supply centre is looked at in a simplified way while the energy carriers and the conversion devices in the user are looked at in more detail. The model will be validated by historical data on brigade level with a warfighting situation. Research and projects of COMMIT will be used as different inputs for the energy types.

1.3. Research questions

The main research question is:

What is the impact of alternative energy types of tactical military vehicles on the military supply chain and what would be the optimal energy type?

With the following sub-questions:

1. How does the current military supply chain operate with the current energy type for tactical vehicles?
2. What are current and future potential energy carriers and conversion devices which could be used?

3. What modelling methodology is most suitable for this problem?
4. What are the relevant parameters which influence the system and how to measure impact on the military supply chain?
5. How can the model be made adaptable to facilitate the ability for different compositions of vehicles and situations?
6. How can the model provide insight into the minimum requirements for potential energy technologies when the impact on the supply line is similar compared to diesel?
7. How can the model be verified and validated?

1.4. Scientific and practical relevance

The scientific relevance of this research lies in the fact that it contributes to the field of renewable fuels and their still lesser-known impact on the MSC. This military environment differs from the civilian environment because of the tough conditions, minimal existing infrastructure, changing conditions, and strict supply capacity. This creates many challenges and requires special needs for operation. The lack of literature available on the topic of military supply of alternative energy carriers and conversion devices for military vehicles, as well as TNO and the Knowledge Center Logistics just starting to do research on this, shows that this research has great relevance.

The practical relevance of this research is that the NLMoD gains insight into the consequences of potential alternatives to diesel fuels by means of KPIs with quantitative values. This can support them in decision-making for future strategic choices they have to make regarding the use of alternative energy types instead of diesel. Another practical relevance is that COMMIT gains a clear insight into the actual operations so that they can better integrate their research with actual operations.

1.5. Methodology

The goal is to optimize real-world operations for future use through the use of a digital model. A physical (scale) model is not possible because the technologies under consideration are not all in operational state, and the system is not suitable for testing at scale due to the many components and situational factors involved.

The methodology used for this research is based on the research methodology proposed by Baharmand et al. [5] and supplemented with the optimization model development steps by Özkaraca [6]. A schematic overview of the research methodology can be seen in Figure 1.1. Baharmand et al. developed a quantitative dominant mixed methods research methodology for humanitarian logistics. The mixed-method research methodology translates the results of qualitative research into a quantitative optimization model, whereby qualitative research is conducted to understand concepts and explore and investigate new phenomena or theories. Quantitative research focuses on quantifying a phenomenon and (dis-)proving existing theories by measuring variables and their relations. Humanitarian logistics is most related to military logistics when compared with commercial logistics because of the unpredictability of situations, scale, and length of operation, type of goods transported, and partners involved.

The research methodology is divided into four phases. Phase 1 involves formulating a problem definition and conducting a state of the art and literature review. This provides the research gap and a definite problem definition, as well as identifying the data required for the system. The model is based on the current MSC and the literature review provide which energy types are included in the model. Phase 2 encompasses on-site and remote data collection. Remote data collection is conducted through desk research, while on-site data collection involves visiting and collecting data from different partners involved in the MSC, such as the knowledge center logistics, supply units, and COMMIT. This provides qualitative data that can be used for phase 3, which involves post-field work where the Vehicle Energy Supply (VESC) model is developed. The steps in the VESC model are provided by the work of Özkaraca [6], resulting in an optimization VESC model. This model integrates features of the current MSC and introduces various enhancements. These enhancements are examined within different policy scenarios. Phase 4 focuses on dissemination, where the VESC model is validated and experiments can be conducted to determine the impact of different scenarios, situations, and policies. This is done by the use of a case study. Initially, all policies are analyzed using the current energy source, diesel. Subsequently, each policy is reassessed with all energy types considered in this study. The last step is report compilation, which yields policy recommendations, a report, and potential future research.

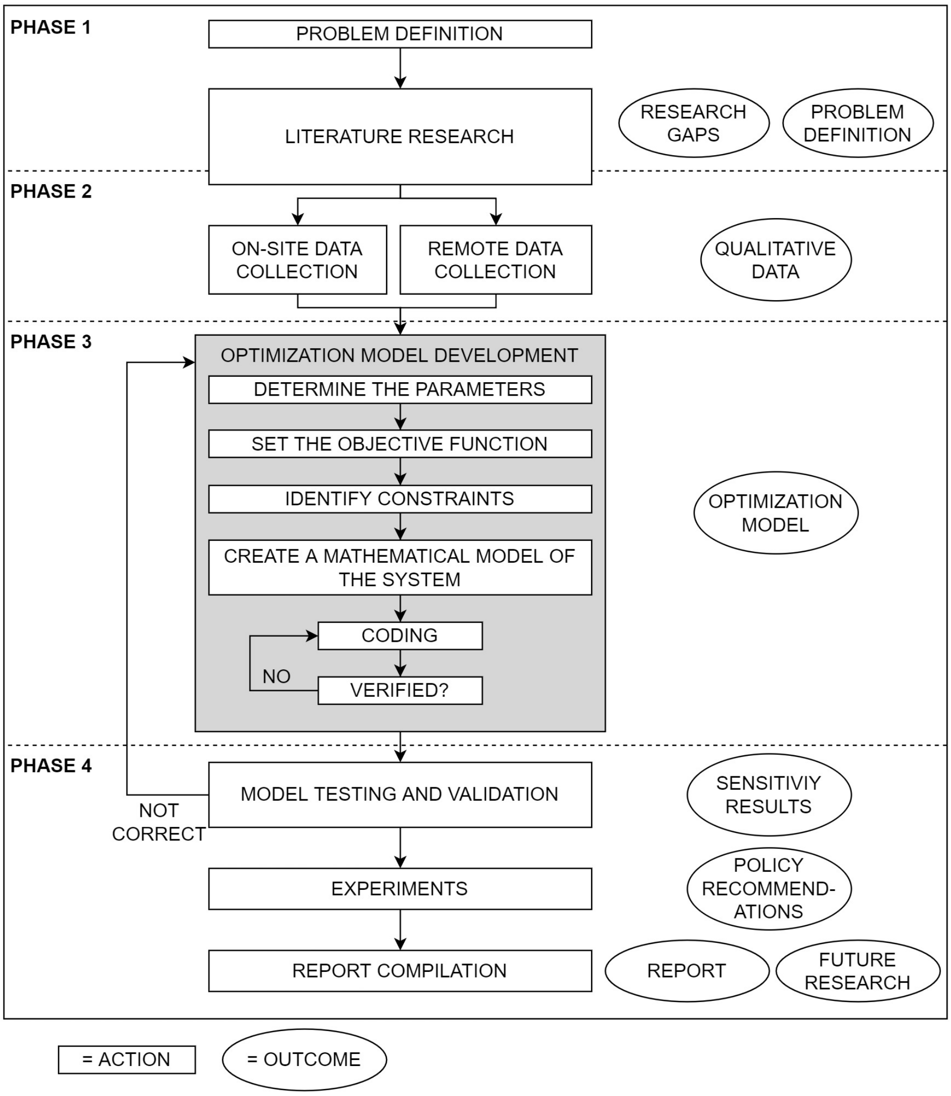

Figure 1.1: Methodology for VESC model based on Baharmand et al. [5] and Özkaraca[6]

2
State of the Art and Literature Research

The MSC is inherently complex, particularly when considering the integration of alternative energy sources. This chapter will delve into the framework within which the MSC operates, along with its structure. Additionally, it will explore the potential energy sources and conversion mechanisms considered in this study. Furthermore, existing literature and research will be analyzed to determine the current state of the MSC and alternative energy sources for vehicles and weapon platforms, as well as identify any gaps in the literature.

2.1. Organization

In order to know the current and potential future MSC, it is required to know the bigger picture of the organization in which it is located. The Dutch armed forces have three main tasks that they must perform, which are:

1. protecting one's own territory and that of allies;
2. promoting the (international) legal order and stability;
3. supporting civil authorities and providing assistance in disasters and crises.

The first main task, also referred to as "warfighting," is defined by the US Marine Corps [7] as: *"a violent clash of interests between or among organized groups characterized by the use of military force. These groups have traditionally been established nation-states, but they may also include any non-state group—such as an international coalition or a faction within or outside of an existing state—with its own political interests and the ability to generate organized violence on a scale sufficient to have significant political consequences."* An example of this is the Ukraine-Russia war of 2022, in which two nation-states engaged in conflict across multiple domains. This conflict prompted the NLMoD to refocus its attention on preparing military capacity for main objective 1. This focus had waned after the end of the Cold War, as the Netherlands primarily participated in coalition peace missions, shifting the emphasis away from main task 1 to main task 2. Main task 3 typically lacks a military character and is primarily aimed at rapidly scaling up manpower or utilizing certain specialist defense capabilities.

This research focuses on deploying military capacity for main task 1 but can also be applied to specific situations within category 2. The main distinction between main tasks 1 and 2 lies in their operational dynamics. Main task 2 typically operates within the same area and from the same base, facing an opponent with inferior military capacity. This means that all patrols and actions originate and conclude at the home base, which also serves as the supply center for the units. Conversely, main task 1 involves facing an opponent of equal or superior military strength, requiring constant mobility to avoid vulnerability to long-range artillery or cruise missiles. Additionally, the shifting front lines result in a dynamic combat zone, necessitating mobile supply and command centers rather than a fixed base. Consequently, the MSC for main task 1 comprises more components and is more complex compared to main task 2, although there remains significant logistical overlap between the two.

2.2. Current energy MSC

Before the current energy MSC is explained, it is vital to understand the different components of the energy chain. These components with explanation can be seen in Figure 2.1 and are based on the steps defined by Mansfield et al. (2020) [8]. This report will use the same terminology as given in Figure 2.1 for the components of the energy chain.

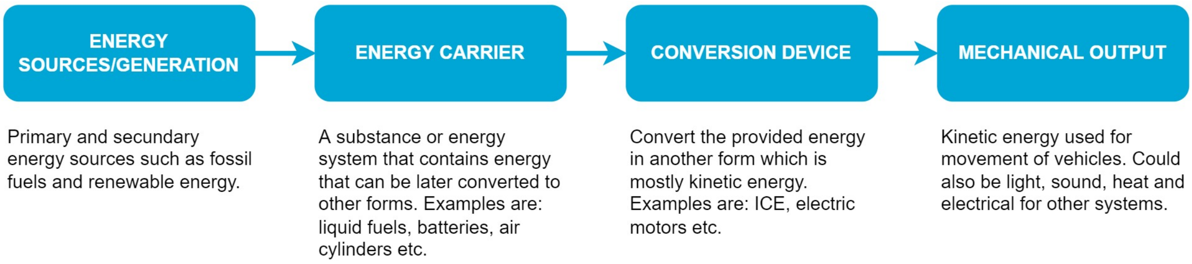

Figure 2.1: Components of the energy chain

2.2.1. Current energy carriers and conversion devices

To enhance MSC efficiency, NATO employs a single fuel policy, meaning all vehicles and weapon platforms utilize the same energy carrier. NATO relies on several fuel types including gasoline (F-57), diesel fuel (F-54), low-temperature diesel/kerosene blend (F-65), and kerosene-based fuel (F-34). F-34, with additives, is compatible with diesel engines, making it suitable for both aircraft and ground vehicles [9]. The NLMoD predominantly utilizes diesel for ground vehicles, which is also the standard in their calculations and vehicle specifications. Incorporating F-34 into diesel engines necessitates fuel improvers or engine adjustments from Euro 6 to Euro 3 standards to prevent engine malfunction or clogging. While diesel is the default energy carrier for NLMoD ground vehicles and weapon platforms, these systems could also operate on F-34 with minor modifications and efficiencies. Diesel offers high energy density, global availability, consistent quality, and competitive pricing due to its widespread use in the civilian market [4]. One liter of diesel stores approximately 10 kWh or 36 MJ of energy, with a specific energy of 42.9 MJ/kg and a density of 0.87 kg/L [10]. Figure 2.2 provides an overview of all bulk fuels utilized by the NLMoD.

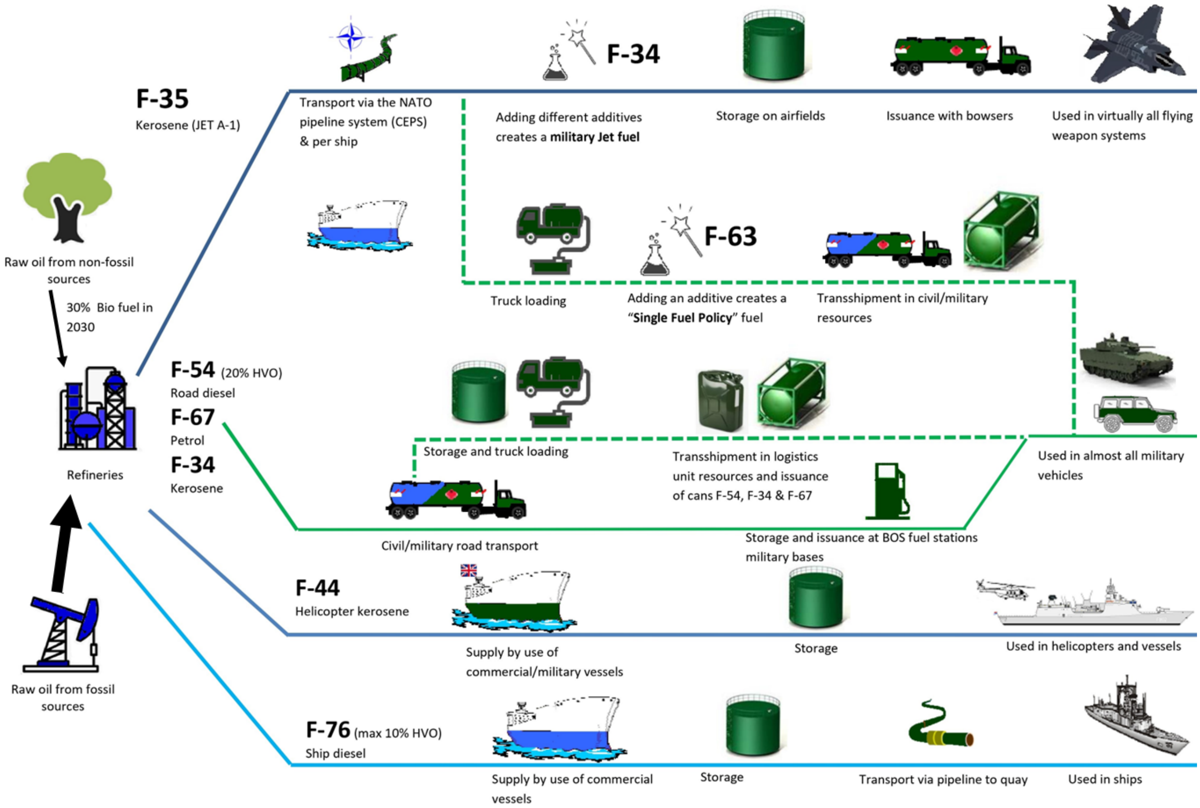

Figure 2.2: All bulk fuels used by NLMoD

The amount of diesel required for operations is calculated according to standardized procedures across all units [11]. Initially, a Standardized Fuel Consumption (GBV) is determined for each vehicle and weapon platform, provided by the manufacturer and validated by NLMoD through road tests, with some reserve capacity included. This represents fuel consumption under normal conditions, specified per day and per 100 km on paved roads. The Fuel Consumption Unit (BVE) aggregates all GBVs of vehicles and platforms. As GBVs are designated for normal conditions, additional Intensity Factors (IF) adjust for variations in movement type, combat types, terrain, weather, and standby periods. These IFs, standardized across vehicles based on NATO doctrines, lack substantiated calculation details. While vehicles exhibit diverse performance on different terrains, the NLMoD mitigates this by always calculating based on worst-case scenarios. Compensation Fuel Consumption (CVV) can be computed based on total distance traveled or time utilized, with specific formulas for movements (Equation 2.1), combat (Equation 2.2), and standby (Equation 2.3).

$$CVV^{movement} = \frac{BVE^{Unit} * IF^{Terrain} * IF^{Weather} * IF^{Movement\ type} * Distance(km)}{100} \tag{2.1}$$

$$CVV^{combat} = \frac{BVE^{Unit} * IF^{Terrain} * IF^{Weather} * IF^{Combat\ type} * Time(Hours)}{24} \tag{2.2}$$

$$CVV^{stand\text{-}by} = \frac{BVE^{Unit} * IF^{stand\text{-}by} * Time(Hours)}{24} \tag{2.3}$$

To compare the energy usage of diesel-driven vehicles with potential alternative conversion devices, it is essential to understand the Fuel-to-Wheel (FTW) efficiency. FTW efficiency is influenced by factors such as the engine, gearbox, and driving conditions, resulting in varying averages across literature. Huang et al. (2011) [12] reports an average FTW efficiency of 20-24% for diesel powertrains, while Nylund and Wenstedt (2019) [13] cite a higher efficiency of 44% for 39-ton diesel trucks. Conversely, NLMoD reports use a different average FTW efficiency of 33% [14]. For this study, the value calculated by the company DNV specifically for Dutch military vehicles is adopted, ensuring relevance to the context of the research.

2.2.2. Military Supply Chain

The MSC and its doctrines are detailed in the supply manuals LAND-LOG-SUPPLY-01 and HB 7-00 D2 LAND-MAN-MECH-04 of the NLMoD [15] [16]. Due to limited capacity, the Dutch Supply & Transport Command operates under central organization and control, diverging from the NATO standard, which typically allows for some level of independent logistics units at battalion level and higher. However, operational units may establish temporary and local decentralized logistics to enhance independence and sustainability. The supply classes managed include:

- Class I: Resources for the livelihood of people and animals such as food and water;
- Class II: Supply items authorized by an authorizing state such as clothing, weapons, tools, spare parts and vehicles;
- Class III: Fuel, oils and lubricants except for flying equipment and specific weapons;
- CLass IIIa: Fuel, oils and lubricants for flying equipment and specific weapons;
- CLass IV: Stock items for which no organic authorization exists. Examples are fortification and construction materials;
- Class V: Munition, explosives and chemical (warfare) agents.

This study focuses on Class III, the current energy carrier used in the NLMoD. The supply manual offers a schematic overview of the generic MSC, depicted in Figure 2.3. The MSC comprises four types of movement: national, strategic, operational, and tactical, though not all types may apply in every situation. The yellow components and red lines pertain to fuel distribution, a focus of this research. It is important to note that fuel suppliers may be involved in both national and operational movements, depending on circumstances. The "X" refers to the maximum distance used in the NLMoD doctrines between Nodes, which is classified data.

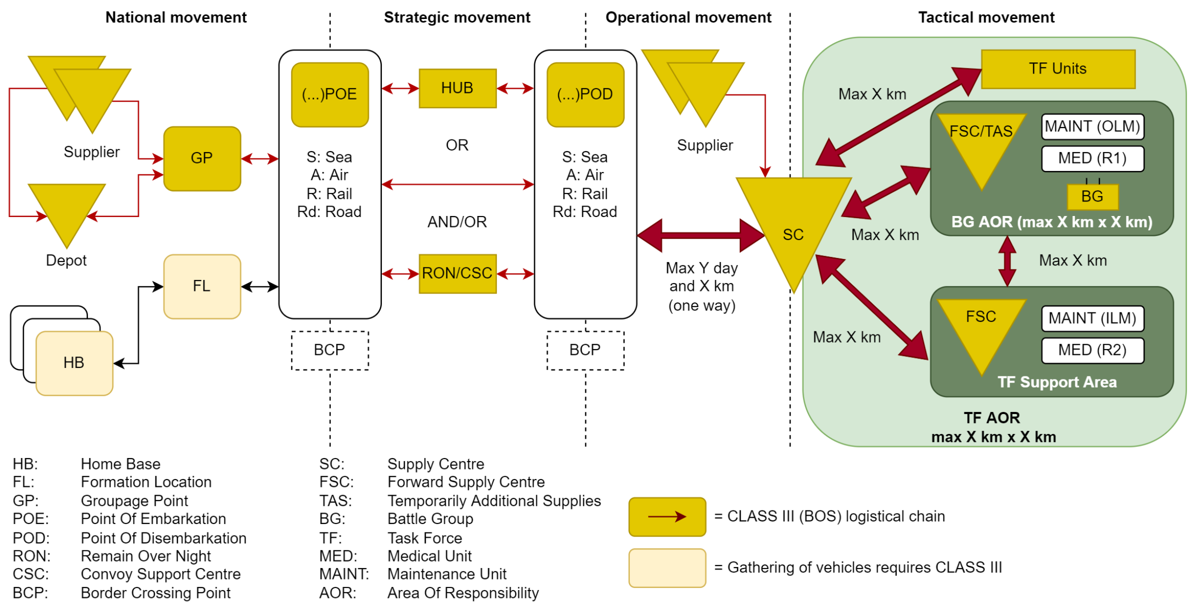

Figure 2.3: Generic MSC based on LAND-LOG-SUPPLY-01 [15]

The research will primarily focus on tactical movement, which involves the MSC from the Supply Centre (SC) to the delivery points at the maneuver units. Tactical movement consists of three phases: preparation, execution, and reorganization. During the preparation phase, units load all required Class I-V supplies, followed by the execution phase where they carry out their mission. The reorganization phase involves restocking supplies for future assignments. Supply in the preparation and reorganization phases mostly occurs at the same facilities and locations, while occasional supply during the execution phase is limited to specific delivery types.

Multiple methods exist for supplying units during tactical movement, as depicted in Figure 2.4. The SC can directly deliver to units using various delivery methods, or a regional or dynamic Forward Supply Centre (FSC) with optional Temporarily Additional Supply (TAS) can serve as intermediaries. A regional FSC provides static support to units in the area, while a dynamic FSC is linked to a specific unit and can move with it if needed. A TAS may be added to shorten delivery times, enhance delivery reliability, or accommodate weapon platforms unable to carry their own supplies. TAS units are always mobile and customized for the specific unit. TAS is not included in this research model. Air supply is exclusive to the Air Mobile Brigade, specifically Unit 11LMB Bevocie, with limited capacity.

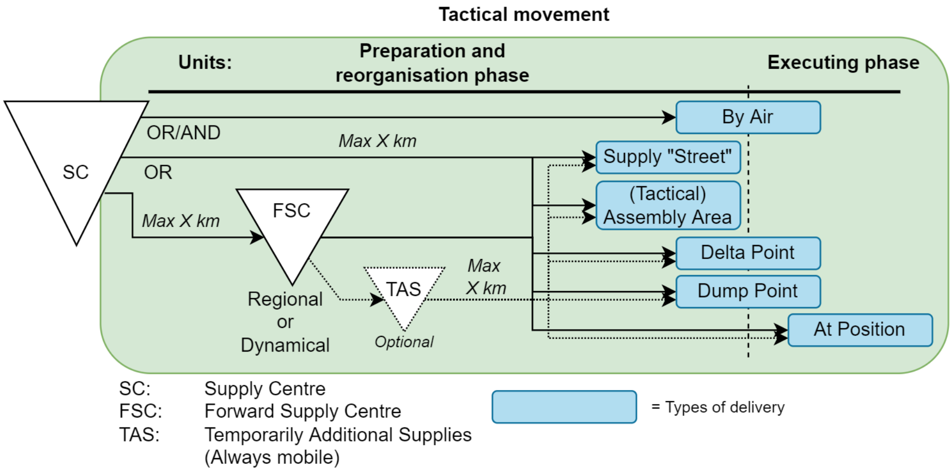

Figure 2.4: Tactical MSC for Class I, III, V which is based on manual HB 7-00 D2 [16]

The difference between the supply for main tasks 1 and 2, as described in section 2.1, lies in the fact that for main task 2, the SC and the base of operation for the units are typically static, whereas this is not the case for main task 1. Due to the nature of warfighting, the SC, along with any optional FSC and TAS, must remain mobile at all times. This complicates the repacking and distribution of goods at the SC, as the entire operation can be relocated at any moment. Additionally, generating energy at the SC becomes challenging since this technology must also be mobile.

Fuel transportation is facilitated by the Scania WLS 165 kN trucks (with 165 kN trailer), known as WLS, and the Scania Gryphus 100 kN trucks (referred to as Gryphus). The WLS can carry fuel containers with a capacity of 15 m^3 without a pump or 12 m^3 with a pump. While these vehicles are used throughout the MSC, they are often replaced by the Gryphus for the final trip to the consumer in the field due to the Gryphus's greater terrain capability. However, the fuel containers of the WLS are not compatible with the Gryphus, so the Gryphus has its own 7 m^3 (6220 L usable fuel) fuel container with a pump. Fuel transfer from the WLS to the Gryphus occurs at the (F)SC. The WLS offers the advantage of self-dropping the fuel container and loading another container or different types of cargo, whereas the Gryphus's fuel container is typically kept on the vehicle at all times due to the need for a crane to remove it.

The IVECO Manticore, a new Medium Tactical Vehicle being procured by the NLMoD, could potentially relieve supply burdens in the future by carrying extra energy supplies for units in the field. Although not currently included in doctrines, the Manticore's pick-up variant with a 20 kN load capacity could be attached to units for this purpose.

CCV calculations, detailed in subsection 2.2.1, are primarily used at the battalion level to determine the required fuel reserves for MSC operations or exercises. These calculations are currently conducted using spreadsheets filled in manually, requiring expertise and experience. However, these spreadsheets cannot adjust to actual unit consumption, varying travel distances, weather conditions, or terrain on a daily basis. They are used solely to estimate and reserve fuel amounts before the start of an exercise or operation and are not utilized during operations. Conversely, units in the field must submit Functional Control reports (FUCO) every 24 hours to their higher command, detailing remaining supplies of food, water, fuel, and ammunition, as well as the condition of their equipment. Higher command aggregates these reports into a Daily Logistic Wish to determine the quantity of supplies needed from the (F)SC for the upcoming supply run, ensuring that the supply capacity is not unnecessarily overloaded. This consumer-requested demand is known as pull-supply. In warfighting situations, supply may also employ the push-supply method, distributing supplies down the line without consumer requests, as there is no return flow of Class III goods and limited time to generate a Daily Logistic Wish. In practice, the calculation sheet is rarely used, and units request fuel amounts based on experience.

2.3. Potential energy carriers and conversion devices

This section will explore potential alternatives to fossil diesel fuels. These alternatives must meet specific criteria:

- They must be suitable for powering heavy military vehicles without occupying excessive space making the vehicles useless;
- Their CO2 equivalent emissions must be lower than those of diesel;
- They should be readily available in the international civil and military transport markets in the future.

The selection of energy carriers for the VESC model (Vehicle Energy Supply Chain model) is based on research conducted by the company DNV on alternative fuels for military use [4] [14] [17] [18]. These reports adhere to the same criteria mentioned earlier. Each alternative energy source is elaborated on, detailing how it functions, its specifications, and a summary of its pros and cons for military applications. While this research does not conduct an in-depth analysis of vehicles with different types of conversion devices, it relies on general assumptions and figures based on available literature sources and reports by the NLMoD. Not all energy carriers are included in the VESC model; only those deemed potentially viable options based on literature are considered, along with options currently under investigation by COMMIT.

Currently, diesel serves as the default energy type, boasting an energy density of 36 MJ/L and a specific energy of 42.5 MJ/kg [19]. The Brake Thermal Efficiency of diesel engines for vehicle use is 33%, while for generator use, it's 46% [14].

Diesel-electric series hybrid

The diesel-electric series hybrid utilizes diesel as its energy carrier, similar to conventional diesel vehicles. However, it employs a series hybrid powertrain configuration, allowing the diesel combustion engine to operate at optimal RPM for maximum efficiency. The vehicle is propelled by electric motors, with a battery pack storing electric energy to power these motors (see Figure 2.5). This system offers several advantages, including higher average efficiency compared to current diesel Internal Combustion Engines (ICEs), while retaining the benefits of diesel fuel such as high energy density, easy transportation, and availability. Additionally, if the battery capacity is sufficient, the vehicle can operate in fully electric mode for certain distances, providing tactical advantages by reducing noise and heat emissions, thus lowering the risk of detection. However, there are drawbacks to consider; reducing the size of the diesel fuel tank to accommodate battery packs diminishes the vehicle's total range, and the use of battery packs increases the vehicle's weight.

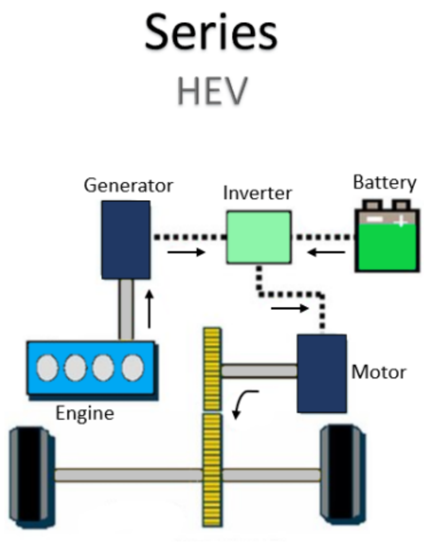

Figure 2.5: Series hybrid powertrain [20]

Hydrogen 700 bar fuel cell and ICE

The energy type hydrogen is represented by two variants in the VESC model, both utilizing a 700-bar storage system. One option employs a fuel cell series hybrid powertrain, while the other uses a hydrogen ICE. The advantages of the fuel cell variant include high efficiency, reaching up to 60%, and the capability for fully electric driving, providing tactical benefits [21]. Meanwhile, hydrogen utilized in a combustion engine achieves a Brake Thermal Efficiency ranging from 25% to 45% [22]. Despite its high mass energy density of 120 MJ/kg, hydrogen has a low volume energy density of 4.8 MJ/L at 700 bars, posing challenges in storing large quantities due to the required large volume. Additionally, special composite cylinders are necessary due to the high pressure, adding expense and occupying extra space in the vehicle. Moreover, hydrogen loss during transfer, attributed to daily evaporation and dispensing losses, could reach up to 13% [23]. Presently, heavy-duty vehicle refueling with hydrogen entails an average mass flow of 10 kg/min but can peak at 25 kg/min [24] [25].

However, hydrogen offers several benefits, including its anticipated availability in the future and its potential for production and use with minimal to zero CO2 equivalent emissions. Furthermore, current hydrogen ICE and fuel cell technologies are advancing rapidly and are already being implemented in practical applications such as hydrogen-powered trucks.

Electric battery swap

Vehicles and weapon platforms equipped with a fully electric drivetrain rely on battery packs for their energy. The most common battery packs used are lithium-ion batteries, known for their high energy density (100-280 Wh/kg), power density, long lifespan, and low self-discharge [26]. An alternative option is LiFePO4 batteries, which offer a longer lifespan and are less prone to catching fire compared to lithium-ion batteries [27]. The greater stability and safety of LiFePO4 batteries make them a more suitable choice for military applications where reliability is paramount in warfare. However, LiFePO4 batteries have a lower energy density, adding more weight to the vehicle for the same amount of stored energy. This drawback is somewhat offset by the high efficiency of the electric drivetrain, typically ranging from 80% to 90% for electric trucks [28].

The advantages of a fully electric drivetrain include reduced vehicle heat signature and noise, providing tactical benefits. Additionally, the electric infrastructure of the vehicle or weapon platform can be optimized for additional sensors, communication systems, and weapon systems that require substantial electrical energy. However, drawbacks include the low energy density of battery packs and long recharge times, resulting in limited range and prolonged downtime for recharging.

Battery swap is one option for supplying energy to vehicles and weapon platforms, with two methods available: manual battery swap or crane-assisted battery swap. Research conducted by the company

DNV on behalf of the NLMoD found that crane-assisted battery swap is the fastest option, taking approximately 3.33 minutes to change a battery pack weighing 1250 kg, whereas manual battery swap is 4-31 times slower [14]. Considering these findings along with the energy density of the battery packs used will determine the supply speed of battery swap. Although current vehicles and weapon platforms are not designed for battery swap as they are built for a diesel drivetrain, this research assumes that battery swap is feasible for these types of vehicles to assess the potential impact on the MSC if the vehicles were redesigned accordingly.

Electric charging

The energy type electric charging is similar to electric battery swap, except that the energy carrier is transferred through charging instead of battery swap. Charging is already common in the field of electric vehicles, utilizing AC and DC (fast) chargers with charge capacities ranging from 5 to 350 kW. A new technology under development is the Megawatt Charging System, capable of reaching a maximum charging power of 3.75 MW with a maximum of 1250 V DC and 3000 A [29]. Specifically designed as a new standard for trucks and large machines, as well as situations where short recharge times are crucial, the Megawatt Charging System holds promise as the most suitable charging technology for military vehicle use. Its high charging power reduces the downtime associated with charging during warfighting scenarios.

Methanol

Methanol consists of four hydrogen, one oxygen, and one carbon atom, making it the simplest member of the organic chemical group alcohols. Methanol is produced from synthesis gas, which is a mixture of CO, CO2, and hydrogen gas. Passing this synthesis gas through a reactor with a catalyst produces methanol and water vapor. Currently, the primary sources for this synthetic gas are natural gas and coal. Green methanol can also be produced using green hydrogen and captured CO2. The advantages of green methanol include significant reductions in emissions of COx, NOx, and SOx, and it can be stored, transported, and refueled similarly to conventional fossil fuels [30]. Methanol is among the top five most traded chemicals globally and finds applications in various fields such as pharmaceuticals, electronics, paint, appliances, and fuel [31]. Methanol can be mixed with gasoline or diesel in blends to create biofuels, or M100 (100% methanol) can be used as a substitute for gasoline. This research focuses solely on M100 methanol fuel due to its potential for complete independence from fossil fuels. Blends with gasoline or diesel offer too many options, resulting in a wide range of efficiencies and emissions. Methanol has a density of 0.792 kg/L and a specific density of 15.8 MJ/L or 19.9 MJ/kg [19]. The Brake Thermal Efficiency of a 4-cylinder, 4-stroke, 1.9L engine running on methanol is 40%, with a peak efficiency of nearly 43% [32].

Ammonia

Ammonia (NH3) is one of the largest chemicals produced in volume worldwide and is commonly used as fertilizer and as a base for chemical synthesis. At 1 atm and cooled to -33 °C, it has a gravimetric and volumetric energy density of 18.6 MJ/kg or 12.7 MJ/L [33]. Ammonia can serve as a carrier for hydrogen, although obtaining hydrogen from it requires thermal decomposition or catalytic cracking. Alternatively, it can be used directly as fuel in ICEs. Tornatore et al. (2022) [34] conducted a study on using ammonia as fuel for ICEs. They discussed various engine types and their advantages and disadvantages but noted that practical applications of ammonia in ICEs are still limited, despite significant attention from the scientific community and industry. Currently, most research and applications focus on the marine sector, particularly for large vessels. The Brake Thermal Efficiency of ammonia ICEs falls within the range of 27-36%.

Ammonia offers several benefits, including being carbon-free (provided production is green), easy to store and transport, and possessing a relatively high-volume energy density. However, there are drawbacks, such as its toxicity, which raises safety concerns, and its poor combustion properties, which limit efficiency.

HVO

Hydrotreated Vegetable Oil (HVO) is derived from vegetable oils, as well as from waste oils and fats. Hydrogen is utilized in the process of converting waste oils and fats into HVO, resulting in a molecule structure similar to that of diesel. HVO can be blended with fossil diesel, with the number after HVO indicating the percentage of HVO in the mix. For this study, only HVO100 is considered, representing pure HVO. HVO100 boasts a comparable energy density to diesel, at 34.4 MJ/L or 44 MJ/kg, with a density of 0.78 kg/L, slightly lower than diesel's 0.85 kg/L [19].

The advantages of HVO(100) include its compatibility with all diesel ICEs, a potential reduction of up to 90% in CO2 equivalent emissions, a slightly higher Brake Thermal Efficiency compared to diesel, and quieter engine operation due to its higher cetane number. Additionally, HVO is non-hygroscopic, maintaining fuel quality for longer periods and exhibiting better performance in lower temperatures [35]. This compatibility makes it easy to integrate into existing Military Supply Chains (MSC), requiring no changes to vehicles or supply methods.

However, the main challenge with HVO is its limited scale availability. HVO production is currently constrained, and there is insufficient waste oil and fat to meet global energy demands. Increasing farmland for HVO production could negatively impact food supplies and biodiversity [36].

LNG

Liquid Natural Gas (LNG) serves a similar purpose to Compressed Natural Gas (CNG), with the key distinction lying in storage methods. While CNG is compressed, LNG is cryogenically cooled to -162 °C, enabling it to be stored in liquid form. This cryogenic storage grants LNG a higher energy density compared to CNG, measuring at 20.8 MJ/L or 48.6 MJ/kg [19].

LNG finds application in both natural gas diesel dual-fuel engines and spark-ignited ICEs. However, this study focuses solely on spark-ignited ICE, as it can operate on 100% LNG, simplifying the MSC by eliminating the need to manage two types of fuel. The Brake Thermal Efficiency of spark-ignited ICE typically ranges from 37% to 41% [37].

The advantages of LNG include potential reductions of up to 13% in Well-to-Wheel (WTW) CO2 equivalent emissions compared to diesel, alongside its higher gravimetric energy density relative to diesel [38]. While LNG meets the criteria outlined in section 2.3, a 13% decrease in CO2 equivalent emissions alone may not justify a complete overhaul of vehicle energy supplies, given the technical challenges involved. Nonetheless, LNG remains a subject of investigation in this research, as comparing its performance against diesel and other alternative energy sources could yield valuable insights.

Drawbacks of LNG include the need for specialized insulated tanks for storage, which are still susceptible to boil-off losses. Boil-off losses during LNG shipping can amount to as much as 10%, with additional refueling losses potentially reaching 5% [39] [40].

Overview Energy Carriers

Figure 2.6 displays all the energy carriers alongside their volumetric and gravimetric energy density in a graph. Anything positioned below the horizontal green line indicates a lower volumetric energy density compared to diesel, implying that less energy is stored for the same volume. The graph illustrates that no energy carrier outperforms diesel in this aspect. On the other hand, energy carriers positioned to the right of the vertical green line boast a higher gravimetric energy density than diesel. While hydrogen exhibits an exceptionally high gravimetric energy density compared to diesel, its volumetric energy density is relatively low, posing a limitation when considering storage in vehicles. For a comprehensive overview of the most significant specifications pertaining to the energy carriers, refer to Table 2.1.

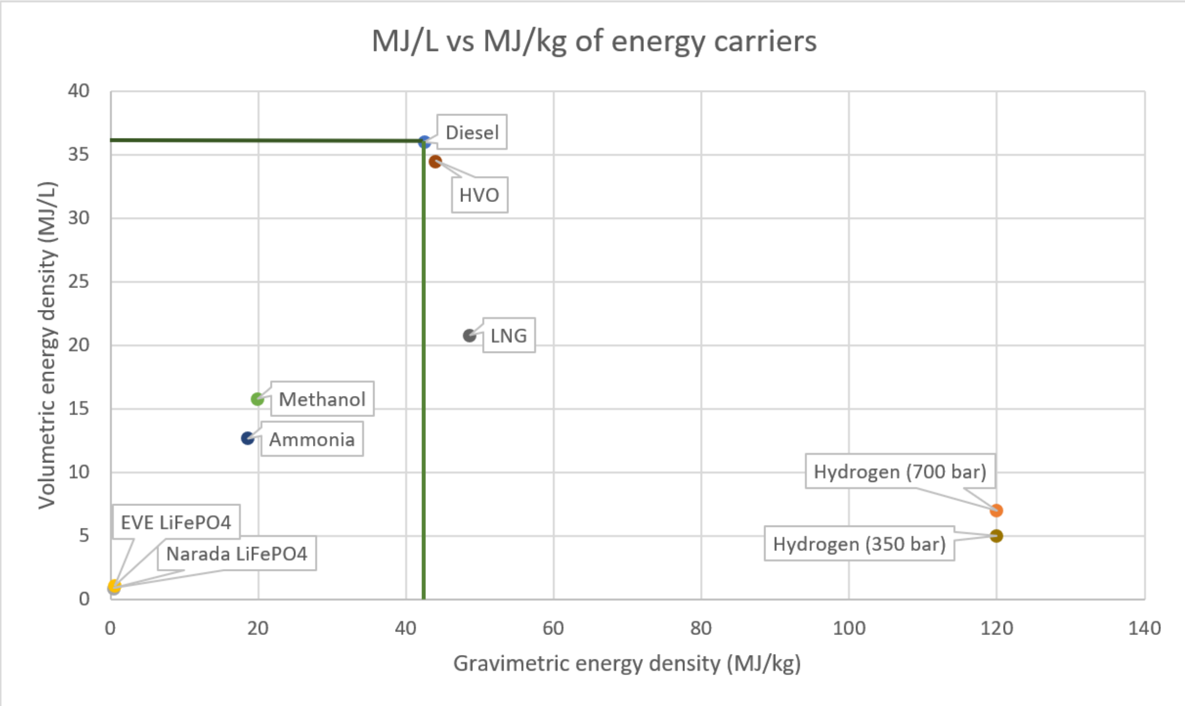

Figure 2.6: Volumetric energy density vs gravimetric energy density [19]

Alternative	Energy carrier					
	Transport method:	**Energy density: [MJ/L]**	**Energy density: [MJ/kg]**	**Energy density: [kWh/kg]**	**Phase:**	**Fill speed: [MJ/min]**
Diesel-electric series hybrid	Steel tanks	36.0	42.5	11.8	Liquid	3600-5400
H2 700 bar	Composite tanks	4.8	120.0	33.3	Gas 700 bar	120-3000
Electric battery swap	Battery	0.5-1.62	0.36-1.26	0.10-0.35	Solid	7-200
Electric charging	AC/DC charging system	0.5-1.62	0.36-1.26	0.10-0.35	Solid	0.3-225
Methanol	Steel tanks	15.8	19.9	5.5	Liquid	1580-2370
Ammonia	Steel tanks	12.7	18.6	5.2	Liquid	1270-1905
HVO	Steel tanks	34.4	44.0	12.2	Liquid	3440-5160
LNG	Steel tanks	20.8	48.6	13.5	Liquid	2080-3120

Table 2.1: Overview of energy carriers [19]

2.4. Potential energy generation

Certain energy types allow for on-site production of 'fuel' within the MSC. This section outlines the energy types for which this is feasible, along with examples of applicable technologies. Only energy types that do not necessitate regular transportation between suppliers and the SC are covered here. Additionally, the technology for energy generation should be compact enough to fit into a standard 20 ft or 40 ft shipping container for convenient transport. The energy types that meet these criteria include electricity battery swap and charging, as well as hydrogen. While this section will not delve deeply into each energy generation option, it will provide a list of possibilities along with their respective pros and cons, ensuring that the VESC model has well-founded input values to utilize.

2.4.1. Electricity

Electric energy required for battery swap or electric charging options can be sourced for the SC or FSC either from the existing electricity grid in the region or generated on-site. While utilizing the electricity grid is the simplest and most high-capacity option, it becomes unreliable in wartime scenarios due to potential damage to infrastructure. Public utility services are safeguarded by the Geneva Convention for civilian populations, but military use risks compromising this protective status. The conflict in Ukraine has highlighted the vulnerability of electricity grids in such scenarios, rendering the grid an unsuitable energy source for the SC and FSC.

On-site electric energy generation can be achieved through various methods. The use of fossil fuel generators is excluded as an option because it still necessitates the supply of multiple energy types required in the MSC, such as battery packs and diesel. Therefore, only renewable on-site generation methods are considered. Small nuclear units are discussed separately in subsection 2.4.2. Possible options for electric energy generation include solar power, small wind turbines, and kite-based systems. Each of these options is accompanied by an off-grid battery container (20 or 40 ft) with a total capacity of up to 2150 kWh and a rated power of up to 1000 kW [41].

Container-sized solar units offer the advantage of quick and easy setup, but they require a large area for the solar panels to unfold and are limited to operation in sunny conditions. Additionally, the panels are easily visible from the air due to their size, posing a potential security risk. An example of such a system is provided by the company ECOSUN, which offers a system capable of deployment in just over an hour with a capacity of 68 kWp [42].

Portable wind turbines have the advantage of producing power throughout the day if wind is available and can be set up and dismantled with ease. They require less cleared ground area but must be placed in open spaces to harness wind effectively. Uprise Energy has developed a functional 15 kW portable wind turbine that fits within a 20 ft container and can be set up in one hour without the need for site improvements [43].

A novel technology in this field involves the use of kites to harness wind energy. Kitepower has developed 30 kW and 100 kW systems that utilize kites to access higher wind zones, ensuring a steady power output [44]. This system offers easy installation, requires minimal materials, operates 24 hours a day, and occupies minimal ground space. However, its implementation is constrained by the need for a clear airspace within a radius of 450 m, designating it as a no-fly zone. Additionally, placing multiple systems close to each other is challenging due to the large required radius.

2.4.2. Nuclear - Electricity

The company DNV conducted a feasibility study on nuclear-powered vehicles on behalf of the NLMoD [45]. The study concluded that nuclear-driven vehicles are not feasible due to the excessive size of the cooling system, which would occupy all available space, rendering the vehicle unusable. Additionally, safety concerns and the unavailability of nuclear technology for vehicles contributed to this conclusion.

Another concept that could be beneficial in the system is a shipping container-sized nuclear reactor capable of producing 1-5 MW and transportable by multiple Scania WLS 165 kN trucks. It could be deployed at the FSC to generate electricity, thereby reducing the energy supply required by the SC and FSC. The World Nuclear Association provides a comprehensive overview of all current operational Small Modular Reactors and those in development [46]. They outline the US Department of Defense's requirements for Small Modular Reactors for use in rapid response scenarios, emphasizing the need for inherent safety features, transportability, and rapid deployment.

Currently, three companies are developing such Small Modular Reactors, with the first prototypes expected to be available in 2024. However, the time required for installation and dismantling makes them unsuitable for use at the FSC, which must have the flexibility to relocate within a day. Even for the SC, the assembly and disassembly process may take too long, as flexibility is crucial in warfighting conditions. If future technological advancements reduce installation time, Small Modular Reactors could become valuable assets for both the SC and FSC.

2.4.3. Hydrogen

On-site hydrogen production requires electric energy, as outlined in subsection 2.4.1, and access to water. An example of a portable hydrogen production plant is the 40 ft container manufactured by Hitz, capable of producing 18 kg/h of hydrogen with a power consumption of 55.6 kWh/kg and a water consumption of 18 L/kg [47]. Green Hydrogen Systems has also developed a hydrogen generation plant slightly larger than a 40 ft shipping container, capable of producing a maximum of 107 kg/h of hydrogen with a power consumption of 51.9 kWh/kg and a water consumption of 9.5 L/kg [48]. However, this system requires demineralized water, posing a drawback.

Both systems output hydrogen at a pressure of 35 bar, necessitating the addition of an additional pump and a 700 bar pressure storage vessel. This complexity in setup reduces the mobility of the SC or FSC. Nonetheless, it can potentially reduce the frequency of transport movements, as transporting stored hydrogen is inefficient.

2.5. Existing research

Research has been conducted in fields relevant to the subject of this study. This encompasses current military supply, MSC management, research on alternative fuels for the military, examination of energy carriers or conversion devices, well-to-wheel analyses, and optimization models for alternative fuel vehicles. The literature is divided into two categories. Firstly, there is open-source literature providing a more general overview of the MSC or conducting research on similar technologies or models related to MSC management. Secondly, there is literature on the current MSC and projects of the NLMoD, which are classified documents for internal use only. Figure 2.7 provides a comprehensive overview of the literature sources.

2.5.1. literature

Kamphuis (2023) [49] compares Dutch warfighting supply capabilities during the Cold War with the current capabilities of the NLMoD. He highlights that the current supply capabilities are inadequate for sustaining three brigades (43^{e} Mechanized Brigade, 11 Air Mobile Brigade, and 13^{e} Light Brigade) simultaneously engaged at the eastern front due to centralized supply units and reduced capacity, in addition to the front distance being tripled. To address this gap, civilian transport companies, under the new concept of *Ecosystem Logistics*, are proposed to handle rear-area supply in the combat zone. Kamphuis suggests a solution by merging Dutch and German military supply capacities. Lobo et al. (2018) [50] focus their research on the class III flow for the US military, particularly examining tools used by army fuel planners. These planners utilize custom-built spreadsheets, which are time-consuming and error-prone. Similarly, the NLMoD uses similar spreadsheets for fuel planning. Lobo et al. propose a transient stochastic simulation-optimization model for the in-theater MSC of class III. However, this model is limited to current workflow and does not account for future alternative energy flows.

"Assessment of Conventional and Alternative Energy Carriers for Use in Military Vehicle Platforms" by Mansfield et al. (2021) [8] offers an in-depth overview of present and near-future energy carriers for military vehicles, focusing primarily on high-mobility or medium tactical wheeled vehicles. The study emphasizes vehicle-related aspects, such as total powertrain mass and stored energy volume, rather than the supply infrastructure. It concludes that current diesel and gasoline fuels remain optimal in terms of powertrain mass and energy carrier volume, with hybrid diesel-electric with NI-MH batteries emerging as a promising alternative. Nilson (2023) [51] conducts similar research on alternative energy carriers for light-duty vehicles for the Swedish Defense Forces through a market survey. The study highlights insufficient market availability of alternative fuels, suggesting further research to assess their impact on military capabilities.

While literature specifically focusing on detailed research on alternative energy carriers for military vehicles and their application is limited, similar research on civilian vehicle applications is more prevalent. Nylund and Wenstedt (2019) [13] investigate the Well-to-Wheel analysis of heavy-duty truck fuels at Scania, considering LNG, Liquid Bio Gas, and diesel. Cunanan et al. (2021) [10] review heavy-duty vehicle powertrain technologies, including Battery Electric Vehicles and hydrogen fuel cell vehicles. They conclude that diesel remains the best short-term option due to infrastructure limitations for electric vehicles and hydrogen fuel cells. Huang and Zhang (2011) [52] examine Biomass-to-Wheel efficiency for various powertrain types, suggesting that Battery Electric Vehicles and Sugar Fuel Cell Vehicles offer the highest FTW efficiencies.

Integrating supply chain management with alternative energy carrier optimization leads to optimization models aimed at minimizing costs and emissions. Lemme et al. (2019) [53] optimize vehicle fleets in car-sharing systems to assess the viability of electric vehicles. The model optimizes for both costs and emissions, with pollution costs factored into the objective function. While the primary focus is on minimizing costs, the model also ensures that pollution remains minimized. Iris and Siu Lee Lam (2021) [54] develop an optimization model for energy management in seaports, focusing on renewable energy utilization under uncertainty. Both models aim to minimize costs, with Iris and Siu Lee Lam emphasizing significant cost savings from renewable energy adoption in ports.

Regarding the management and optimization of MSC for vehicles and weapon platforms using alternative energy, there is a lack of published research to the author's knowledge. However, existing literature on MSC management and optimization offers valuable insights. For instance, Agshami et al. (2024) [55] focus on optimizing military-based humanitarian supply chains, employing a bi-objective MINLP model to minimize total costs and injury time. Meanwhile, Leila et al. (2018) [56] examine the military's adoption of drop-in biofuels to reduce carbon emissions, using the MILP method to assess renewable biofuel production in California and its associated costs, concluding that the state can meet a significant portion of its renewable biofuel targets.

Mixed-Integer Linear Programming (MILP)

The optimization problem outlined in chapter 1 is well-suited for formulation as a MILP problem. MILP is a subset of MIP (Mixed-Integer Programming), with another subset being Mixed-Integer Nonlinear Programming (MINLP), capable of addressing problems with both discrete and continuous variables. While MINLP can handle nonlinear relationships, it is generally less efficient than MILP due to the complexity of nonlinear constraints. To mitigate lengthy computation times, nonlinear terms can be linearized, allowing MILP to be employed [57]. In supply chain management, MILP models typically feature a single objective function related to costs, though it is also feasible to incorporate multiple objectives concurrently. Various solvers, such as branch-and-bound or cutting-plane techniques, can be utilized to solve MILP models, thereby reducing computational time [58].

2.5.2. NLMoD reports

Reports produced by the NLMoD are strictly for internal use and contain sensitive information regarding strategy, material data, and doctrines. The sole publicly available report is the *Roadmap Energy Transition Operational Equipment* [2], which aims to provide insights into the possibilities, opportunities, and threats associated with the energy transition in the operational domain. This roadmap outlines the conditions under which the NLMoD must operate, including adherence to regulations, coordination with partners such as NATO, and alignment with market trends. It also sets goals for reducing fossil fuel dependency by at least 70% by 2050 compared to 2010 levels. Quantitatively, in 2020, the combined energy consumption of all equipment amounted to 5000 TJ, with diesel accounting for 15%.

To develop a model of the system, it is imperative to understand the current MSC. Operational doctrines are detailed in manuals like *Handboek Bevoorrading* [15], *Zakboek Logistiek* [11], and *Tactiek voor het Gemechaniseerde Team* [16], which provide comprehensive descriptions of the MSC.

DNV, on behalf of the NLMoD, conducted studies on alternative fuels for military vehicles and their implications on supply movements. Although these reports are not publicly accessible, they explore the best alternative energy carriers and conversion devices based on factors such as vehicle performance, technological advancements, market availability, and initial assessments of transport movements and refueling times [4] [14] [17] [18].

Paper\subject	Literature review	Optimization/ math model fuel/vehicles	Optimization SCM	Well-to-wheel analysis	Well-to-tank analysis	Tank-to-wheel analysis	Energy carrier	Conversion device	Refueling time	Military SCM	Alternative fuel military	Reports MoD
Lemme et al. (2019)	X	X	X				X	X				
Nylund and Wenstedt (2019)	X			X		X						
Huang et al. (2011)	X			X		X	X	X				
Cunanan et al. (2021)	X				X	X	X	X	X			
Kamphuis (2023)										X		
Mansfield et al. (2020)							X				X	
Lobo et al. (2018)		X								X		
Iris and Siu Lee Lam (2021)		X	X									
Caunhye et al. (2012)	X	X	X							X		
Aghsami et al. (2024)			X							X		
Klanšek (2014)		X	X									
Leila et al. (2018)			X							X		
Smith and Taskin (2008)		X	X									
Nilson (2013)	X						X	X			X	
Roadmap Energy MoD (2023)											X	X
LAND-LOG (2015)							X			X		X
LAND-MAN-MECH (2022)										X		X
Zakboek-LOG (2023)							X			X		X
DNV-SUS-FUELS (2023)							X			X	X	X
DNV-logmovements (2023)					X		X			X	X	X
DNV-energievormen (2022)							X	X			X	X
DNV-herbospeed (2023)							X		X	X	X	X

Figure 2.7: Overview of literature

2.6. Research gap

As noted in section 2.5, there is considerable existing research with similarities to this study. However, there is a notable absence of literature in public or NLMoD sources that specifically examines the implications of alternative energy sources for vehicles on the current MSC, particularly within the Dutch context. The reports produced by DNV come closest to addressing this topic, as they calculate the impact of alternative energy carriers on transport movements and refueling times. Nevertheless, these reports only cover a limited aspect of the MSC and are based on general assumptions.

This gap in the literature has also been recognized by the *Knowledge Centre Logistics* of the NLMoD and TNO, both of which are currently investigating this issue. This study aims to bridge these areas by integrating optimization models, alternative energy for vehicles, and military supply chain management.

2.7. Conclusion

This chapter delves into the military context, current MSC, and potential energy sources and conversion technologies relevant to the research. The MSC examined here pertains to the NLMoDs main objective of safeguarding its territory and that of its allies. Utilizing existing military fuel calculations outlined in subsection 2.2.1, this research delineates the MSC in subsection 2.2.2, focusing particularly on tactical movements from the Supply Centre to the Forward Supply Center and onward to deployed military units.

Considered energy options include diesel-electric series hybrids, hydrogen 700 bar fuel cells and ICE, electric battery swapping and charging, methanol, ammonia, HVO, and LNG. These choices are informed by prior DNV research, deemed suitable for military vehicles due to their lower CO2 emissions and anticipated future availability in civilian and military transport markets. Electricity and hydrogen are the only energy types potentially generated within the MSC at various Nodes.

Literature primarily concentrates on vehicle-centric aspects rather than MSC optimization. While some research exists on MSC optimization, its integration with alternative energy sources for vehicles and weapon platforms is limited. Nonetheless, internal military reports offer foundational insights into the interplay between alternative energy sources and the MSC.

3
Conceptual Model

This chapter outlines the development of the Vehicle Energy Supply Chain (VESC) model, aimed at assessing the influence of various energy sources of military vehicles on the MSC. Initially, the method for assessing the impact on the MSC is established, employing Key Performance Indicators (KPIs). Subsequently, the conceptual framework of the VESC model is detailed, highlighting its essential components without constructing a complete model. Finally, the assumptions and limitations of the VESC model are delineated.

3.1. Key Performance Indicators

Measuring the impact on the MSC is complex. Most supply optimization models focus on minimizing costs, as seen in literature (section 2.5). The MSCs impact can be assessed by changes in total system costs. Key Performance Indicators (KPIs) are used to evaluate supply processes. While commercial supply chains link KPIs to cost reduction, the MSC aims *to deliver quickly with minimal equipment and personnel, prioritizing operational continuity despite enemy actions.* Comparing MSCs with commercial chains is challenging due to differing KPIs and optimization objectives. Multiple KPIs can be attributed to the goal of MSCs which are:

- Costs of transport in €
- Number of transport movements (number of personnel/equipment required)
- Refuelling time in minutes or hours
- Capacity ratio weight/volume in kg/L
- Ratio energy supplied/used by supply vehicles
- CO2 equivalent emissions (Fossil fuel dependency) in kg

Some of these KPIs are challenging to relate to costs because reducing transport movements aims to minimize exposure to enemy fire, rather than solely reducing expenses. For instance, a transport method that reduces movements may be costlier than a cheaper alternative requiring more movements and personnel. Consequently, the VESC model for the MSC cannot solely aim to reduce costs, as it is not the primary goal. However, if all KPIs are linked to weighted costs, cost reduction can be an objective. For example, a cost penalty can be applied to refueling time, where longer times incur higher costs. Yet, this approach is subjective, as quantifying the cost penalty for increased risk due to delayed supply depends on various factors like equipment costs, personnel value, and situational risks. Hence, comparing with other studies is difficult unless using consistent cost concepts and penalty factors. Multiple objective functions for the VESC model are preferable, optimizing for specific KPIs that offer valuable insights into logistical performance and facilitate comparisons with other studies. Lowering refueling time or transport movements remains preferable in warfighting conditions, reducing vulnerability to enemy attacks regardless of the situation or risk.

According to various doctrines and interviews with experts from the *Knowledge Centre Logistics* and military logistical personnel from the unit 130 BevoCie, the most crucial KPIs are refueling time and required supply capacity, which translates to the number of transport movements. Refueling time is considered the most critical because when supply capacity remains static, the risk of being targeted by enemy operations is highest. Following closely is the required supply capacity, encompassing supply vehicles, bulk containers, and personnel. These three factors are combined into the KPI ”number of transport movements.” The reason for its significance is the limited supply capacity of the Dutch army due to past budget cuts, personnel shortages, and equipment deficits. Reducing the required supply capacity enhances the effectiveness of available resources. However, reliance on a few high-capacity supply trucks or bulk containers poses risks—if these are compromised, all supply capacity is jeopardized. Hence, employing multiple low-capacity supply trucks offers resilience, ensuring operational continuity even if some units are lost. Nonetheless, reducing the number of transport movements decreases the overall supply capacity required. The VESC model does not prioritize the type of vehicles used (large or small capacity supply trucks) but aims to minimize supply trips using the same vehicle type for different energy sources. The final KPI analyzed by this VESC model is CO2 equivalent emissions. While this metric does not directly benefit the operational capability, it indirectly impacts future fuel availability, aligning with NLMoD's goal of reducing reliance on fossil fuels, as CO2 emissions are closely tied to fossil fuel dependency.

The other previously listed KPIs are not utilized for optimization as they do not significantly influence the MSC and would overly complicate the VESC model. However, some of these KPIs, such as weight/volume ratios, could be used as outputs for informational purposes. The VESC model employs the three KPIs of refuel time, number of transport movements, and CO2 equivalent emissions as objective functions, with detailed descriptions provided in subsection 4.1.1.

3.2. Overview of the VESC model

The VESC model is founded on the logistics doctrines of the NLMoD, as elucidated in section 2.2. It is confined to only 4 Nodes, SUPPLIER-SC-FSC-UNITS, where the energy carrier is processed, and it encompasses 3 paths, A-C, wherein movements of the energy carriers occur. Node 4 stands out compared to 1-3, as it involves the movement of vehicles in combat and hence the energy consumption of the units. The national, strategic, and some operational movements are excluded from the VESC model because these movements vary significantly depending on the situation and are mainly handled by civilian partners. Node 1 and path A represent operational movement, and from Node 2 onwards, it transitions to tactical movement. Node 1 and path A are incorporated into the VESC model solely to illustrate the energy needed from the suppliers, with the energy required for path A omitted from the VESC model.

The current MSC VESC model, based on NLMoD doctrines, is modified and expanded in several ways:

- Introduction of multiple energy types: unlike the current MSC, which only accommodates diesel fuel, this VESC model incorporates 10 different energy types alongside diesel fuel. These energy types are listed in section 2.3.
- Introduction of the possibility to generate energy at Node 2 and 3 for renewable energy types.
- Addition of Manticore supply trucks at Node 4: These vehicles are new additions to the model. They serve as buffers for the UNITS at Node 4, allowing small amounts of energy required on supply days to be sourced from these Manticore supply trucks instead of larger Gryphus supply trucks traveling over path C. Additionally, these Manticore supply trucks serve as extra refueling points, which can reduce refueling time.

An overview of the entire system is depicted in Figure 3.1, with a detailed description of the model provided in chapter 4.

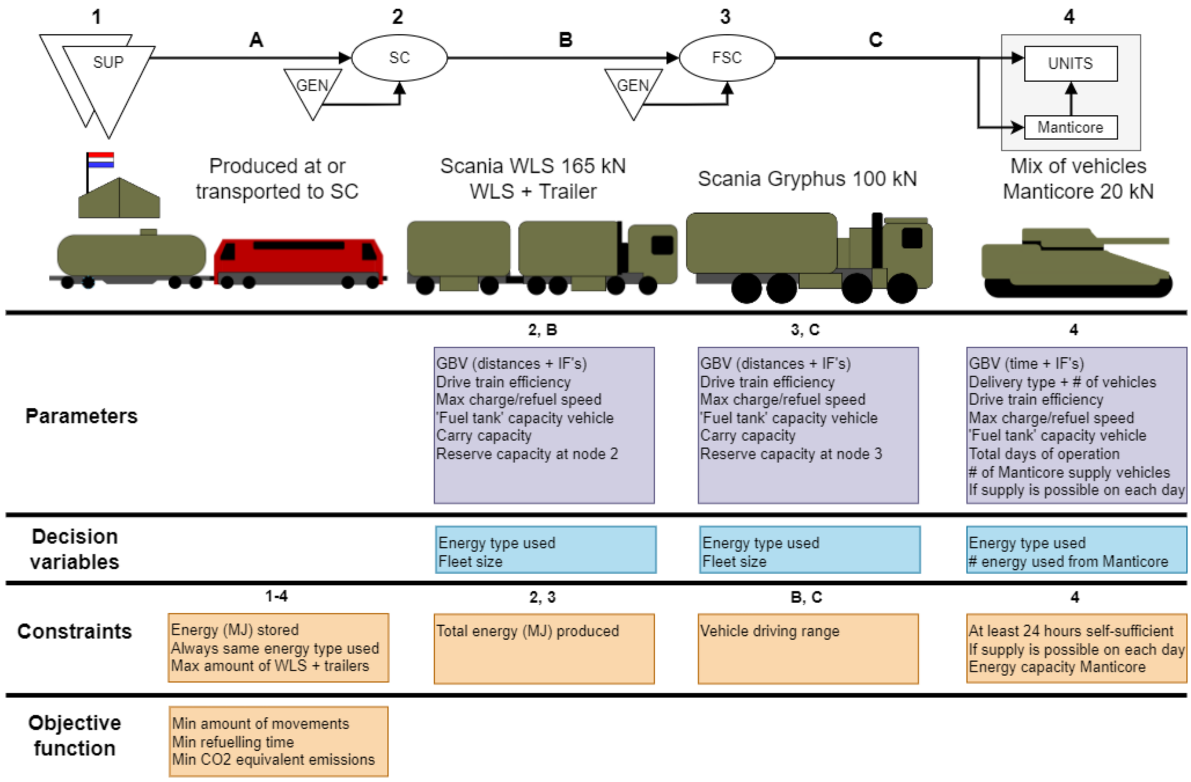

Figure 3.1: General overview of the VESC model

3.3. Assumptions and Boundaries

The MSC is a complex system, necessitating several assumptions and boundaries to simplify and constrain it. These assumptions and boundaries are outlined for the input data and each node and path and are listed in the section.

3.3.1. Input data

This research examines the impact of alternative energy types on military vehicles and weapon platforms within the MSC. The selected energy types are chosen for their carbon-free or carbon-reduced characteristics and technological advancement. It is assumed in this research that technological hurdles are resolved without introducing operational complexities or significant changes. Additionally, it is assumed that these energy types do not present safety concerns such as toxicity or corrosion. The data concerning these energy types is based on technological feasibility within the next 5-15 years.

3.3.2. General

Assumptions and boundaries applicable to the entire VESC model are outlined below:

- In real-world scenarios, energy required at Node 4 should be delivered at least one day prior at Node 3 and two days prior at Node 2 for timely delivery. However, this VESC model simplifies this by setting all deliveries on the same day for all Nodes to avoid complexity;
- Maximum one supply run per day;
- All supply trucks per Node commence supplying simultaneously for optimal efficiency (so most optimum scenario);
- The standard Day Of Supply (DOS) represents the average energy consumption at Node 4 across all days;
- The entire supply line is mobile;
- Only one type of energy carrier may be used to supply all vehicles and weapon platforms on all days;
- If supply is not feasible on a given day, the energy consumption of day i will be added to day $i+1$;

- One-way supply due to warfighting conditions;
- The option to use Auxiliary Power Units (APUs) for vehicles during standby time, with all vehicles at Node 4 equipped with APUs if utilized;
- Weight and road configuration of all vehicles remain constant, resulting in consistent energy requirements for all energy types. If the weight of an alternative energy drive system exceeds that of the default diesel system, payload capacity is reduced;
- Only FTW CO2 equivalent emissions are considered in the VESC model, correlating with the energy used per vehicle or weapon platform;
- For methanol and LNG, current FTW CO2 equivalent emissions from fossil fuels are utilized unless otherwise specified, due to limited production of bio-versions;
- It is assumed that global production of the energy types used is sufficient to support large-scale implementation of these fuels.

3.3.3. Nodes

An overview of the Nodes can be seen in Figure 3.1. The ”X” stated in the assumptions refers to the input value for how much DOS should be reserved for these Nodes. The ”Y” refers to the maximum distance used in the NLMoD doctrines between Nodes, which is classified data. The assumptions and boundaries are given per Node starting with Node 1, the supplier, and are as follows:

- The supplier is the start of the MSC for this system;
- The supplier has unlimited energy at its disposal;
- Details regarding energy production and its greenhouse gas emissions are not included in the VESC model.

For Node 2, the SC, the assumptions are:

- It stores an ”X” amount of DOS reserve capacity which is delivered on day $i = 1$;
- It can have an energy generation option for policies 3 and 4 for days $i \neq 1$. Surplus production on day i can be used on day $i + 1$;
- It is operational 24/7;
- Maximum ”Y” km behind Node 3;
- Refuel time at this Node is not included in the VESC model.

The assumptions for Node 3, FSC, are:

- It stores an ”X” amount of DOS reserve capacity which is delivered on day $i = 1$;
- It can have an energy generation option for policies 3 and 4 for days $i \neq 1$. Surplus production on day i can be used on day $i + 1$;
- Maximum ”Y” km behind Node 4.

And for Node 4, units:

- It is the last Node in the MSC;
- Energy types are excluded if the required energy exceeds the storage capacity of the vehicles;
- The combination of vehicles remains constant throughout the operation;
- Energy consumption is calculated by GBV;
- An average distance to the refuel point at Node 4 is used to calculate the energy consumption for vehicles to refuel;
- Manticores can be used as a buffer for energy storage and refuelling;
- If Manticores are used, the energy consumption is reduced by the number of vehicle trips saved multiplied by the distance;
- The number of Manticores is not a decision variable but a constant.

3.3.4. Paths

The three paths, A to C, represent the transportation of the energy carriers, as shown in Figure 3.1. The assumptions and boundaries for each path are as follows:

- The GBV of this transport is not considered in this VESC model because it is mostly conducted by civilian partners and therefore unknown;
- CO2 equivalent emissions for this trip are not accounted for.

For path B:

- Only military transport is used, which is the Scania WLS 165 kN with an optional 165 kN trailer;
- Trailers are limited resources and therefore have a maximum limit;
- The GBV and CO2 equivalent emissions of this transport are included in the VESC model.

For path C:

- Only military transport is used, which is the Scania Gryphus 100 kN;
- The GBV and CO2 equivalent emissions of this transport are included in the VESC model.

3.4. Conclusion

This chapter explores how to measure the impact on the military supply chain (MSC), defines the Vehicle Energy Supply Chain (VESC) model, and outlines its underlying assumptions and boundaries. The impact of energy types on the MSC is assessed through three Key Performance Indicators (KPIs): the number of transport movements, refueling time, and CO2 equivalent emissions. The VESC model consists of four Nodes, SUPPLIER-SC-FSC-UNITS, and three paths, labeled A to C, as described in section 3.2. Expanding on the current MSC framework, the model now includes energy generation capabilities at various Nodes, as well as the use of small supply trucks as energy buffers at the final Node.

The major assumptions and boundaries of the VESC model include operating under an optimal scenario where all supply trucks start delivery simultaneously at each Node. Deliveries occur once every 24 hours to align with current operational practices. Due to NATO's single fuel policy, only one energy type is utilized for all vehicles throughout all days. Additionally, CO2 equivalent emissions only account for Fuel to Wheel emissions.

4 Mathematical Model

The VESC model is built upon the current MSC framework of the NLMoD as outlined in their doctrines, with adaptations made for renewable energy types, as detailed in section 3.2 and section 3.3. It can be conceptualized as a Mixed Integer Linear Programming (MILP) model due to its deterministic nature, relying solely on deterministic values, and its static approach, considering the entire time-frame of operations rather than specific intervals. Notably, the VESC model does not incorporate nonlinear objective functions or constraints. To solve this MILP model, the VESC model has the following parts:

- Parameters
- Decision variables
- Constraints
- Multiple objective functions

The parameters are fixed inputs that define the system, while the decision variables, though unknown, are bounded and may take binary, discrete, or continuous values. Decision variables can also be seen as constraint variables whereby the model gives the optimal value or best option for the given inputs and constraints. The constraints are needed in order for the VESC model to be within the given limits. Objective functions guide the model's optimization process, though multiple objectives may necessitate specialized solving techniques, detailed in section 4.2.

Parameter calculations are divided between an Excel sheet, housing input data, and a Python script. This bifurcation separates the input data and parameter calculations in section 4.3 from the optimization model in section 4.1, where objective functions and constraints are specified.

4.1. VESC model

This section begins with a comprehensive list of all sets, parameters, and decision variables. Subsequently, it details the mathematical expressions governing the objective functions and constraints employed within the VESC model, offering thorough elucidation. Parameters outlined are computed within the input sheet, with additional clarification available in section 4.3.

Sets:	
T	Set of days $(t \in 0, 1, \ldots, D)$ whereby D is the total days of operation
I	Set of energy types $(i \in 0, 1, \ldots, C)$ whereby C is total energy types
General parameters:	
fc^4_{ti}	Energy consumption in MJ per day $(t \in T)$ for energy type $(i \in I)$ at Node 4
fc^3_{ti}	Energy consumption in MJ per day $(t \in T)$ for energy type $(i \in I)$ at Node 3
$fcpv^{to\_supply}_{ti}$	Average energy consumption per vehicle to supply point at Node 4 in MJ per day $(t \in T)$ for energy carrier type $(i \in I)$
$avfc^{vehicle}_{ti}$	Average energy consumption per vehicle at Node 4 in MJ per day $(t \in T)$ for energy carrier type $(i \in I)$
del^4_{ti}	Binary values to tell if deliver is possible per day $(t \in T)$ per energy type $(i \in I)$

$tc_i^{gryphus}$	Carrying capacity of the Gryphus supply truck per energy type $(i \in I)$ in MJ
$tc_i^{manticore}$	Carrying capacity of the Manticore per energy type $(i \in I)$ in MJ
$cvv_i^{gryphus}$	CVV for the Gryphus supply truck per energy type $(i \in I)$ in MJ
cvv_i^{WLS}	CVV for the WLS supply truck per energy type $(i \in I)$ in MJ
$ft_i^{gryphus}$	Fuel tank capacity for the Gryphus supply truck per energy type $(i \in I)$ in MJ
ft_i^{WLS}	Fuel tank capacity for the WLS supply truck per energy type $(i \in I)$ in MJ
$tot_i^{capacity\_vehicles}$	Total energy capacity of vehicles per energy type $(i \in I)$
ef_i^{refuel}	Efficiency of refueling per energy type $(i \in I)$
$am^{manticore}$	Number of Manticores attached to UNITS at Node 4
Number of supply movement parameters:	
tr_{ti}^{pathB}	Total number of WLS and WLS+trailer trips per day $(t \in T)$ per energy type $(i \in I)$ for path B
$tr_{ti}^{pathB\_WLS}$	Number of WLS trips per day $(t \in T)$ per energy type $(i \in I)$ for path B
$tr_{ti}^{pathB\_WLS+trailer}$	Number of WLS+trailer trips per day $(t \in T)$ per energy type $(i \in I)$ for path B
Refuel time parameters:	
$av_i^{refuel\_time}$	Average refuel time per energy type $(i \in I)$ in MJ/min
rt_{ti}^{extra}	Extra refuel time at Node 4 per vehicle per day $(t \in T)$ per energy type $(i \in I)$
rtp_i^{extra}	Extra refuel time for pump at Node 3 per vehicle per energy type $(i \in I)$
$rp_i^{gryphus}$	Number of refuel points for Gryphus per energy type $(i \in I)$
$rp_{ti}^{Node\_4}$	Number of refuel points for Node 4 per day $(t \in T)$ per energy type $(i \in I)$
pu_i^{debit}	Pump debit in MJ/min at Node 3 per energy type $(i \in I)$
am^{pumps}	Number of pumps at Node 3
$am_{ti}^{gr\_or\_ma}$	Has value of the lowest number of either Gryphus or Manticore vehicles per day $(t \in T)$ per energy type $(i \in I)$ for path C/Node 4
rt^{extra3}	Extra refuel time at Node 3 due to build/break up of supply truck
rt^{extra4}	Extra refuel time at Node 4 due to build/break up of supply truck
Emission parameters:	
ec_{ti}^4	CO2 equivalent emissions in kg/day $(t \in T)$ for energy type $(i \in I)$ at Node 4
$av_{ti}^{emissions}$	Average CO2 equivalent emissions per vehicle to drive to supply point at Node 4 per day $(t \in T)$ per energy type $(i \in I)$ in kg
$em_i^{gryphus}$	CO2 equivalent emissions of the Gryphus for energy type $(i \in I)$ in kg
em_i^{WLS}	CO2 equivalent emissions of the WLS for energy type $(i \in I)$ in kg
$em_i^{WLS+trailer}$	CO2 equivalent emissions of the WLS+trailer for energy type $(i \in I)$ in kg
Decision variables:	
$Sn_{ti}^4 \in \mathbb{B}$	Binary variable representing whether to supply energy type $(i \in I)$ at Node 4 for day $(t \in T)$
$Sn_{ti}^3 \in \mathbb{B}$	Binary variable representing whether to supply energy type $(i \in I)$ at Node 3 for day $(t \in T)$
$Sn_{ti}^2 \in \mathbb{B}$	Binary variable representing whether to supply energy type $(i \in I)$ at Node 2 for day $(t \in T)$
$Rt_{ti}^4 \in \mathbb{B}$	Binary variable representing whether to supply energy type $(i \in I)$ at Node 4 for day $(t \in T)$ when looked at refuel time
$Rt_{ti}^3 \in \mathbb{B}$	Binary variable representing whether to supply energy type $(i \in I)$ at Node 4 for day $(t \in T)$ when looked at refuel time
$Em_{ti} \in \mathbb{B}$	Binary variable representing whether to supply energy type $(i \in I)$ for day $(t \in T)$ when looked at CO2 equivalent emissions
$Tr_{ti}^C \in \mathbb{R}$	Discrete variable representing how many Gryphus trips take place at C per energy type $(i \in I)$ for day $(t \in T)$
$En_{ti}^{manticore} \in \mathbb{R}$	Continuous variable representing how much energy the Manticore supplies in Node 4 for energy type $(i \in I)$ for day $(t \in T)$
$Fi_{ti}^{manticore} \in \mathbb{R}$	Continuous variable representing with how much energy the Manticore is filled up in Node 4 for energy type $(i \in I)$ for day $(t \in T)$
$Re_{ti}^{manticore} \in \mathbb{R}$	Continuous variable representing with how much energy remains in the Manticores at Node 4 for energy type $(i \in I)$ for day $(t \in T)$

4.1.1. Objective functions

The VESC model encompasses three objective functions that the model can optimize. The interplay between these objective functions and the method of solving the MILP model is expounded upon in section 4.2. This subsection provides the mathematical expressions for each individual objective function. One of the objective functions aims to minimize the number of supply movements for paths B and C. Equation 4.1 defines this objective function, which aggregates the total supply trips for paths B and C per day (t) and energy type (i). Binary decision variables determine the energy type utilized to minimize the number of supply trips. The number of trips for path C is calculated by dividing the required supply energy for Node 4 by the Gryphus capacity and rounding up to the nearest integer. The required energy for supply at Node 4 is computed as the energy consumption at Node 4 minus the energy supplied by the Manticores, plus the fill-up energy of the Manticores, minus the saved energy consumption of vehicles that do not need to travel to the supply point at Node 4 because they can be resupplied by the Manticores. The energy supplied and fill-up of the Manticores are decision variables, allowing the VESC model to obtain optimal values for each day. The number of supply trips for path B is already calculated for all energy types in parameter tr_{ti}^{pathB}, so the binary decision variable selects the best energy type. This objective function is represented as decision variable Tr_{ti}^{C}, allowing its use in the objective function for refuel time, as illustrated in Equation 4.36. A schematic overview of this objective function is depicted in Figure 4.1.

$$MIN \sum_{t \in D} \sum_{i \in C} [Sn_{ti}^{4} \cdot \left\lceil \frac{fc_{ti}^{4} - En_{ti}^{manticore} + Fi_{ti}^{manticore} - \frac{En_{ti}^{manticore} \cdot fcpv_{ti}^{to\_supply} \cdot 2}{avfc_{ti}^{vehicle}}}{tc_{i}^{gryphus}} \right\rceil + Sn_{ti}^{3} \cdot tr_{ti}^{pathB}] \tag{4.1}$$

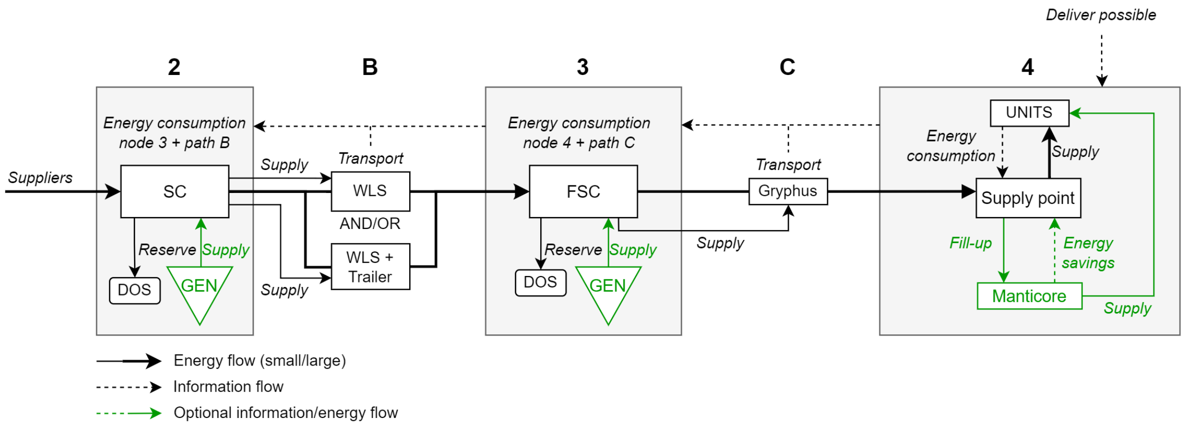

Figure 4.1: Overview of number of supply movements objective function

Another objective function aims to minimize the total refueling time at Node 3 and 4. The refueling time in Equation 4.2 represents the time required for supply trucks to refuel all necessary vehicles. subsection 3.3.2 assumes that all supply trucks at each Node start refueling simultaneously, representing the most optimal scenario. Therefore, the total refueling time comprises the refueling time for all vehicles and weapon platforms at Node 4, plus the refueling time for the Gryphus supply trucks at Node 3. This total refueling time accounts for the duration that Gryphus supply trucks remain stationary at either Node 3 or Node 4.

The objective function is divided into two parts, calculating the refueling time for Node 4 and 3 separately, each with its own binary decision variable determining the optimal energy type. For Node 4, the refueling time is further divided into four parts. Firstly, it calculates the time required to pump/charge the necessary energy from the Gryphus supply trucks to the vehicles. This is determined by dividing the required energy amount in MJ ($fc_{ti}^{4} - En_{ti}^{manticore} - saved\ energy$) by the average pump/charge speed in MJ/min, then dividing by the total available refueling points, which is the number of Gryphus supply trucks multiplied by the number of refueling points per truck. The second part calculates the fill-up energy time for the Manticores, considering the lowest value between the number of Gryphus or Manticore supply trucks as the determinant for the number of refueling points, see Equation 4.37. The third part accounts for the extra time for vehicles and weapon platforms to connect to the Gryphus supply trucks and disconnect (pairing), factoring in the method of supply and energy type. This is calculated based on the number of vehicles needing resupply (higher $En_{ti}^{manticore}$ meaning fewer vehicles) multiplied by the extra time (rt_{ti}^{extra}) and divided by the number of refueling points. The last part accounts for the time required for supply trucks to prepare and disassemble. For Node 4, this includes building a platform for the operator to supply fuel, compensated by rt^{extra4}.

The refueling time at Node 3 also comprises three parts similar to Node 4. Firstly, it calculates the time to pump/charge the required energy (energy consumption at Node 3 minus the Manticore part) from the WLS(+trailer) to the Gryphus, divided by the available pumps/chargers. The second part involves the number of Gryphus supply trucks needed for refueling, multiplied by the extra time required to connect/disconnect to the resupply at Node 3. The third part is the extra time needed to prepare for supplying, considering that the fuel containers from the WLS must be placed on the ground before refueling can commence. rt^{extra3} compensates for these actions. A schematic overview is provided in Figure 4.2, with refueling time measured in minutes.

For electric charging, the variable am^{pumps} is replaced by tr_{ti}^{pathB}. This adjustment is made because electric charging does not rely on external pumps or cranes; instead, each WLS energy container has its own charging station.

The section highlighted in red is not utilized for calculating the refueling time. This exclusion is due to the variability in how energy is supplied to Node 2, which depends on the situation and commercial supplier and is not accounted for in this VESC model. Additionally, given that Node 2 is positioned at a considerable distance from the front line, the refueling time at the SC is deemed less critical than that at Node 3 and 4.

$$
\begin{aligned}
MIN \sum_{t \in D} \sum_{i \in C} \Bigg[Rt_{ti}^{4} \cdot \Bigg(\Bigg(\frac{fc_{ti}^{4} - En_{ti}^{manticore} - \frac{En_{ti}^{manticore} \cdot fcpv_{ti}^{to\_supply} \cdot 2}{avfc_{ti}^{vehicle}}}{av_{i}^{refuel\_time}} \cdot \frac{1}{rp_{ti}^{Node\_4}} \Bigg) + \\
\Bigg(\frac{Fi_{ti}^{manticore}}{av_{i}^{refuel\_time}} \cdot \frac{1}{am_{ti}^{gr\_or\_ma} \cdot rp_{i}^{gryphus}} \Bigg) + \\
\Bigg(\frac{fc_{ti}^{4} - En_{ti}^{manticore} - \frac{En_{ti}^{manticore} \cdot fcpv_{ti}^{to\_supply} \cdot 2}{avfc_{ti}^{vehicle}}}{avfc_{ti}^{vehicle}} \cdot \frac{rt_{ti}^{extra}}{rp_{ti}^{Node\_4}} \Bigg) + rt^{extra4} \cdot del_{ti}^{4} \Bigg) + \\
Rt_{ti}^{3} \cdot \Bigg(\Bigg(\frac{fc_{ti}^{3.1} - En_{ti}^{manticore} + Fi_{ti}^{manticore} - \frac{En_{ti}^{manticore} \cdot fcpv_{ti}^{to\_supply} \cdot 2}{avfc_{ti}^{vehicle}}}{pu_{i}^{debit}} \cdot \frac{1}{am^{pumps}} \Bigg) + \\
\Bigg\lceil \frac{fc_{ti}^{4} - En_{ti}^{manticore} + Fi_{ti}^{manticore} - \frac{En_{ti}^{manticore} \cdot fcpv_{ti}^{to\_supply} \cdot 2}{avfc_{ti}^{vehicle}}}{tc_{i}^{gryphus}} \Bigg\rceil \cdot \frac{rtp_{i}^{extra}}{am^{pumps}} \Bigg) + rt^{extra3} \cdot del_{ti}^{4} \Bigg]
\end{aligned}
\tag{4.2}
$$

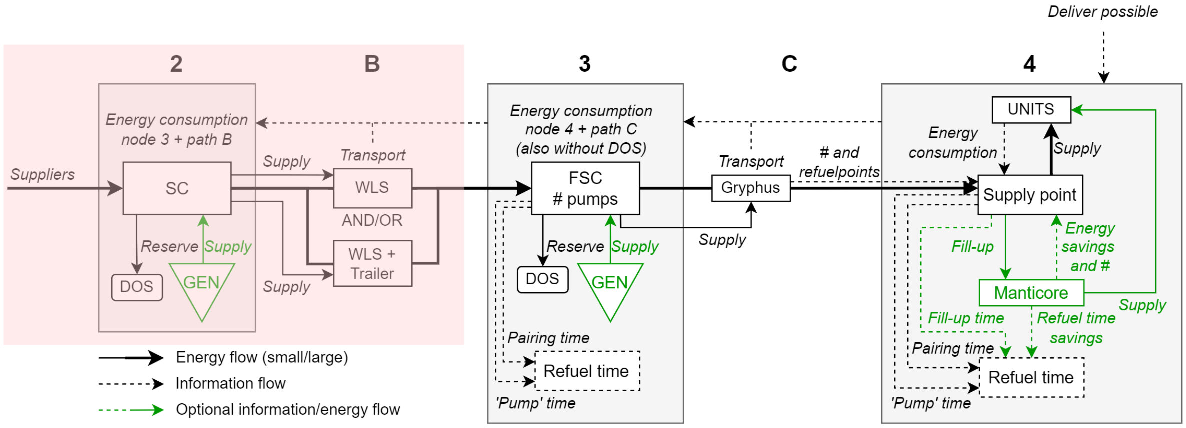

Figure 4.2: Overview of refuel time objective function

The final objective function minimizes CO2 equivalent emissions, as depicted in Equation 4.3. This objective function comprises three components. The first component pertains to emissions associated with UNITS at Node 4. These emissions for all energy types are calculated in Equation 4.18 but are adjusted by subtracting the reduced emissions resulting from Manticores directly supplying the UNITS, thus eliminating the need for UNITS to travel to the refueling point at Node 4. The second component addresses emissions linked to Gryphus supply trucks, calculated by multiplying the number of Gryphus trips by the emissions per Gryphus trip. Similarly, the third component, focusing on emissions related to WLS and WLS+trailer for path B, follows a similar calculation method as the second component.

The decision variable, multiplied by all three components of the objective function, determines the energy type with the lowest CO2 equivalent emissions. Refer to Figure 4.3 for an overview of this objective function. CO2 equivalent emissions are measured in kilograms.

$$MIN \sum_{t\in D}\sum_{i\in C}\Bigg[Em_{ti}\cdot\Bigg(\Bigg(ec^4_{ti}-\frac{En^{manticore}_{ti}}{avfc^{vehicle}_{ti}}\cdot av^{emissions}_{ti}\cdot 2\Bigg)+ \left(\left\lceil \frac{fc^4_{ti}-En^{manticore}_{ti}+Fi^{manticore}_{ti}-\frac{En^{manticore}_{ti}\cdot fcpv^{to\_supply}_{ti}\cdot 2}{avfc^{vehicle}_{ti}}}{tc^{gryphus}_i}\right\rceil\cdot em^{gryphus}_i\right)+ tr^{pathB\_WLS}_{ti}\cdot em^{WLS}_i + tr^{pathB\_WLS+trailer}_{ti}\cdot em^{WLS+trailer}_i\Bigg)\Bigg] \tag{4.3}$$

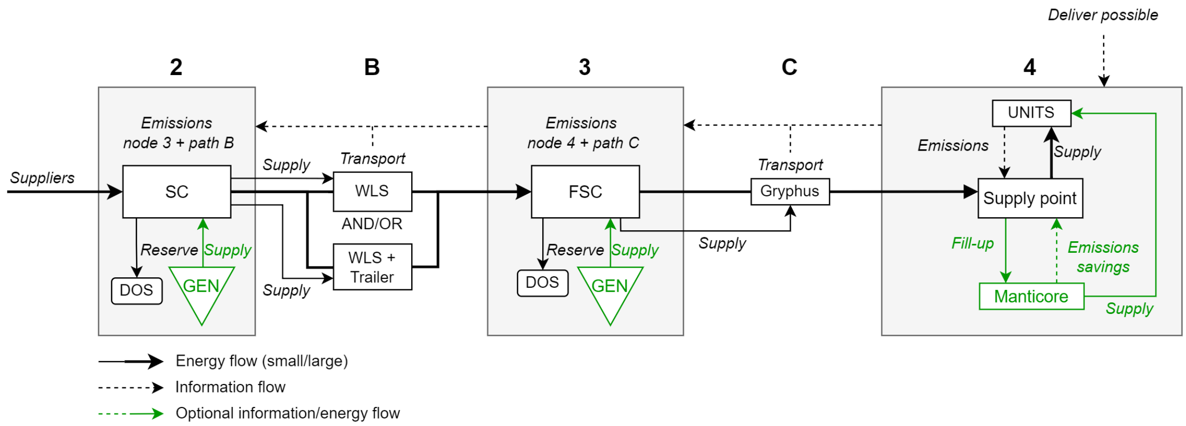

Figure 4.3: Overview of CO2 equivalent emissions objective function

4.1.2. Constraints

The VESC model is constrained by several limitations, each of which will be elaborated on in this subsection.

The initial constraint ensures that on any given day, only one energy type is utilized for both supply movements and refueling time. This adheres to NATO's "one fuel policy," stipulating that all vehicles operate on the same energy type. Implementing multiple energy types for various vehicles and weapon platforms would overly complicate the MSC. As depicted in Equation 4.4, the sum of all energy types per day must equal one, indicating that only a single energy type can be selected daily. The decision variable for emissions, as depicted in Equation 4.6 with Sn^4_{ti}, is also subject to this constraint.

$$\text{for } t \in \{0, 1, \ldots, \text{D}\}: \quad \sum_{\text{i}=0}^{\text{C}} Sn^4_{ti} == 1 \quad , \quad \sum_{\text{i}=0}^{\text{C}} Rt^4_{ti} == 1 \tag{4.4}$$

It is further mandated that all days within the model employ the same energy type. This is due to the impracticality of vehicles and weapon platforms altering energy types during operations. Once an energy type is selected in the VESC model, it remains constant for the entire operational duration. The constraint outlined in Equation 4.5 stipulates that the total sum of days per energy type equals the product of the total days (D) and the value of either Sn^4_{0i} or Rt^4_{0i} for the initial day.

$$\text{for } i \in \{0, 1, \ldots, C\}: \quad \sum_{t=0}^{D} Sn^4 == D \times Sn^4_{0i}, \quad \sum_{t=0}^{D} Rt^4 == D \times Rt^4_{0i} \tag{4.5}$$

The VESC model can evaluate the optimal choice for each Node or path. However, it is constrained by the requirement that ultimately, each Node or path must supply the same energy type. This is enforced by constraint Equation 4.6, which links all decision variables related to supply movements and emissions. While decision variables for refuel time could also be incorporated into this constraint, they are kept separate to allow for independent optimization of refuel time.

$$\text{for t} \in \{0, 1, \ldots, \text{D}\}, \text{for i} \in \{0, 1, \ldots, \text{C}\}:$$

$$Sn^4_{ti} == Sn^3_{ti} == Sn^2_{ti} == Em_{ti} \tag{4.6}$$

Constraint Equation 4.7 is equal to Equation 4.6 whereby the Nodes and path should supply the same energy type but only for the refuel time.

$$\text{for t} \in \{0, 1, \ldots, \text{D}\}, \text{for i} \in \{0, 1, \ldots, \text{C}\}:$$

$$Rt^4_{ti} == Rt^3_{ti} \tag{4.7}$$

Constraint Equation 4.8 is designed to eliminate energy types that cannot fulfill the demands of the situation, particularly when the daily energy requirement exceeds the storage capacity of vehicles at Node 4. When energy consumption surpasses the total storage capacity of vehicles or when supply trucks consume more energy for their round-trip than they can store, Sn^4_{ti} is set to zero. Since all other decision variables depend on Sn^4_{ti}, this constraint is universally applicable. It is imposed because the VESC model operates under the assumption of a single supply run every 24 hours. Should this assumption change to allow for multiple supply runs per day, this constraint will need to be adjusted accordingly.

$$\text{for } t \in \{0, 1, \ldots, D\}, \text{for } i \in \{0, 1, \ldots, C\}:$$

$$Sn^4_{ti} == \begin{cases} 0 & fc^4_{ti} > tot^{capacity\_vehicles}_i \mid\mid cvv^{gryphus}_i < ft^{gryphus}_i \mid\mid cvv^{WLS}_i < ft^{WLS}_i \\ Sn^4_{ti} & \text{otherwise} \end{cases} \tag{4.8}$$

For certain policies, additional constraints are necessary when using the small Manticore supply trucks at Node 4. These Manticores are connected to the UNITS at Node 4 and begin each day at $t = 0$ with full storage capacity. They have the capability to supply energy to the units daily, and constraints are implemented to determine their maximum supply capacity and the remaining energy. Each day, the Manticores can also undergo refueling if necessary.

The remaining energy in the Manticores at day t is calculated as the leftover energy from day $t-1$ minus the energy supplied on day t, plus any energy refilled on day t. On day $t=0$, the remaining energy is determined by multiplying the number of Manticores attached to Node 4 by the full storage capacity of a Manticore supply truck. Since there is a loss in energy during refueling for certain energy types, the energy delivered from the Manticores is divided by the refueling efficiency. Equation 4.9 illustrates this constraint. The deployment options for the Manticores are depicted in Figure 4.4, with only the supply occurring within the yellow box being considered in the total supply time.

$$\text{for } t \in \{0,1,\ldots,D\}, \text{for } i \in \{0,1,\ldots,C\}:$$

$$Re_{ti}^{manticore} == \begin{cases} am^{manticore} \times tc_i^{manticore} - \frac{En_{ti}^{manticore}}{ef_i^{refuel}} & t=0 \\ Re_{t-1i}^{manticore} - \frac{En_{ti}^{manticore}}{ef_i^{refuel}} + Fi_{ti}^{manticore} & \text{otherwise} \end{cases} \tag{4.9}$$

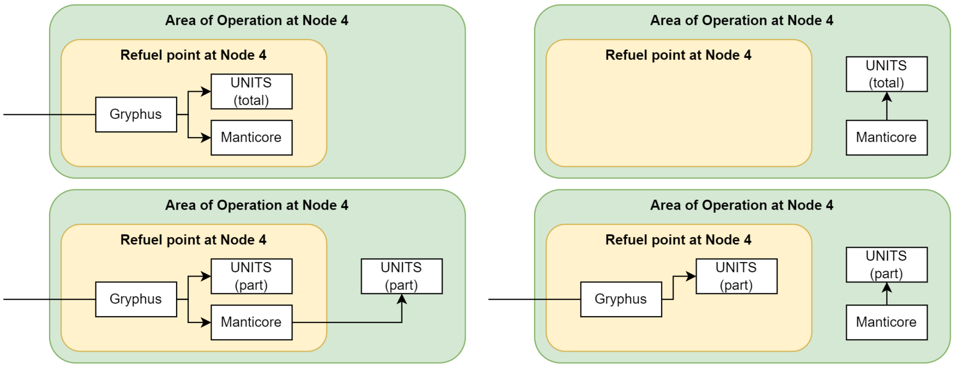

Figure 4.4: Schematic representation of the various deployment options of the Manticore.

The Manticore supply trucks cannot refill their capacity or supply energy to UNITS if no supply occurs on a given day. Therefore, the decision variables are multiplied by del_{ti}^4, ensuring that if no delivery occurs on a particular day, the decision variable values are zero, as depicted in Equation 4.10. Additionally, the fill-up capacity of the Manticore supply trucks cannot exceed the total capacity minus the remaining energy inside the Manticores. Moreover, it is not feasible for the Manticores to supply more energy to the UNITS than they require on day t.

$$\text{for t} \in \{0,1,\ldots,\text{D}\}, \text{for i} \in \{0,1,\ldots,\text{C}\}:$$

$$\begin{aligned} Fi_{ti}^{manticore} &== Fi_{ti}^{manticore} \times del_{ti}^4 \\ En_{ti}^{manticore} &== En_{ti}^{manticore} \times del_{ti}^4 \\ Fi_{ti}^{manticore} &<= am^{manticore} \cdot tc_i^{manticore} - Re_{ti}^{manticore} \\ En_{ti}^{manticore} &<= fc_{ti}^4 - \frac{En_{ti}^{manticore} \cdot fcpv_{ti}^{to\_supply} \cdot 2}{avfc_{ti}^{vehicle}} \end{aligned} \tag{4.10}$$

4.2. Optimization Solver Method

To solve this MILP model, various approaches can be considered [59]. However, the blended objectives approach, which combines multiple objectives into a single function using weights, is not suitable for this VESC model. The outputs of individual objectives vary significantly in magnitude, with some in the range of tenths or hundreds, while CO2 equivalent emissions, for instance, can reach the range of hundreds of thousands, depending on the inputs. Consequently, employing the blended objective approach with weights is not feasible for the VESC model.

Instead, the solver method utilized for the VESC model is the Hierarchical Objectives approach. This method allows for the assignment of priorities to each objective, enabling optimization in decreasing priority order. The solver conducts separate optimization passes for each objective, finding the best solution for the objective with the highest priority, and then proceeding to solve for lower-priority objectives in descending order. Generally, the best solutions for lower-priority objectives do not compromise the solutions of higher-priority objectives. However, adjustments can be made to specify how much a lower-priority objective can affect the solution of a higher-priority one, either as a relative number or an absolute tolerance [59].

While this approach offers benefits, it presents drawbacks as well. As more objectives are introduced, solving becomes increasingly challenging because each solved objective becomes a constraint for the subsequent ones in the VESC model, potentially leading to infeasibility later on. Additionally, certain soft constraints may not be evaluated effectively when the VESC model is fragmented, potentially resulting in the oversight of globally high-quality solutions [60].

Nonetheless, the reason for selecting this solver method is its ability to prioritize objectives based on their importance, as outlined in section 3.1. Priority ranking is crucial in military operations, where minimizing the risk of supply failure is paramount, a determination typically made through expert opinion. In this context, risk encompasses the threat of being disabled by enemy fire or experiencing supply chain failures.

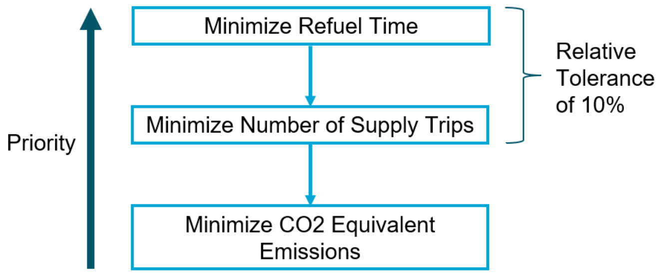

Figure 4.5: Schematic representation of the Hierarchical Objectives approach

For this VESC model, the priorities for each objective are:

- Refuel time has priority 2, relative tolerance of 0,1;
- Number of transport movements has priority 1, relative tolerance of 0,1;
- CO_2 equivalent emissions has priority 0.

The priorities are established based on insights from experts in the field. Refuel time is deemed the most critical aspect of combat supply, as remaining stationary near the front lines significantly heightens the risk of being targeted by enemy fire. Therefore, refuel time is assigned priority 2, the highest priority in the VESC model. Following closely, the second priority is given to supply capacity requirements due to their scarcity, designated as priority 1, one step lower than refuel time. Conversely, the objective of minimizing CO_2 equivalent emissions is assigned the lowest priority. While it may not directly impact combat scenarios, it holds strategic significance, considering the potential scarcity of fossil fuels in the future. As such, this objective is assigned priority number 0.

A relative tolerance of 10% is set for both refuel time and the number of transport movements. This percentage is deemed sufficiently small to be acceptable for higher-priority objectives while still offering the potential for significant improvements in lower-priority objectives.

The VESC model is implemented in Python, leveraging the Gurobi Optimizer package version 10.0.3. This implementation aligns with the mathematical model outlined in this chapter and utilizes the solver methodology described in the preceding sections.

4.3. Experiments Input Data Sheet

The VESC model relies on various parameters as inputs, which are derived from the input values outlined in chapter 5. However, the mathematical relationships governing these parameters are elucidated in this section.

Sets:	
T	Set of days ($t \in 0, 1, \ldots, D$) whereby D is the total days of operation
V	Set of types of vehicles ($v \in 0, 1, \ldots, E$) with E the total types of vehicles
I	Set of energy types ($i \in 0, 1, \ldots, C$) with C the total number of energy types
General/number of supply movement parameters:	
fc_{ti}^{APU}	Energy consumption of APU in MJ per day ($t \in T$) for energy type ($i \in I$) at Node 4
$fc_{ti}^{3.1}$	Energy consumption in MJ per day ($t \in T$) for energy type ($i \in I$) at Node 3 without reserve DOS
eg_i^2	Energy generation at Node 2 per energy type ($i \in I$)
eg_i^3	Energy generation at Node 3 per energy type ($i \in I$)
eo_{ti}^3	Energy surplus at Node 3 per day ($t \in T$) per energy type ($i \in I$)
eo_{ti}^2	Energy surplus at Node 2 per day ($t \in T$) per energy type ($i \in I$)
bve_i	BVE of all vehicles and weapon platforms at Node 4 per energy type ($i \in I$)
bve_i^{APU}	BVE of APU (stand-by time) of all vehicles and weapon platforms at Node 4 per energy type ($i \in I$)
tc_i^{WLS}	Carrying capacity of the WLS truck for energy type ($i \in I$) in MJ
$tc_i^{WLS+trailer}$	Carrying capacity of the WLS+trailer truck for energy type ($i \in I$) in MJ
$am_v^{vehicles}$	number of vehicles per vehicle type ($v \in V$)
$am^{WLS+trailer}$	number of WLS + trailers available
DOS	Standard day of supply in MJ
$tot^{vehicles}$	Total vehicles at Node 4
rf^3	Amount of DOS extra for day one as a reserve to be kept in the FSC
rf^2	Amount of DOS extra for day one as a reserve to be kept in the SC
apu^{used}	Has value 1 if APUs are used and value 0 if not
$cvv_i^{gryphus}$	CVV value for Gryphus per energy type ($i \in I$)
cvv_i^{WLS}	CVV value for WLS per energy type ($i \in I$)
$cvv_i^{WLS+trailer}$	CVV value for WLS+trailer per energy type ($i \in I$)
FTW_{vi}	FTW efficiencies per vehicle type ($v \in V$) per energy type ($i \in I$)
$gbv_{vi}^{vehicles}$	GBV values in MJ per vehicle type ($v \in V$) per energy type ($i \in I$)
$gbv_{vi}^{APU\_vehicles}$	GBV values of APUs in MJ per vehicle type ($v \in V$) per energy type ($i \in I$)
gbv_{vi}^{supply}	GBV value in MJ per supply vehicle type ($v \in 0, \ldots, 2$) per energy type ($i \in I$)
Situation parameters:	
day^{to_AoO}	Number of days to travel to Area of Operation (AoO) for UNITS
day^{from_AoO}	Number of days to travel back from AoO for UNITS
day^{combat}	Number of days combat operations for UNITS
dis^{to_AoO}	Distance to travel to AoO for UNITS in km
dis^{from_AoO}	Distance to travel back from AoO for UNITS in km
dis^{2-3}	Distance from Node 2 to Node 3 in km
dis^{3-4}	Distance from Node 3 to Node 4 in km
dis^{mov1_sup4}	Distance for UNITS to travel to supply point at Node 4 for movement to AoO in km
dis^{mov2_sup4}	Distance for UNITS to travel to supply point at Node 4 for return from AoO in km
dis^{com_sup4}	Distance for UNITS to travel to supply point at Node 4 while in combat days in km
hrs^{com}	Hours of combat actions per day for UNITS at Node 4
hrs^{sby_mov1}	Hours of stand-by for movement to AoO for UNITS at Node 4
hrs^{sby_mov2}	Hours of stand-by for movement back from AoO for UNITS at Node 4
hrs^{sby_com}	Hours of stand-by for combat days for UNITS at Node 4
hrs^{sby_sup2-3}	Hours of stand-by for supply from Node 2 to 3
hrs^{sby_sup3-4}	Hours of stand-by for supply from Node 3 to 4
if^{sby}	Intensity factor for stand-by time
if^{ter_mov1}	Intensity factor for terrain for movement to AoO
if^{ter_mov2}	Intensity factor for terrain for movement back from AoO
if^{ter_com}	Intensity factor for terrain for combat days
if^{ter_sup2-3}	Intensity factor for terrain for supply from Node 2 to 3
if^{ter_sup3-4}	Intensity factor for terrain for supply from Node 3 to 4
if^{wea_mov1}	Intensity factor for weather for movement to AoO
if^{wea_mov2}	Intensity factor for terrain for movement back from AoO
if^{wea_com}	Intensity factor for terrain for combat days
if^{wea_sup2-3}	Intensity factor for weather for supply from Node 2 to 3
if^{wea_sup3-4}	Intensity factor for weather for supply from Node 3 to 4

if^{mov_mov1}	Intensity factor for type of movement for movement to AoO
if^{mov_mov2}	Intensity factor for type of movement for movement back from AoO
if^{mov_com}	Intensity factor for type of movement for combat days
if^{mov_sup2-3}	Intensity factor for type of movement for supply from Node 2 to 3
if^{mov_sup3-4}	Intensity factor for type of movement for supply from Node 3 to 4
if^{com}	Intensity factor for type of combat
Refuel time parameters:	
$rt_{vi}^{vehicles}$	Average refuel time per vehicle $(v \in V)$ per energy type $(i \in I)$ in MJ/min
rp_i^{WLS}	Number of refuel points for WLS per energy type $(i \in I)$
$rp_i^{WLS+trailer}$	Amount of refuel points for WLS+trailer per energy type $(i \in I)$
$rp_i^{manticore}$	Amount of refuel points for Manticore per energy type $(i \in I)$
$tr_{ti}^{gryphus}$	Number of Gryphus trips per day $(t \in T)$ per energy type $(i \in I)$ for path C
Emission parameters:	
ec_{ti}^{APU}	CO2 equiv emissions for APU in kg/day $(t \in T)$ for energy type $(i \in I)$ at Node 4
bve_i^{emis}	BVE CO2 equivalent emissions of UNITS at Node 4 per energy type $(i \in I)$ in kg
$bve_i^{emis\_APU}$	BVE CO2 equivalent emissions for APU use in stand-by at Node 4 per energy type $(i \in I)$ in kg
em_{vi}^{supply}	CO2 equivalent emissions in kg/MJ per supply vehicle type $(v \in 0, \ldots, 2)$ per energy type $(i \in I)$
$ftw_{vi}^{vehicles}$	FTW CO2 equivalent emissions in kg per day or 100 km per supply vehicle type $(v \in 0, \ldots, 2)$ per energy type $(i \in I)$
$ftw_{vi}^{vehicles\_APU}$	FTW CO2 equivalent emissions in kg per day per supply vehicle type $(v \in 0, \ldots, 2)$ per energy type $(i \in I)$
$em_i^{manticore}$	CO2 equivalent emissions of the Manticore for energy type $(i \in I)$ in kg

The energy consumption per vehicle for driving 100 km under optimal conditions is referred to as the GBV. While the GBV values for diesel fuel are known, including fuel tank capacity, refueling speed, and range, these values need to be calculated for other energy types. This calculation involves utilizing FTW efficiencies and energy densities. The FTW efficiency is determined for each type of drivetrain by multiplying the efficiencies of individual components. These efficiencies per drivetrain are illustrated in Figure 4.6, and the FTW utilized is the composite of the colored components, as the differential and propeller/drive shaft efficiencies remain consistent across all energy types.

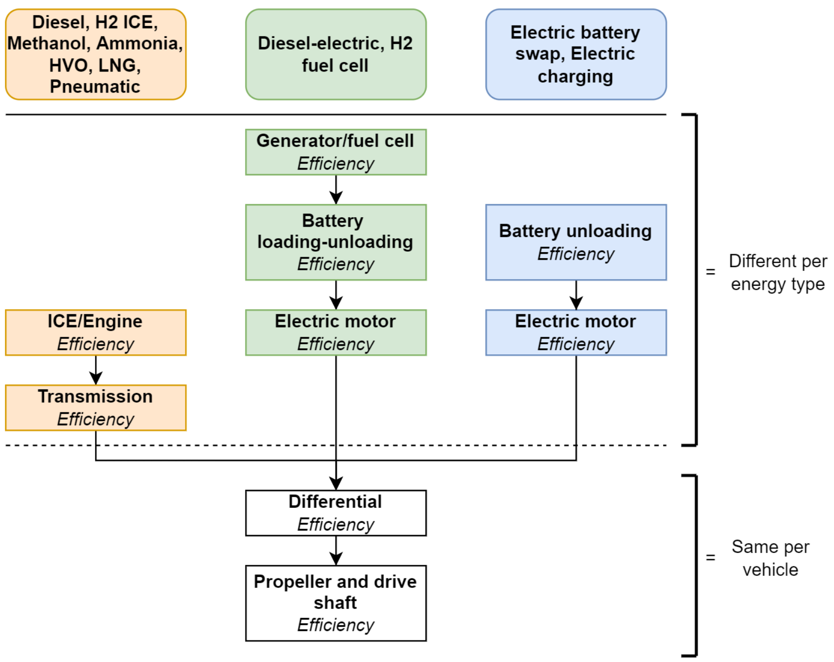

Figure 4.6: Efficiency calculation graph of each energy type

The GBV values for energy types $i \leq 0$ are calculated by multiplying the GBV value of the known energy type diesel by the ratio of FTW_{diesel}/FTW_i.

$$\text{for v} \in \{0, 1, \ldots, \text{E}\}, \text{for i} \in \{0, 1, \ldots, \text{C}\}:$$
$$gbv_{vi}^{vehicles} = gbv_{v0}^{vehicles} \cdot \frac{FTW_{v0}}{FTW_{vi}} \tag{4.11}$$

The BVE represents the total of all GBVs for all vehicles employed in the scenario under standard conditions. In essence, it signifies the energy consumption of UNITS under normal circumstances for a distance of 100 km on flat terrain. The BVE is computed for all energy types.

$$\text{for i} \in \{0, 1, \ldots, \text{C}\}:$$
$$bve_i = \sum_{v=0}^{E} am_v^{vehicles} \cdot gbv_{vi}^{vehicles} \tag{4.12}$$

The energy consumption for Node 4 is determined using the CVV formulas provided in subsection 2.2.1. For all three phases involving the UNITS—namely, movement to the AoO, combat, and movement back from the AoO—the energy consumption is calculated using the BVE and intensity factors. For movements, the distance in kilometers and stand-by time in hours are utilized, while for combat, the number of combat and stand-by hours, along with the distance to the supply point at Node 4, are considered.

$$fc_{ti}^{4} = \begin{cases} \frac{bve_i \cdot (dis^{to\_AoO} + dis^{mov1\_sup4}) \cdot if^{ter\_mov1} \cdot if^{wea\_mov1} \cdot if^{mov\_mov1}}{100} + \frac{bve_i \cdot hrs^{sby\_mov1} \cdot if^{wea\_mov1} \cdot if^{sby}}{24} & i \leq day^{to\_AoO} \\ \frac{bve_i \cdot (dis^{from\_AoO} + dis^{mov2\_sup4}) \cdot if^{ter\_mov2} \cdot if^{wea\_mov2} \cdot if^{mov\_mov2}}{100} + \frac{bve_i \cdot hrs^{sby\_mov2} \cdot if^{wea\_mov2} \cdot if^{sby}}{24} & i > day^{to\_AoO} + day^{combat} \\ \frac{bve_i \cdot hrs^{com} \cdot if^{ter\_com} \cdot if^{wea\_com} \cdot if^{com}}{24} + \frac{bve_i \cdot hrs^{sby\_com} \cdot if^{wea\_com} \cdot if^{sby}}{24} + \frac{bve_i \cdot dis^{com\_sup4} \cdot if^{ter\_com} \cdot if^{wea\_com} \cdot if^{mov\_com}}{100} & \text{otherwise} \end{cases} \tag{4.13}$$

The energy consumption to the supply point at Node 4 per vehicle or weapon platform is given in Equation 4.14. The calculation is similar to Equation 4.13 but only the distance to the supply point at Node 4 for all three stages of UNITS are considered.

$$fcpv_{ti}^{to\_supply} = \begin{cases} \frac{bve_i \cdot dis^{mov1\_sup4} \cdot if^{ter\_mov1} \cdot if^{wea\_mov1} \cdot if^{mov\_mov1}}{100} & i \leq day^{to\_AoO} \\ \frac{bve_i \cdot dis^{mov2\_sup4} \cdot if^{ter\_mov2} \cdot if^{wea\_mov2} \cdot if^{mov\_mov2}}{100} & i > day^{to\_AoO} + day^{combat} \\ \frac{bve_i \cdot dis^{com\_sup4} \cdot if^{ter\_com} \cdot if^{wea\_com} \cdot if^{mov\_com}}{100} & \text{otherwise} \end{cases} \tag{4.14}$$

The CVV values of all transport trucks are needed in order to calculate the energy consumption for path B and C. The formula from subsection 2.2.1 is again used for this. The distance to the FSC or UNITS is multiplied by 2 because it is a round-trip. See Equation 4.15.

$$\begin{aligned} cvv_i^{gryphus} &= \frac{gbv_{0i}^{supply} \cdot 2 \cdot dis^{3-4} \cdot if^{ter\_sup3-4} \cdot if^{wea\_sup3-4} \cdot if^{mov\_sup3-4}}{100} \\ cvv_i^{WLS} &= \frac{gbv_{1i}^{supply} \cdot 2 \cdot dis^{2-3} \cdot if^{ter\_sup2-3} \cdot if^{wea\_sup2-3} \cdot if^{mov\_sup2-3}}{100} \\ cvv_i^{WLS+trailer} &= \frac{gbv_{2i}^{supply} \cdot 2 \cdot dis^{2-3} \cdot if^{ter\_sup2-3} \cdot if^{wea\_sup2-3} \cdot if^{mov\_sup2-3}}{100} \end{aligned} \tag{4.15}$$

The average refuel time in MJ/min is calculated by the sum of all the refuel times (MJ/min) for each vehicle divided by the total number of vehicles, and that for every energy type, see Equation 4.16.

$$\text{for i} \in \{0, 1, \ldots, \text{C}\}:$$
$$av_i^{refuel\_time} = \frac{\left(\sum_{v=0}^{E} am_v^{vehicles} \cdot rt_{vi}^{vehicle}\right)}{tot^{vehicles}} \tag{4.16}$$

For the CO2 equivalent calculations at Node 4, firstly the emissions of the BVE (Equation 4.12) should be known. This is done by multiplying the number of vehicles per vehicle type with the FTW in kg CO2/MJ corresponding with that vehicle type. The result is kg CO2/MJ per 100 km. Equation 4.18 divides it by 100 so it becomes per km. See formula can be seen in Equation 4.17.

$$\text{for i} \in \{0, 1, \ldots, \text{C}\}:$$
$$bve_i^{emis} = \sum_{v=0}^{E} am_v^{vehicles} \cdot ftw_{vi}^{vehicles} \tag{4.17}$$

The CO2 equivalent emissions for Node 4 are calculated in similar way as Equation 4.13 but instead of bve_i, bve_i^{emis} is used. The mathematical expression is given in Equation 4.18.

$$\text{for i} \in \{0, 1, \ldots, \text{C}\}:$$
$$ec_{ti}^4 = \begin{cases} \frac{bve_i^{emis} \cdot (dis^{to\_AoO} + dis^{mov1\_sup4}) \cdot if^{ter\_mov1} \cdot if^{wea\_mov1} \cdot if^{mov\_mov1}}{100} + \frac{bve_i^{emis} \cdot hrs^{sby\_mov1} \cdot if^{wea\_mov1} \cdot if^{sby}}{24} & i \leq day^{to\_AoO} \\ \frac{bve_i^{emis} \cdot (dis^{from\_AoO} + dis^{mov2\_sup4}) \cdot if^{ter\_mov2} \cdot if^{wea\_mov2} \cdot if^{mov\_mov2}}{100} + \frac{bve_i^{emis} \cdot hrs^{sby\_mov2} \cdot if^{wea\_mov2} \cdot if^{sby}}{24} & i > day^{to\_AoO} + day^{combat} \\ \frac{bve_i^{emis} \cdot hrs^{com} \cdot if^{ter\_com} \cdot if^{wea\_com} \cdot if^{com}}{24} + \frac{bve_i^{emis} \cdot hrs^{sby\_com} \cdot if^{wea\_com} \cdot if^{sby}}{24} + \frac{bve_i \cdot dis^{com\_sup4} \cdot if^{ter\_com} \cdot if^{wea\_com} \cdot if^{mov\_com}}{100} & \text{otherwise} \end{cases} \tag{4.18}$$

The average CO2 equivalent emissions for vehicles to the supply point at Node 4 should be known in order to subtract it from the total if the Manticore vehicles are used for resupply, see Equation 4.3. The expression is given in Equation 4.19.

$$av_{ti}^{emisions} = \begin{cases} \frac{bve_i^{emis} \cdot dis^{mov1\_sup4} \cdot if^{ter\_mov1} \cdot if^{wea\_mov1} \cdot if^{mov\_mov1}}{100} & i \leq day^{to\_AoO} \\ \frac{bve_i^{emis} \cdot dis^{mov2\_sup4} \cdot if^{ter\_mov2} \cdot if^{wea\_mov2} \cdot if^{mov\_mov2}}{100} & i > day^{to\_AoO} + day^{combat} \\ \frac{bve_i^{emis} \cdot dis^{com\_sup4} \cdot if^{ter\_com} \cdot if^{wea\_com} \cdot if^{mov\_com}}{100} & \text{otherwise} \end{cases} \tag{4.19}$$

The CO2 equivalent emissions for the supply trucks are similar in calculation as Equation 4.15 but use em_{vi}^{supply} instead of gbv_{0i}^{supply}, see Equation 4.20.

$$\begin{aligned} em_i^{gryphus} &= \frac{em_{0i}^{supply} \cdot dis^{3-4} \cdot if^{ter\_sup3-4} \cdot if^{wea\_sup3-4} \cdot if^{mov\_sup3-4}}{100} \\ em_i^{WLS} &= \frac{em_{1i}^{supply} \cdot dis^{2-3} \cdot if^{ter\_sup2-3} \cdot if^{wea\_sup2-3} \cdot if^{mov\_sup2-3}}{100} \\ em_i^{WLS+trailer} &= \frac{em_{2i}^{supply} \cdot dis^{2-3} \cdot if^{ter\_sup2-3} \cdot if^{wea\_sup2-3} \cdot if^{mov\_sup2-3}}{100} \end{aligned} \tag{4.20}$$

The VESC model employs the ICE or main conversion device to meet the energy requirements during stand-by time, as indicated in Equation 4.13 and Equation 4.18. This mirrors the current practice with existing vehicles. Currently, COMMIT is conducting research to potentially replace the ICE (main engine) with an APU during stand-by time, aiming to reduce energy consumption and minimize wear and tear on the ICE. The energy consumption formula for stand-by time, derived from 'Zakboek logistiek' [11], involves multiplying the BVE by the applicable intensity factors and dividing by the number of hours used. The intensity factor for stand-by (if^{sby}) maintains a standard value of 0.25, indicating that only a quarter of the normal energy consumption is utilized during stand-by time for all vehicle types. To assess the impact of transitioning from ICE to APU for stand-by time, the BVE of the APUs is first determined by multiplying the number of vehicles by their respective APU GBV values, as outlined in Equation 4.21.

$$\text{for i} \in \{0, 1, \ldots, \text{C}\}:$$
$$bve_i^{APU} = \sum_{v=0}^{E} am_v^{vehicles} \cdot gbv_{vi}^{APU\_vehicles} \tag{4.21}$$

The energy consumption during stand-by time is accounted for in fc^4_{ti}, as shown in Equation 4.13. If the VESC model aims to optimize solutions while employing APUs for stand-by time instead of ICE, a new parameter, fc^{APU}_{ti}, should be introduced. This parameter represents the difference between the APU energy consumption and the ICE energy consumption for stand-by time, as demonstrated in Equation 4.22. By subtracting this difference from fn^4_{ti} in the VESC model, only the APU energy consumption for stand-by time is considered.

$$fc^{APU}_{ti} = \begin{cases} \frac{bve_i \cdot hrs^{sby\_mov1} \cdot if^{wea\_mov1} \cdot if^{sby}}{24} - \frac{bve^{APU}_i \cdot hrs^{sby\_mov1} \cdot if^{wea\_mov1}}{24} & i \leq day^{to\_AoO} \\ \frac{bve_i \cdot hrs^{sby\_mov2} \cdot if^{wea\_mov2} \cdot if^{sby}}{24} - \frac{bve^{APU}_i \cdot hrs^{sby\_mov2} \cdot if^{wea\_mov2}}{24} & i > day^{to\_AoO} + day^{combat} \\ \frac{bve_i \cdot hrs^{sby\_com} \cdot if^{wea\_com} \cdot if^{sby}}{24} - \frac{bve^{APU}_i \cdot hrs^{sby\_com} \cdot if^{wea\_com}}{24} & \text{otherwise} \end{cases} \quad (4.22)$$

Similar for the energy consumption, the CO2 equivalent emissions are also affected by the use of APUs. The formulas are similar to Equation 4.17 and Equation 4.22 and can be seen in Equation 4.23 and Equation 4.24.

$$\text{for i} \in \{0, 1, \ldots, \text{C}\}:$$

$$bve^{emis\_APU}_i = \sum_{v=0}^{E} am^{vehicles}_v \cdot ftw^{vehicles\_APU}_{vi} \quad (4.23)$$

$$ec^{APU}_{ti} = \begin{cases} \frac{bve_i \cdot hrs^{sby\_mov1} \cdot if^{wea\_mov1} \cdot if^{sby}}{24} - \frac{bve^{emis\_APU}_i \cdot hrs^{sby\_mov1} \cdot if^{wea\_mov1}}{24} & i \leq day^{to\_AoO} \\ \frac{bve_i \cdot hrs^{sby\_mov2} \cdot if^{wea\_mov2} \cdot if^{sby}}{24} - \frac{bve^{emis\_APU}_i \cdot hrs^{sby\_mov2} \cdot if^{wea\_mov2}}{24} & i > day^{to\_AoO} + day^{combat} \\ \frac{bve_i \cdot hrs^{sby\_com} \cdot if^{wea\_com} \cdot if^{sby}}{24} - \frac{bve^{emis\_APU}_i \cdot hrs^{sby\_com} \cdot if^{wea\_com}}{24} & \text{otherwise} \end{cases} \quad (4.24)$$

The energy consumption at Node 4 is calculated in Equation 4.13, but certain situational parameters influence the energy consumption at this node. If supply is not possible on day t, the energy consumption for that day is set to 0. However, in reality, energy consumption still occurs. Therefore, this energy consumption is added to day $t+1$, meaning that supply still needs to deliver the required energy but within less days. Since fc^4_{ti} also includes the energy required for vehicles at Node 4 to travel to the supply point, this trip is not undertaken when no supply takes place. Consequently, this energy needs to be subtracted from the total energy required, as depicted in Equation 4.25.

$$fc^4_{ti} = \begin{cases} 0 & \text{if } del^4_{ti} = 0 \\ fc^4_{t+1i} = fc^4_{ti} + fc^4_{t+1i} - fcpv^{to\_supply}_{ti} \cdot tot^{vehicles} \cdot 2 - apu^{used} \cdot fc^{APU}_{ti} \cdot 2 & \\ fc^4_{ti} - apu^{used} \cdot fc^{APU}_{ti} & \text{otherwise} \end{cases} \quad (4.25)$$

The average energy consumption per vehicle at Node 4 should be known in order for the calculation how many vehicles need to be resupplied, see Equation 4.1. The average energy consumption at Node 4 is the energy consumption at Node 4 divided by the total vehicles attached to UNITS at Node 4, see Equation 4.26.

$$avfc^{vehicle}_{ti} = \frac{fc^4_{ti}}{tot^{vehicles}} \quad (4.26)$$

The supply line has reserve capacity build into in case of situation change or supply failure. This reserve is stored at Node 2 and 3. The quantitative value is calculated per Node by a constant rf^{2or3} times the DOS, see Equation 4.28 and Equation 4.30. Whereby the DOS is calculated as the average energy consumption at Node 4 divided by the refuel efficiency, see Equation 4.27.

$$DOS = \frac{1}{\text{D}} \sum_{t=1}^{\text{D}} \frac{fc^4_{ti}}{ef^{refuel}_i} \quad (4.27)$$

Energy consumption at Node 3 is calculated by adding the required energy at Node 4 and dividing it by the efficiency of refueling, due to losses during refueling. On day $t = 0$, supply has to deliver the required energy at Node 4 as well as the reserve DOS for Node 3. Refuel efficiency is not calculated for the reserve DOS because it is stored on wheels in its original container. Additionally the energy consumption of the number of Gryphus trips for path C is added. For $t \neq 0$ there is no supply of the reserve DOS because it is already at Node 3. For certain energy types energy generation is possible at Node 3 (eg_i^3). Energy generation at the Node is not possible at day $t = 0$ because it takes time to set up. If energy generated is more than required on that day, this surplus energy can be used for the next day and the energy required at Node 3 will be set to 0, as shown in Equation 4.31. The required energy at Node 3 is subtracted by the energy it can generate by itself and surplus energy of previous days, see Equation 4.28.

$$fc_{ti}^3 = \begin{cases} DOS \cdot rf^3 + \frac{fc_{ti}^4}{ef_i^{refuel}} + \frac{fc_{ti}^4}{ef_i^{refuel}} \cdot \frac{1}{tc_i^{gryphus}} \cdot cvv_i^{gryphus} & \text{if } t = 0 \\ \frac{fc_{ti}^4}{ef_i^{refuel}} - eg_i^3 - eo_{t-1i}^3 + \frac{fc_{ti}^4}{ef_i^{refuel}} \cdot \frac{1}{tc_i^{gryphus}} \cdot cvv_i^{gryphus} & \text{otherwise} \\ 0 & fc_{ti}^3 < 0 \end{cases} \quad (4.28)$$

For the refuel time calculations the required energy at Node 3 should be known without the reserve DOS at day $t = 0$ because it stays stationary on wheels at Node 3. The rest of Equation 4.29 equals Equation 4.28.

$$fc_{ti}^{3.1} = \begin{cases} \frac{fc_{ti}^4}{ef_i^{refuel}} + \frac{fc_{ti}^4}{ef_i^{refuel}} \cdot \frac{1}{tc_i^{gryphus}} \cdot cvv_i^{gryphus} & \text{if } t = 0 \\ \frac{fc_{ti}^4}{ef_i^{refuel}} - eg_i^3 - eo_{t-1i}^3 + \frac{fc_{ti}^4}{ef_i^{refuel}} \cdot \frac{1}{tc_i^{gryphus}} \cdot cvv_i^{gryphus} & \text{otherwise} \\ 0 & fc_{ti}^{3.1} < 0 \end{cases} \quad (4.29)$$

Energy consumption at Node 2 follows a similar pattern as Equation 4.28. On day $t = 0$, the reserve DOS is added. On subsequent days, the energy required at Node 3 divided by the refuel efficiency is added, along with the energy needed to supply Node 3 by the WLS(+trailer) for path B. The energy required for the supply trucks is adjusted for refueling efficiency. For days $i \neq 0$ there is the possibility to generate energy at the Node 2 itself. The required energy at Node 2 is therefore subtracted with the energy it can generate at that day or surplus energy of the day before, see Equation 4.30. If more energy is generated than required, fc_{ti}^2 will be set to 0.

$$fc_{ti}^2 = \begin{cases} \frac{fc_{ti}^3}{ef_i^{refuel}} + DOS \cdot rf^2 + \frac{tr_{ti}^{pathB\_WLS} \cdot cvv_i^{WLS} + tr_{ti}^{pathB\_WLS+trailer} \cdot cvv_i^{WLS+trailer}}{ef_i^{refuel}} & \text{if } t = 0 \\ \frac{fc_{ti}^3}{ef_i^{refuel}} - eg_i^2 - eo_{t-1i}^2 + \frac{tr_{ti}^{pathB\_WLS} \cdot cvv_i^{WLS} + tr_{ti}^{pathB\_WLS+trailer} \cdot cvv_i^{WLS+trailer}}{ef_i^{refuel}} & \text{otherwise} \\ 0 & fc_{ti}^2 < 0 \end{cases} \quad (4.30)$$

Surplus energy generated at Node 2 and 3 can be stored and used for the next day. The VESC model uses for this surplus energy the parameter $eo_{ti}^{2/3}$. Surplus energy is available if $fc_{ti}^{2/3}$ is negative, see Equation 4.31.

$$eo_{ti}^{2/3} = \begin{cases} -fc_{ti}^{2/3} & \text{if } fc_{ti}^{2/3} \leq 0 \\ 0 & \text{otherwise} \end{cases} \quad (4.31)$$

The number of supply trips for path B is calculated by adding up the trips made by WLS and WLS+trailer. Although the availability of WLS+trailers is limited, they are more efficient than WLS alone. Hence, initially, WLS+trailers are prioritized for path B supply trips. Since even a partial use of WLS(+trailer) capacity counts as a full trip, values are rounded up. The VESC model also favors using a WLS over a WLS+trailer if the required capacity is less than half of a WLS+trailers capacity, even if WLS+trailers are available. This decision is determined by comparing the rounded WLS+trailer trips with the rounded-up WLS+trailer trips. Details of these calculations can be found in Equation 4.32, Equation 4.33 and Equation 4.34.

$$tr_{ti}^{pathB} = \begin{cases} \left\lfloor \frac{fc_{ti}^3}{tc_i^{WLS+trailer}} \right\rceil & \frac{fc_{ti}^3}{tc_i^{WLS+trailer}} \leq am^{WLS+trailer} \\ am^{WLS+trailer} + \left\lceil \frac{fc_{ti}^3 - am^{WLS+trailer} \times tc_i^{WLS+trailer}}{tc_i^{WLS}} \right\rceil & \frac{fc_{ti}^3}{tc_i^{WLS+trailer}} > am^{WLS+trailer} \\ tr_{ti}^{pathB} = tr_{ti}^{pathB} + \left\lceil \frac{fc_{ti}^3 - tr_{ti}^{pathB} \cdot tc_i^{WLS+trailer}}{tc_i^{WLS}} \right\rceil & \left\lfloor \frac{fc_{ti}^3}{tc_i^{WLS+trailer}} \right\rceil < \left\lceil \frac{fc_{ti}^3}{tc_i^{WLS+trailer}} \right\rceil \end{cases} \quad (4.32)$$

Path B is divided into two parts: WLS and WLS+trailer, to accurately calculate the energy consumption for path B. The formula for determining the number of supply trips for WLS+trailer is provided in Equation 4.33.

$$tr_{ti}^{pathB\_WLS+trailer} = \begin{cases} \left\lfloor \frac{fc_{ti}^{3}}{tc_{i}^{WLS+trailer}} \right\rceil & \frac{fc_{ti}^{3}}{tc_{i}^{WLS+trailer}} \leq am^{WLS+trailer} \\ am^{WLS+trailer} & \text{otherwise} \end{cases} \tag{4.33}$$

TThe number of supply trips for WLS in path B is determined using the two parameters mentioned earlier, as illustrated in Equation 4.34.

$$tr_{ti}^{pathB\_WLS} = \begin{cases} tr_{ti}^{pathB} - tr_{ti}^{pathB\_WLS+trailer} & \left\lfloor \frac{fc_{ti}^{3}}{tc_{i}^{WLS+trailer}} \right\rceil < \left\lceil \frac{fc_{ti}^{3}}{tc_{i}^{WLS+trailer}} \right\rceil \\ tr_{ti}^{pathB} - am^{WLS+trailer} & \text{otherwise} \end{cases} \tag{4.34}$$

When aiming to minimize transport movements, the VESC model calculates the number of Gryphus trips for path C as a decision variable. However, to minimize refuel time, it is essential to know the number of Gryphus trucks utilized to determine the available refuel points at Node 4. Due to coding limitations, the decision variable for the number of trips on path C cannot be directly used within an if-statement condition. Consequently, a parameter calculation is employed for path C, albeit less precise since it does not account for the impact of Manticore supply trucks. However, this discrepancy arises only if Manticore vehicles are utilized; otherwise, the value remains constant. Despite its slight impact on the VESC models outcome, this sub-optimal approach is adopted. The number of Gryphus trips for path C, specifically for refuel time calculations, is computed by dividing the total required energy at Node 4 by the Gryphus' supply capacity. This value is then rounded up to the nearest integer to ensure that the entire truck is dispatched, even if only a portion of its capacity is required. Equation 4.35 illustrates this expression.

$$tr_{ti}^{gryphus} = \left\lceil \frac{fc_{ti}^{4}}{tc_{i}^{gryphus}} \right\rceil \tag{4.35}$$

Determining the number of refuel points is crucial for calculating refuel time. This quantity is constrained by the number of Gryphus supply trucks stationed at Node 4, each equipped with a fixed number of refuel points, or by the number of vehicles requiring refueling. Due to the inability to directly incorporate decision variables into if-statement conditions, the less precise parameter $tr_{ti}^{gryphus}$ is utilized instead of Tr_{ti}^{C}. Refer to Equation 4.36 for details.

$$rp_{ti}^{Node\_4} = \begin{cases} Tr_{ti}^{C} \cdot rp_{i}^{gryphus} & tr_{ti}^{gryphus} \cdot rp_{i}^{gryphus} < tot^{vehicles} \\ tot^{vehicles} & \text{otherwise} \end{cases} \tag{4.36}$$

To calculate the refuel time for the Manticores fill-up energy, the number of refuel points is capped by the minimum of either the Gryphus supply trucks or the attached Manticores at Node 4. A new parameter is introduced to represent this constraint, as shown in Equation 4.37. The reasoning behind using parameters instead of decision variables in if-statement conditions, as explained in Equation 4.36, also holds true in this scenario.

$$am_{ti}^{gr\_or\_ma} = \begin{cases} Tr_{ti}^{C} & tr_{ti}^{gryphus} < am^{manticore} \\ am^{manticore} & \text{otherwise} \end{cases} \tag{4.37}$$

The emissions for Node 4 are calculated in Equation 4.18. However, two factors influence these already calculated emissions in the input sheet. This occurs if delivery cannot take place on a certain day and if APUs are used in the situation. If delivery cannot take place, the vehicles do not have to travel to the resupply point at Node 4, and therefore, these emissions are subtracted from the total of that day. Equation 4.38 is similar to Equation 4.25 but for CO2 equivalent emissions instead of energy consumption.

$$ec_{ti}^{4} = \begin{cases} 0 & \text{if } del_{ti}^{4} = 0 \\ ec_{t+1i}^{4} = ec_{ti}^{4} + ec_{t+1i}^{4} - av_{ti}^{emissions} \cdot tot^{vehicles} \cdot 2 - apu^{used} \cdot ec_{ti}^{APU} \cdot 2 & \\ ec_{ti}^{4} - apu^{used} \cdot ec_{ti}^{APU} & \text{otherwise} \end{cases} \tag{4.38}$$

5 Experiments, Results and Validation

This chapter will discuss the experiments conducted with the VESC model for various policies and their results, along with the validation of the VESC model. The scenario utilized for both the experiments and the validation will be the same, as explained in section 5.1.

5.1. Input data

For the input data, firstly the general situation of the modelled exercise is described. This establishes the operational conditions and thus the model inputs. Additionally, the input parameters related to vehicles, energy generation, resupply time, and emissions are stated. Table 5.1 provides an overview of the sources used for the input data.

Data input	**Access**
Situation	NLMoD
Vehicles & supply trucks	NLMoD
Energy carriers	Open source
Energy generation	Open source
Resupply time fill speed	Open source
Resupply time delivery types	NLMoD
Emissions	Open source

Table 5.1: Data sources

General situation

The setting used for the experiments is derived from the warfighting exercise ”Allied Spirit,” which occurred in Hohenfels, Germany, in March 2024. The exercise aims to train all aspects of warfighting. The 43rd Mechanized Brigade leads for the Dutch side, with the unit 44PAINFBAT participating in the exercise. It is conducted in a multinational environment with other NATO partners. Dutch logistic units supply the participating Dutch units, primarily through Push supply, while Daily Logistic Wish, as explained in subsection 2.2.2, is utilized only for urgent supplies. Table 5.2 provides an overview of the exercise details, sourced from internal NLMoD documents or inferred from the data in these documents. This exercise is well-suited for use in the VESC model due to its large unit size and the presence of nearly all aspects of the MSC.

"Allied Spirit"

Type of exercise	Warfighting
Duration	9 days (warfighting scenario)
Personnel	500 pax
Vehicles	50x wheeled, 40x tracked
Terrain	Hilly
Weather	Between -5 and 20 ° Celsius
Movement	Tactical
Combat	Attack and defend
Distance to assembly point in AoO	70 km
Distance from SC to FSC	70 km
Distance from FSC to UNITS	+/- 15 km
Distance to resupply point	+/- 5 km
Cannot deliver supplies on day(s)	(2, 4)
Resupply type	Supply Street

Table 5.2: Details exercise "Allied Spirit"

The SC is situated within the Neurenberg rail yard area for easy strategic movement connections. An FSC is positioned at the center of the Area of Operation (AoO), approximately 70 km from the SC. This location also serves as the Area of Assembly for the UNITS, delineated by a 50x45 km box. Distances between the FSC, UNITS, and the resupply point for the UNITS are approximations based on the AoO dimensions. Movement from the SC to the FSC is non-tactical for both the UNITS and the supply trucks. However, all movements from the FSC into the AoO box are considered tactical. Figure 5.1 provides a map of the area. While this setup reflects the exercise scenario, in actual warfighting situations, the distances between the SC, FSC, and UNITS would be much greater due to long-range artillery and aerial threats. Additionally, the FSC would be positioned farther from the front line, rather than being centrally located within the AoO.

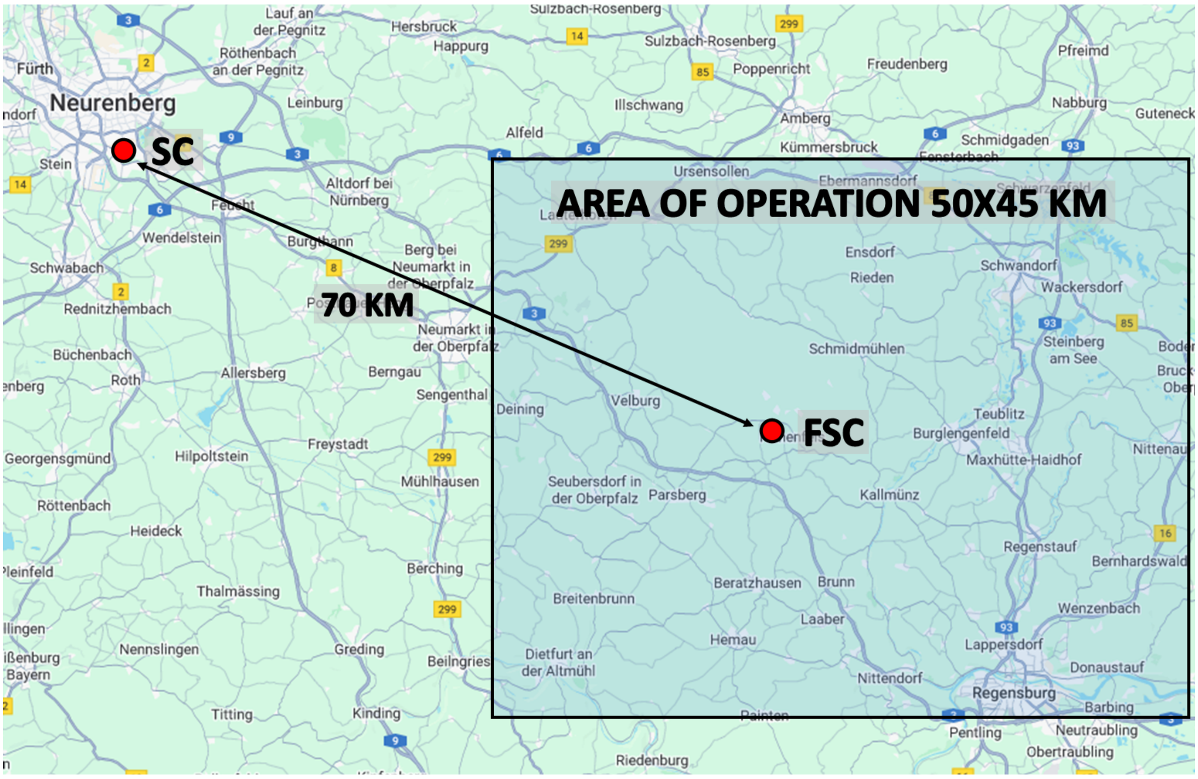

Figure 5.1: Map of exercise "Allied Spirit"

An overview of vehicle types and the number of vehicles used in the case study is provided in Table 5.3. The primary forces include CV90 infantry fighting vehicles and Leopard 2 main battle tanks, which are utilized alongside infantry operating from the CV90s. Fennek light reconnaissance and surveillance vehicles are employed for reconnaissance purposes, while Boxer armored wheeled vehicles serve as ambulances or mobile command posts. The Kodiak combat engineering vehicle and Leopard 2 PRB armored recovery vehicle are both tracked support vehicles capable of towing broken vehicles or constructing/deconstructing obstacles. Scania WLS 165 kN and Tropco 400/650 kN tractor-trailer combinations are utilized for supply or transporting heavy equipment. Additionally, 5 Manticore 20 kN supply vehicles are included for certain policies. It's worth noting that the total number of vehicles listed in Table 5.3 may not align with the total provided in Table 5.2 due to the inclusion of numerous support vehicles attached to the exercise but not utilized in the warfighting scenario.

CV90	30
Fennek	20
Boxer	6
Kodiak	1
Leopard 2 PRB	2
Leopard 2 MBT	7
Scania Gryphus 100 kN	6
Scania WLS 165 kN	8
Tropco 400/650 kN	2
Manticore 20 kN	(5)

Table 5.3: Vehicle types and numbers used during ”Allied Spirit”

Situation

The input parameters related to the situation, as detailed in Table 5.1, such as the various IFs explained in subsection 2.2.1, are directly derived from the internal NLMoD doctrines [11]. The warfighting exercise spans a total of 9 days, with 4 days allocated for offensive combat and 4 days for defensive combat. The first day is designated for movement to the AoO. However, the case study used for this experiment comprises only 5 days, with the first day dedicated to movement to the AoO and the subsequent 4 days focused on offensive combat, as outlined in Table 5.4.

Action	Time [days]	Distance [km/day]	Combat [h/day]	Stand-by [h/day]	Resupply [type]	Movement [type]	combat [type]	Distance to RP [km]
Move to AoO	1	70	0	8	Assembly Area	Not tactical	n/a	2
Combat	4	0	10	14	Supply Street	Tactical	Attack	5

Table 5.4: Input parameters for the situation

Additionally, a number of reserve DOS are required to be stored at the SC and FSC, which are brought in on day $i = 1$. The SC stores 16 reserve DOS (Node 2), while the FSC (Node 3) stores 4 reserve DOS. The high reserve DOS count at the SC is due to the exercise spanning one month, whereas the DOS reserve at the FSC is only utilized for the 9-day warfighting exercise. The VESC model focuses solely on a 1-day road move and 4 days of combat. The number of DOS at the SC does not influence the models outputs because it solely considers Node 3 and 4 for its objective functions.

Vehicle data and energy carriers

The input parameters for standard diesel configurations are sourced from internal NLMoD datasheets, encompassing GBV values, fuel tank capacity, weight, and range [11]. Efficiencies for conversion devices and vehicle components are outlined in Table 5.6, distinguishing between direct vehicle power and generator usage. Energy carrier data is provided in Table 5.5, with alternative energy types offering comparable volume or weight to standard diesel vehicles. However, diesel-electric has 0.8 times the volume, H2 fuel cell boasts 2.6 times, and H2 ICE holds twice the volume of diesel. Electric energy types vary depending on vehicle type, ranging from 1 to 3 times the volume, considering the potential for added energy storage while managing weight concerns. These values are derived from the E-Fenneks conversion to a fully electric powertrain, with diesel components replaced by battery packs. For battery selection, Narada LiFePO4 and EVE LiFePO4 are chosen for their NLMoD use or imminent implementation. Narada weighs 32 kg with a volume of 16.5 L and a 4.2 kWh capacity, while EVE weighs 26 kg, has a 13.4 L volume, and matches the 4.2 kWh capacity.

Energy carrier per energy type:	**Energy density: [MJ/L]**	**Energy density: [MJ/kg]**	**Fill speed: [MJ/min]**
Diesel(-electric series hybrid)	36.0	42.5	5400
H2 700 bar (Fuel cell and ICE)	4.8	120.0	2760
Electric battery swap (Narada LiFePO4)	0.90	0.47	177
Electric charging (EVE LiFePO4)	1.12	0.58	225
Methanol	15.8	19.9	2370
Ammonia	12.7	18.6	1905
HVO	34.4	44.0	5160
LNG	20.8	48.6	3120

Table 5.5: Input parameters for energy carriers

Component:	**BTE/efficiency:**	
	Vehicle use	**Generator use**
ICE Diesel [14] [61]	33%	46%
ICE Methanol [62]	40%	43%
ICE Ammonia [34] [63]	27%	36%
ICE HVO [61] [64]	36%	47%
ICE LNG [37]	35%	41%
ICE H2 [22]	31%	45%
Electric motor	88%	-
Battery (un)loading	92%	-
H2 fuel cell [21]	-	60%
Transmission	94%	

Table 5.6: Efficiencies of conversion devices and vehicle components. The relation between the components and energy types is given in section 4.3.

If APUs replace the ICE for stand-by time, vehicles will utilize generators ranging from 6-20 kVA, with diesel models consuming approximately 1-6 liters per hour at full capacity. Generator selection depends on the power consumption of the vehicles. Fuel consumption for other energy types is determined using efficiencies outlined in Table 5.6.

Supply trucks

The VESC model utilizes standard supply trucks currently available, including the Scania WLS 165 kN, Scania Gryphus 100 kN, and the new Manticore pick-up 20 kN, to be implemented. The supply capacity of these trucks is known for diesel, as well as the volume and weight. For other energy types, the maximum supply capacity is calculated based on either the maximum volume or weight, depending on which is the limiting factor. A residual fuel amount of 3% is factored in, and the weight of pump units or cranes for transferring battery packs is also considered. Fuel losses during refueling, which are less than 1%, are treated as 0%. Table 5.7 provides an overview of the supply capacity for each supply vehicle per energy type, with a maximum of 2 trailers available for the WLS in this scenario.

Energy type:	$\mathbf{tc}_i^{Gryphus}$ **[MJ]**	$\mathbf{tc}_i^{WLS}$ **[MJ]**	$\mathbf{tc}_i^{WLS+trailer}$ **[MJ]**	$\mathbf{tc}_i^{Manticore}$ **[MJ]**	$\mathbf{ef}_i^{refuel}$ **[%]**
Diesel(-electric)	223,200	511,200	1,022,400	52,200	0%
H2 fuel cell/ICE	33,600	72,000	144,000	7,200	10%
Electric battery swap	4,680	7,722	15,444	936	0%
Electric charging	5,760	9,504	19,008	1,152	15%
Methanol	107,282	229,890	459,780	22,989	0%
Ammonia	88,900	190,500	381,000	19,050	0%
HVO	233,576	500,520	1,001,040	50,052	0%
LNG	145,600	312,000	624,000	31,200	2%

Table 5.7: Carrying capacity in MJ of supply trucks

Energy generation

For policies utilizing the current 'fossil fuel' MSC, energy generation for Node 2 and 3 is set to 0. In policies employing the 'renewable energy' MSC, energy generation for Node 2 and 3 is detailed in Table 5.8. The selection of specific energy generation types is based on their suitability for each Node. Solar containers, Small Modular Reactors, and hydrogen production plants are deemed impractical for Node 3 due to size, cost, vulnerability, or implementation time constraints, as outlined in section 2.4. Additionally, the energy consumption of the hydrogen production plant, requiring electric energy alongside water, must be equal to or less than the energy generation of electric energy at that Node.

Energy generation type:	**Capacity**	**Generation [MJ/day]**	**# used Node 2**	**# used Node 3**	$\mathbf{eg}_i^2$ **[MJ]**	$\mathbf{eg}_i^3$ **[MJ]**	**Elec consumption [MJ/day]**
Solar container	68 kWp	570	1	-	570	-	-
Portable wind turbine	15 kW	864	1	1	864	864	-
Kitepower	100 kW	6,912	1	1	6,912	6,912	-
SMR	1,000 kW	82,080	1	-	82,080	-	-
Hydrogen production plant	18 kg/h	51,840	1	-	51,840	-	86,469

Table 5.8: Energy generation options for Node 2 and 3

Resupply time

The resupply time depends on the fill speed of the supply trucks at Node 4, the pumps at Node 3, and the number of refuel points on the supply vehicles. Refer to Table 5.9 for the input values used for this purpose. The pump capacity for liquid fuels with a small nozzle is 60 L/min, and with a large nozzle, it's 150 L/min. The provided fill speed for supply trucks represents the average value for the vehicle types used. The pump capacity for liquid fuels during bulking is 450 L/min at an RPM of 3000. Other energy types utilize the same pump capacity as the supply trucks. For hydrogen and electric charging/battery swap, the maximum pump/charging speed is employed. The quantity of large pumps at Node 3 is restricted due to their container-like size and complex/expensive nature. In practice, the standard pump of the 12 m^3 fuel container could be utilized to transfer fuel from the WLS fuel container to the Gryphus 7 m^3 fuel container. However, the 15 m^3 WLS fuel container is more commonly used by the NLMoD, which is why it is employed in the VESC model in conjunction with external high-flow pumps.

Energy type:	$av_i^{refuel\_time}$ [MJ/min]	$rp_i^{Gryphus}$/ $rp_i^{Manticore}$	rp_i^{WLS}	$rp_i^{WLS+trailer}$	am^{pumps}	pu_i^{debit} [MJ/min]
Diesel(-electric)	4,664	2	2	4	2	16,200
H2 fuel cell/ICE	1,200	2	2	4	4	8,280
Electric battery swap	177	2	2	4	6	177
Electric charging	225	2	4	8	# WLS containers	225
Methanol	2,047	2	2	4	2	7,110
Ammonia	1,645	2	2	4	2	5,715
HVO	4,456	2	2	4	2	15,480
LNG	4,160	2	2	4	2	13,800

Table 5.9: Fill speed in MJ/min and number of refuel points for supply trucks and pumps at Node 3 and 4

The additional refueling time per vehicle is contingent upon the type of supply at Node 4 and the energy type utilized. The additional refueling time for diesel(-electric) is derived from real-life data provided by the military supply unit 130 Bevocie. Energy types with comparable refueling mechanisms as diesel require the same amount of time. For energy types with more intricate refueling mechanisms, the time is multiplied by a factor of 1.5 or 2, as outlined in Table 5.10. There is an additional refueling time of 10 minutes due to the WLS fuel container being placed on the ground and needing to be picked up at Node 3. Similarly, there is a 4 minute extra refueling time required to prepare the Gryphus and dismantle it again at Node 4.

Energy type:	Supply Street	Assembly Area	Delta Point	Dump Point	At Position
Build/break up	8	10	8	5	10
Diesel(-electric)	0.5	0.75	0.5	0	5
H2 fuel cell/ICE	0.75	1.13	0.75	0	7.5
Electric battery swap	1	1.5	1	0	10
Electric charging	0.5	0.75	0,5	0	5
Methanol	0.5	0.75	0.5	0	5
Ammonia	0.5	0.75	0.5	0	5
HVO	0.5	0.75	0.5	0	5
LNG	0.5	0.75	0.5	0	5

Table 5.10: Extra refuel time in minutes per vehicle at Node 4 and build/break up time for supply trucks

CO2 equivalent emissions

The CO2 equivalent emissions from both vehicles and weapon platforms are expressed in kg CO2/MJ, based on either WTW or FTW measurements, as detailed in Table 5.11. For this research, green hydrogen is utilized. Policies incorporating fossil fuels include LNG and methanol, while those without fossil fuels utilize bio-LNG and bio-methanol, as outlined in section 5.2.

Fuel:	kg CO2/MJ	
	WTW	FTW
Diesel	0.092	0.070
HVO	0.010	0.001
LNG	0.075	0.061
Bio-LNG	0.029	0.004
Hydrogen (grey)	0.104	0.000
Hydrogen (green)	0.010	0.000
Electricity (grey)	0.127	0.000
Electricity (green)	0.000	0.000
Methanol	0.086	0.069
Bio-methanol	-	0.010
Ammonia	1.800	0.000

Table 5.11: CO2 equivalent emissions per energy type for WTW and FTW [65] [66]

5.2. Policies

The impact of alternative energy types on military logistics also depends on the assumptions made. The system can be based on various assumptions, leading to different outcomes. Hence, multiple policies are formulated to examine these differences.

Firstly, the comparison is made between using the 'renewable energy' MSC and the current MSC. The former involves energy generation at multiple nodes and the use of Manticore supply trucks as energy buffers at Node 4. Secondly, the utilization of APUs is assessed. Thirdly, the investigation focuses on the impact of fossil fuels, considering scenarios where they become scarce in the future or are prohibited due to environmental concerns. Fourthly, the effects of longer intervals between supplies are analyzed. Fifthly, the compatibility of equipment for fuel/energy containers at Node 3 is explored to understand its implications. Lastly, adjustments to input parameters are examined to determine the necessary improvements for competitiveness with current diesel. An overview of all policies is given in Table 5.12.

Policy	'Renewable energy' MSC	APU	Fossil fuels	Min 48 h self sufficient	Compatible equipment at Node 3	Input change
P1	×	×	✓	×	×	×
P1.A	×	✓	✓	✓	×	×
P1.B	×	×	✓	×	✓	×
P2	✓	✓	✓	×	×	×
P2.A	✓	✓	×	✓	×	×
P2.B	✓	✓	✓	×	✓	×
P3	✓	✓	✓	×	×	✓

Table 5.12: Overview of different policies

5.2.1. P1 - Current Military Supply Chain

The first policy encompasses all energy carriers, including the existing diesel fuel. It retains the current version of the MSC, where the energy carrier enters the MSC at its inception, sourced from the supplier and conveyed to the SC. Subsequently, the energy carrier is transported through the MSC to the end users, which are the units in the field. This policy offers the advantage of encompassing all energy carriers for comparison within the existing MSC framework. By maintaining the operational methodology of the MSC and solely adjusting the involved technology, it provides insight into the implications of alternative energy types within current doctrines. Consequently, no new technologies are necessary for energy generation at the Nodes of the system. This policy necessitates supply every 24 hours.

5.2.2. P1.A

This policy is a variation of subsection 5.2.1, with the distinction being that the UNITS operate independently for 48 hours or more during combat. This approach is considered more realistic than receiving supplies every 24 hours in active warfighting conditions. Being self-sufficient for 48 hours entails no delivery on days 2 and 4. Additionally, vehicles in this policy utilize an APU for standby time.

5.2.3. P1.B

This policy includes an additional feature: compatibility between equipment used on paths B and C. This ensures that the containers storing the energy carriers can be utilized interchangeably on both the WLS and the Gryphus, resulting in identical capacities. Consequently, the Gryphus becomes the limiting factor, leading to a reduction in WLS capacity. However, refueling time at Node 3 is eliminated, except for the time required to switch the fuel container from the WLS to the Gryphus. By decoupling rt^{Node3} from tr^{pathC} and making it dependent solely on rt^{extra3}, the VESC model will maximize trips for path C due to the highest priority of minimizing refueling time. This outcome is undesirable and unrealistic. Therefore, for P1.B and P2.B, the objective function to minimize the number of trips is given higher priority than refueling time. To compensate for this priority adjustment, the relative tolerance of the objective function to minimize the number of transport movements is increased to 30%.

5.2.4. P2 - 'Renewable energy' Military Supply Chain

This second policy encompasses all energy types but transitions the MSC from the current 'fossil fuel' supply chain to a new 'renewable energy' supply chain. The distinction lies in the fact that renewable energy sources are not exclusively supplied by a supplier at the onset of the MSC; they can also be generated at different nodes of the system. For instance, electricity can be generated at the SC through solar or wind turbines, or even via a container-sized nuclear power unit attached to the FSC, thereby reducing the need for energy transportation between the initial nodes of the MSC. However, energy generation is not feasible for the units themselves. Therefore, a new concept is introduced by affixing a number of cargo versions of the new Manticore 20kN vehicle to the units, which store additional fuel and serve as a buffer. This setup reduces the need for supply runs and can augment refuel time by adding more refuel points. Additionally, the impact of APUs is examined.

5.2.5. P2.A

This policy examines the implications of achieving at least 48 hours of self-sufficiency during combat within the framework of the 'renewable energy' MSC. Additionally, fossil fuels, specifically diesel, are excluded. Diesel-electric vehicles will utilize HVO instead of diesel, and only bio-LNG and bio-methanol will be utilized. Furthermore, the HVO-electric energy type will utilize its generator for standby time, a departure from subsection 5.2.2. Other aspects remain consistent with subsection 5.2.4.

5.2.6. P2.B

The final adjustment explored for policy 2 involves assessing the effect of compatible equipment at Node 3 on the 'renewable energy' MSC. Fossil fuels remain excluded in this scenario.

5.2.7. P3 - Tweaked input energy types parameters

This policy examines the minimal requirements of alternative energy types needed to achieve comparable outputs to current diesel, making them competitive. Parameters such as energy density, refuel time, and FTW efficiency are adjusted to determine the necessary changes for alternative fuels to become viable alternatives to diesel. Table 5.13 provides the adjusted input parameters and their respective ranges, representing the theoretically maximal feasibility under ideal conditions. Energy density for battery packs in diesel-electric energy types is not considered; instead, the focus is on the FTW efficiency of the drivetrain. The maximum refuel energy flow for electric battery swap is calculated based on the time provided in section 2.3 and the maximum energy density of battery packs. Research into quantum charging, which promises significantly faster electric charging times, is also explored. Breakthroughs in this area could result in substantial improvements in charging speed, with the upper limit of this research being ten times the current megawatt charging system [67].

Energy type:	Energy density [MJ/L]	Energy density [MJ/kg]	Refuel speed [MJ/min]	FTW
Electric battery swap	-	0.58-4.32 [68]	175-1620	81-95% [69]
Electric charging	-	0.58-4.32 [68]	225-2250 [67]	81-95% [69]
H2 fuel cell	4.8-17.3 [70]	-	1200-3000	45-76% [71]
H2 ICE	4.8-17.3 [70]	-	1200-3000	29-57% [72]
Diesel-electric	-	-	-	34-48% [73]

Table 5.13: Input parameter change per energy type with what is theoretical maximally feasible

5.3. Results

5.3.1. General results

Before running the VESC model, calculating the input parameters provides insight into the ratio between different energy types. Firstly, the range of vehicles is affected by the change in energy type due to differences in energy density and efficiency. Figure 5.2 illustrates the range of vehicles for each energy type compared to current diesel. The results indicate that Diesel-electric series hybrid and HVO are comparable to current diesel. Both energy types store less energy onboard the vehicle than diesel, but the higher efficiency of the drivetrain compensates for this, resulting in similar outcomes. Fully electric drivetrain options have the lowest range due to the lower energy density of the energy carriers. However, the range of these options is sufficient for the experiments scenario.

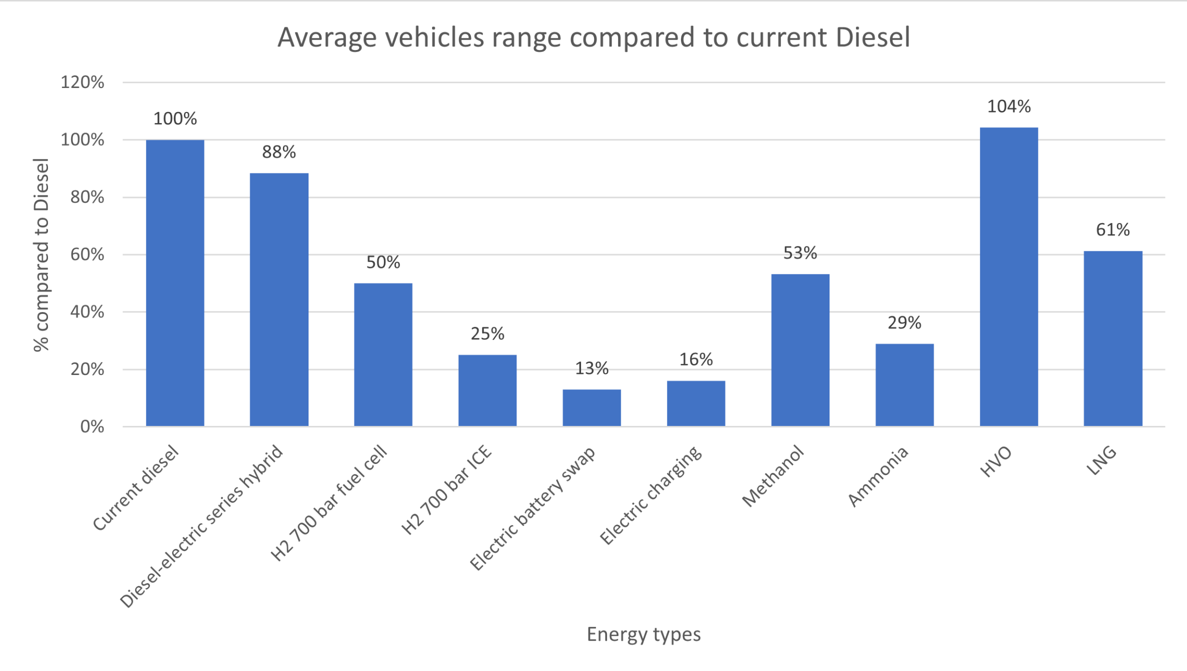

Figure 5.2: Average range of vehicles for all energy types compared to current Diesel

The comparison of the energy capacity carried by the supply trucks relative to standard diesel is depicted in Figure 5.3. The key distinction between the Gryphus/Manticore and the WLS(+trailer) lies in the utilization of the full volume and weight capacity of the WLS to store the energy carrier, facilitated by external pumps for fuel exchange to another supply truck. In contrast, the Gryphus and Manticore require their own equipped pumps. Only HVO is comparable to current diesel in terms of the stored energy in the supply trucks and the equivalent trips needed. The electric options exhibit the lowest energy capacity, requiring approximately 39-67 trips to transport an equivalent amount of energy compared to one truck of diesel.

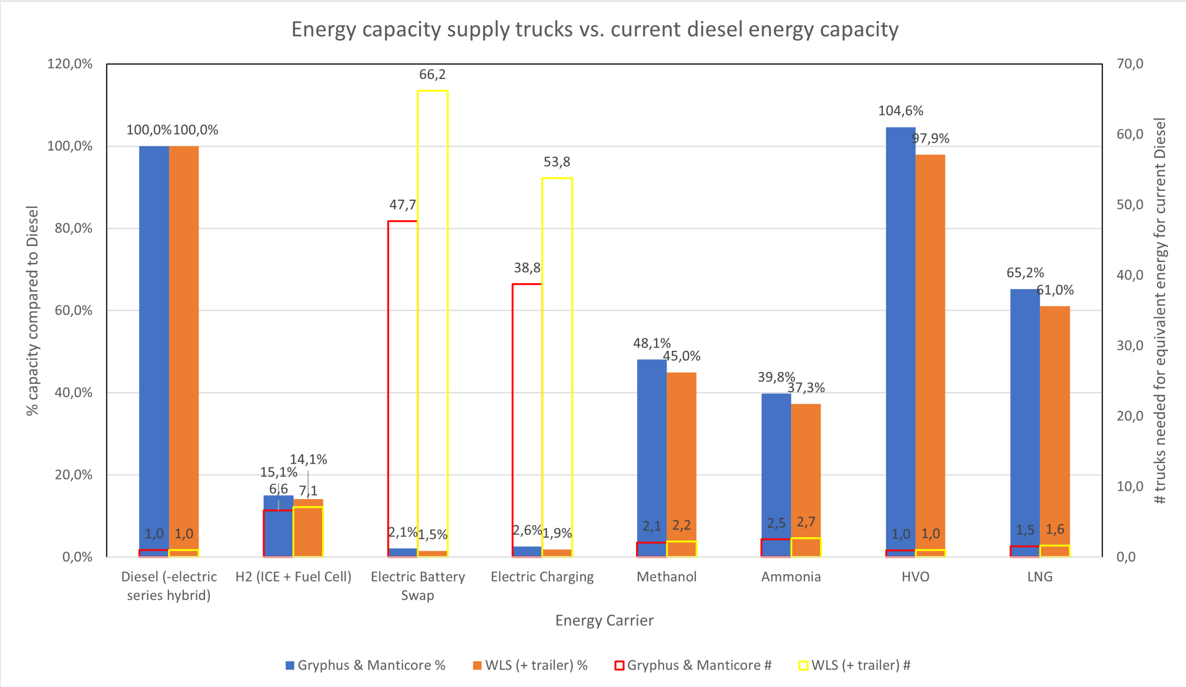

Figure 5.3: Energy capacity supply trucks for all energy types compared to current Diesel

5.3.2. Baseline Diesel

First, the baseline is established for all policies using current diesel. The VESC model is executed for each policy with diesel as the sole available energy type. This provides baseline results against which the other energy types can be compared. P1, utilizing only diesel, yields results reflecting the current operational procedures of the NLMoD. These outputs can be cross-referenced with real-life data to assess the models accuracy. P1 serves as the baseline for comparison with other policies, as it represents the current NLMoD MSC policy. All subsequent policies introduce new elements as variants.

The outputs for diesel across all policies are presented in Table 5.14. The number of trips ($tr^{pathB/pathC}$) and refuel time ($rt^{Node3/Node4}$) outputs are disaggregated to provide a clearer understanding of where the actual changes occur. Additionally, the total energy required from the supplier at Node 2, excluding the reserve DOS of Node 2, is provided as output. The effects of the policy change on the MSC are visually depicted in Figure 5.4.

Policy	**tr**^{pathB} [#]	**tr**^{pathC} [#]	**rt**^{Node3} [min]	**rt**^{Node4} [min]	**emis**^{total} [kg CO2]	**tot**^{energy} [MJ]
P1	7	14	177	156	161,969	4,136,461
P1.A	4	10	129	100	135,052	3,451,921
P1.B	16	20	50	116	163,623	4,173,583
P2	6	9	139	119	140,125	3,817,513
P2.A	4	9	117	70	132,878	3,481,547
P2.B	15	12	50	108	141,694	3,854,635

Table 5.14: Results of the baseline diesel for different policies

P1.A utilizes APUs for vehicle standby time, and the UNITS are self-sufficient for 48 hours. This results in a 17% reduction in energy consumption, mainly attributed to the APUs for UNITS vehicles and partly to reduced supply movements. The energy reduction also translates to a decrease in CO2 equivalent emissions. The reduced tr^{pathC} is primarily due to the decreased energy consumption of the APUs. With the energy required for days 2-5 at Node 4 being just above the capacity of 2 Gryphus trucks for P1, the energy reduction from the APUs ensures a snug fit within the available supply capacity. The reduction in refuel time is largely due to the once-every-48-hours supply, reducing the extra refuel time for vehicles at Node 4 and supply vehicles at Node 3 by half. For detailed daily outputs, refer to section A.1.

P1.B differs in that the fuel containers used on the WLS and Gryphus are compatible. This leads to a 56% reduction in the size of the WLS fuel container due to Gryphus weight limitations. The total number of trips (tr^{total}) increases by 71% compared to P1. While one would expect only an increase in supply trips for path B and not for path C, Figure 5.5 suggests otherwise. This is because the VESC model prioritizes minimizing the number of trips, with a 30% relative tolerance to improve rt^{total}. More Gryphus trips for path C result in shorter rt^{Node4}, prompting the VESC model to add more tr^{pathC} to lower rt^{total}. As fuel only needs to be transferred between vehicles rather than pumped from a 15 m^3 to a 7 m^3 container at Node 3, refuel time there is reduced to just 10 minutes per day, a 72% decrease. The overall reduction in rt^{total}, including the extra Gryphus trips, is 50%, with these extra trips causing only a 1% reduction in CO2 equivalent emissions.

The effects of the ”renewable energy” MSC are studied in P2(.A/B). With no diesel generation possible at Node 2 or 3, only the use of Manticore supply trucks at the Node 4, UNITS, will affect diesel usage. P2 also utilizes APUs, prioritizing reducing refuel time over reducing the number of supply trips. Consequently, the Manticores operate at maximum capacity daily, reducing the number of trips at path C by 4 and path B by one. Initially storing 261,000 MJ of diesel, the Manticores save an additional Gryphus trip. The effects of the Manticores are best seen when comparing P2.A with P1.A, showing a 7% improvement in path C trips reduction. They significantly impact refuel time, reducing it by 9% at Node 3 and 30% at Node 4, while also decreasing CO2 equivalent emissions by almost 2%.

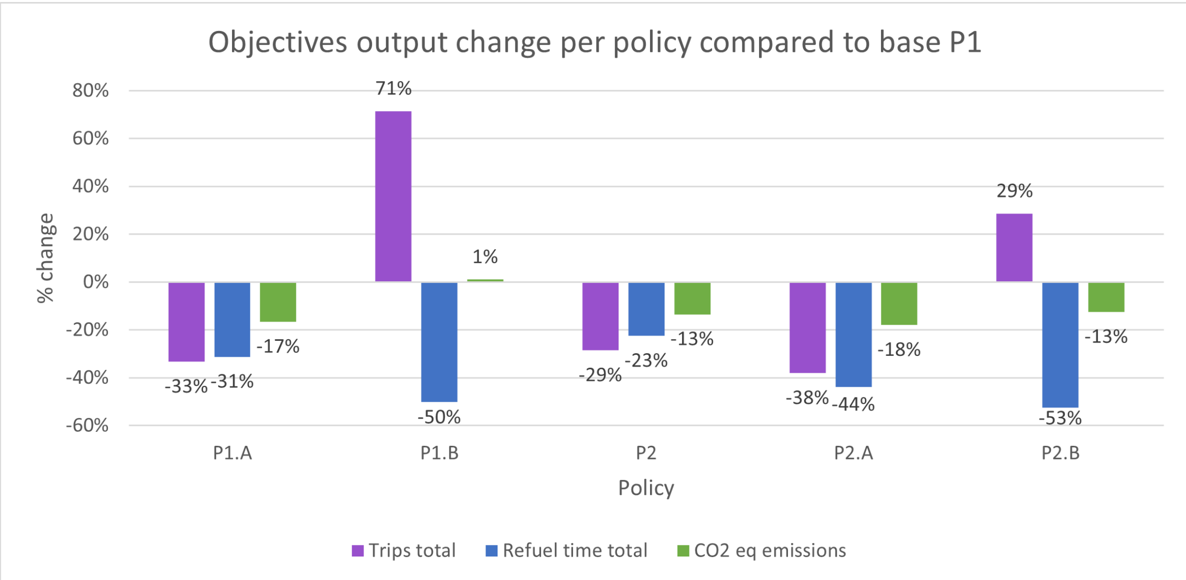

Figure 5.4: Objective output change per policy compare to base P1 for diesel only

P2 and P2.B are compared to assess the effect of the compatible equipment. As expected, the number of trips at path B and the refuel time at Node 3 are mostly affected. The increase in tr^{pathC} is again attributed to the change in prioritization of the objective functions. An 80% increase in trips results in a 39% reduction in total refuel time. It is notable that tr^{pathB} and rt^{Node3} are mostly affected, either negatively or positively, while tr^{pathC} and rt^{Node4}, which are more critical in warfighting, are impacted to a lesser extent.

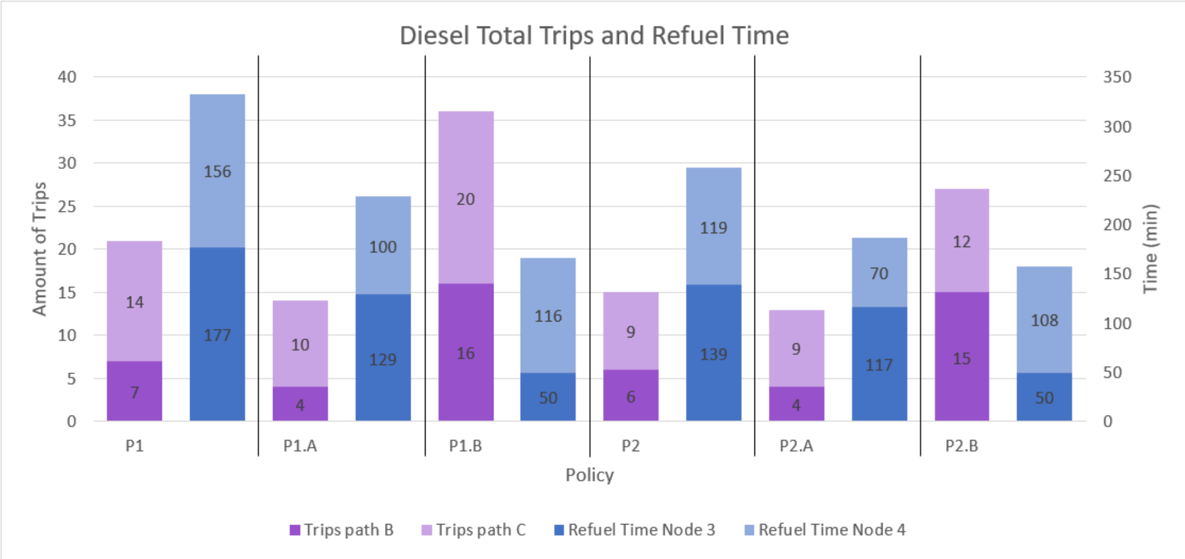

Figure 5.5: Number of trips and refuel time for diesel for different policies

5.3.3. P1

The VESC model identifies HVO as the best result. Results are presented in Table 5.15, and a detailed overview of all outputs for each day is provided in section A.2. The $energy^{total}$ for day 1 is higher due to the transport of 4 DOS reserve to Node 3. Day 2-5 show equal output values because the input values of these four combat days are also consistent. While the VESC model could potentially increase the number of tr^{pathC} to reduce the rt^{Node4}, it opted not to, likely due to the restriction of the reltol of 10%.

	$\mathbf{tr}^{pathB}$ [#]	$\mathbf{tr}^{pathC}$ [#]	$\mathbf{rt}^{Node3}$ [min]	$\mathbf{rt}^{Node4}$ [min]	$\mathbf{emis}^{total}$ [kg CO2]	$\mathbf{energy}^{total}$ [MJ]
Day 1	2	2	27	37	275	1,971,806
Day 2	1	3	37	29	420	454,050
Day 3	1	3	37	29	420	454,050
Day 4	1	3	37	29	420	454,050
Day 5	1	3	37	29	420	454,050

Table 5.15: Results of best solution P1, HVO

The VESC model is repeatedly run until no feasible results are possible anymore, with the best energy type being excluded after each run for the next iteration. The compiled results provide a clear picture of how the different energy types relate to one another, as illustrated in Figure 5.6. Firstly, it shows that electric battery swap and charging are not viable options for this scenario. This is because the energy required per day for the UNITS exceeds the energy storage capacity of the vehicles at Node 4. Additionally, the range of the WLS is insufficient for a round trip for both energy types. The VESC model prioritizes minimizing rt^{total} as its highest priority, followed by minimizing tr^{total}. The second-best solutions score better or nearly equal in these areas compared to HVO, as shown in Table 5.16. However, HVO significantly outperforms them in terms of CO2 equivalent emissions, which are nearly 99% lower than baseline diesel. Due to the VESC model being set with a relative tolerance of 10%, as outlined in section 4.2, HVO is considered a superior option to diesel-electric. The three energy types with the best performance in CO2 equivalent emissions are still not comparable to baseline diesel, with Ammonia and H2 requiring 152-552% more trips and 81-164% more refuel time.

	$\mathbf{tr}^{total}$ [#]	$\mathbf{tr}^{pathB}$ [#]	$\mathbf{tr}^{pathC}$ [#]	$\mathbf{rt}^{total}$ [min]	$\mathbf{rt}^{Node3}$ [min]	$\mathbf{rt}^{Node4}$ [min]	$\mathbf{emis}^{total}$ [kg CO2]	$\mathbf{energy}^{total}$ [MJ]
HVO	20	6	14	325	174	152	1,958	3,788,006
Diesel-electric SH	19	6	13	331	166	165	146,501	3,741,543
Diesel	21	7	14	332	177	156	161,969	4,136,461
LNG	28	9	19	325	206	118	131,837	4,137,928
Methanol	29	10	19	438	259	179	131,631	3,433,148
Ammonia	53	20	33	602	428	174	0	5,149,217
H2 Fuel cell	88	37	51	627	524	102	0	3,654,038
H2 ICE	137	62	75	875	776	99	0	5,721,263

Table 5.16: Results of P1 with all feasible energy types

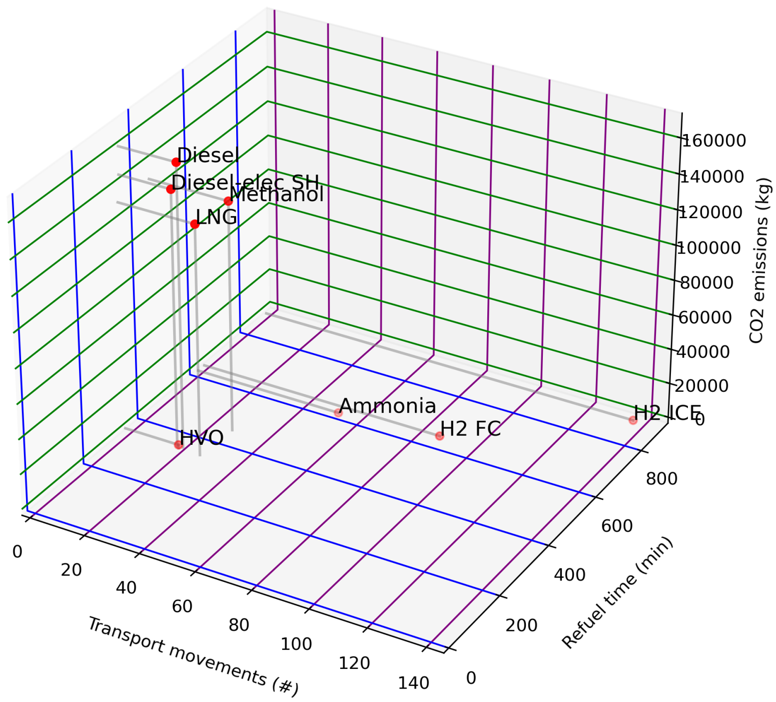

Figure 5.6: All feasible results for P1 with number of trips, refuel time and CO2 equivalent emissions results

5.3.4. P1.A

Due to the supply occurring once every 48 hours, the outputs of day 2 and 4 are zero. HVO emerges as the best result according to the VESC model, as indicated in Table 5.17. The single trip for path B at day 3 and 4 is a WLS + trailer. Detailed results are in section A.2. The longer rt^{Node3} compared to rt^{Node4} is attributed to only 2 pumps being available at Node 3 while at Node 4 all 4 Gryphus supply trucks can unload at the same time. In comparison to P1, the $energy^{total}$, $emis^{total}$ and rt^{total} are all lower because less energy is consumed, requiring fewer round trips to the supply points and saving additional coupling time.

	$\mathbf{tr}^{pathB}$ [#]	$\mathbf{tr}^{pathC}$ [#]	$\mathbf{rt}^{Node3}$ [min]	$\mathbf{rt}^{Node4}$ [min]	$\mathbf{emis}^{total}$ [kg CO2]	$\mathbf{energy}^{total}$ [MJ]
Day 1	2	2	27	35	255	1,675,419
Day 2	0	0	0	0	0	0
Day 3	1	4	50	31	690	746,408
Day 4	0	0	0	0	0	0
Day 5	1	4	50	31	690	746,408

Table 5.17: Results of the best solution P1.A, HVO

Due to the minimum 48-hour self-sufficiency requirement of UNITS at Node 4, both H2 options and Ammonia are no longer feasible because the energy storage capacity of vehicles is insufficient, as shown in Figure 5.7. HVO, diesel, and diesel-electric are comparable in terms of the number of supply trips and refuel time. It is noteworthy that the diesel option has a lower rt^{total} and $emis^{total}$ than diesel-electric, as indicated in Table 5.18. The reason for this is that this policy utilizes APUs for stand-by time. The APU generator used for diesel is more fuel-efficient than the large generator used for the diesel-electric energy type. This is because the diesel-electric setup has only one generator that is tailored to driving the vehicle. There is no small APU installed due to lack of storage space. In practice, the diesel-electric energy type should be more efficient than these results show because for stand-by time, the vehicle could first use its battery pack and then charge its battery pack at full load for a short time. The VESC model assumes that the generator is used throughout the stand-by time at low idle, which is not the most efficient approach.

	$\mathbf{tr}^{total}$ [#]	$\mathbf{tr}^{pathB}$ [#]	$\mathbf{tr}^{pathC}$ [#]	$\mathbf{rt}^{total}$ [min]	$\mathbf{rt}^{Node3}$ [min]	$\mathbf{rt}^{Node4}$ [min]	$\mathbf{emis}^{total}$ [kg CO2]	$\mathbf{energy}^{total}$ [MJ]
HVO	14	4	10	224	127	98	1,637	3,168,235
Diesel	14	4	10	229	129	100	135,052	3,451,921
Diesel-electric SH	14	4	10	233	131	102	139,964	3,577,037
LNG	22	8	14	235	153	81	110,409	3,466,706
Methanol	26	9	17	309	210	99	110,580	2,883,415

Table 5.18: Results of P1A with all feasible energy types

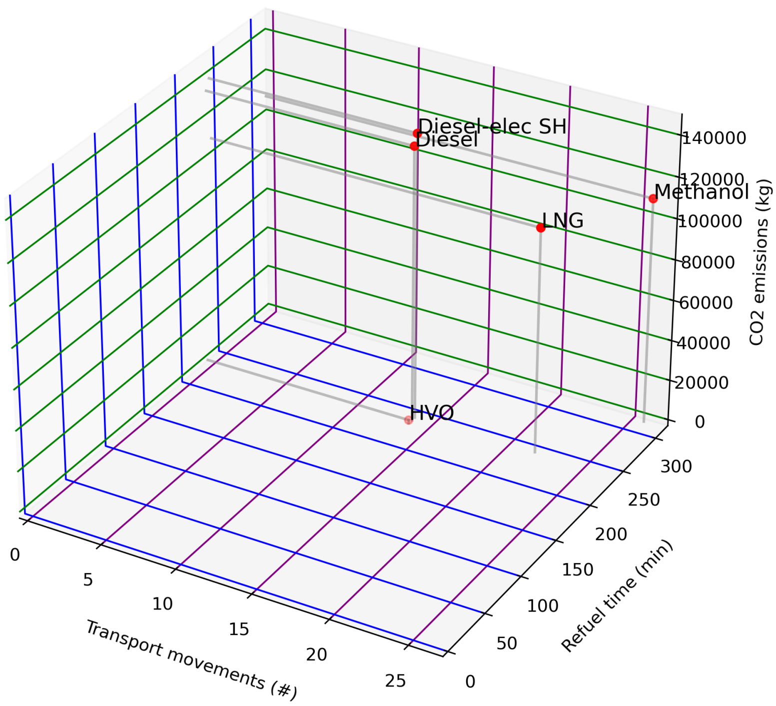

Figure 5.7: All feasible results for P1A with number of trips, refuel time and CO2 equivalent emissions results

5.3.5. P1.B

Once again, according to the VESC model, HVO emerges as the optimal solution. With the WLS fuel container now compatible with the Gryphus container, the refuel time at Node 3 is reduced to just 10 minutes each day, marking up to a 73% reduction in refuel time for Node 3. Another significant change is observed in the number of tr^{pathB} trips on day 1. The DOS kept in reserve are now stored in smaller fuel containers, necessitating more trips. For days 2-5, the VESC model utilizes only one WLS + trailer but employs three Gryphus trucks for path C. This arrangement is feasible only if the fuel from the WLS + trailer containers is transferred to the Gryphus fuel containers, or if one of the reserve DOS is utilized for multiple days. Since this policy does not involve pumping, it is assumed that reserve DOS are utilized. The inclusion of the third Gryphus supply truck is not necessary for the energy capacity but is included due to constraints within the VESC model, shortening the rt^{Node4}.

	tr^{pathB} [#]	**tr**^{pathC} [#]	**rt**^{Node3} [min]	**rt**^{Node4} [min]	**emis**^{total} [kg CO2]	**energy**^{total} [MJ]
Day 1	7	3	10	26	281	1,985,752
Day 2	1	3	10	29	421	456,281
Day 3	1	3	10	29	421	456,281
Day 4	1	3	10	29	421	456,281
Day 5	1	3	10	29	421	456,281

Table 5.19: Results of the best solution P1.B, HVO

When all the feasible results of P1.B are compared with those of P1, it becomes evident that the tr^{total} and rt^{total} are most affected by the compatible equipment. The tr^{total} increases in the range of 30-101% depending on the energy type, while rt^{total} decreases by 41-87%. As a side effect of the compatible equipment, the tr^{pathC} trips are also increased because rt^{Node3} is no longer affected by the number of trips for path C. The availability of am^{pumps} is limited, and increasing the number of trips for path C will elevate the refuel time at Node 3. This policy no longer utilizes pumps; instead, fuel containers can be simultaneously loaded from the WLS to the Gryphus. The VESC model assumes that refueling is optimized for efficiency, meaning that all supply vehicles begin resupplying at the same time. Consequently, regardless of the number of supply trucks, if the number of supply trucks matches the vehicles requiring resupply, the refuel time remains constant—in this case, 50 minutes for Node 3. Table 5.20 demonstrates that energy types with low energy density and/or low FTW efficiency, which necessitate a high number of trips, exhibit the lowest rt^{total}. This is because each vehicle at UNITS has its own resupply vehicle, or even more than one for certain energy types. However, when there are more supply vehicles than vehicles at UNITS (as seen with H2), there is no further improvement in refuel time because all vehicles are already refueling simultaneously. In practice, refuel time would likely increase as supply trucks would have to wait for each other, resulting in additional refuel time.

	tr^{total} [#]	**tr**^{pathB} [#]	**tr**^{pathC} [#]	**rt**^{total} [min]	**rt**^{Node3} [min]	**rt**^{Node4} [min]	**emis**^{total} [kg CO2]	**energy**^{total} [MJ]
HVO	26	11	15	191	50	141	1,968	3,810,876
Diesel-electric SH	25	11	14	197	50	147	147,409	3,764,133
Diesel	36	16	20	166	50	116	163,451	4,173,583
LNG	47	21	26	143	50	93	133,154	4,182,744
Methanol	50	23	27	183	50	133	133,032	3,473,812
Ammonia	105	48	57	159	50	109	0	5,253,343
H2 Fuel cell	180	88	92	115	50	65	0	3,773,719
H2 ICE	276	138	138	113	50	63	0	5,994,781

Table 5.20: Results of P1B with all feasible energy types

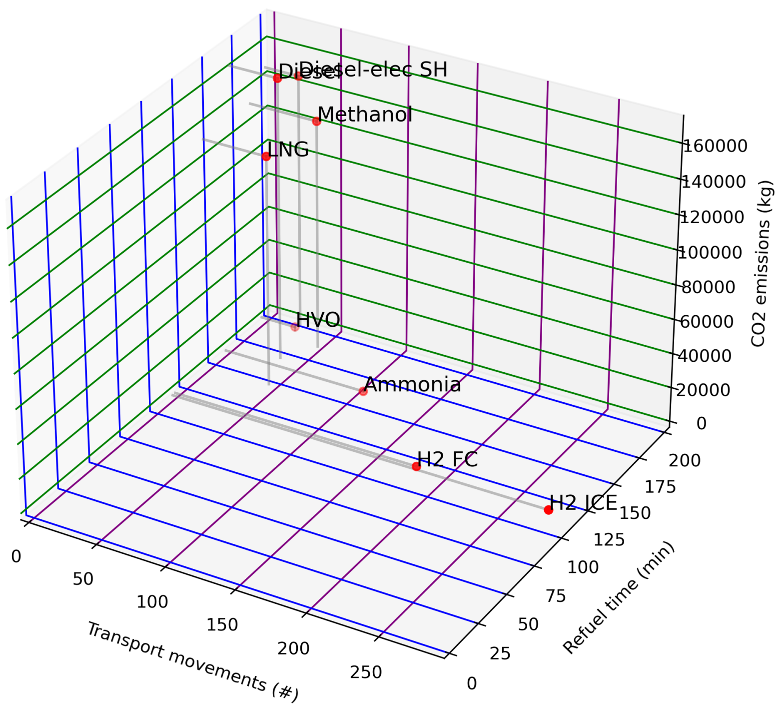

Figure 5.8: All feasible results for P1B with number of trips, refuel time and CO2 equivalent emissions results

5.3.6. P2

For P2, HVO emerges as the best solution. The only factor influencing the outputs due to the 'renewable energy' MSC is the utilization of the Manticore supply trucks. As illustrated in Table 5.21, the Manticores operate at full capacity every day. This occurs because the VESC model prioritizes minimizing rt^{total}. Consequently, the vehicles supplied by the Manticores no longer require resupplying at Node 4 by the Gryphus supply trucks. The $Fi^{manticore}$ is 0 on day 1 since the Manticores commence the scenario at full capacity. On subsequent days, the Manticores utilize the $Fi^{manticore}$ for that specific day.

	$\mathbf{tr}^{pathB}$ [#]	$\mathbf{tr}^{pathC}$ [#]	$\mathbf{rt}^{Node3}$ [min]	$\mathbf{rt}^{Node4}$ [min]	$\mathbf{emis}^{total}$ [kg CO2]	$\mathbf{energy}^{total}$ [MJ]	$\mathbf{En}^{manticore}$ [MJ]	$\mathbf{Fi}^{manticore}$ [MJ]
Day 1	2	1	14	5	244	1,825,227	250,260	0
Day 2	1	2	31	31	362	419,176	250,260	250,260
Day 3	1	2	31	31	362	419,176	250,260	250,260
Day 4	1	2	31	31	362	419,176	250,260	250,260
Day 5	1	2	31	31	362	419,176	250,260	250,260

Table 5.21: Results of the best solution P2, HVO

Table 5.22 demonstrates that diesel-electric achieves equal or better performance in terms of tr^{total} and rt^{total} but is relegated to second place due to $emis^{total}$ being 8123% higher compared to HVO. H2 is the sole energy type with energy generation at Node 2. However, this does not impact the outputs since strategic supply to Node 2 is not factored into the VESC model. For H2 FC, the energy generated at Node 2 accounts for 6% of the total required energy over the 5 days, and for H2 ICE, it is nearly 4%.

	$\mathbf{tr}^{total}$ [#]	$\mathbf{tr}^{pathB}$ [#]	$\mathbf{tr}^{pathC}$ [#]	$\mathbf{rt}^{total}$ [min]	$\mathbf{rt}^{Node3}$ [min]	$\mathbf{rt}^{Node4}$ [min]	$\mathbf{emis}^{total}$ [kg CO2]	$\mathbf{energy}^{total}$ [MJ]
HVO	15	6	9	268	136	131	1,692	3,501,931
Diesel-electric SH	15	6	9	256	139	118	139,133	3,771,658
Diesel	15	6	9	258	139	119	140,125	3,817,513
LNG	22	9	13	303	169	135	117,412	3,833,482
Methanol	27	10	17	398	229	169	118,180	3,185,684
Ammonia	47	19	28	569	379	190	0	4,748,927
H2 Fuel cell	85	38	47	620	512	108	0	3,477,742
H2 ICE	134	62	72	871	768	104	0	5,558,160

Table 5.22: Results of P2 with all feasible energy types

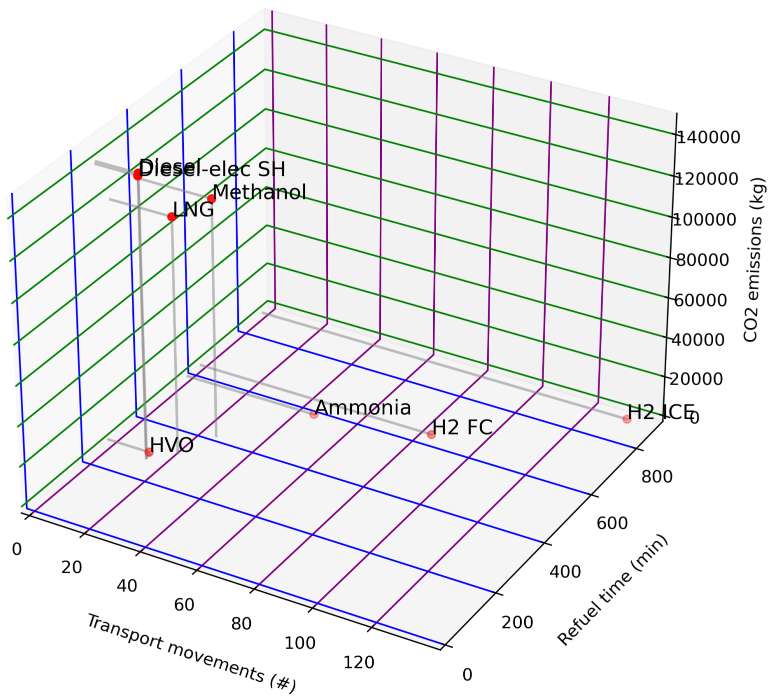

Figure 5.9: All feasible results for P2 with number of trips, refuel time and CO2 equivalent emissions results

5.3.7. P2.A

HVO-electric emerges as the best solution in this scenario. The key difference from P1.A is that the energy stored in the Manticores is additional and utilized on day 1, resulting in no tr^{pathC} needed for that day and consequently zero refuel time. The Manticores even retain some energy capacity, which reduces the resupply time on day 3. Compared to P1.A, tr^{total} is reduced by 29%, rt^{total} by 30%, and $emis^{total}$ by almost 10%. These enhancements stem from the APU utilization of HVO-electric, a feature absent in P1.A for diesel-electric. The use of APUs saved enough energy, enabling the Manticores' energy capacity to suffice for resupply on day 1. The combination of energy reduction through APU use and the Gryphus supply trucks high energy capacity for HVO resulted in one less tr^{pathC} per combat day. The Gryphus supply trucks higher energy capacity is attributed to HVOs lower density compared to diesel, with the limitation on the Gryphus being weight rather than volume.

	tr^{pathB} [#]	**tr**^{pathC} [#]	**rt**^{Node3} [min]	**rt**^{Node4} [min]	**emis**^{total} [kg CO2]	**energy**^{total} [MJ]	**En**^{manticore} [MJ]	**Fi**^{manticore} [MJ]
Day 1	2	0	0	0	220	1,616,008	245,836	0
Day 2	0	0	0	0	0	0	0	0
Day 3	1	3	43	34	627	718,701	250,260	245,836
Day 4	0	0	0	0	0	0	0	0
Day 5	1	3	44	35	627	718,701	250,260	250,260

Table 5.23: Results of the best solution P2.A, HVO-electric

There are only 4 feasible results for this policy, with fossil fuels being excluded, see Figure 5.10. This policy employs the bio-fuel options, leading to a significant reduction in $emis^{total}$ for the series hybrid, LNG and Methanol by 99%, 86% and 86%, respectively. When comparing HVO from P1.A with P2.A, which differs only in the use of the Manticores, it is evident that they reduce tr^{total} by 14% and rt^{total} by 16%.

	tr^{total} [#]	**tr**^{pathB} [#]	**tr**^{pathC} [#]	**rt**^{total} [min]	**rt**^{Node3} [min]	**rt**^{Node4} [min]	**emis**^{total} [kg CO2]	**energy**^{total} [MJ]
HVO-electric	10	4	6	156	87	69	1,479	3,053,410
HVO	12	4	8	188	110	78	1,610	3,195,539
LNG	21	8	13	222	144	79	15,317	3,496,710
Methanol	25	9	16	294	197	96	15,933	2,908,503

Table 5.24: Results of P2A with all feasible energy types

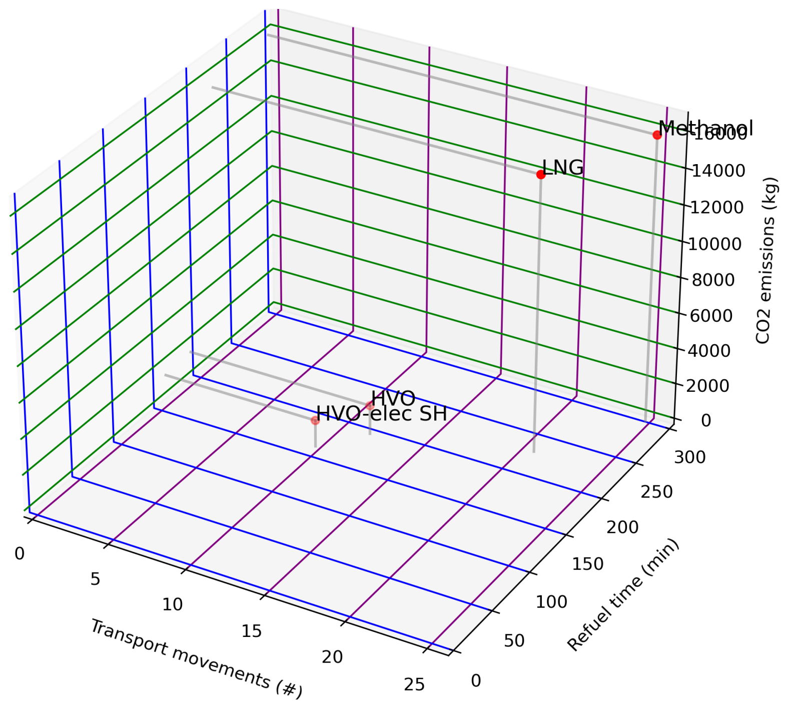

Figure 5.10: All feasible results for P2A with number of trips, refuel time and CO2 equivalent emissions results

5.3.8. P2.B

P2.B yields the best results with HVO. The difference between P1.B and P2.B lies in the use of the 'Renewable energy' MSC and the integration of APUs. When comparing the results, it reveals a 27% reduction in tr^{total} and a 5% reduction in rt^{total}. The decrease in the number of trips is primarily due to energy savings from the use of APUs. The reduction in refuel time is attributed to the Manticores, with the most significant impact observed on day 1, where the initial energy capacity of the Manticores is utilized. P1.B employed three Gryphus supply trucks for each combat day, supplying 16% more energy than P2.B, which used only 2 Gryphus supply trucks in conjunction with the Manticores. However, P2.B exhibits a 7% higher rt^{Node4} than P1.B, indicating that the number of tr^{pathC} has a greater impact on the refuel time than the use of Manticores. This is because the Manticores solely reduce rt^{extra} and diminish energy consumption for vehicles that do not need to travel to the resupply point. The greater the rt^{extra} and distance to the resupply point at Node 4, the more significant the impact of the Manticores on the refuel time.

	$\mathbf{tr}^{pathB}$	$\mathbf{tr}^{pathC}$	$\mathbf{rt}^{Node3}$	$\mathbf{rt}^{Node4}$	$\mathbf{emis}^{total}$	$\mathbf{energy}^{total}$	$\mathbf{En}^{manticore}$	$\mathbf{Fi}^{manticore}$
	[#]	[#]	[min]	[min]	[kg CO2]	[MJ]	[MJ]	[MJ]
Day 1	6	1	10	5	249	1,836,383	250,260	0
Day 2	1	2	10	31	363	421,407	250,260	250,260
Day 3	1	2	10	31	363	421,407	250,260	250,260
Day 4	1	2	10	31	363	421,407	250,260	250,260
Day 5	1	2	10	31	363	421,407	250,260	250,260

Table 5.25: Results of the best solution P2.B, HVO

When examining all feasible energy types, Figure 5.11 indicates that the H2 options and Ammonia have a lower rt^{total} compared to the other energy types, which contrasts with the findings of P2 and P2.A. The reason for this parallels the explanation provided in subsection 5.2.3. The elevated rt^{total} for these three energy types in P2 and P2.A stems from the limited availability of pumps at Node 3, resulting in a high rt^{Node3}. This issue is resolved with the implementation of compatible fuel containers for the WLS and the Gryphus. However, this solution comes with the trade-off of requiring an increase of 405-1342% in supply trips.

	tr^{total} [#]	tr^{pathB} [#]	tr^{pathC} [#]	rt^{total} [min]	rt^{Node3} [min]	rt^{Node4} [min]	emis^{total} [kg CO2]	energy^{total} [MJ]
HVO	19	10	9	181	50	131	1,701	3,522,011
Diesel-electric SH	26	15	11	159	50	109	140,527	3,805,268
Diesel	27	15	12	158	50	108	141,694	3,854,635
LNG	38	20	18	154	50	104	118,760	3,875,350
Methanol	44	22	22	186	50	136	119,587	3,223,838
Ammonia	96	46	50	163	50	113	0	4,861,239
H2 Fuel cell	175	88	87	117	50	67	0	3,595,076
H2 ICE	274	139	135	114	50	63	0	5,835,281

Table 5.26: Results of P2B with all feasible energy types

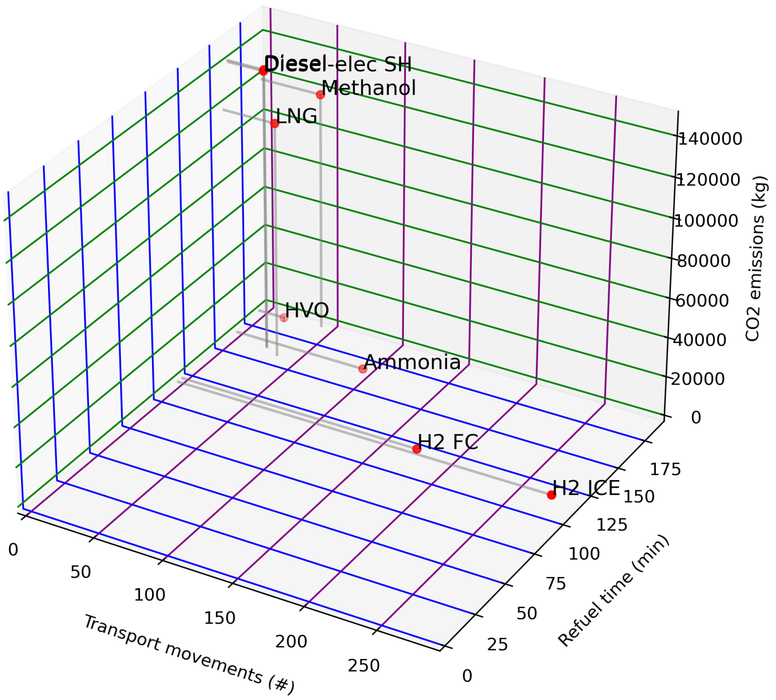

Figure 5.11: All feasible results for P2B with number of trips, refuel time and CO2 equivalent emissions results

5.3.9. P3

This policy assesses the necessary technological advancements required for alternative energy types to compete with current diesel. The examination entails altering a single type of input parameter to observe the resultant differences, using the same case study as previous policies. Baseline P2 closely resembles P3 and serves as a basis for comparison. Baseline P2 yields outputs for diesel, including a tr^{total} of 15 trips, an rt^{total} of 258 minutes, and an $emis^{total}$ of 140,125 kg CO2.

Electric battery swap and charging

In previous policies, electric battery swap and charging were deemed infeasible due to the limited range of electric vehicles and the extensive distances and operational hours outlined in the case study. However, when the energy density of battery packs is increased from 0.47 MJ/kg or 0.58 MJ/kg to 1.18 MJ/kg, the VESC model becomes viable for this case study. Unless stated otherwise, the input value of 1.18 MJ/kg is utilized, representing the minimum value for model feasibility. Figure 5.12 illustrates the average vehicle range in comparison to the current average range of diesel vehicles. The Argonne Research Centre is currently developing a lithium-air battery capable of achieving an energy density of 1.2 kWh/kg or 4.32 MJ/kg [68]. The graph in Figure 5.12 demonstrates that by integrating such a battery pack into vehicles, which typically require 1.5-2.6 times more volume for energy storage than standard diesel, vehicle range could exceed the current diesel fleets average by over 20%. With the presumed volume and weight allocation per vehicle for energy storage, an energy density of 3.38 MJ/kg for battery packs would provide a range equivalent to that of current diesel vehicles.

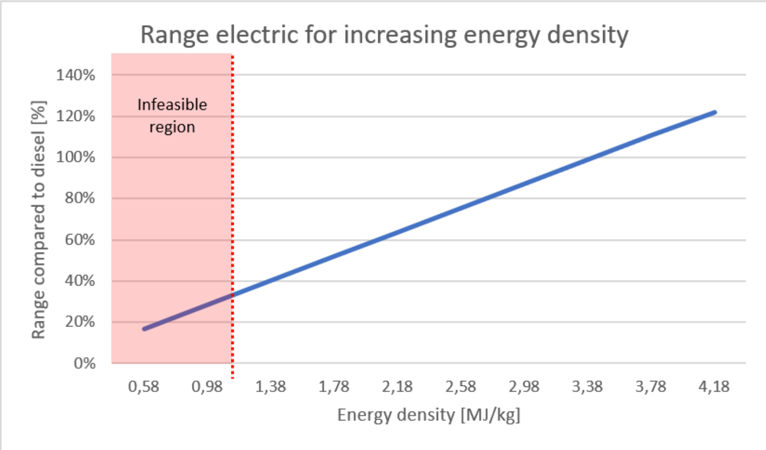

Figure 5.12: Average vehicle range compared to current diesel for increasing energy density of electric battery packs

The VESC model runs for all energy densities ranging from 1.18 to 4.32 MJ/kg for both electric battery swap and charging. Values below 1.18 yield infeasible solutions and are consequently excluded. The outputs are depicted in Figure 5.13. $emis^{total}$ is consistently zero for both energy types. The graph illustrates a clear decrease in tr^{total} for both energy types initially, followed by a leveling off. A closer examination of the results, detailed in section A.4, reveals that the VESC model employs more tr^{pathC} than necessary for supply but utilizes these additional Gryphus supply trucks to maintain a similar refuel time or prevent excessive increases in rt^{total}. Prioritizing tr^{total} reduction over rt^{total} would result in a more pronounced decrease in tr^{total} but an increase in rt^{total} due to the lower energy flow during refueling and a smaller ratio of supply trucks to UNITS vehicles. In the case of battery swap, a fixed number of cranes are utilized at Node 3 to facilitate battery exchanges between the WLS and Gryphus. Charging, on the other hand, utilizes the WLS battery system itself to charge the Gryphus battery container, with the number of available chargers equating to the number of WLS containers. Consequently, a reduction in tr^{pathB} leads to an increase in rt^{Node3}, as evident in Figure 5.13. Even with an increase in battery pack energy density, tr^{total} remains 320-333% higher than baseline diesel. Increasing energy density has minimal to no impact on rt^{total} and may even lead to an increase, particularly in the case of electric charging.

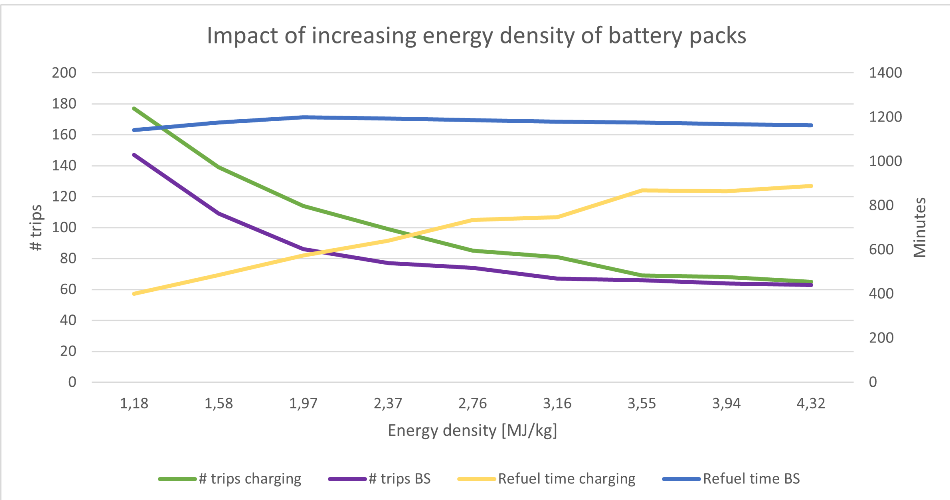

Figure 5.13: Impact of increasing energy density of battery packs for energy types electric battery swap and charging

Increasing the energy flow during refueling does not affect tr^{total}, but it significantly reduces rt^{total}, which stabilizes for higher energy flow values. This occurs because a portion of the refuel time, known as rt^{extra}, is unrelated to energy flow and represents the additional time required for vehicles to couple with the supply vehicle. As energy flow increases, the proportion of rt^{extra} also increases, resulting in a flattening of the graph, as illustrated in Figure 5.14.

In electric charging, rt^{total} remains consistent at an energy flow of 435 MJ/min, while tr^{total} increases by 987%. Electric battery swap approaches the performance of current diesel only when the energy flow reaches its maximum of 1735 MJ/min. In this scenario, tr^{total} is 880% higher than for current diesel.

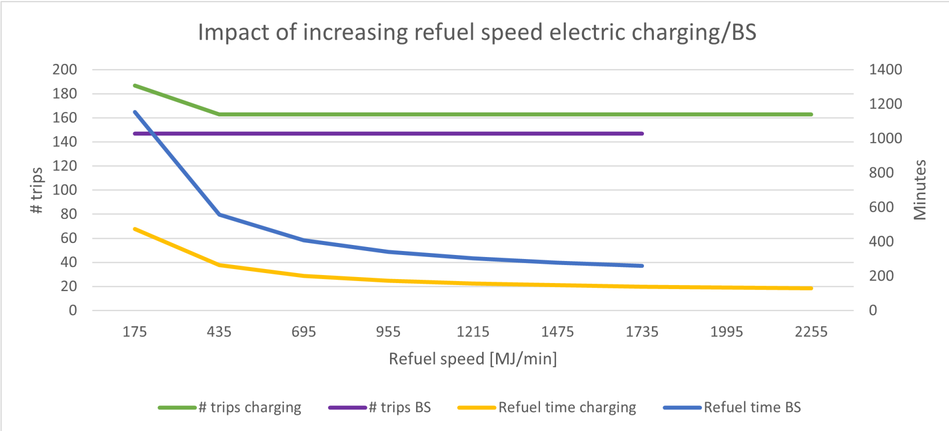

Figure 5.14: Impact of increasing energy density of battery packs for energy types electric battery swap and charging

Increasing the FTW efficiency results in decreased outputs, except for the rt^{total} of electric charging, which fluctuates around 400 minutes. The energy consumption of UNITS decreases, leading to lower refuel time and a reduced number of trips. However, the decrease in the number of trips increases refuel time. In this scenario, these two effects balance each other out, as shown in Figure 5.15.

Simply increasing the FTW efficiency alone will not produce output values comparable to current diesel. The most optimal results for tr^{total} are still 813% and 740% higher than diesel, while for rt^{total}, these figures are 55% and 289%. This is because the FTW efficiency is already quite high and can only be increased by a maximum of 7%.

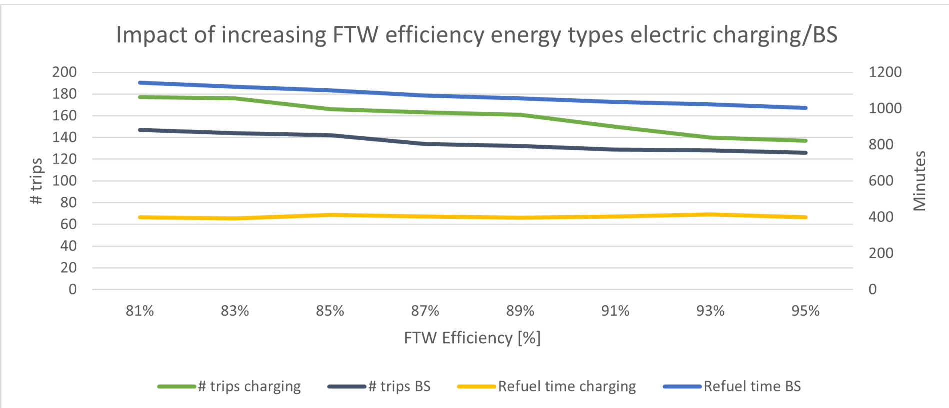

Figure 5.15: Impact of increasing FTW efficiency for energy types electric battery swap and charging

Through trial and error, it is found that combining various inputs for the electric battery swap energy type shows that all three input values should be near their maximum for outputs similar to current diesel, as shown in Table 5.27. When all inputs are optimal, the rt^{total} can be comparable to diesel, but the tr^{total} remains 133% higher.

Energy density [MJ/kg]	Energy flow [MJ/min]	FTW [%]	tr^{total} [#]	rt^{total} [min]
4.32	1,735	95%	35	247
3.16	1,186	93%	44	298
2.37	890	93%	61	338

Table 5.27: Combination of inputs with their outputs for energy type electric battery swap

Performing the same analysis for electric charging reveals that rt^{total} can be matched, but tr^{total} is still 160% higher in the most optimal scenario. The reason for this is that the ratio of the energy capacity of the supply trucks to the average energy consumption of vehicles is larger for diesel supply trucks than for electric variants. For diesel, the ratio for Gryphus is 1:10 and for the WLS is 1:24. However, for electric, the ratio for the Gryphus is 1:9 and for the WLS is 1:15. This difference arises because more volume and weight are used in the vehicles of UNITS to accommodate extra battery packs, while this is not feasible for the supply trucks due to weight limitations.

Energy density [MJ/kg]	Energy flow [MJ/min]	FTW [%]	tr^{total} [#]	rt^{total} [min]
4.32	955	93%	39	323
4.32	1,186	93%	35	240
2.37	2,255	91%	62	187

Table 5.28: Combination of inputs with their outputs for energy type electric charging

H2 FC and ICE

Table 5.13 shows that the energy types H2 fuel cell and ICE can be enhanced by increasing the volumetric energy density, refuel speed, and FTW. The impact of increasing the volumetric energy density of H2 is illustrated in Figure 5.16. The most optimal value for H2 ICE is 93%, while H2 fuel cell matches the range of diesel with an increase of 12 MJ/L. This is attributed to the higher FTW efficiency of H2 fuel cell.

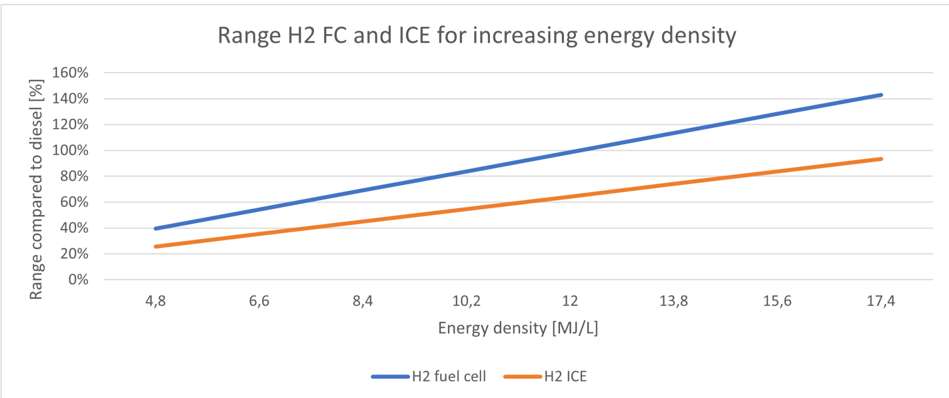

Figure 5.16: Impact of increasing volumetric energy density on the vehicle range for energy types H2 fuel cell and ICE

Raising the volumetric energy density of H2 leads to a reduction in tr^{total} and a slight increase in rt^{total}. The increase in refuel time is attributed to the decrease in Gryphus supply trucks at Node 4, as noted in Figure 5.13. Even with a volumetric energy density of 17.4 MJ/L, the energy capacity of the Gryphus remains at 43% compared to diesel, resulting in 93-153% more tr^{total}.

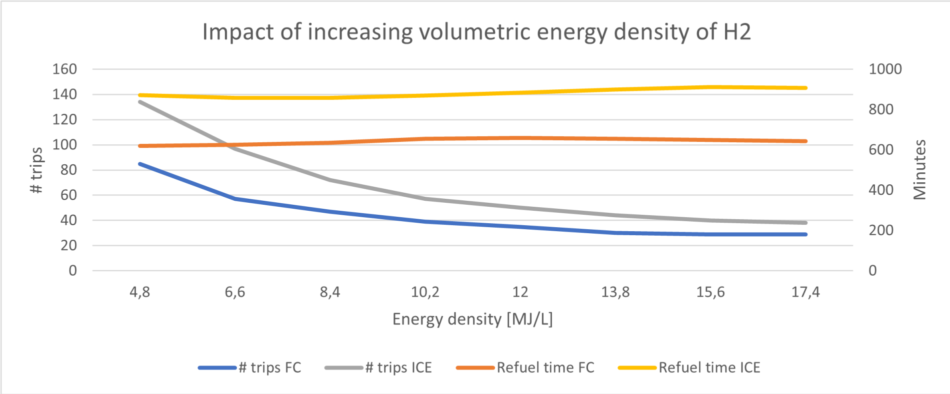

Figure 5.17: Impact of increasing volumetric energy density for energy types H2 fuel cell and ICE

The increase of refuel speed has no effect on the tr^{total} for both H2 energy types. The rt^{total} decrease as expected with the best solution being 39-88% more depending on the energy type.

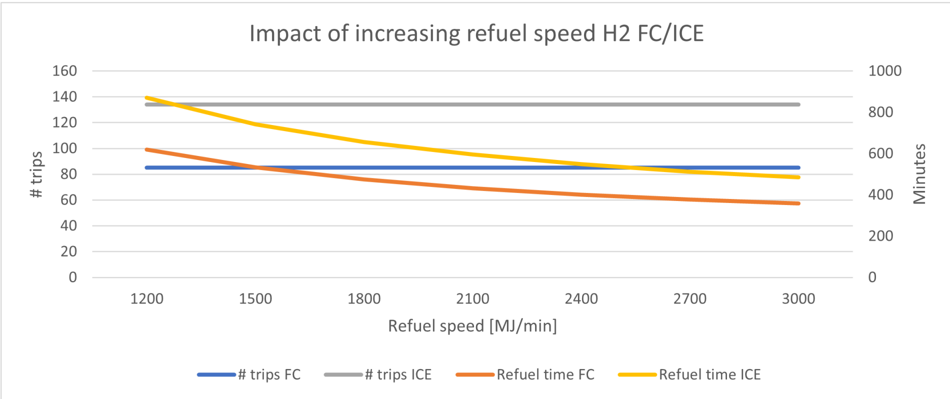

Figure 5.18: Impact of increasing refuel speed for energy types H2 fuel cell and ICE

The difference between the energy type H2 fuel cell and ICE is in the FTW efficiency of the technology which can be clearly seen in Figure 5.19 because the results match each other perfectly. The FTW efficiency for H2 ICE is lower and can theoretically improve to meet the lower range of H2 fuel cell.

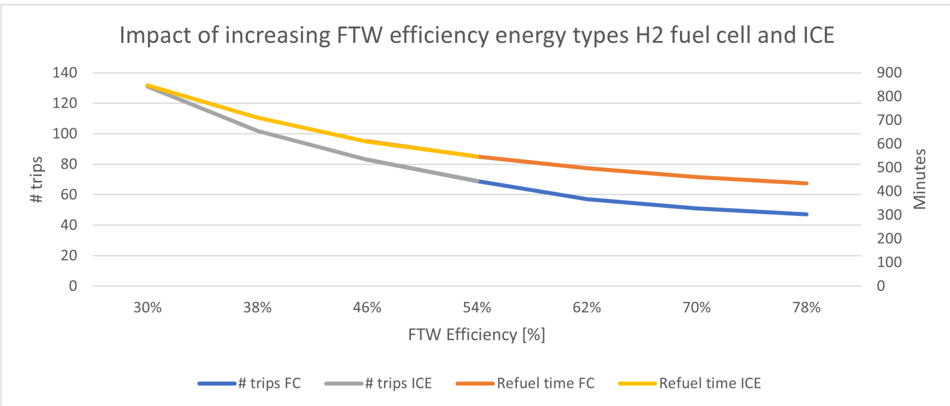

Figure 5.19: Impact of increasing FTW efficiency for energy types H2 fuel cell and ICE

H2 fuel cell would be preferred instead of H2 ICE because of it higher FTW efficiency. Results of combination of different input values can be seen in Table 5.29.

Energy density [MJ/L]	Energy flow [MJ/min]	FTW [%]	tr^{total} [#]	rt^{total} [min]
12.0	2,100	61%	26	393
15.6	2,700	61%	24	344
17.4	3,000	70%	22	306

Table 5.29: Combination of inputs with their outputs for energy type H2 fuel cell

Diesel-electric series hybrid

As explained in subsection 5.2.7, the FTW efficiency of diesel-electric is the only parameter that will be studied for increase. The efficiencies of the diesel generator, battery charging, and electric motor are increased until the total FTW efficiency reaches a maximum of 48%. While the utilized FTW efficiency of 34% for the VESC model is higher than that of diesel used, the average vehicle range was only 84% of that of diesel. The reason for this is that the fuel tank capacity is 80% of the original diesel capacity because room had to be made to store the extra battery capacity. Increasing the FTW efficiency also increased the average vehicle range, as seen in Figure 5.20. Diesel-electric has a similar vehicle range to diesel when the FTW efficiency is 39%, which is 18% higher than the FTW efficiency of diesel. The energy type diesel-electric makes no use of an APU, and for the calculation of the energy consumption for standby hours, the formula given in Equation 2.3 is used.

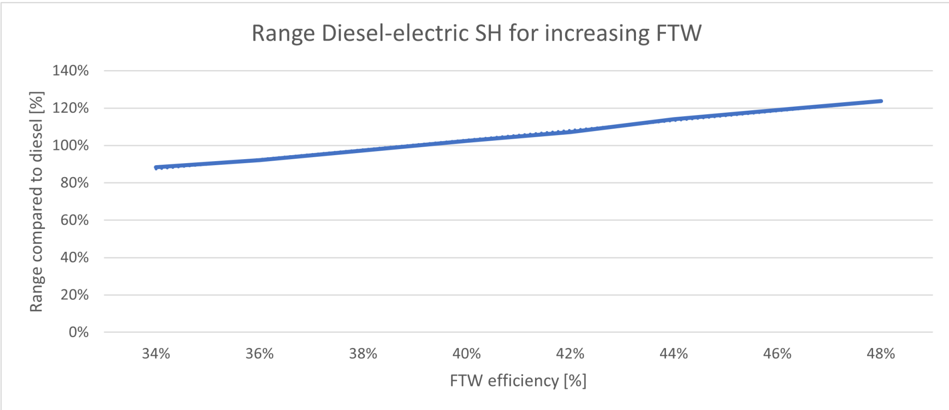

Figure 5.20: Impact of increasing FTW efficiency on the average vehicle range for diesel-electric series hybrid

The increasing FTW efficiencies are incorporated into the VESC model, and the results shown in Figure 5.21 indicate that all three objective outputs are decreasing. The decrease in tr^{total} is not solely attributable to the reduced energy consumption due to the increasing efficiency but also to the use of the Manticores supply vehicles. Due to the reduced energy use, the energy to be supplied falls below a threshold, which means that on some days the Manticores can replace a Gryphus, as detailed in the outputs in section A.4. If the Manticores are not used, the tr^{total} would remain at 15 for an FTW efficiency of 48%, resulting in a 0% reduction. With the use of the Manticores, the tr^{total} is reduced by 13%.

The reduction of rt^{total} is due to less fuel needed to pump from the supply vehicles to the vehicles. The significant decrease in refuel time for the FTW efficiency of 38% is because on day 1, no Gryphus trucks are needed because all refueling is done by the already attached Manticore supply vehicles. This reduces the rt^{total} not only by eliminating the need to pump fuel over but also cancels out two instances of rt^{extra}, which in this scenario is 14 minutes each time. The CO2 equivalent emissions have a directly proportional relationship with the energy used by the vehicles.

The energy type diesel-electric is equal to or better than current diesel for all FTW efficiencies in the range of 34-48%. In the most optimal scenario with an FTW efficiency of 48%, the tr^{total} is reduced by 13%, the rt^{total} is reduced by 25%, and the $emis^{total}$ is reduced by 30%.

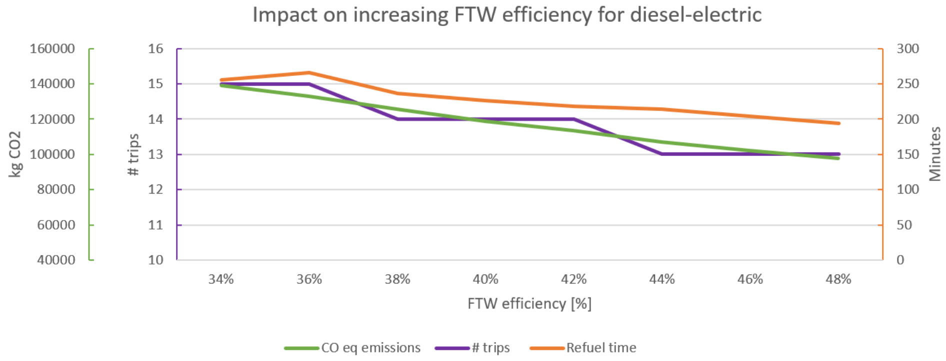

Figure 5.21: Impact of increasing FTW efficiency for diesel-electric series hybrid

5.4. Validation and Model Testing

The VESC model developed in chapter 4 needs to be validated to ensure that it is built correctly, based on accurate data, and that the methodology used effectively addresses the research problem. The VESC model comprises two parts: data related to the current situation (energy type diesel) and data for potential future scenarios (all other energy types and alternative MSC). Validating the data for potential future operations is challenging, as these energy systems may not currently exist or are still in development and not yet deployed in military settings.

Therefore, the only part of the VESC model that can be validated with available data is when the model is run for the energy type diesel only, without the involvement of Manticores supply trucks, APUs, or energy generation at the Nodes. This reflects the current operational procedures. The necessary data includes energy consumption, mileage, terrain and weather conditions, and exercise details of a significant group of vehicles or weapon platforms engaged in warfighting scenarios over multiple days. Here, a substantial group is defined as at least the size of a battalion.

The warfighting exercise "Allied Spirit," outlined in Table 5.1, could have provided the validation data. However, due to a fatal incident, the exercise timeline and tactical setting were altered, and there was no longer an opportunity to collect the required data. Consequently, the formula for energy consumption of vehicles and weapon platforms for current diesel, as provided in subsection 2.2.1 and chapter 4, could not be validated. Nevertheless, the VESC model relies on the CVV, GBV, and BVE calculations, which have been in use by the NLMoD for several decades and provide fuel use estimates that are within the same order of magnitude as actual consumption.

5.4.1. Validation input data

The VESC model relies on a comprehensive dataset, and its results are contingent upon the accuracy of this data. This section elucidates the validation process for the input data. The input data undergoes scrutiny against internal NLMoD vehicle documentation, reports, datasets, and field data collected on-site. Table 5.30 provides a synopsis of the data alongside the corresponding validation method.

Data	Validation Method
Current vehicle and situation parameters	The data is compared with multiple NLMoD reports such as ”Handboek Bevoorrading” (2015) [15], ”Tactiek voor het gemechaniseerde team” (2022) [16] and ”Zakboek Bevoorrading en Transport” (2023) [11] and input parameters are similar.
Alternative energies for supply vehicle capacity and refuel time results	The results are compared with prior research done by the company DNV which looked into the impact of alternative fuels on the supply trucks (2023) [4], (2023) [14] and (2023) [18]. Similar results for simplification of VESC model.
Extra refuel time due to coupling to supply trucks	Times recorded at a fuel pump while different types of vehicles were refueling. Recorded average extra refuel time was 30% higher than value used but was in relaxed and safe setting. Detailed values see Table B.1.
CO2 equivalent emissions	The CO2 equivalent emissions from the co2emissiefactoren.nl dataset [65] are compared with the GHG Protocol dataset [74] and give similar results.
Alternative energy types vehicle data	The data of the E-Fennek and hybrid Boxer are compared with the results of this research and fall within the same class in terms of size.

Table 5.30: Input data validation

5.4.2. Model testing

The VESC model underwent testing for all policies, encompassing various vehicle compositions and scenarios, to identify and rectify any errors. The models basic functions were initially tested, gradually increasing in complexity until all functions were integrated. The model outputs were then compared against expected outcomes and manually checked, where feasible, through calculations. The conducted tests are documented in Table 5.31.

Test	Check
General	
Each path en Node should have for every day the same energy type.	✓
If delivery is not possible on a $day = i$, no energy is used that day and the $day = i + 1$ has energy consumption of both days.	✓
If the tank capacity is less than the required energy for a day in range D, the energy type is excluded from the possible options.	✓
If the number of Manticores attached is zero, the remain, fill-up and energy used from the Manticores is also zero.	✓
If the Manticores are used for resupply, the energy consumption for Node 4 is reduces by the amount of energy saved from reduces movements to supply point.	✓
If APUs are used, the stand-by energy consumption is adjusted for energy types with APUs.	✓
If more energy is generated on $day = i$ than consumed, the surplus energy is used firstly at $day = i + 1$.	✓
If the highest priority is given to minimize refuel time for all policies 2, the Manticore supply vehicles will be used at max for every day en will have 0 remain energy because Manticore to UNITS supply time is not included in the refuel time. When highest priority is given to minimize number of supply trips, the Manticores will have remain energy for certain days.	✓
number of transport movements	
If less than one WLS capacity is needed, a WLS is used instead of a WLS + trailer.	✓
Surplus energy from Gryphus at Node 4 is used to fill-up Manticores if the capacity of the Manticores is not full yet.	✓
Refuel time	
If more there are more Gryphus supply trips at path C instead of Manticores at Node 4, the refuel points at Node 4 for the Manticores are determined by the Manticores.	✓
If there are more supply trucks than vehicles at Node 4, the refuel points are at Node 4 are limited by the maximum number of vehicles of the UNTIS.	✓
The number of DOS delivered to Node 2 and 3 have no impact on the refuel time because they are stored on wheels.	✓
If no supply trucks are used on a day where supply is possible, the refuel time should be zero for that day.	✓
Emissions	
If the Manticores are used for resupply, the emissions for Node 4 are reduced by the amount of emissions saved due to reduced movements to supply point.	✓

Table 5.31: Model tests

6 Discussion and Recommendations

This research introduces an optimization model designed to evaluate the influence of various energy types on military vehicles and weapon platforms within the supply chain. Developed with specific assumptions and boundaries to navigate the intricacies of the MSC and refine its scope, the models outcomes are influenced by these assumptions, extensively deliberated upon in this chapter. The insights gleaned from this study pave the way for recommendations aimed at enhancing the VESC model and suggest avenues for further research. This will be discussed in section 6.2.

6.1. Discussion

The VESC model developed in this research should be looked at as a general optimization model of a MSC with various energy types. It is based on the current MSC of the NLMoD and a MILP optimization model is developed. The assumptions and boundaries given in section 3.3 are discussed in this section as well as the model and data limitations.

6.1.1. Assumptions and boundaries

The assumptions and boundaries affecting the results are listed and discussed in this subsection.

Energy types

The energy types and combinations examined in the VESC model are not confined to a finite selection. While the energy types explored in this study demonstrate potential for future application, technological advancements could reshape this landscape. This study assumes that global production of the energy types used is ample to support large-scale implementation. However, this assumption may pose challenges for HVO due to insufficient crop waste availability for its production on a large scale. Scaling up HVO production could lead to deforestation and consequently have a net negative environmental impact, potentially rendering this option obsolete. However, HVO could still find utility in the niche market of heavy military vehicles, albeit at increased fuel costs.

CO2 equivalent emissions

The CO2 equivalent emissions for the different energy types are based on FTW emissions rather than WTW emissions. This decision is due to the significant variability in national and strategic movements across warfighting scenarios, making it challenging to determine WTW emissions. Moreover, this VESC model does not encompass these movements, providing insights into only a segment of CO2 equivalent emissions. The absence of alternative energy types' impact on the entire MSC is a current limitation. Additionally, the utilization of fossil-dependent FTW CO2 equivalent emissions for methanol and LNG, owing to limited availability of bio-versions, results in elevated CO2 equivalent emission levels for these energy types. Running P2.A with the bio-versions of these energy types offers valuable insights into disparities in fuel production methods.

Paths and Nodes

Given the complexity and unpredictability of the MSC, not every facet is modeled in this VESC model. The focus primarily rests on operational and tactical movement, integral to warfighting. It is unnecessary to encompass all paths and nodes similar to this VESC model for warfighting purposes. While every MSC varies due to the dynamic nature of warfighting, fundamental principles remain consistent. Hence, the warfighting exercise ”Allied Spirit” serves merely as an illustrative example of an MSC. The precise values from the case study used in this research cannot be universally applied to all warfighting scenarios due to inherent differences. While trends in results may mirror each other, exact values can fluctuate based on input parameters.

An unchanged input parameter in the model is the number of pumps available at Node 3. The limited factor for rt^{Node3} remains the number of available pumps. As the number of supply trucks fluctuates based on circumstances and policies, the number of pumps is fixed based on typical UNITS sizes. Incorporating a pump or charging cable alongside the fuel container for energy types like H2, ammonia, methanol, and electric charging could diminish refuel time at Node 3.

Supply trucks

The supply trucks employed in the VESC model mirror those currently utilized by the NLMoD. The only alteration lies in the fuel container transported by these trucks, which varies according to energy type. Given the utilization of current vehicles, the transfer of fuel from the WLS container to the Gryphus container becomes necessary at Node 3. In scenarios P1.B and P2.B, the fuel container is engineered to be compatible with both the WLS and the Gryphus. However, this necessitates new equipment, as the new fuel container must be accessible via the WLS system, which the Gryphus lacks, thus requiring the use of a crane. While this adjustment may increase transport movements, it significantly diminishes refuel time at Node 3. The solution to this issue should not be sought solely in technical remedies but rather in a redesign of the supply chain. The discrepancy in off-road capabilities between the two vehicles dictates their deployment paths. In certain scenarios, it may be feasible for the WLS to directly supply the UNITS at Node 4 if the terrain permits easy access, a preference as it would reduce rt^{total}.

The inclusion of Manticore supply vehicles, attached to the UNITS at Node 4, introduces a novel concept. The primary aim of the Manticores is to reduce both tr^{total} and rt^{total}. Although the addition of Manticores does not factor into tr^{total}, it does constitute an additional permanent trip, requiring an extra vehicle and two personnel. Consequently, while it alleviates strain on the supply units, it places a heavier burden on the fighting units, which must manage a supply vehicle themselves. The results indicate a reduction in MSC impact due to the utilization of these Manticore supply trucks, thus recommending their use. Moreover, the Manticore supply vehicle could serve a dual purpose by also functioning as a communication or drone operator vehicle. Combining it with a drone operator proves advantageous, as these operators typically operate near the front but behind the fighting units, allowing for easy refueling of drones at the vehicle itself.

Vehicles and weapon platforms

The vehicles and weapon platforms utilized in this study are currently operational within the NLMoD. Input data for alternative energy types is derived from the diesel specifications of these vehicles, with assumptions generalized across all models. Refuel speed, additional volume, and weight allowances for battery packs and H2 are determined per vehicle type based on their specifications. However, transitioning these vehicles from diesel to alternative energy sources poses numerous technical challenges due to their specialized design for diesel use. While this research assumes these challenges can be overcome, the optimal scenario would involve vehicles being specifically designed for their respective energy types. For instance, in the case of battery swap implementation, batteries should be strategically located for easy access. Furthermore, modifications to the drivetrain layout for different energy types could potentially increase fuel capacity, resulting in greater vehicle range compared to the findings of this research.

APU

The vehicles utilize their ICE to charge their battery packs while in stand-by. The CVV stand-by calculates the energy consumption by multiplying the BVE by an IF for the stand-by time. This method, standard within the NLMoD, is also employed in this research. The inclusion of an APU option for vehicles reduces energy consumption during stand-by time, calculated by the fuel consumption of the installed APU at full capacity. However, the energy type diesel-electric does not utilize an APU, as it already incorporates a generator. Consequently, the VESC model employs the standard CVV stand-by formula with the IF for stand-by time to calculate the energy consumption of diesel-electric during stand-by time. This results in a higher fuel consumption for stand-by time than realistic, as the vehicles can operate for extended periods on their large battery pack, with recharging achievable in a short time due to the generator's design for vehicle movement, which necessitates higher energy output. Thus, the results for diesel-electric in this research are suboptimal. While compensated for in P2.A with HVO-diesel series electric, this compensation does not extend to other options.

The utilization of APUs reduces the energy consumption of vehicles, crucial due to the lower energy density of alternative energy types. Every unit of saved energy necessitates fewer supply trips and consequently less impact on the MSC. Thus, APUs are a necessary addition to vehicles and weapon platforms.

>48 hours self-sufficient

The results presented in subsection 5.3.2 suggest that enhancing the self-sufficiency of UNITS over 48 hours reduces the impact on the MSC. Fewer days required for resupply lead to fewer transport movements and less refuel time, directly tied to vehicle range and thus the energy density of the energy carrier and FTW efficiency. Enhanced self-sufficiency is advantageous from an MSC perspective, lowering the risk of combat power loss due to resupply failure if vehicles and weapon platforms are self-sufficient for longer periods.

Energy generation

Energy generation in this VESC model occurs primarily at Node 2, with a minimal amount at Node 3. The limited time and space constraints of the FSC at Node 3, combined with the tactical nature of UNITS at Node 4, render energy generation at Node 4 impractical for vehicle use. Energy generation at Node 2 primarily impacts the energy required from suppliers, affecting strategic movement not included in this research. While energy generation at Node 3 reduces the number of WLS trips, it does not impact refuel time at Node 3. Energy generation primarily influences strategic and operational movement, objectives not addressed in this research. Vehicle propulsion requires significant amounts of energy. The energy generated at Node 3 is not in proportion to what is consumed for movement by the vehicles. However, this generated energy can be used for standby time and for command posts.

MILP solver

The selection and utilization of the MILP solver significantly influence the models results. A blended objectives approach would necessitate linking all three objectives to cost, requiring an analysis of how each objective translates to cost due to risk and operational actions. The hierarchical objectives approach utilized in this model employs priority and relative tolerance to solve model objectives. The objective with the highest priority is optimized first, with the optimal result subject to change by relative tolerance if it significantly optimizes lower-priority objectives. Changing the priority of refuel time and the number of transport movements would not substantially alter results, except in cases where equipment compatibility for paths B and C eliminates certain refueling relationships, thereby increasing transport movements while decreasing refuel time. The use of relative tolerance impacts outcomes; if not utilized, diesel-electric may yield better results for some policies due to superior performance in refuel time and/or the number of transport movements.

6.1.2. Model and data limitations

MSC

The model is limited by not including national and strategic movement. The reason for this is the complexity of these movements because transport is mostly done by civilian partners and it is extremely changeable per warfighting situation. If this were included, it would show the total impact on the MSC, especially the CO2 equivalent emissions, which would be the WTW emissions instead of the TTW emissions. How the energy carrier is produced has an enormous impact on the CO2 equivalent emissions.

The VESC model looks at the supply in time periods of 24 hours because that is the current standard. It is not possible to look at shorter time spans than 24 hours or at time periods when supply is needed instead of fixed 24-hour supply times. Optimizing for when supply is needed gives the optimization model more space to optimize per energy type for all three objectives.

In warfighting, the SC and FSC should be mobile at all times. The idea is that they could change locations from time to time to prevent enemy artillery from zeroing in on them. The VESC model takes that into account by calculating the required supply equipment in the number of supply trucks so the SC and FSC are on wheels. However, changing the locations of the SC and FSC during the warfighting scenario is not included in the model. The reason for this was that the chosen case study did not involve moving the SC and FSC during the exercise.

Vehicle and weapon platform fleet

The VESC model is limited to the current available vehicle and weapon platform fleet in use by the NLMoD. This is because only these vehicles' basic specifications are known. Vehicles and weapon systems currently in development are not included, such as various drones and unmanned vehicles. The use of these kinds of systems influences energy consumption, and even the doctrines of the MSC could be revised to implement these kinds of systems.

Energy types

The VESC model uses 10 different energy types. These were chosen because of previous research done by the company DNV and similar research in literature. Blended versions of these energy types are not included but could lead to interesting results. The use of H2, ammonia, methanol, LNG, or HVO is limited in this research by using only 100% blends of these fuels, but they can also be mixed so their properties can be improved. Series hybrid is in the model only as diesel-electric, and for P2.A, HVO-electric. More combinations are possible for series hybrid.

6.2. Recommendations

1. Validation

The models validation for the current energy type, diesel, was hindered by the absence of data from the warfighting exercise "Allied Spirit." This data is crucial for verifying the accuracy of the formulas used by the NLMoD to calculate the required fuel amounts for warfighting scenarios. Without this validation, the models reliability for diesel and other energy types remains uncertain. Obtaining energy consumption and refuel time data from future warfighting exercises is imperative to enhance the model's accuracy.

2. Extension of VESC model

Expanding the VESC model to encompass national and strategic movement is essential for a comprehensive assessment of alternative energy types' impact on the MSC. This extension would provide insights into the overall impact of alternative energy types on warfighting scenarios. However, this addition must distinguish between military objectives and civilian objectives because most strategic movement is carried out by civilian partners. Additionally, incorporating cost minimization as an objective aligns with commercial supply chain optimization practices and addresses the NLMoD's considerations of technology acquisition costs.

Allowing the SC and FSC to relocate during warfighting scenarios would enhance the models realism. However, this relocation would increase energy consumption and CO2 equivalent emissions. To address supply interruptions during relocation, ensuring a minimum self-sufficiency of 48 hours for military units in the field is recommended.

3. Input data

The input data could be enhanced by incorporating a wider range of energy types and mixed fuels. Mixed fuels, like a combination of ammonia and hydrogen, can boost brake thermal efficiency, leading to reductions in the overall number of trips, refuel time, and CO2 equivalent emissions.

Conducting more detailed analyses of vehicle types for each energy type is recommended, particularly for hydrogen and electric variants. These energy sources necessitate additional volume and weight for storing the energy carrier, and their drivetrain significantly differs from that of traditional diesel vehicles.

Furthermore, integrating new vehicle and weapon platform concepts, such as drones and autonomous vehicles and weapon stations, into the model would provide insights into potential future warfighting scenarios. Autonomous vehicles and weapon stations are typically smaller and lighter since they do not require accommodations for human occupants, resulting in lower energy requirements and reduced supply needs. Future research could delve into determining the optimal blend of autonomous and conventional vehicles and weapon platforms within the military supply chain, prioritizing combat effectiveness.

4. Smaller supply trucks
Lessons learned from the war in Ukraine show that supply is vulnerable, and supply units are scarce and are selected as primary targets by enemy fire. Unit 230 Bevocie therefore prefers smaller and more supply trucks instead of the large ones currently in use. Smaller supply trucks will increase the number of supply trips but reduce the refuel time, as can be seen in the results of P1.B and P2.B in subsection 5.3.2. Further research into the optimal size of these supply trucks and their relation to minimizing the risk of destroyed supply lines is recommended.

5. Technological complexity and maintenance
The VESC model does not account for the impact of alternative energy types on the technical complexity of vehicles and the maintenance required for these energy systems. Focusing solely on the supply chain, without considering the vehicles themselves, overlooks the potential implications of breakdowns and maintenance needs. Addressing these concerns may necessitate the deployment of recovery vehicles and the provisioning of spare parts.

To address this gap, technological complexity could be introduced as an additional objective function. This metric could quantify the repair and maintenance hours required per vehicle within a specific timeframe. Given that repair and maintenance activities directly impact combat capacity and resource allocation, this objective could be prioritized similarly or even given higher precedence than the number of supply trips in the hierarchical objectives approach.

Future research endeavors should delve into these aspects for each vehicle type and energy system, ensuring a comprehensive understanding of their implications on operational effectiveness and logistical sustainability.

7 Conclusion

The NLMoD has set the goal of reducing dependency on fossil fuels by at least 20% by the year 2030 and at least 70% by the year 2050 compared to the year 2010. To achieve these goals, GWS as part of COMMIT conducts research into alternative fuels for vehicles, and they came up with a list of potential alternative energy types for their vehicle and weapon platform fleet. Recent research, both academic and from industry and COMMIT, suggests that diesel-electric series hybrid, H2, electric, ammonia, methanol, HVO and LNG are high-potential alternatives for heavy duty vehicles. However, the focus of COMMIT is on the vehicle and weapon platform technology itself, and the impact of these alternative energy types on the Military Supply Chain (MSC) is largely unknown. Because supply is one of the most important factors in warfighting, mapping out the impact of alternative fuels on the MSC is crucial so that it can be taken into account in choosing a future-proof energy type for the Dutch military. These alternative fuels should not lead to a deterioration of operational task performance. This challenge results in the main research question, as formulated in chapter 1:

What is the impact of alternative energy types of tactical military vehicles on the military supply chain and what would be the optimal energy type?

In the first part of this research, the current MSC was mapped, including which parameters influenced the system and how the impact could be measured. This led to the development of a MILP optimization model, simulating a Vehicle Energy Supply Chain. This model optimizes for three different objectives, which show the impact on the MSC: minimizing refuel time, number of supply trips and CO2 equivalent emissions. The model is based on the current MSC and uses vehicle, situation and energy types data. The current MSC has been expanded to include energy generation at the Supply Centre and Forward Supply Centre, Auxiliary Power Units (APUs) use for vehicles for stand-by time, and the addition of small supply trucks which act as energy buffer for the UNITS in the field. The intricacies of MSC design and vehicle utilization played pivotal roles in shaping outcomes, prompting the implementation of multiple policies to gauge their impact effectively.

The warfighting exercise ”Allied Spirit” served as the case study. The baseline for all policies was established by running the model solely for the current energy type, diesel. It shows that the use of APUs in vehicles will reduce the energy consumption and thus the CO2 equivalent emissions by 7-10%. In combination with supplying only once every 48 hours, it will reduce the total supply trips by 33%, the total refuel time by 31%, and CO2 equivalent emissions by 17%. For energy carriers with a high energy density and high fill speed such as diesel, refueling only once in 48 hours or even longer will greatly reduce the number of trips and refuel time. This is because for such energy carriers, high energy density leads to high vehicle range, and most refuel time is due to extra refuel time related to coupling of vehicles to the supply truck. The use of the Manticores supply vehicles will further minimize all three objectives. Even though 5 extra vehicles are attached, they save 7% extra supply trips and reduce the refuel time by 18% and CO2 equivalent emissions by almost 2%. This is because some of the vehicles no longer have to drive to the supply point because some of the vehicles are refueled at their position by the Manticores. Using compatible fuel containers for both paths will decrease the refuel time by 50%. However, for diesel, this will increase the number of trips needed by 71% because the smallest fuel container sets the limit. Using the Manticores will reduce this problem by 25%.

For all policies except for the policy without any fossil fuels, HVO comes out best. Diesel-electric scores similar or sometimes even better on total supply trips and refuel time but has CO2 equivalent emissions are higher compared to HVO, depending on the policy. Both Hydrogen fuel cell and ICE options have the highest number of supply trips and refuel time but have zero CO2 equivalent emissions. These results show that hydrogen is currently not competitive with diesel. Both electric energy types were infeasible for this warfighting scenario. For the policy where fossil fuels are excluded, HVO-electric series hybrid is the best result. If HVO-electric was included in the other policies, then the 3% improved Fuel To Wheel (FTW) efficiency of HVO-electric compared to HVO would have made HVO-electric the better option.

Policy 3 looked at how the alternative energy types should improve to have similar results as current diesel. For fully electric, this requires improvements in energy density, fill speed and FTW efficiency all together. The energy density should be above 4 MJ/kg, and the fill speed above 1000 MJ/min, which is almost 5 times the capacity of the Megawatt Charging System. The refuel time will be similar, but the total supply trips are 100% more than current diesel. With a FTW efficiency of 88% and the already extra used space and weight in the vehicles, an energy density of at least 1.18 MJ/kg is required to make electric feasible for this case study. An energy density of 3.78 MJ/kg will make the vehicle range similar to diesel. The bottleneck is the energy capacity of the supply trucks due to weight limitations. For Hydrogen fuel cells, the combined volumetric energy density of 17.4 MJ/L, 3000 MJ/min and FTW of 70% still has an increase in total supply trips of 32% and a refuel time of 19%. Diesel-electric FTW efficiency should increase to 39% to have a similar vehicle range.

In conclusion, the results show a trend whereby alternative energy types with the current technology available will increase the number of supply trips and refuel time en decrease the CO2 equivalent emissions. However, HVO-electric or diesel-electric series hybrid and HVO have similar or even better results than diesel. Changing energy types also requires changing the MSC to better match its use. Due to the lower energy density of these alternative energy types, as much energy as possible must be saved. Therefore, the results show that the use of APUs, energy buffer through the Manticores, longer self-sufficiency of the UNITS, and any energy generation drastically reduce the impact on the MSC. When looked at from the MSC perspective, HVO-electric series hybrid is the best energy type to be used for military vehicles.

Bibliography

Articles

[5] Hossein Baharmand et al. “A methodology for developing evidence-based optimization models in humanitarian logistics”. In: *Ann. Oper. Res.* 319.1 (Dec. 2022), pp. 1197–1229.

[6] Osman Özkaraca. “A REVIEW ON USAGE OF OPTIMIZATION METHODS IN GEOTHERMAL POWER GENERATION”. In: *Mugla Journal of Science and Technology* 4 (June 2018), pp. 130–136. DOI: 10.22531/muglajsci.437340.

[8] A. Mansfield, A. Boehman, and D. Gorsich. “Assessment of Conventional and Alternative Energy Carriers for Use in Military Vehicle Platforms”. In: *Journal of Energy Resources Technology* 143.4 (Sept. 2020), p. 041302. ISSN: 0195-0738. DOI: 10.1115/1.4048253. eprint: https://asmedigitalcollection.asme.org/energyresources/article-pdf/143/4/041302/6567963/jert_143_4_041302.pdf. URL: https://doi.org/10.1115/1.4048253.

[9] Robert Spudic, Kresimir Somek, and Vlado Kovacevic. “Single Fuel Concept for Croatian Army Ground Vehicles”. In: *Promet - Traffic - Traffico* 20 (May 2008), pp. 181–187. DOI: 10.7307/ptt.v21i3.1000.

[10] Carlo Cunanan et al. “A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles”. In: *Clean Technologies* 3.2 (2021), pp. 474–489. ISSN: 2571-8797. DOI: 10.3390/cleantechnol3020028. URL: https://www.mdpi.com/2571-8797/3/2/28.

[12] Wei-Dong Huang and Y-H Percival Zhang. “Energy Efficiency Analysis: Biomass-to-Wheel Efficiency Related with Biofuels Production, Fuel Distribution, and Powertrain Systems”. In: *PLOS ONE* 6.7 (July 2011), pp. 1–10. DOI: 10.1371/journal.pone.0022113. URL: https://doi.org/10.1371/journal.pone.0022113.

[22] Seyed Ehsan Hosseini and Brayden Butler. “An overview of development and challenges in hydrogen powered vehicles”. In: *International Journal of Green Energy* 17.1 (2020), pp. 13–37. DOI: 10.1080/15435075.2019.1685999. URL: https://doi.org/10.1080/15435075.2019.1685999.

[24] Hla Tun et al. “Thermodynamic parametric analysis of refueling heavy-duty hydrogen fuel-cell electric vehicles”. In: *International Journal of Hydrogen Energy* 48.74 (2023), pp. 28869–28881. ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2023.04.075. URL: https://www.sciencedirect.com/science/article/pii/S0360319923018104.

[26] F.M. Nizam Uddin Khan et al. “Maximizing energy density of lithium-ion batteries for electric vehicles: A critical review”. In: *Energy Reports* 9 (2023). Proceedings of 2022 7th International Conference on Renewable Energy and Conservation, pp. 11–21. ISSN: 2352-4847. DOI: https://doi.org/10.1016/j.egyr.2023.08.069. URL: https://www.sciencedirect.com/science/article/pii/S2352484723012118.

[28] Thomas Earl et al. “Analysis of long haul battery electric trucks in EU Marketplace and technology, economic, environmental, and policy perspectives”. In: 2018. URL: https://api.semanticscholar.org/CorpusID:195801767 (visited on 03/27/2024).

[29] Jakob Schneider et al. “The novel Megawatt Charging System standard: Impact on battery size and cell requirements for battery-electric long-haul trucks”. In: *eTransportation* 17 (2023), p. 100253. ISSN: 2590-1168. DOI: https://doi.org/10.1016/j.etran.2023.100253. URL: https://www.sciencedirect.com/science/article/pii/S2590116823000280.

[32] Matthew J. Brusstar et al. “High Efficiency and Low Emissions from a Port-Injected Engine with Neat Alcohol Fuels”. In: 2002. URL: https://api.semanticscholar.org/CorpusID:56537107.

[34] Cinzia Tornatore et al. “Ammonia as Green Fuel in Internal Combustion Engines: State-of-the-Art and Future Perspectives”. In: *Frontiers in Mechanical Engineering* 8 (2022). ISSN: 2297-3079. DOI: 10.3389/fmech.2022.944201. URL: https://www.frontiersin.org/articles/10.3389/fmech.2022.944201.

[37] Hengbing Zhao, Andrew Burke, and Lin Zhu. “Analysis of Class 8 Hybrid-Electric Truck Technologies Using Diesel, LNG, Electricity, and Hydrogen, as the Fuel for Various Applications”. In: Nov. 2013. DOI: 10.1109/EVS.2013.6914957.

[39] Ainun Rahmania and Widodo W. Purwanto. “Simulation of boil-off gas effect along LNG supply chain on quantity and quality of natural gas”. In: *AIP Conference Proceedings* 2223.1 (Apr. 2020), p. 040004. ISSN: 0094-243X. DOI: 10.1063/5.0000853. eprint: https://pubs.aip.org/aip/acp/article-pdf/doi/10.1063/5.0000853/14210012/040004_1_online.pdf. URL: https://doi.org/10.1063/5.0000853.

[40] Amir Sharafian, Omar E. Herrera, and Walter Mérida. “Performance analysis of liquefied natural gas storage tanks in refueling stations”. In: *Journal of Natural Gas Science and Engineering* 36 (2016), pp. 496–509. ISSN: 1875-5100. DOI: https://doi.org/10.1016/j.jngse.2016.10.062. URL: https://www.sciencedirect.com/science/article/pii/S1875510016308009.

[50] Benjamin J. Lobo et al. “A transient stochastic simulation–optimization model for operational fuel planning in-theater”. In: *European Journal of Operational Research* 264.2 (2018), pp. 637–652. ISSN: 0377-2217. DOI: https://doi.org/10.1016/j.ejor.2017.06.057. URL: https://www.sciencedirect.com/science/article/pii/S0377221717305982.

[51] Julia Nilsson. “A changing energy security environment–a review of alternative energy carriers for light duty vehicles”. In: *Swedish Defence University* (2023).

[52] Weidong Huang and Yi-Heng P. Zhang. “Energy Efficiency Analysis: Biomass-to-Wheel Efficiency Related with Biofuels Production, Fuel Distribution, and Powertrain Systems”. In: *PloS one* 6 (July 2011), e22113. DOI: 10.1371/journal.pone.0022113.

[53] Rafael F.F. Lemme, Edilson F. Arruda, and Laura Bahiense. “Optimization model to assess electric vehicles as an alternative for fleet composition in station-based car sharing systems”. In: *Transportation Research Part D: Transport and Environment* 67 (2019), pp. 173–196. ISSN: 1361-9209. DOI: https://doi.org/10.1016/j.trd.2018.11.008. URL: https://www.sciencedirect.com/science/article/pii/S1361920918304656.

[54] Çağatay Iris and Jasmine Siu Lee Lam. “Optimal energy management and operations planning in seaports with smart grid while harnessing renewable energy under uncertainty”. In: *Omega* 103 (2021), p. 102445. ISSN: 0305-0483. DOI: https://doi.org/10.1016/j.omega.2021.102445. URL: https://www.sciencedirect.com/science/article/pii/S0305048321000542.

[55] Amir Aghsami et al. “A bi-objective mixed-integer non-linear programming model with Grasshopper Optimization Algorithm for military-based humanitarian supply chains”. In: *Decision Analytics Journal* 10 (2024), p. 100409. ISSN: 2772-6622. DOI: https://doi.org/10.1016/j.dajour.2024.100409. URL: https://www.sciencedirect.com/science/article/pii/S2772662224000134.

[56] Mohamed Leila, Joann Whalen, and Jeffrey Bergthorson. “Strategic spatial and temporal design of renewable diesel and biojet fuel supply chains: Case study of California, USA”. In: *Energy* 156 (2018), pp. 181–195. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2018.04.196. URL: https://www.sciencedirect.com/science/article/pii/S0360544218308089.

[57] Uroš Klanšek. “A comparison between MILP and MINLP approaches to optimal solution of Nonlinear Discrete Transportation Problem”. In: *Transport* 30 (Sept. 2014), pp. 1–10. DOI: 10.3846/16484142.2014.933361.

[58] J Cole Smith and Z Caner Taskin. “A tutorial guide to mixed-integer programming models and solution techniques”. In: *Optimization in medicine and biology* (2008), pp. 521–548.

[60] Rong Qu et al. “A Survey of Search Methodologies and Automated Approaches for Examination Timetabling”. In: *Journal of Scheduling - SCHEDULING* (Jan. 2006), pp. 55–89.

[61] Shantanu Pardhi et al. “Optimal Powertrain Sizing of Series Hybrid Coach Running on Diesel and HVO for Lifetime Carbon Footprint and Total Cost Minimisation”. In: *Energies* 15 (Sept. 2022), p. 6974. DOI: 10.3390/en15196974.

[62] M. Brusstar et al. “High Efficiency and Low Emissions from a Port-Injected Engine with Neat Alcohol Fuels”. In: *SAE Technical Paper* (2002). ISSN: 0148-7191. DOI: https://doi.org/10.4271/2002-01-2743. URL: https://archive.epa.gov/otaq/technology/web/pdf/sae-2002-01-2743-v2.pdf.

[63] Ebrahim Nadimi et al. “Effects of using ammonia as a primary fuel on engine performance and emissions in an ammonia/biodiesel dual-fuel CI engine”. In: *Energy Research* 46 (2022), pp. 15347–15361. ISSN: 0148-7191. DOI: https://doi.org/10.1002/er.8235. URL: https://onlinelibrary.wiley.com/doi/full/10.1002/er.8235.

[64] G.M. Pinto et al. “Experimental investigation of performance and emissions of a CI engine operating with HVO and farnesane in dual-fuel mode with natural gas and biogas”. In: *Energy* 277 (2023), p. 127648. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2023.127648. URL: https://www.sciencedirect.com/science/article/pii/S0360544223010423.

[71] Y. Haseli. “Maximum conversion efficiency of hydrogen fuel cells”. In: *International Journal of Hydrogen Energy* 43.18 (2018), pp. 9015–9021. ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2018.03.076. URL: https://www.sciencedirect.com/science/article/pii/S0360319918308371.

[72] Rafig Babayev et al. “Hydrogen double compression-expansion engine (H2DCEE): A sustainable internal combustion engine with 60% brake thermal efficiency potential at 45 bar BMEP”. In: *Energy Conversion and Management* 264 (2022), p. 115698. ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2022.115698. URL: https://www.sciencedirect.com/science/article/pii/S0196890422004940.

Reports NLMoD

[4] DNV. *Verduurzaming logistieke brandstof Defensie*. Tech. rep. DNV, 2023.

[14] DNV. *Kwantificatie van de transportbehoefte tussen depot, kampement en veld bij gebruik van alternatieve energiedragers*. Tech. rep. DNV, 2023.

[17] DNV. *Verschillende energievormen in voertuigen*. Tech. rep. DNV, 2022.

[18] DNV. *Verhogen herbevoorradingssnelheid in het veld met alternatieve energietransport mogelijkheden*. Tech. rep. DNV, 2023.

[45] DNV. *Haalbaarheidsstudie nuclear*. Tech. rep. DNV, 2023.

Publications

[1] Ministerie van Defensie. *CV90-infanteriegevechtsvoertuig*. 2023. URL: https://www.defensie.nl/organisatie/landmacht/materieel/voertuigen/combat-vehicle-90 (visited on 10/02/2023).

[2] Ministerie van Defensie. *ROADMAP ENERGIETRANSITIE OPERATIONEEL MATERIEEL*. 2023. URL: https://www.defensie.nl/binaries/defensie/documenten/publicaties/2023/01/31/roadmap-energietransitie-materieel/202250371+_DIGITALE_Roadmap+Energietransitie.pdf (visited on 09/11/2023).

[3] TheLogisticsofLogistics.com. *Famous Logistics Quotes*. 2013. URL: https://www.thelogisticsoflogistics.com/wp-content/uploads/2013/01/Famous-Logistics-Quotes-01-02-2013.pdf (visited on 04/10/2024).

[7] U.S. Marine Corps. *MCDP1 Warfighting*. 1997. URL: https://www.marines.mil/Portals/1/Publications/MCDP%201%20Warfighting.pdf (visited on 10/24/2023).

[19] The Engineering ToolBox. *Fuels - Higher and Lower Calorific Values*. 2003. URL: https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html (visited on 02/13/2024).

[20] shradha jadhav shradha. *Hybrid Electric Vehicle Types*. 2021. URL: https://www.linkedin.com/pulse/hybrid-electric-vehicle-types-shradha-jadhav/ (visited on 03/14/2024).

[21] U.S. department of energy. *Fuel cell technologies office*. 2015. URL: https://www.energy.gov/eere/fuelcells/articles/fuel-cells-fact-sheet (visited on 03/11/2024).

[23] GenH2 Staff. *THE SECRET TO ZERO-LOSS TRANSFER*. 2024. URL: https://genh2hydrogen.com/blog/unlocking_the_secret_to_zero-loss_transfer/#:~:text=Throughout%20the%20refueling%20process%2C%20significant,%2C%20becomes%20gaseous%2C%20and%20vents. (visited on 03/14/2024).

[25] FTI Group Ltd. *Hydrogen Dispensers*. 2024. URL: https://www.fuelingtech.com/products/hydrogen-dispensers/ (visited on 03/29/2024).

[27] Anker. *LiFePO4 vs Lithium Ion Batteries: Which Is Better for Solar Generators?* 2023. URL: https://www.anker.com/blogs/others/lifepo4-vs-lithium-ion (visited on 03/27/2024).

[30] VIL. *Mobile Methanol Utilisation*. 2023. URL: https://vil.be/en/project/mobile-methanol-utilisation/ (visited on 02/02/2024).

[31] Tammy Klein. *Methanol: A Future-Proof Fuel*. 2020. URL: https://www.methanol.org/wp-content/uploads/2020/03/Future-Fuel-Strategies-Methanol-Automotive-Fuel-Primer.pdf (visited on 02/02/2024).

[33] Jari N Klüssmann et al. *Ammonia Application in IC Engines*. 2020. URL: https://iea-amf.org/app/webroot/files/file/other%20publications/Ammonia%20Application%20in%20IC%20Engines.pdf (visited on 03/16/2024).

[35] van Staveren. *Het verschil tussen HVO en fossiele diesel?* 2023. URL: https://www.staveren.nl/kennisbank-categorie/wat-is-het-verschil-tussen-hvo-en-fossiele-diesel/#:~:text=Naast%20de%20emissiereducties%20zorgt%20het,snel%20dan%20bijvoorbeeld%20fossiele%20diesel. (visited on 03/15/2024).

[36] Tyler Moore. *HVO Hydrotreated Vegetable Oil: What Changes & What Doesn't*. 2022. URL: https://axi-international.com/hvo-what-changes-and-what-doesnt/ (visited on 03/15/2024).

[38] The Climate Technology Centre and Network (CTCN). *Liquefied Natural Gas in trucks and cars*. 2012. URL: https://www.ctc-n.org/technologies/liquefied-natural-gas-trucks-and-cars (visited on 03/16/2024).

[41] Boltainer. *BOLT-40*. 2024. URL: https://boltainer.com/products/40-cont (visited on 02/28/2024).

[42] Ecosun. *The mobile solar solution for short-term projects and mobile operations*. 2024. URL: https://www.ecosuninnovations.com/en/products/mobil-wattr-solar-container (visited on 02/28/2024).

[43] Uprise Energy. *Mobile Power Station - The World's First 15kW Portable Wind Turbine*. 2024. URL: https://upriseenergy.com/ (visited on 02/28/2024).

[44] Kitepower. *Plug & Play, Mobile Wind Energy*. 2024. URL: https://thekitepower.com/ (visited on 02/28/2024).

[46] world-nuclear.org. *Small Nuclear Power Reactors*. 2023. URL: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx (visited on 11/15/2023).

[47] Hitachi Zosen Corporation. *Hydrogen Generation Systems*. 2024. URL: https://www.hitachizosen.co.jp/english/business/field/electrolytic-hydrogen/hydrogen-generator.html (visited on 02/28/2024).

[48] Green Hydrogen Systems. *HYPROVIDE® X-SERIES*. 2024. URL: https://www.greenhydrogensystems.com/ (visited on 02/28/2024).

[49] C. Kamphuis. *Lessen uit de Koude Oorlog #2*. 2023. URL: https://carre.nederlandseofficierenvereniging.nl/carr-nr-6-2023/lessen-uit-de-koude-oorlog-2 (visited on 10/02/2023).

[59] Gurobi Optimization. *Working With Multiple Objectives*. 2023. URL: https://www.gurobi.com/documentation/current/refman/working_with_multiple_obje.html (visited on 01/23/2024).

[65] CO2 emissiefactoren. *Lijst emissiefactoren*. 2024. URL: https://www.co2emissiefactoren.nl/lijst-emissiefactoren/ (visited on 03/05/2024).

[66] The Methanol Institute. *carbon footprint of methanol*. 2022. URL: https://www.methanol.org/wp-content/uploads/2022/01/CARBON-FOOTPRINT-OF-METHANOL-PAPER_1-31-22.pdf (visited on 03/28/2024).

[67] Institute for Basic Science. *New technology to make charging electric cars as fast as pumping gas*. 2022. URL: https://www.ibs.re.kr/cop/bbs/BBSMSTR_000000000738/selectBoardArticle.do?nttId=21132&pageIndex=1&searchCnd=&searchWrd= (visited on 04/05/2024).

[68] Daniel Bleakley. *Scientists hail new battery with 4 times energy density of lithium-ion*. 2023. URL: https://thedriven.io/2023/04/03/scientists-hail-new-battery-with-4-times-energy-density-of-lithium-ion/ (visited on 03/29/2024).

[69] Lauren Nagel. *What is the Average Efficiency of an Electric Motor*. 2023. URL: https://www.tytorobotics.com/blogs/articles/what-is-the-average-efficiency-of-an-electric-motor (visited on 03/28/2024).

[70] Paul McClure. *Ultra-high density hydrogen storage holds twice as much as liquid H2*. 2024. URL: https://newatlas.com/energy/high-density-hydrogen-storage/#:~:text=They%20found%20that%20Mg(BH,you%20get%20from%20solid%20hydrogen. (visited on 03/28/2024).

[73] dieselnet. *Weichai launches a 52% BTE diesel, 54% BTE natural gas engine*. 2022. URL: https://dieselnet.com/news/2022/11weichai.php (visited on 03/28/2024).

[74] GHG Protocol. *A Calculation Tool for GHG Emissions from Fuel Use*. 2011. URL: https://ghgprotocol.org/sites/default/files/Emission_Factors_from_Cross_Sector_Tools_March_2017.xlsx (visited on 04/08/2024).

A
Output Files

A.1. Baseline diesel

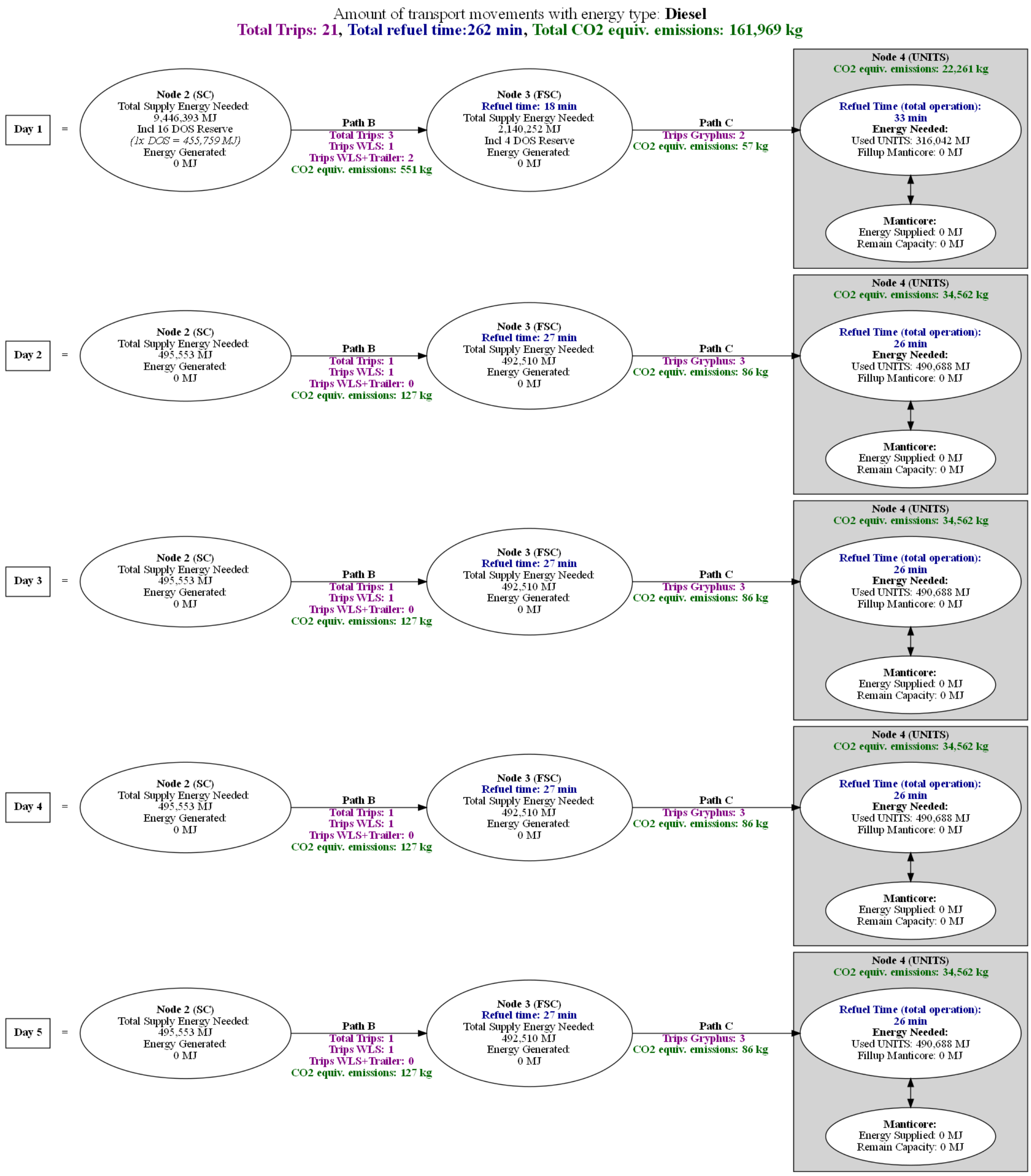

Figure A.1: Results for baseline diesel for policy P1

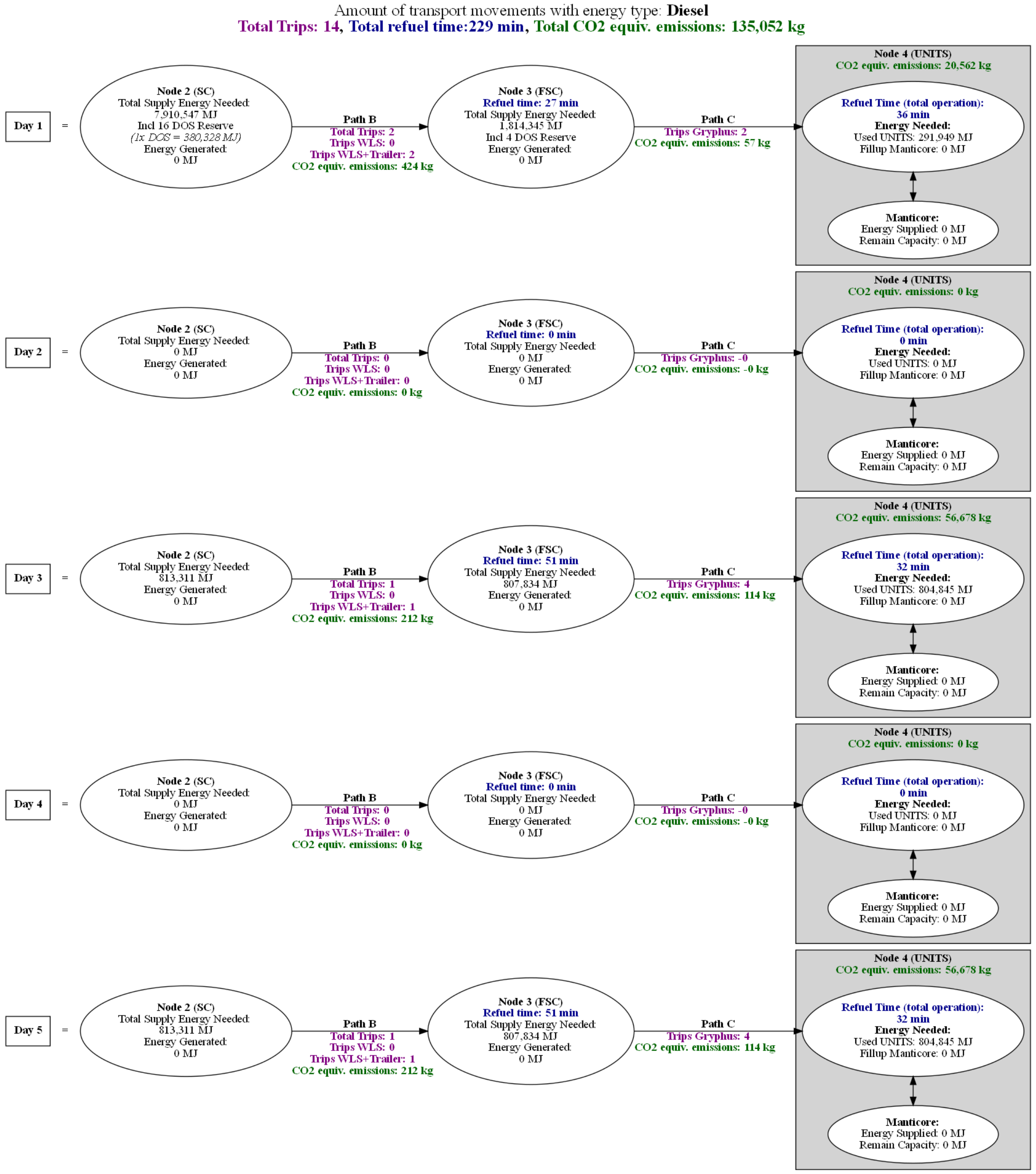

Figure A.2: Results for baseline diesel for policy P1.A

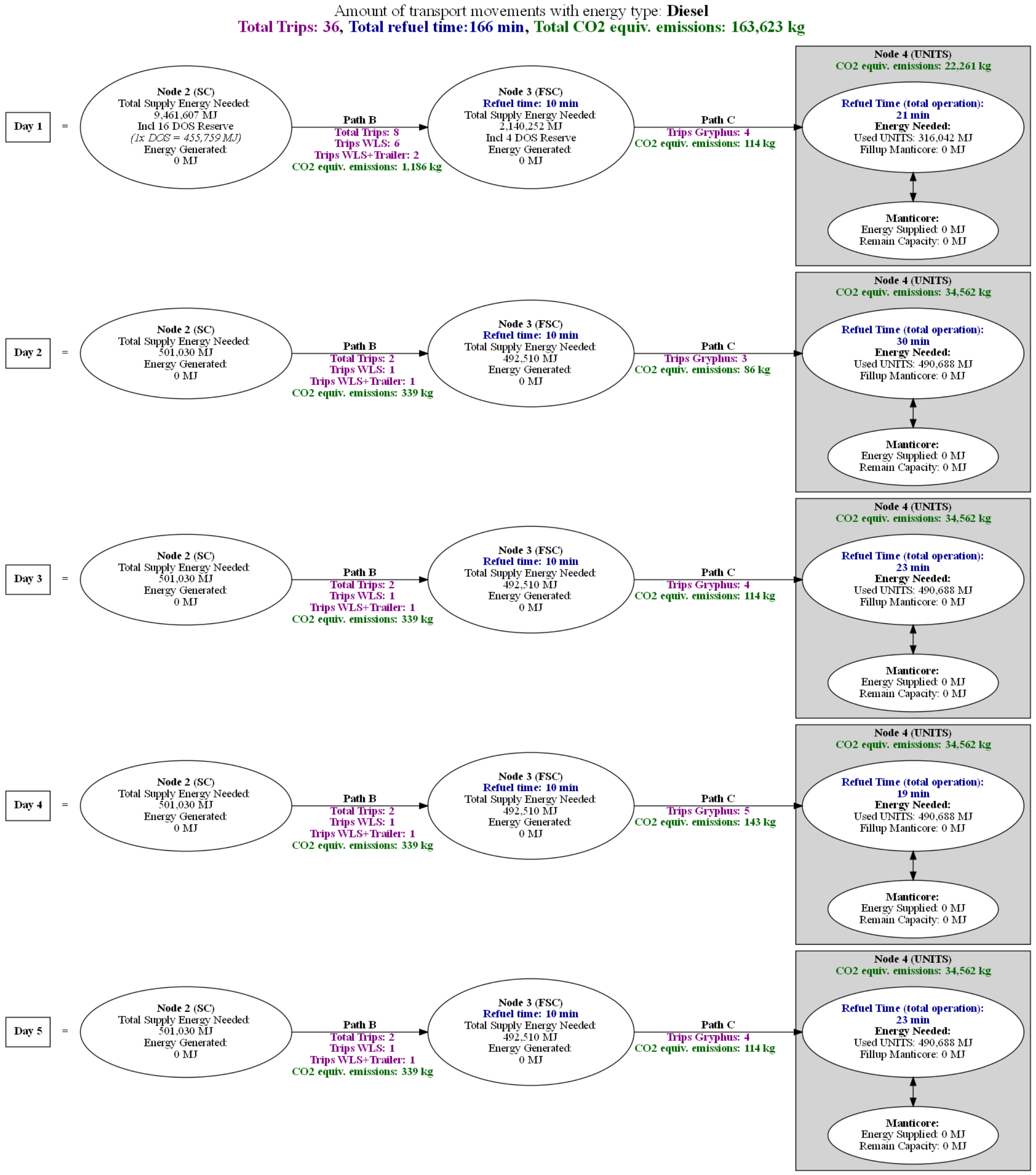

Figure A.3: Results for baseline diesel for policy P1.B

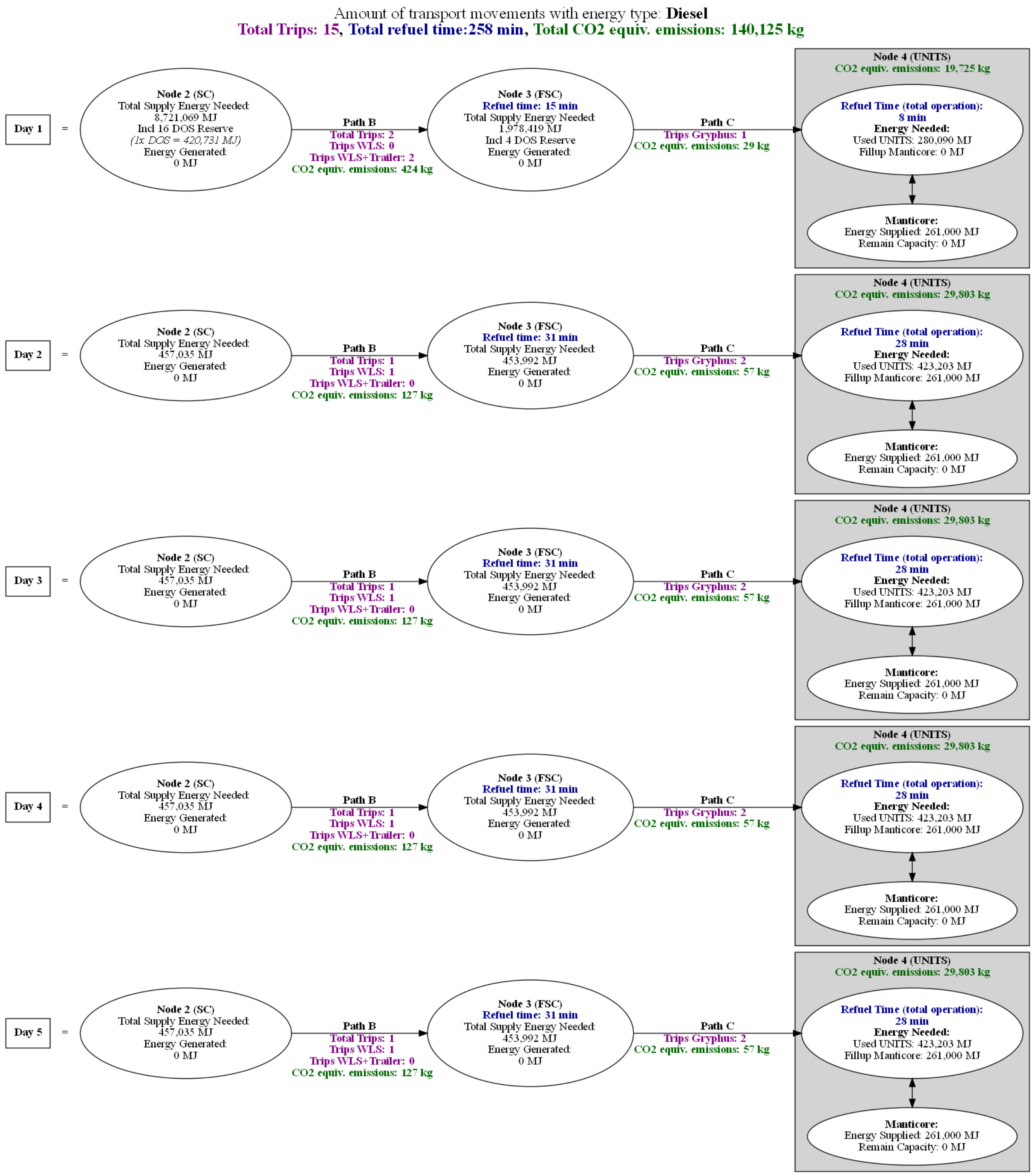

Figure A.4: Results for baseline diesel for policy P2

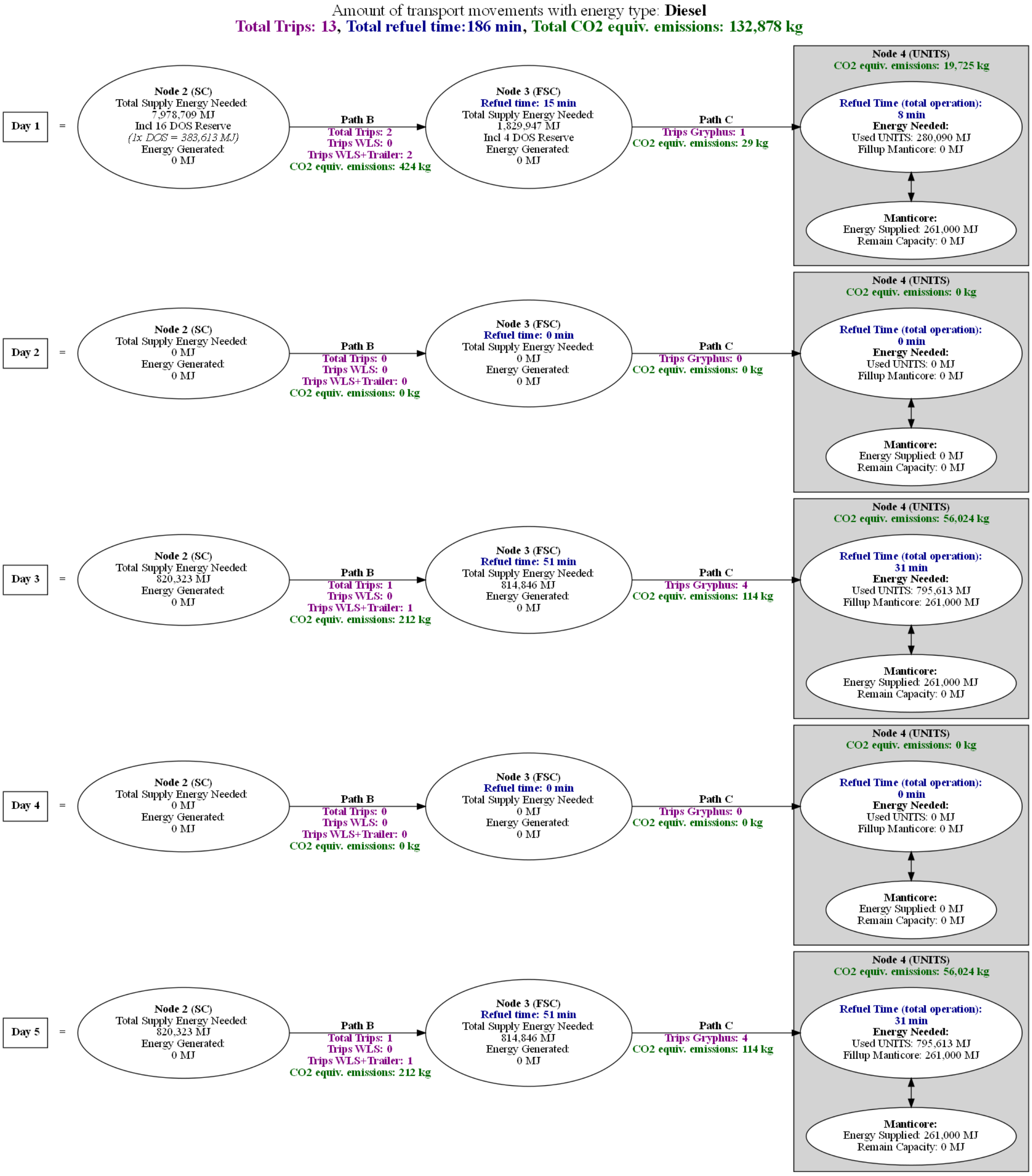

Figure A.5: Results for baseline diesel for policy P2.A

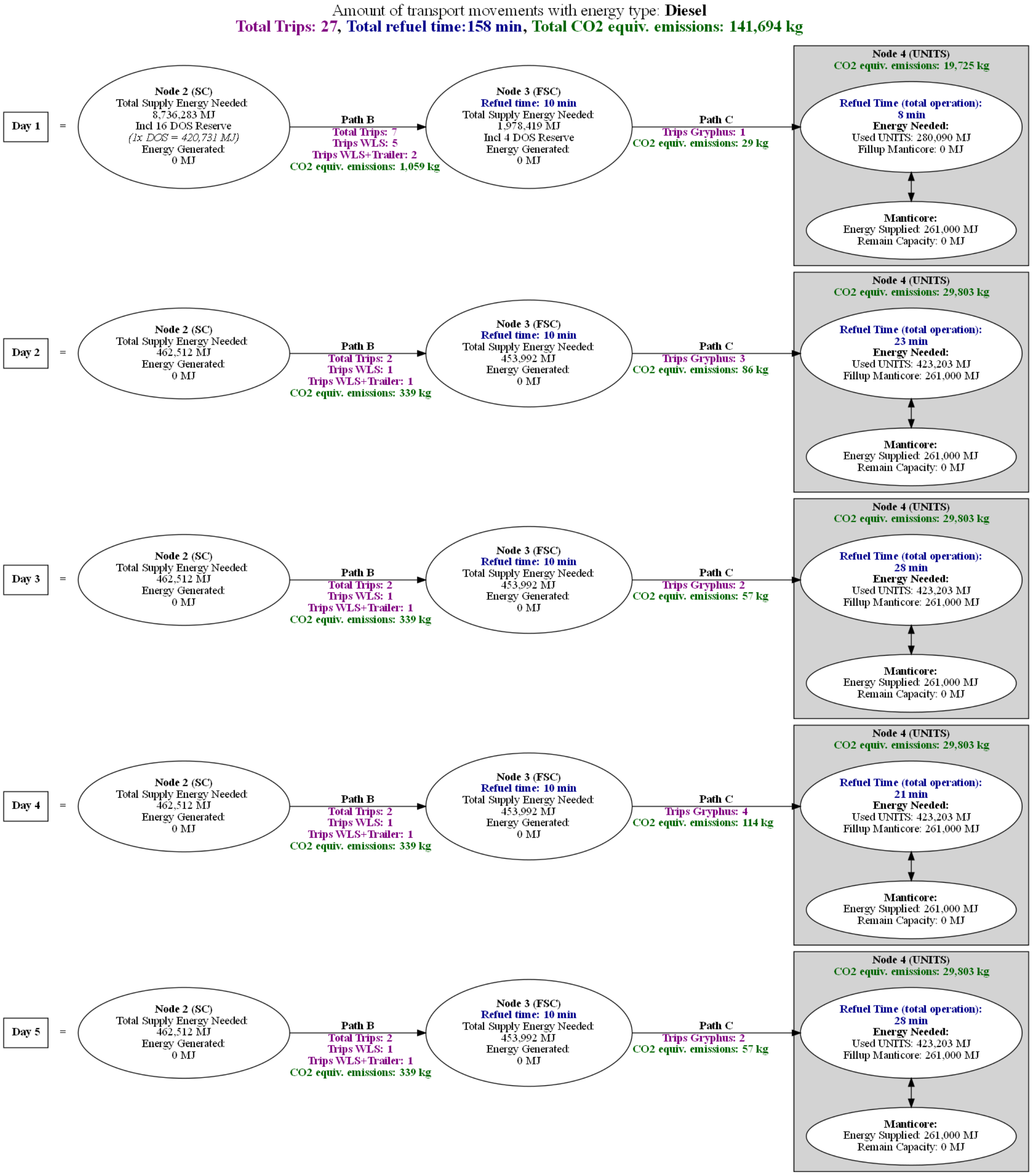

Figure A.6: Results for baseline diesel for policy P2.B

A.2. P1

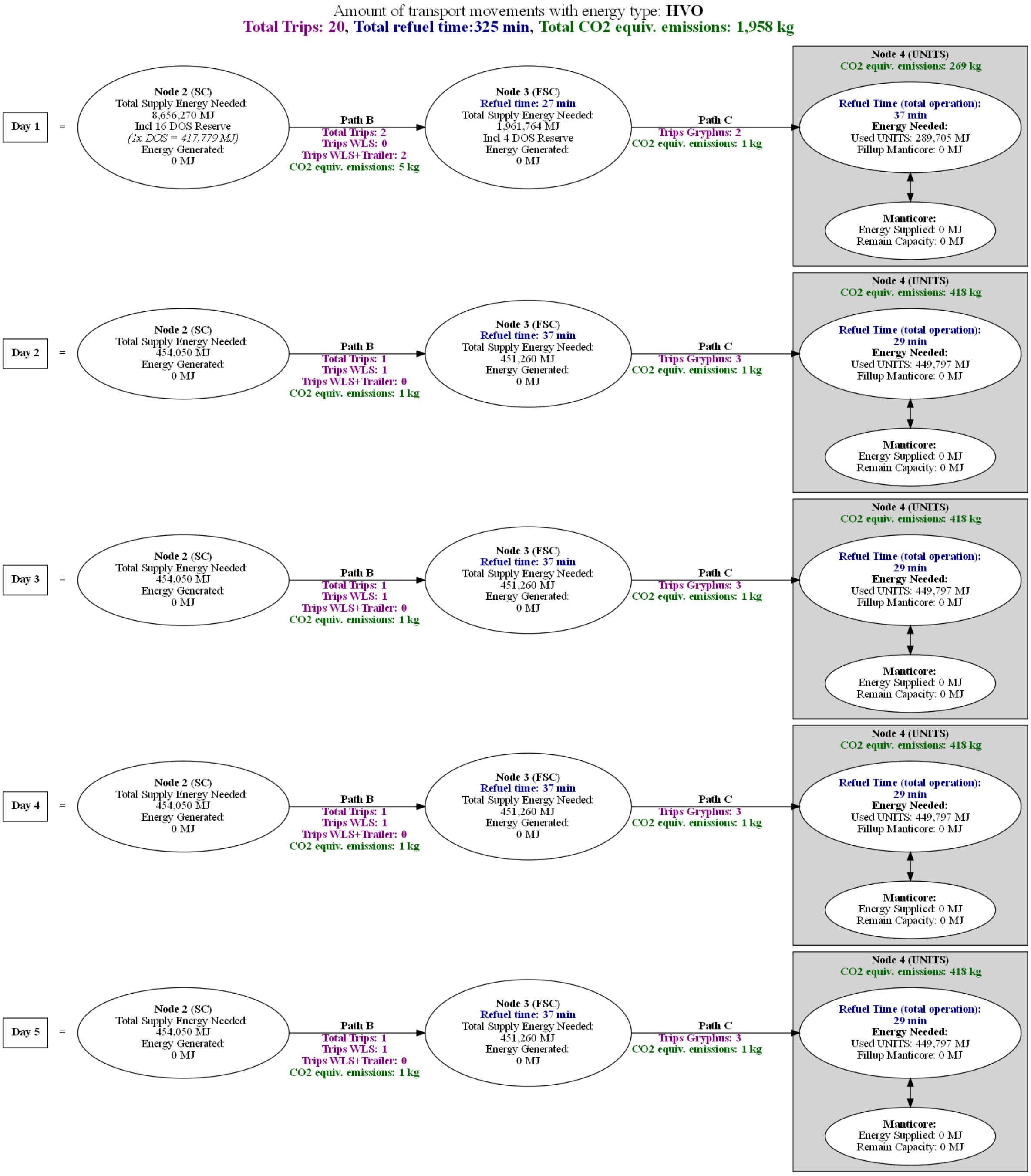

Figure A.7: Results policy P1

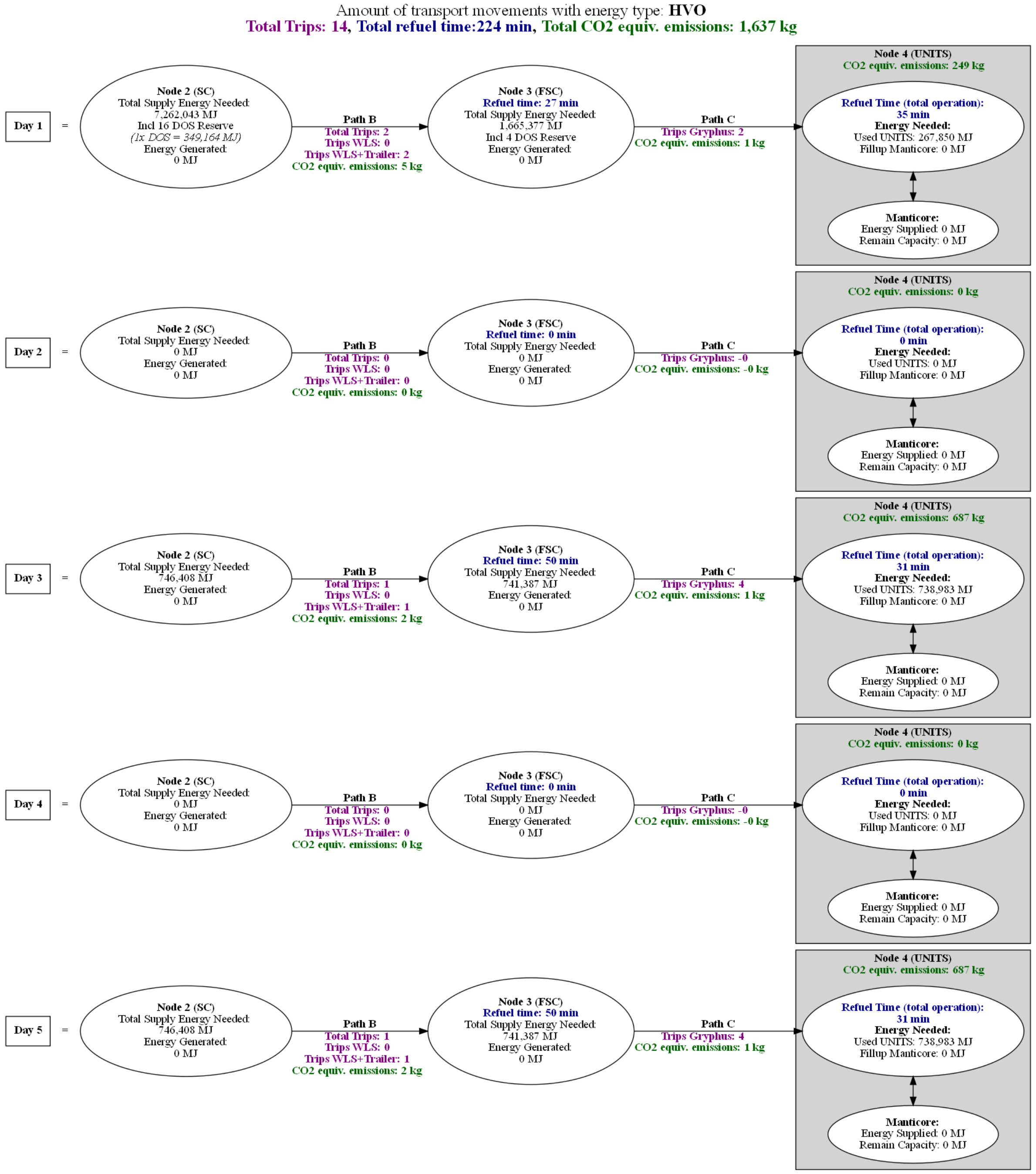

Figure A.8: Results policy P1.A

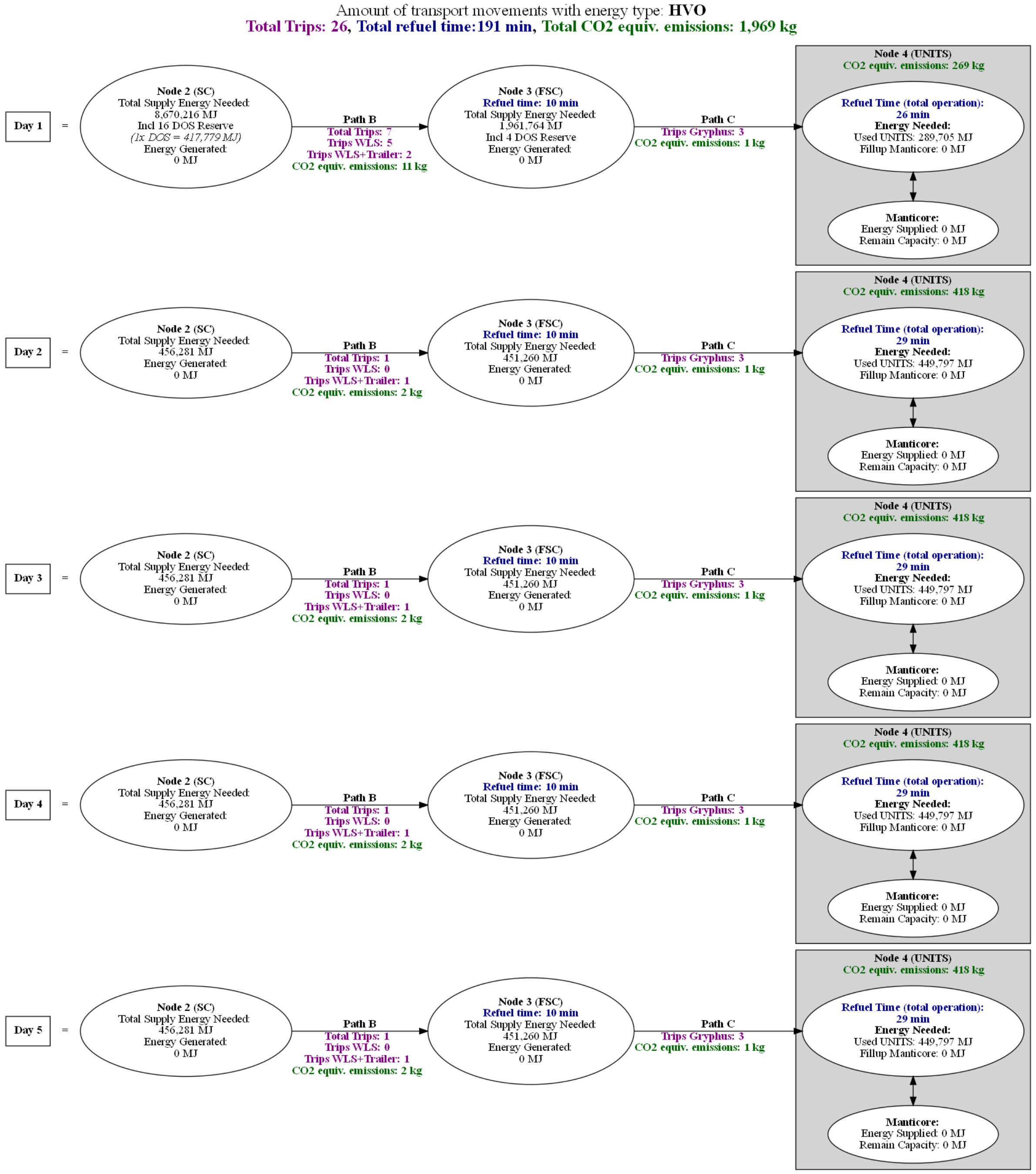

Figure A.9: Results policy P1.B

A.3. P2

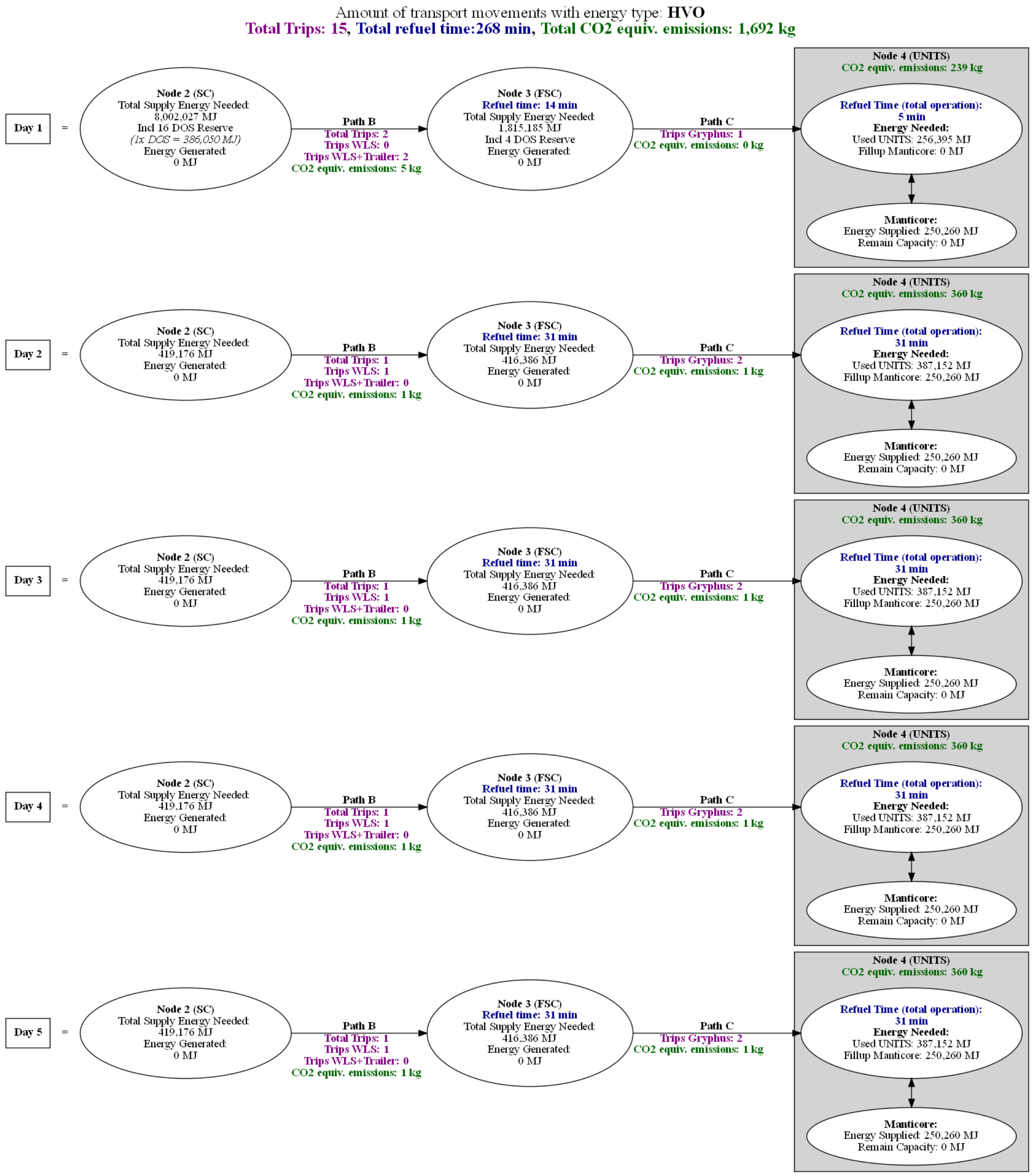

Figure A.10: Results policy P2

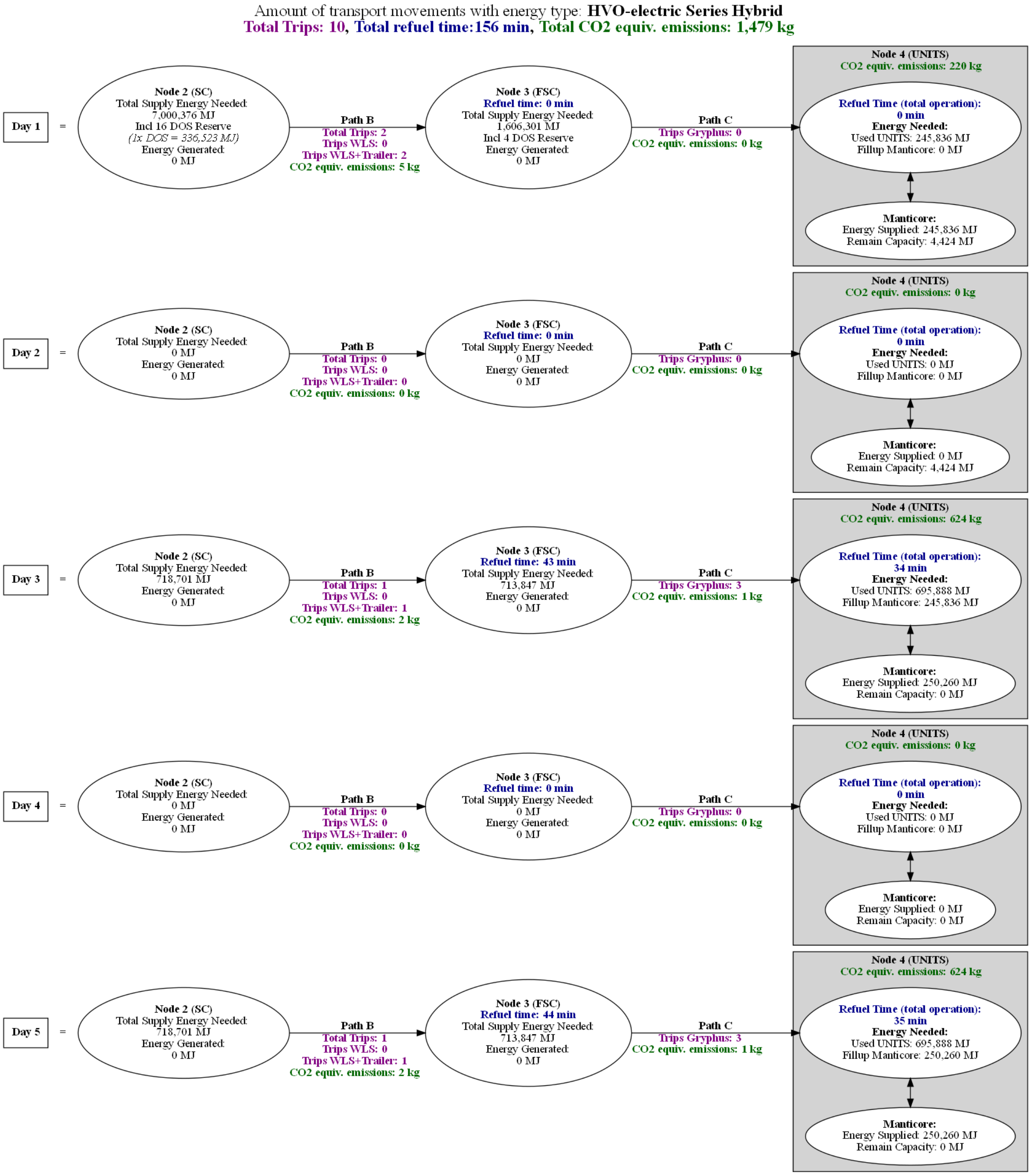

Figure A.11: Results policy P2.A

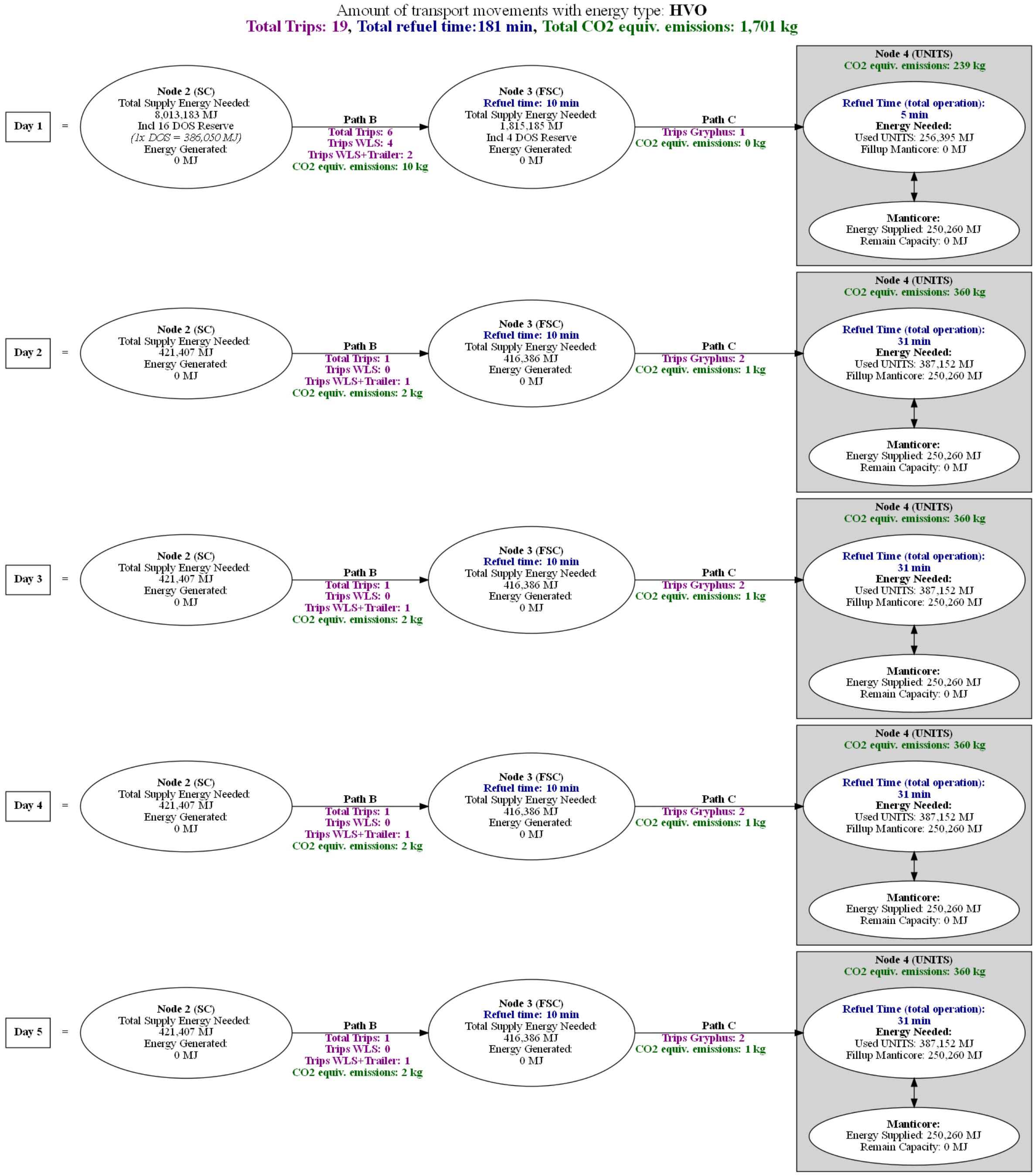

Figure A.12: Results policy P2.B

A.4. P3

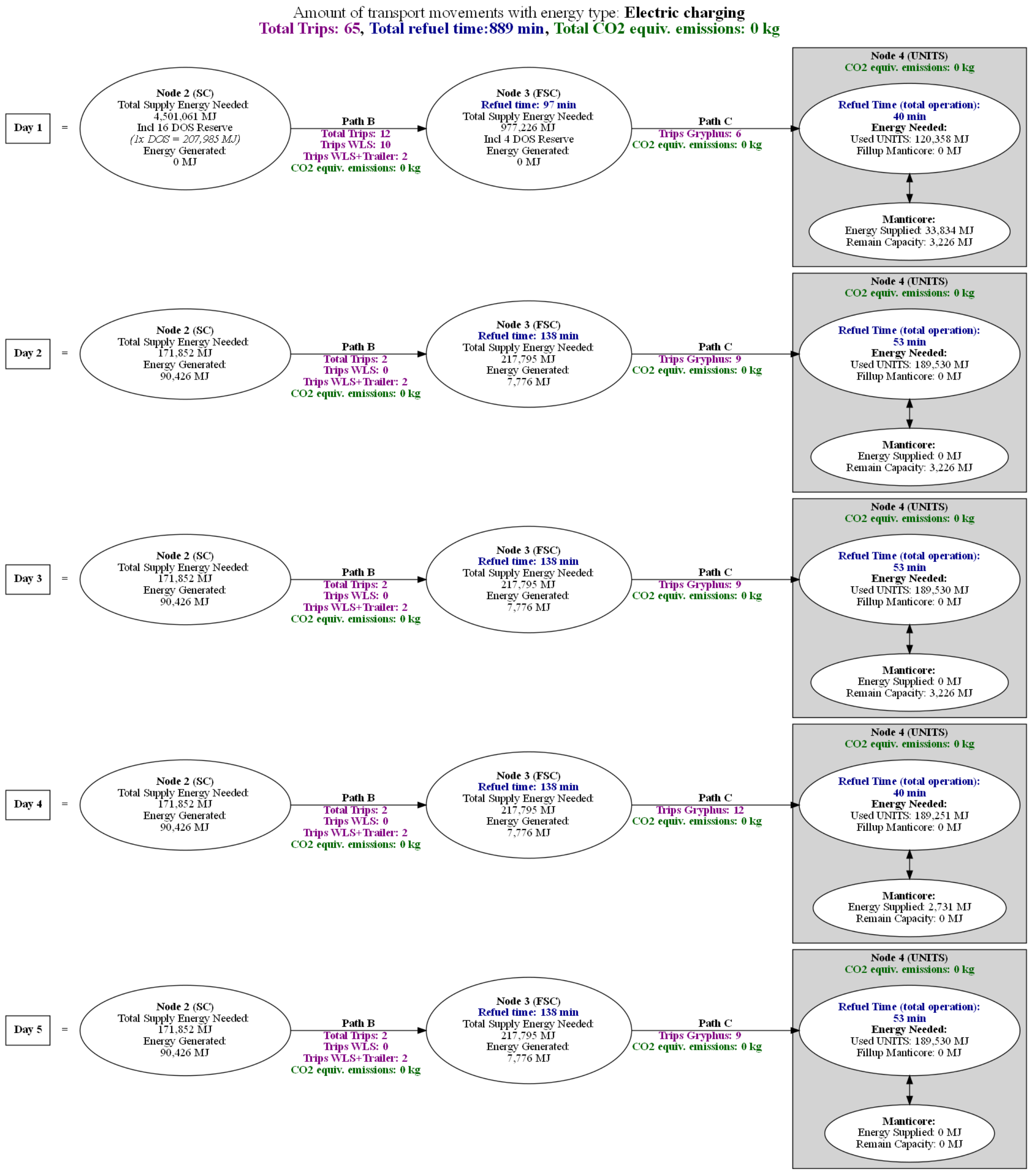

Figure A.13: Results policy P3 with maximal energy density for electric charging

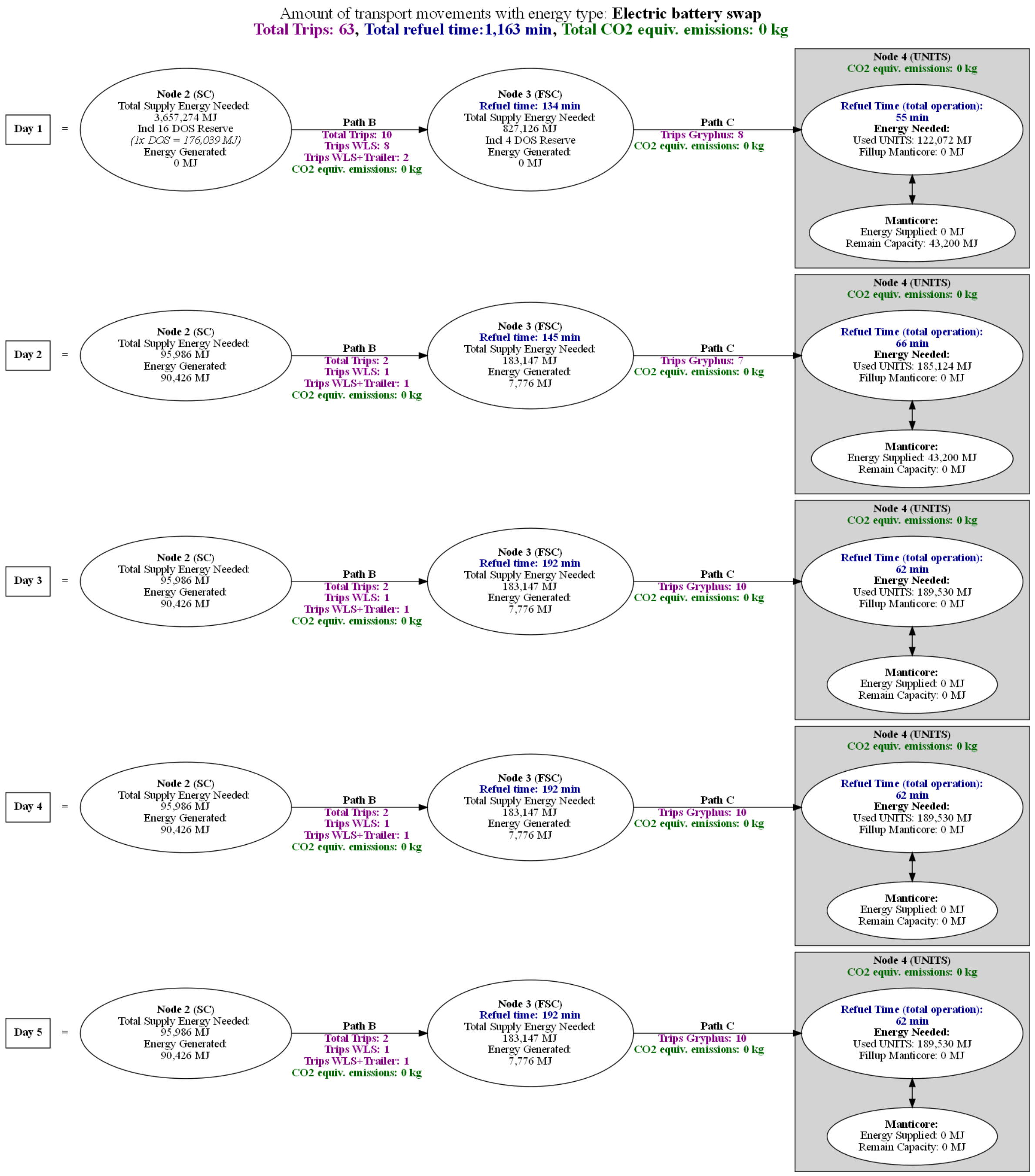

Figure A.14: Results policy P3 with maximal energy density for electric battery swap

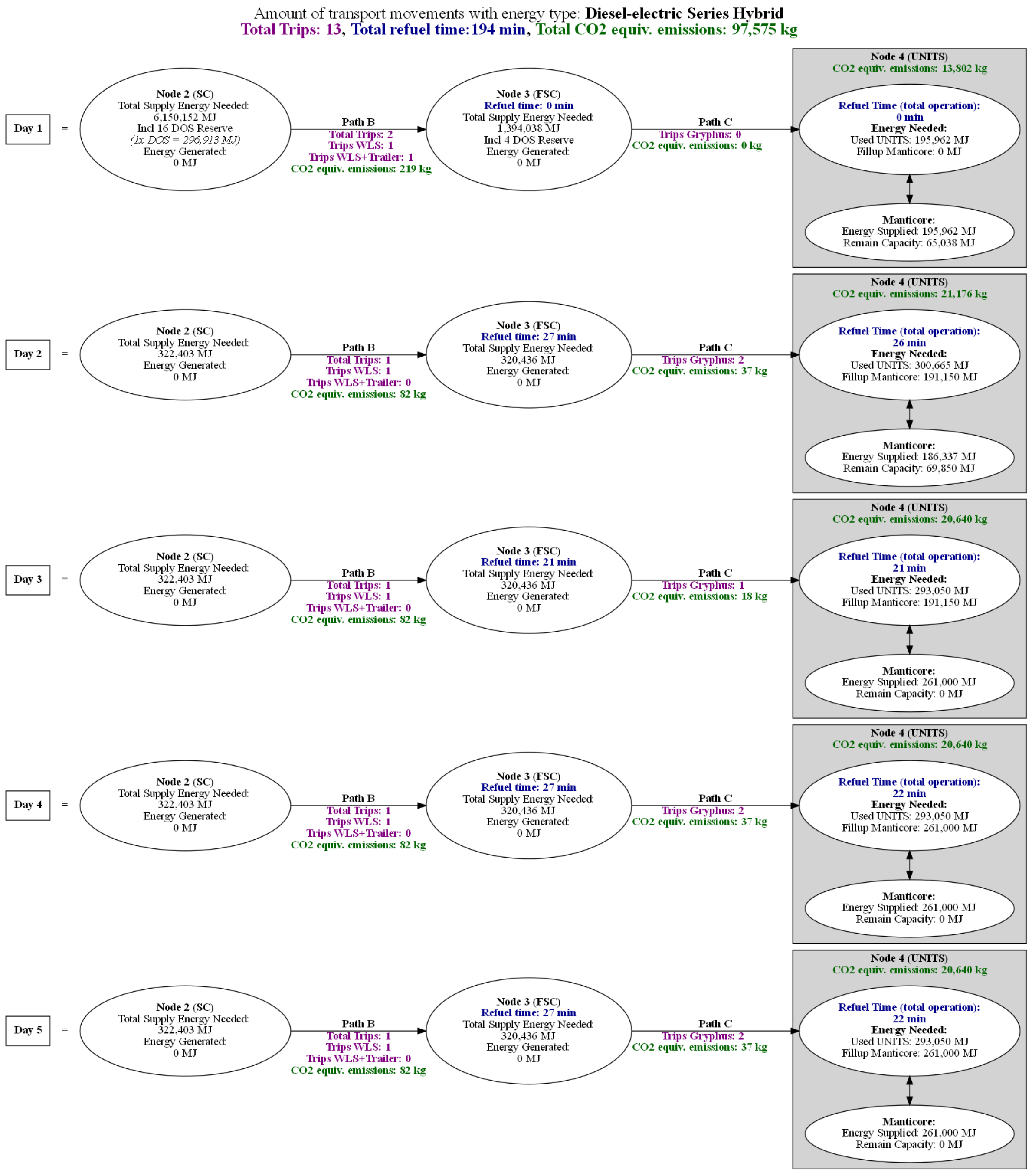

Figure A.15: Results policy P3 with maximal FTW efficiency for diesel-electric

B

Validation data

Vehicle type	Time
VW Amarok	32 sec, 17 sec, 28 sec, 35 sec
Leopard 2 MBT	58 sec, 86 sec, 66 sec, 35 sec
Scania WLS	18 sec, 25 sec
Boxer	45 sec, 26 sec
Fuel container	4 min 21 sec, 3 min 58 sec
Average time vehicles	39 sec
Average time fuel container	4 min 10 sec

Table B.1: The time it takes for a vehicle to start moving until the fuel dispenser is in the fuel tank for different vehicle types

C

Paper

Impact of different energy types of military vehicles on the supply chain

M.W. van Maldegem

The Dutch Ministry of Defence aims to reduce fossil fuel dependency by 70% by 2050 compared to 2010, with research focusing on transitioning diesel vehicles and weapon platforms to alternative energy sources, yet overlooking their impact on the Military Supply Chain. A Mixed Integer Linear Programming model has been developed to assess the Military Supply Chain impact of energy types, minimizing refuel time, supply trips, and CO2 emissions. The model integrates APUs, energy generation at Nodes, small supply trucks as buffers, compatible materials, and longer self-sufficiency times across various policies, revealing that energy types with lower CO2 emissions often have longer refuel times and more supply trips, highlighting the trade-offs inherent in transitioning energy sources within the military context. The results show that HVO and HVO-electric hybrids have the least impact on the Military Supply Chain. Hydrogen and electric energy types require substantial improvements in density, fill speed, and efficiency to match diesel results.

I. Introduction

Military operations heavily rely on energy consumption across various sectors, including living facilities, communication, logistics, vehicles, and weapon platforms, predominantly fueled by diesel. The Dutch Ministry of Defense (NLMoD) has committed to reducing fossil fuel dependency, with a targeted reduction of 70% by 2050 compared to 2010 [1]. To achieve this goal, the NLMoD is exploring the transition of military vehicles and weapon platforms to alternative energy sources such as electric or sustainable fuels. This transition must not compromise operational effectiveness but has the potential to offer tactical advantages such as reduced heat signatures and safer operations. However, the impact of these energy transitions on the Military Supply Chain (MSC) remains inadequately understood, necessitating comprehensive research.

Within the NLMoD, the Materiel and IT Command (COMMIT) focuses on developing modern, robust, and safe materiel, and for this case particularly in the realm of alternative energy for ground-based weapon platforms. While various projects explore alternative energy sources, the holistic impact on the MSC is overlooked. Understanding this impact is crucial, given the centrality of supply in military operations and the current MSC tailored to diesel distribution.

The evolving threat landscape, exemplified by the war in Ukraine, underscores the need to reassess MSC's for warfighting scenarios, which demand greater mobility and flexibility. This research looks at the MSC in warfighting conditions. Warfighting is defined as a violent clash between military forces of nation states, international coalitions or factions [2]. COMMIT currently lacks a quantitative method to assess the impact of energy types on the MSC, necessitating the development of a scientific tool for informed decision-making.

Hence, this paper aims to develop a model to evaluate the impact of alternative energy types on the MSC, specifically focusing on tactical military vehicles and weapon platforms. By identifying the energy type with the lowest impact on the MSC, this research seeks to provide actionable insights for COMMIT. The research question guiding this endeavor is: W*hat is the impact of alternative energy types of tactical military vehicles on the military supply chain, and what would be the optimal energy type?*

II. Methodology

To address the research question, the methodology involves several steps. Firstly, a comprehensive review of the current state of the art and literature is conducted to gain insights into the MSC, methods of measuring its impact, potential energy types applicable to the model, and to collect data on MSC components and NLMoD vehicles. This phase incorporates desk research and on-site data collection conducted by various stakeholders such as the knowledge center logistics, military supply units, and COMMIT.

Secondly, a Vehicle Energy Supply Chain (VESC) model with multiple objectives is developed. This model integrates features of the current MSC and introduces various enhancements. These enhancements are examined within different policy scenarios. The VESC model utilizes a Mixed-Integer Linear Programming (MILP) approach, a well-established method for linear supply models [3].

Thirdly, a case study is conducted. Initially, all policies are analyzed using the current energy source, diesel. Subsequently, each policy is reassessed with all energy types considered in this study.

Finally, the findings from the case study are analyzed and conclusions are drawn based on the results.

III. State of the Art and Literature

A. Military Supply Chain

This section outlines the MSC and its doctrines according to the NLMoD manuals LAND-LOG-SUPPLY-01 and HB 7-00 D2 [4] [5]. Unlike the NATO standard, the Dutch Supply & Transport Command operates with centralized control due to limited capacity. Nevertheless, temporary decentralized logistics are possible for operational units to enhance independence and sustainability.

This study concentrates on Class III (Fuel, oils and lubricants). Diesel is the current energy carrier for vehicles in the NLMoD. The MSC has four types of movement: national, strategic, operational, and tactical. The tactical movement, detailed in Figure 1, from the Supply Centre (SC) to manoeuvre unit delivery points, is the research focus. This movement encompasses preparation, execution, and reorganization phases, with various supply methods, including Forward Supply Centres (FSCs).

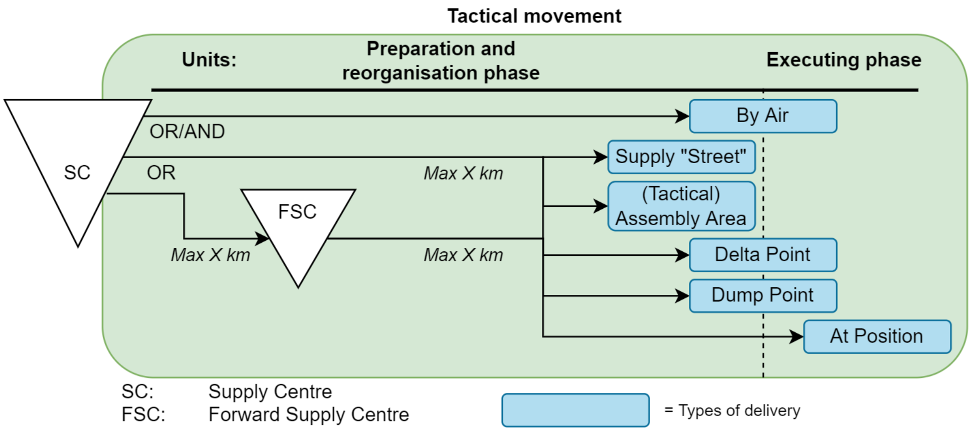

Figure 1. Tactical MSC for Class III which is based on manual HB 7-00 D2 [5]

The logistics for warfighting differ from peace keeping missions, with peace keeping missions involving mostly static SCs and bases of operation, while warfighting demands mobility. Fuel transport relies on Scania 165 kN WLS trucks, Scania Gryphus 100 kN vehicles and yet to be implemented IVECO Manticore 20kN small supply truck. Their fuel containers are not compatible with each other. The fuel consumption is calculated by the Compensation Fuel Consumption calculations (Dutch abbreviation CVV), see Equation 1. BVE is the sum of all vehicles fuel consumption for 100 km drive or 24 hours of operation in normal conditions and these are multiplied by Intensity Factors (IF). This aid in fuel reserve planning but lack adaptability to real-time conditions. Units submit Functional Control reports to request supplies, ensuring efficient supply. In operational scenarios, units often request fuel based on experience rather than relying on calculation sheets.

$$CVV^{movement} = \frac{BVE^{Unit} * IF^{Terrain} * IF^{Weather} * IF^{Movement\ type} * Distance(km)}{100}$$
$$CVV^{combat} = \frac{BVE^{Unit} * IF^{Terrain} * IF^{Weather} * IF^{Combat\ type} * Time(Hours)}{24} \tag{1}$$
$$CVV^{stand\text{-}by} = \frac{BVE^{Unit} * IF^{stand\text{-}by} * Time(Hours)}{24}$$

B. Potential Energy Types

This section explores alternatives to fossil diesel fuels for military vehicles, guided by specific criteria:

1) Suitability for heavy military vehicles without compromising space making the vehicle obsolete;
2) Lower CO2 emissions compared to diesel;
3) Future availability in international civil and military markets.

Energy carriers selected for the VESC model are based on previous research by DNV, meeting the same criteria [6] [7] [8] [9]. The energy types used are: diesel-electric series hybrid, hydrogen 700 bar fuel cell and ICE, electric battery swap and charging, methanol, ammonia, HVO and LNG. While this research doesn't delve deeply into vehicle-specific conversion devices, it relies on general assumptions and figures from literature and NLMoD reports. Only energy carriers deemed promising by literature and COMMIT's ongoing investigations are included in the VESC model.

Some energy types can be produced on-site within the MSC instead of being transported from the beginning of the supply line. These are energy types that require potentially no regular transport between suppliers and the SC. Additionally, the technology required for energy generation should be compatible with a standard 20 ft or 40 ft shipping container for easy transport. The energy types that meet these criteria include electricity battery swap and charging, as well as hydrogen.

C. Literature

Lobo et al. (2018) [10] developed a simulation-optimization model for class III fuel management in theater, focusing solely on current workflows without considering future alternative energy options. Mansfield et al. (2021) [11] provided an extensive review of present and near-future energy carriers for military vehicles, highlighting diesel and gasoline as optimal choices based on powertrain mass and energy carrier volume. Hybrid diesel-electric with NI-MH batteries emerged as a promising alternative. Nilson (2023) [12] conducted similar research on alternative energy carriers for light-duty vehicles for the Swedish Defence forces, emphasizing market availability challenges.

Combining supply chain management with alternative energy carriers allows for optimization models focusing on cost and emissions reduction. Lemme et al. (2019) [13] optimized vehicle fleets in car-sharing systems, prioritizing cost while considering pollution. Iris and Siu Lee Lam (2021) [14] developed an optimization model for energy management, emphasizing cost savings through renewable energy use.

While specific research on managing and optimizing MSCs for alternative energy vehicles and weapon platforms is lacking, existing literature offers insights into military-based humanitarian supply chain optimization (Agshami et al., 2024) [15] and the military use of drop-in biofuels to reduce carbon emissions (Leila et al., 2018) [3].

IV. Model

The optimization problem discussed in this research is well-suited for formulation as a MILP problem, which is a subset of MIP along with Mixed-Integer Nonlinear Programming (MINLP). MILP handles both discrete and continuous variables and is commonly used in supply chain management for cost optimization. While MINLP can handle nonlinear relationships, it's less efficient due to computational complexity [16]. To mitigate long computation times, nonlinear terms can be linearized, enabling MILP utilization. MILP models typically focus on minimizing costs but can accommodate multiple objectives simultaneously, such as is the case in the VESC model.

A. Math Model

This section presents and elaborates upon the mathematical expressions for the objective functions and constraints utilized in the VESC model. An overview of all three objective functions is given in Figure 2.

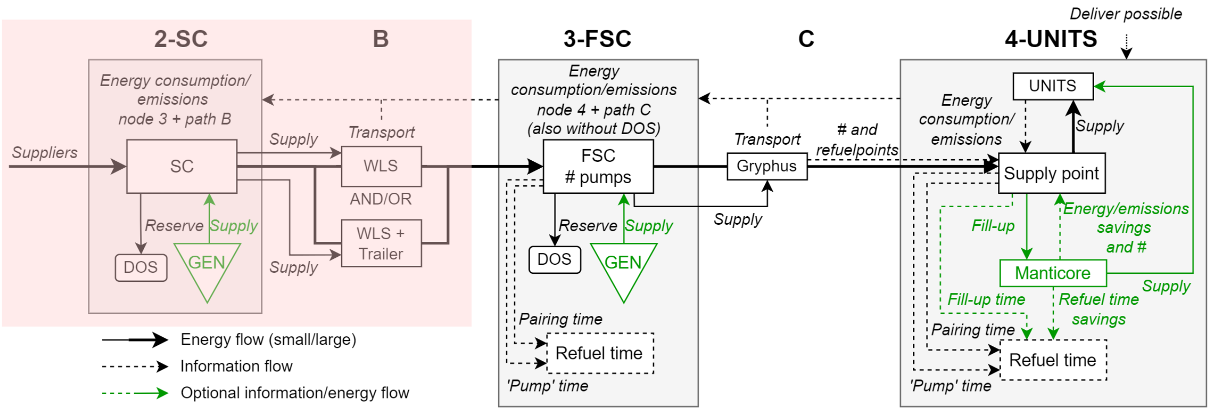

Figure 2. Total overview of all three objective functions. The refuel time is not calculated for the highlighted red part. The model has three Nodes (2-4) and two Paths (B,C).

The VESC model includes three objective functions for optimization. A list of all sets, parameters, and decision variables is given in subsection VII.A. Following that, One objective is to minimize supply movements for paths B and C. Equation 2 calculates this objective by summing the total supply trips for paths B and C per day and energy type. Binary decision variables determine the energy type. The number of trips for path C is computed by dividing the required supply energy for Node 4 by Gryphus capacity, rounded up. Required energy at Node 4 is the consumption minus energy supplied by Manticores, plus Manticores' fill-up energy, minus saved vehicle consumption. Manticores' energy supply and fill-up are decision variables. Trips for path B are pre-calculated in parameter tr^B_{ti}, with binary variables choosing the optimal energy type.

$$MIN \sum_{t\in D}\sum_{i\in C}[Sn^4_{ti} \cdot \left\lceil \frac{fc^4_{ti} - En^{mant}_{ti} + Fi^{mant}_{ti} - \frac{En^{mant}_{ti} \cdot fcv^{to\_sup}_{ti} \cdot 2}{avfc^{vehicle}_{ti}}}{tc^{gry}_{i}} \right\rceil + Sn^3_{ti} \cdot tr^B_{ti}] \tag{2}$$

Another objective function aims to minimize the total refuel time at Nodes 3 and 4. Equation 3 calculates this as the sum of refuel times for all vehicles and weapon platforms at Node 4, plus the refuel time for Gryphus supply trucks at Node 3. This refuel time represents the duration these trucks are stationary at either Node 3 or Node 4.

The objective function consists of two parts, each calculating refuel time for Nodes 4 and 3, respectively, with their binary decision variables determining the optimal energy type. At Node 4, refuel time is divided into four parts: pumping/charging energy from Gryphus trucks to vehicles, filling up Manticores, vehicle-truck pairing time, and truck setup time. Similar calculations are conducted for Node 3, including energy transfer, vehicle-truck pairing, and setup time.

The refuel time, represented in minutes, does not consider the energy supply method at Node 2 due to its variability and less critical nature compared to Nodes 3 and 4. Additionally, for electric charging, the calculation uses tr_{ti}^{B} instead of am^{pumps}, as each WLS energy container has its charging station.

$$MIN \sum_{t \in D} \sum_{i \in C} \Bigg[Rt_{ti}^{4} \cdot \Bigg(\Bigg(\frac{fc_{ti}^{4} - En_{ti}^{mant} - \frac{En_{ti}^{mant} \cdot fcv_{ti}^{to\_sup} \cdot 2}{avfc_{ti}^{vehicle}}}{av_{i}^{rt}} \cdot \frac{1}{rp_{ti}^{Node4}} \Bigg) + \Bigg(\frac{Fi_{ti}^{mant}}{av_{i}^{rt}} \cdot \frac{1}{am_{ti}^{gr\_ma} \cdot rp_{i}^{gry}} \Bigg) + \Bigg(\frac{fc_{ti}^{4} - En_{ti}^{mant} - \frac{En_{ti}^{mant} \cdot fcv_{ti}^{to\_supply} \cdot 2}{avfc_{ti}^{vehicle}}}{avfc_{ti}^{vehicle}} \cdot \frac{rt_{ti}^{extra}}{rp_{ti}^{Node4}} \Bigg) + rt^{extra4} \cdot del_{ti}^{4} \Bigg) + Rt_{ti}^{3} \cdot \Bigg(\Bigg(\frac{fc_{ti}^{3.1} - En_{ti}^{mant} + Fi_{ti}^{mant} - \frac{En_{ti}^{mant} \cdot fcv_{ti}^{to\_sup} \cdot 2}{avfc_{ti}^{vehicle}}}{pu_{i}^{debit}} \cdot \frac{1}{am^{pumps}} \Bigg) + \left\lceil \frac{fc_{ti}^{4} - En_{ti}^{mant} + Fi_{ti}^{mant} - \frac{En_{ti}^{mant} \cdot fcv_{ti}^{to\_sup} \cdot 2}{avfc_{ti}^{vehicle}}}{tc_{i}^{gry}} \right\rceil \cdot \frac{rtp_{i}^{extra}}{am^{pumps}} \Bigg) + rt^{extra3} \cdot del_{ti}^{4} \Bigg] \tag{3}$$

The final objective function minimizes CO2 equivalent emissions, Equation 4, comprising three components. Firstly, emissions related to UNITS at Node 4 are calculated, then adjusted to account for reduced emissions due to Manticores supplying UNITS directly. Secondly, emissions from Gryphus supply trucks are determined by multiplying the number of Gryphus trips by emissions per trip. Lastly, emissions from WLS and WLS+trailer for path B are calculated similarly to Gryphus emissions. A decision variable, multiplied by all three parts, identifies the energy type with the lowest CO2 equivalent emissions.

$$MIN \sum_{t \in D} \sum_{i \in C} \Bigg[Em_{ti} \cdot \Bigg(\Bigg(ec_{ti}^{4} - \frac{En_{ti}^{mant}}{avfc_{ti}^{vehicle}} \cdot av_{ti}^{emissions} \cdot 2 \Bigg) + \Bigg(\left\lceil \frac{fc_{ti}^{4} - En_{ti}^{mant} + Fi_{ti}^{mant} - \frac{En_{ti}^{mant} \cdot fcv_{ti}^{to\_sup} \cdot 2}{avfc_{ti}^{vehicle}}}{tc_{i}^{gry}} \right\rceil \cdot em_{i}^{gry} \Bigg) + tr_{ti}^{B\_WLS} \cdot em_{i}^{WLS} + tr_{ti}^{B\_WLS+tr} \cdot em_{i}^{WLS+tr} \Bigg) \Bigg] \tag{4}$$

The VESC model is subject to various constraints. The initial constraint mandates that each day, only one energy type is utilized for supply movements and refueling. NATO's "one fuel policy" necessitates uniformity in energy usage across all vehicles to simplify the MSC. As depicted in Equation 5, the daily sum of all energy types must equal one, allowing for the selection of only one energy type per day. Additionally, Equation 7 links the decision variable for emissions Sn_{ti}^{4} to this constraint.

$$\text{for } t \in \{0, 1, \ldots, \mathrm{D}\}: \quad \sum_{\mathrm{i}=0}^{\mathrm{C}} Sn_{ti}^{4} == 1 \quad , \quad \sum_{\mathrm{i}=0}^{\mathrm{C}} Rt_{ti}^{4} == 1 \tag{5}$$

Additionally, all days must utilize the same energy type, as vehicles and weapon platforms cannot switch energy types during operations. In the VESC model, the selected energy type remains constant throughout the situation. Equation 6 enforces this constraint by ensuring that the sum of all days per energy type equals the total days (D) multiplied by the value of Sn^4_{0i} or Rt^4_{0i} of the first day.

$$\text{for } i \in \{0, 1, \ldots, C\}: \quad \sum_{t=0}^{D} Sn^4 == D \times Sn^4_{0i}, \quad \sum_{t=0}^{D} Rt^4 == D \times Rt^4_{0i} \tag{6}$$

The VESC model can assess the optimal energy type for each Node or path. However, the constraint requires that ultimately, each Node or path supplies the same energy type. This is enforced in Equation 7, where all decision variables for supply movements and emissions are interconnected. While the decision variables for refuel time could also be linked to this constraint, they remain separate to allow for optimization solely for refuel time.

$$\text{for t} \in \{0, 1, \ldots, \text{D}\}, \text{for i} \in \{0, 1, \ldots, \text{C}\}:$$
$$Sn^4_{ti} == Sn^3_{ti} == Sn^2_{ti} == Em_{ti} \tag{7}$$

Constraint Equation 8 is the same as Equation 7 whereby the Nodes and path should supply the same energy type but only for the refuel time.

$$\text{for t} \in \{0, 1, \ldots, \text{D}\}, \text{for i} \in \{0, 1, \ldots, \text{C}\}:$$
$$Rt^4_{ti} == Rt^3_{ti} \tag{8}$$

Constraint Equation 9 is implemented to exclude energy types incapable of meeting the situation's demands, where the daily energy requirement exceeds the vehicles' capacity at Node 4. This constraint assigns Sn^4_{ti} a value of zero if the energy consumption surpasses the total storage capacity of the vehicles. Similarly, if supply trucks consume more energy for their round-trip than they can store, Sn^4_{ti} is set to zero. Since all other decision variables are linked to Sn^4_{ti}, this constraint applies universally. It is imposed because the VESC model operates under the condition of a single supply run every 24 hours.

$$\text{for } t \in \{0, 1, \ldots, D\}, \text{for } i \in \{0, 1, \ldots, C\}:$$
$$Sn^4_{ti} == \begin{cases} 0 & fc^4_{ti} > tot^{capacity\_vehicles}_i \,||\, cvv^{gry}_i < ft^{gry}_i \,||\, cvv^{WLS}_i < ft^{WLS}_i \\ Sn^4_{ti} & \text{otherwise} \end{cases} \tag{9}$$

Certain policies necessitate additional constraints for the use of small Manticore supply trucks at Node 4. These trucks are linked to UNITS at Node 4 and begin each day at $t = 0$ with full storage capacity. They supply energy to the units daily, with the constraint determining their maximum supply capacity and remaining energy. The remaining energy at day t is calculated based on the energy supplied and filled-up that day, relative to the previous day's remaining energy. Equation 10 illustrates this constraint, considering refuel efficiency for certain energy types. The deployment of Manticores occurs in four different ways, as depicted in Figure 3, with only the supply within the yellow box factored into the total supply time.

$$\text{for } t \in \{0, 1, \ldots, D\}, \text{for } i \in \{0, 1, \ldots, C\}:$$
$$Re^{mant}_{ti} == \begin{cases} am^{mant} \times tc^{mant}_i - \frac{En^{mant}_{ti}}{ef^{refuel}_i} & t = 0 \\ Re^{mant}_{t-1i} - \frac{En^{mant}_{ti}}{ef^{refuel}_i} + Fi^{mant}_{ti} & \text{otherwise} \end{cases} \tag{10}$$

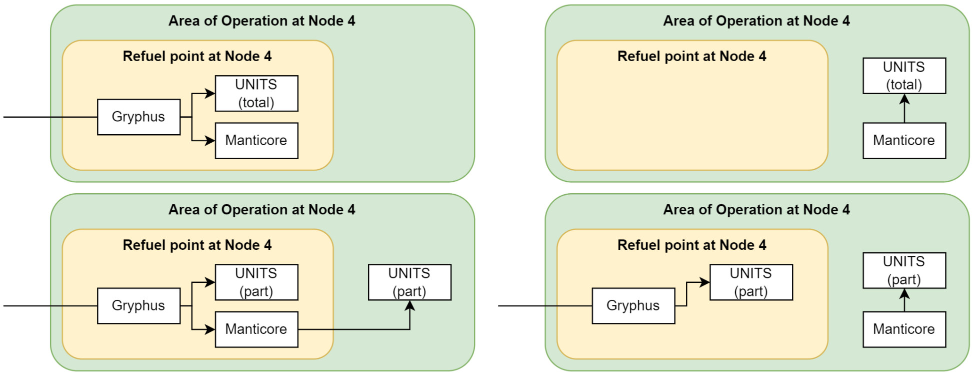

Figure 3. Schematic representation of the various deployment options of the Manticore.

The Manticore supply trucks cannot fill up or supply energy to UNITS on days when no delivery occurs. Thus, decision variables are multiplied by del_{ti}^{4} to ensure their value becomes zero on such days (Equation 11). Additionally, the fill-up capacity of Manticore trucks cannot exceed the total capacity minus the remaining energy inside them. Furthermore, the energy supplied from Manticores to UNITS on a given day cannot exceed the UNITS' energy requirement for that day.

$$\begin{aligned} &\text{for t} \in \{0, 1, \ldots, \text{D}\}, \text{for i} \in \{0, 1, \ldots, \text{C}\} : \\ &Fi_{ti}^{mant} == Fi_{ti}^{mant} \times del_{ti}^{4} \\ &En_{ti}^{mant} == En_{ti}^{mant} \times del_{ti}^{4} \\ &Fi_{ti}^{mant} <= am^{mant} \cdot tc_{i}^{mant} - Re_{ti}^{mant} \\ &En_{ti}^{mant} <= fc_{ti}^{4} - \frac{En_{ti}^{mant} \cdot fcv_{ti}^{to\_sup} \cdot 2}{avfc_{ti}^{vehicle}} \end{aligned} \tag{11}$$

B. Solver

The VESC model employs the Hierarchical Objectives approach, enabling priority assignment to objectives for optimization in decreasing order. It conducts separate optimization passes for each objective priority level, starting with the highest priority. Solutions for lower-priority objectives should ideally not compromise higher-priority ones, but this can be regulated by relative tolerance which defines how much a lower-priority objective can affect the higher-priority solution [17]. However, this method can increase computational complexity and potentially lead to model infeasibility. Additionally, it may overlook globally high-quality solutions due to fragmentation [18]. Despite these drawbacks, it's chosen due to its ability to rank objectives by importance, especially in combat scenarios where minimizing refuel time near front lines is crucial for reducing exposure to enemy fire.

In the VESC model, refuel time is deemed the most critical aspect, followed by supply capacity, and then minimizing CO2 emissions. Refuel time has the highest priority (2), reflecting its significance in combat scenarios. Supply capacity, being scarce, follows with priority 1. Minimizing CO2 emissions, while less immediate in combat, necessary to achieve NLMoD goals, hence priority 0.

Relative tolerance for refuel time and transport movements is set at 10%, balancing acceptable compromise for higher-priority objectives with potential improvements for lower-priority ones. Implemented in Python, the VESC model utilizes the Gurobi Optimizer package (version 10.0.3), leveraging the described mathematical model and solver.

V. Case-study and Results

The experimental setting is drawn from the war exercise "Allied Spirit" held in Hohenfels, Germany, in March 2024, designed to train various aspects of warfighting. Input data are sourced from internal NLMoD documents or inferred from them. This exercise is ideal for the VESC model due to its large unit size and comprehensive representation of the MSC.

The case-study consists of 5 days with one day road movement and four days of offensive combat. The FSC is centrally positioned within the Area of Operation (AoO), approximately 70 km from the SC, also serving as the Unit Assembly Area. The AoO measures 50x45 km, with tactical movements from the SC to FSC and tactical operations within the AoO.

The primary forces consist of 30 CV90 infantry fighting vehicles and 7 Leopard 2 main battle tanks, supplemented by infantry operating from the CV90s. Additionally, 20 Fennek light reconnaissance and surveillance vehicles, 6 Boxer armored wheeled vehicles for medical support or as mobile command posts, and 3 Kodiak combat engineering vehicles alongside a Leopard 2 PRB armored recovery vehicle are deployed. Sixteen wheeled trucks are also included, with an additional 5 Manticore 20 kN supply vehicles for specific policies.

A. Policies

The impact of alternative energy types on military logistics also depends on the assumptions made. The system can be based on various assumptions, leading to different outcomes. Hence, multiple policies are formulated to examine these differences.

Firstly, the comparison is made between using the 'renewable energy' MSC and the current MSC. The former involves the new implemented energy generation at multiple nodes and the use of Manticore supply trucks as energy buffers at Node 4. Secondly, the utilization of APUs is assessed. Thirdly, the investigation focuses on the exclusion of fossil fuels, considering scenarios where they become scarce in the future or are prohibited due to environmental concerns. Fourthly, the effects of longer intervals between supplies are analyzed. Fifthly, the compatibility of equipment for fuel/energy containers at Node 3 is explored to understand its implications. Lastly, adjustments to input parameters are examined to determine the necessary improvements for competitiveness with current diesel. An overview of all policies is given in Table 1.

Policy	'Renewable energy' MSC	APU	Fossil fuels	Min 48 h self sufficient	Compatible equipment at Node 3	Input change
P1	×	×	✓	×	×	×
P1.A	×	✓	✓	✓	×	×
P1.B	×	×	✓	×	✓	×
P2	✓	✓	✓	×	×	×
P2.A	✓	✓	×	✓	×	×
P2.B	✓	✓	✓	×	✓	×
P3	✓	✓	✓	×	×	✓

Table 1. Overview of different policies

B. Results

First, establish the baseline by running the VESC model with current diesel for all policies. This provides a benchmark for comparing other energy types. Policy P1 represents current NLMoD operations and serves as a baseline for comparison with new policies. Results can be seen in Figure 4.

P1.A introduces APUs for standby time and 48-hour self-sufficiency for UNITS, resulting in a 17% energy consumption reduction, mainly from UNITS vehicles' APUs and reduced supply movements. The reduction extends to CO2 emissions and refuel time.

In P1.B, WLS and Gryphus fuel containers become compatible, reducing WLS container size by 56%. This leads to a 71% increase in total trips compared to P1. Notably, refuel time at Node 3 is cut by 72%, significantly reducing rt^{total}.

P2 explores renewable energy scenarios, utilizing Manticores and APUs. The Manticores decrease refuel time, number of trips and CO2 emissions, they notably impact refueling at Node 4. Comparing P2.A with P1.A highlights Manticores' benefits: a 7% improvement in path C trips, 9% reduction in Node 3 refuel time, 30% in Node 4, and nearly 2% lower CO2 emissions.

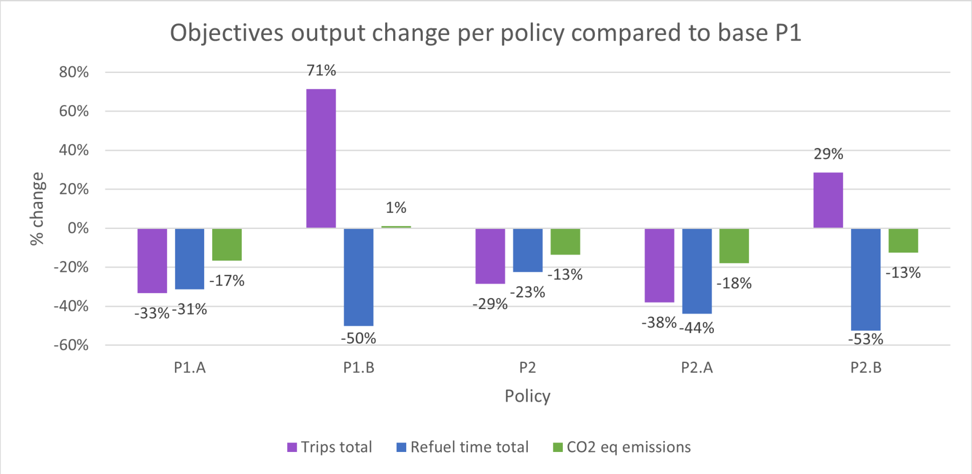

Figure 4. Impact of policy change compared to current MSC P1

When the VESC model is run for all policies, in most cases, HVO yields the best results, except for P2.A, where HVO-electric performs the best. The results for all policies are provided in Table 2. The best results for all policies demonstrate similar differences between policies as those of baseline diesel.

Policy	$\mathbf{tr}^{total}$ [#]	$\mathbf{tr}^{pathB}$ [#]	$\mathbf{tr}^{pathC}$ [#]	$\mathbf{rt}^{total}$ [min]	$\mathbf{rt}^{Node3}$ [min]	$\mathbf{rt}^{Node4}$ [min]	$\mathbf{emis}^{total}$ [kg CO2]	$\mathbf{energy}^{total}$ [MJ]
P1 (HVO)	20	6	14	325	174	152	1,958	3,788,006
P1.A (HVO)	14	4	10	224	127	98	1,637	3,168,235
P1.B (HVO)	26	11	15	191	50	141	1,968	3,810,876
P2 (HVO)	15	6	9	268	136	131	1,692	3,501,931
P2.A (HVO-electric)	10	4	6	156	87	69	1,479	3,053,410
P2.B (HVO)	19	10	9	181	50	131	1,701	3,522,011

Table 2. Results best result for all policies

Table 3 shows the results of all feasible outputs for policy P2. HVO, diesel-electric, and diesel exhibit similar results for tr^{total} and rt^{total}. However, the $emis^{total}$ is significantly lower for HVO, making it the best option. Ammonia and hydrogen have zero emissions total but high tr^{total} and rt^{total} values, rendering them impractical compared to current diesel. Electric battery swap and charging yield infeasible results for all policies due to insufficient vehicle range for the case study scenario.

	$\mathbf{tr}^{total}$ [#]	$\mathbf{tr}^{pathB}$ [#]	$\mathbf{tr}^{pathC}$ [#]	$\mathbf{rt}^{total}$ [min]	$\mathbf{rt}^{Node3}$ [min]	$\mathbf{rt}^{Node4}$ [min]	$\mathbf{emis}^{total}$ [kg CO2]	$\mathbf{energy}^{total}$ [MJ]
HVO	15	6	9	268	136	131	1,692	3,501,931
Diesel-electric SH	15	6	9	256	139	118	139,133	3,771,658
Diesel	15	6	9	258	139	119	140,125	3,817,513
LNG	22	9	13	303	169	135	117,412	3,833,482
Methanol	27	10	17	398	229	169	118,180	3,185,684
Ammonia	47	19	28	569	379	190	0	4,748,927
H2 Fuel cell	85	38	47	620	512	108	0	3,477,742
H2 ICE	134	62	72	871	768	104	0	5,558,160

Table 3. Results of P2 with all feasible energy types

Both electric battery swap and charging were previously deemed impractical due to electric vehicles' short range and the case study's long distances and combat hours. However, increasing battery pack energy density to 1.18 MJ/kg makes the VESC model feasible. Research indicates lithium-air batteries could reach 4.32 MJ/kg, increasing the vehicle range significantly, see Figure 5 [19].

Running the VESC model with energy densities ranging from 1.18 to 4.32 MJ/kg for both charging and battery swap reveals a decrease in total trips initially, stabilizing later. Further analysis shows the model prioritizes reducing refuel/charging time, therefore using more supply trucks than needed. Increasing energy density alone still results in significantly higher total trips compared to diesel.

Enhancing refueling/charging energy flow reduces refuel/charging time but has little impact on total trips, flattening out at higher flow values due to coupling time. Electric charging shows lower total trips but significantly higher refuel time compared to diesel, due to less trucks with charging points available, while electric battery swap approaches diesel levels only at maximum energy flow. Increasing Fuel to Wheel (FTW) efficiency decreases energy consumption but does not bring output values close to diesel due to high initial efficiency levels.

Combining the increase in energy density, refuel speed and FTW efficiency results in comparable or better refuel speed with diesel for both battery swap and charging but number of trips are still 160% or 133% higher.

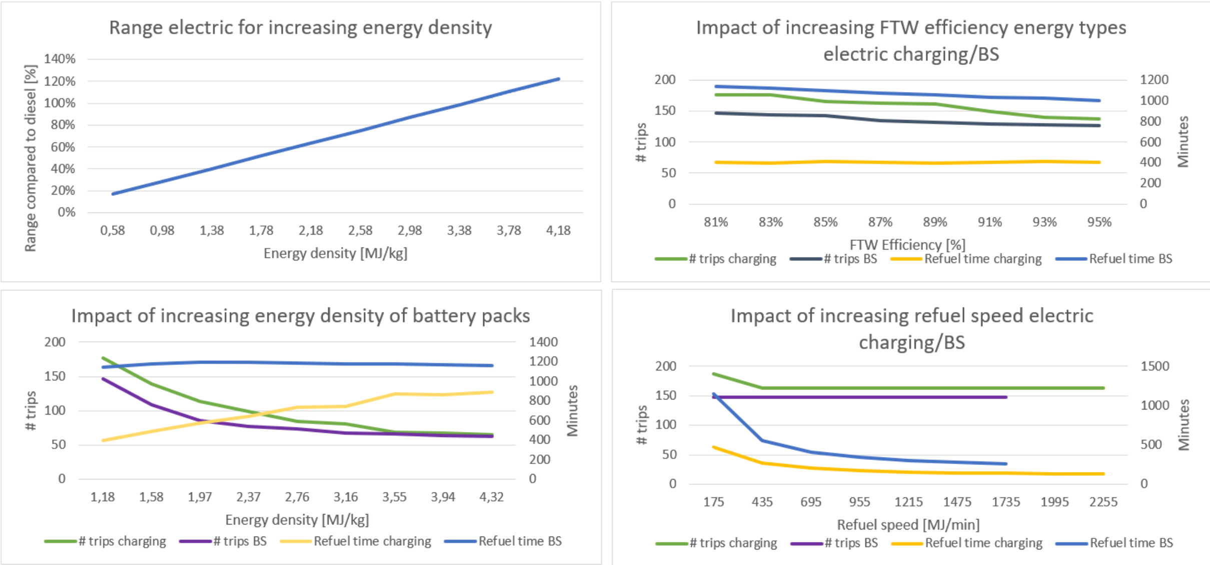

Figure 5. P3 results for electric battery swap and charging

VI. Discussion

In this subsection, we discuss the assumptions and boundaries impacting the results. The VESC model's energy types are not restricted to a fixed list, allowing for potential changes with technological advancements. However, HVO's viability may be limited due to insufficient crop waste for large-scale production, potentially leading to negative environmental consequences. The model calculates CO2 equivalent emissions based on Fuel-to-Wheel data, Well-to-Wheel emissions are challenging to determine. This approach offers insights into a portion of emissions, but not the entire MSC impact.

The VESC model focuses on operational and tactical movements critical for warfighting, excluding the entire MSC due to its complexity. While warfighting exercises like "Allied Spirit" provide examples, exact values can vary depending on the scenario. Further, the chosen energy types may not represent blended versions, offering potential areas for exploration.

The model utilizes current NLMoD supply trucks, adapting fuel containers for different energy types. Compatibility improvements reduce refuel time but may increase transport movements. Assumptions for alternative energy types are based on diesel specifications, with challenges in transitioning due to technical constraints.

Vehicles typically use their ICE to charge battery packs during standby. Energy consumption during standby is calculated using the CVV standby formula. The APU reduces the energy consumption usage during standby. However, diesel-electric vehicles, which already utilize a generator, do not require an APU. Consequently, the VESC model uses the CVV formula for diesel-electric vehicles, resulting in higher fuel consumption during standby than is realistic. This discrepancy impacts the accuracy of diesel-electric vehicle results in the research. APUs play a vital role in reducing vehicle energy consumption, especially for alternative energy types with lower energy density, ultimately decreasing their impact on the MSC.

The results indicate that increasing the self-sufficiency of UNITS reduces the MSC's impact. This is logical as fewer days for supply lead to fewer transport movements and less refuel time. UNITS' self-sufficiency is directly tied to vehicle range, energy density, and Fuel-to-Wheel efficiency. Longer self-sufficiency is beneficial for the MSC, reducing the risk of combat power loss due to resupply failures.

Energy generation occurs primarily at Node 2 and to a lesser extent at Node 3 in this VESC model. Node 3's limited time and space, along with the tactical nature of UNITS at Node 4, make generating energy there impractical. Energy generated at Node 2 doesn't impact the model's results directly but affects the energy required from suppliers, which isn't part of this research. Generating energy at Node 3 is challenging due to tactical constraints, but it reduces the need for WLS trips without affecting refuel time. While energy generation primarily impacts strategic and operational movement, it can be used for standby time and command posts.

The MILP solver choice heavily influences model results. A blended objectives approach would link all objectives to cost, requiring a study on expressing each objective's cost due to risk and operational actions. The hierarchical objectives approach prioritizes objectives and adjusts outcomes based on relative tolerance. Changing priority for refuel time and transport movements doesn't significantly alter results, except for cases with compatible equipment, where refueling relations change. Relative tolerance affects outcomes; without it, diesel-electric would perform better in some policies due to its advantages in refuel time and transport movements.

A. Recommendations

Validation: obtain data from future warfighting exercises to validate the model, especially for current diesel energy type and the accuracy of NLMoD's fuel calculation formulas for warfighting scenarios.

Extension of VESC model: supplement the VESC model with national and strategic movement to understand the full impact of alternative energy types on the MSC; Consider differentiating between military and civilian objectives for strategic movement; Include the objective of minimizing costs in the VESC model for peace-time operations; Allow the SC and FSC to move locations during warfighting scenarios to enhance realism, considering increased energy consumption and CO2 emissions.

Input data: include more combinations of energy types and mixed fuels to improve efficiency and reduce emissions; Conduct detailed analyses of vehicle types per energy type, particularly for hydrogen and electric variants; Incorporate new vehicle and weapon platform concepts like drones and autonomous systems to reflect potential future scenarios.

Smaller supply trucks: consider smaller supply trucks instead of larger ones to mitigate supply vulnerabilities and reduce the risk of destroyed supply lines; Further research into the optimal size of supply trucks to minimize risks is recommended.

Technological complexity and maintenance: assess the impact of alternative energy types on vehicle complexity and maintenance requirements; Add technological complexity as an objective function in the model to measure repair and maintenance hours per vehicle; Investigate the implications of repair and maintenance needs for combat capacity and support personnel.

VII. Conclusion

The NLMoD aims to reduce fossil fuel dependency by 70% by 2050. COMMIT research identifies potential alternative energy types for vehicles, including diesel-electric series hybrid, H2, electric, ammonia, methanol, HVO, and LNG. However, the focus remains on vehicle technology rather than the impact on the Military Supply Chain (MSC). Understanding this impact is crucial for future-proofing energy types.

Research investigates the impact of alternative energy types on tactical military vehicles and determines the optimal energy type. A MILP optimization model simulates the vehicle energy supply chain, optimizing for objectives such as minimizing refuel time, supply trips, and CO2 emissions.

Experiments, based on the "Allied Spirit" exercise, reveal that APUs in vehicles reduce energy consumption and CO2 emissions. Policies incorporating Manticore supply vehicles further minimize the objectives. HVO(-electric) emerges as the best alternative, followed by diesel-electric series hybrid, while hydrogen and electric options are currently impractical.

For electric options to match diesel performance, energy density and fill speed must significantly improve.

Similarly, hydrogen fuel cell efficiency and diesel-electric FTW efficiency need enhancement.

In summary, alternative energy types impact supply trips, refuel time, and emissions. However, HVO(-electric) or diesel-electric series hybrids show promising results. Adapting the MSC to accommodate these alternatives is essential, emphasizing the importance of APUs, energy buffers, and self-sufficiency. From the MSC perspective, HVO-electric series hybrids is the optimal energy type for military vehicles.

References

[1] Ministerie van Defensie, "Roadmap energietransitie operationeel matereel," , 2023. URL https://www.defensie.nl/binaries/defensie/documenten/publicaties/2023/01/31/roadmap-energietransitie-materieel/202250371+_DIGITALE_Roadmap+Energietransitie.pdf(Accessed: 08-05-2024).

[2] U.S. Marine Corps, *MCDP1 Warfighting*, 1st ed., United States Government, Washington, D.C, 1997, Chap. 1.

[3] Leila, M., Whalen, J., and Bergthorson, J., "Strategic spatial and temporal design of renewable diesel and biojet fuel supply chains: Case study of California, USA," *Energy*, Vol. 156, 2018, pp. 181–195. doi: https://doi.org/10.1016/j.energy.2018.04.196, URL https://www.sciencedirect.com/science/article/pii/S0360544218308089.

[4] Landmacht, D. C. K., *Handboek Bevoorrading*, Ministerie van Defensie, clas2015018112 ed., 11 2015.

[5] C-Opleidings-en Trainingscommando, *Tactiek voor het gemechaniseerde team*, Ministerie van Defensie, clas2022008258 ed., 07 2022.

[6] DNV, "Verduurzaming logistieke brandstof Defensie," , DNV, 2023.

[7] DNV, "Kwantificatie van de transportbehoefte tussen depot, kampement en veld bij gebruik van alternatieve energiedragers," , DNV, 2023.

[8] DNV, "Verschillende energievormen in voertuigen," , DNV, 2022.

[9] DNV, "Verhogen herbevoorradingssnelheid in het veld met alternatieve energietransport mogelijkheden," , DNV, 2023.

[10] Lobo, B. J., Brown, D. E., Gerber, M. S., and Grazaitis, P. J., "A transient stochastic simulation–optimization model for operational fuel planning in-theater," *European Journal of Operational Research*, Vol. 264, No. 2, 2018, pp. 637–652. doi: https://doi.org/10.1016/j.ejor.2017.06.057, URL https://www.sciencedirect.com/science/article/pii/S0377221717305982.

[11] Mansfield, A., Boehman, A., and Gorsich, D., "Assessment of Conventional and Alternative Energy Carriers for Use in Military Vehicle Platforms," *Journal of Energy Resources Technology*, Vol. 143, No. 4, 2020, p. 041302. doi: 10.1115/1.4048253, URL https://doi.org/10.1115/1.4048253.

[12] Nilsson, J., "A changing energy security environment–a review of alternative energy carriers for light duty vehicles," *Swedish Defence University*, 2023.

[13] Lemme, R. F., Arruda, E. F., and Bahiense, L., "Optimization model to assess electric vehicles as an alternative for fleet composition in station-based car sharing systems," *Transportation Research Part D: Transport and Environment*, Vol. 67, 2019, pp. 173–196. doi: https://doi.org/10.1016/j.trd.2018.11.008, URL https://www.sciencedirect.com/science/article/pii/S1361920918304656.

[14] Çağatay Iris, and Lam, J. S. L., "Optimal energy management and operations planning in seaports with smart grid while harnessing renewable energy under uncertainty," *Omega*, Vol. 103, 2021, p. 102445. doi: https://doi.org/10.1016/j.omega.2021.102445, URL https://www.sciencedirect.com/science/article/pii/S0305048321000542.

[15] Aghsami, A., Sharififar, S., Moghaddam, N. M., Hazrati, E., and Jolai, F., "A bi-objective mixed-integer non-linear programming model with Grasshopper Optimization Algorithm for military-based humanitarian supply chains," *Decision Analytics Journal*, Vol. 10, 2024, p. 100409. doi: https://doi.org/10.1016/j.dajour.2024.100409, URL https://www.sciencedirect.com/science/article/pii/S2772662224000134.

[16] Klanšek, U., "A comparison between MILP and MINLP approaches to optimal solution of Nonlinear Discrete Transportation Problem," *Transport*, Vol. 30, 2014, pp. 1–10. doi: 10.3846/16484142.2014.933361.

[17] *Working With Multiple Objectives*, 2023. URL https://www.gurobi.com/documentation/current/refman/working_with_multiple_obje.html.

[18] Qu, R., Burke, E., Mccollum, B., Merlot, L., and Lee, S., "A Survey of Search Methodologies and Automated

Approaches for Examination Timetabling," *Journal of Scheduling - SCHEDULING*, 2006, pp. 55–89.
[19] *Scientists hail new battery with 4 times energy density of lithium-ion*, 2023. URL https://thedriven.io/2023/04/03/scientists-hail-new-battery-with-4-times-energy-density-of-lithium-ion/.

Nomenclature

AoO	=	Area of Operation
APU	=	Auxiliary Power Unit
COMMIT	=	Command Materiel and IT
CVV	=	Compensation Fuel Consumption
FSC	=	Forward Supply Centre
FTW	=	Fuel To Wheel
IF	=	Intensity Factor
MILP	=	Mixed-Integer Linear Programming
MINLP	=	Mixed-Integer Nonlinear Programming
MSC	=	Military Supply Chain
NLMoD	=	Dutch Ministry of Defence
SC	=	Supply Centre
VESC	=	Vehicle Energy Supply Chain

Appendix

A. Math Model Parameters and Variables

Sets:	
T	Set of days ($t \in 0, 1, \ldots, D$) whereby D is the total days of operation
I	Set of energy types ($i \in 0, 1, \ldots, C$) whereby C is the total number of energy types
General parameters:	
fc^4_{ti}	Energy consumption in MJ per day ($t \in T$) for energy type ($i \in I$) at Node 4
fc^3_{ti}	Energy consumption in MJ per day ($t \in T$) for energy type ($i \in I$) at Node 3
$fcv^{to\_sup}_{ti}$	Average energy consumption per vehicle to supply point at Node 4 in MJ per day ($t \in T$) for energy carrier type ($i \in I$)
$avfc^{vehicle}_{ti}$	Average energy consumption per vehicle at Node 4 in MJ per day ($t \in T$) for energy carrier type ($i \in I$)
del^4_{ti}	Binary values to tell if deliver is possible per day ($t \in T$) per energy type ($i \in I$)
tc^{gry}_i	Carrying capacity of the Gryphus supply truck per energy type ($i \in I$) in MJ
tc^{mant}_i	Carrying capacity of the Manticore per energy type ($i \in I$) in MJ
cvv^{gry}_i	CVV for the Gryphus supply truck per energy type ($i \in I$) in MJ
cvv^{WLS}_i	CVV for the WLS supply truck per energy type ($i \in I$) in MJ
ft^{gry}_i	Fuel tank capacity for the Gryphus supply truck per energy type ($i \in I$) in MJ
ft^{WLS}_i	Fuel tank capacity for the WLS supply truck per energy type ($i \in I$) in MJ
$tot^{capacity\_vehicles}_i$	Total energy capacity of vehicles per energy type ($i \in I$)
ef^{refuel}_i	Efficiency of refueling per energy type ($i \in I$)
am^{mant}	Number of Manticores attached to UNITS at Node 4
Number of supply movement parameters:	
tr^B_{ti}	Total number of WLS and WLS+trailer trips per day ($t \in T$) per energy type ($i \in I$) for path B
$tr^{B\_WLS}_{ti}$	Number of WLS trips per day ($t \in T$) per energy type ($i \in I$) for path B
$tr^{B\_WLS+tr}_{ti}$	Number of WLS+trailer trips per day ($t \in T$) per energy type ($i \in I$) for path B
Refuel time parameters:	
av^{rt}_i	Average refuel time per energy type ($i \in I$) in MJ/min
rt^{extra}_{ti}	Extra refuel time at Node 4 per vehicle per day ($t \in T$) per energy type ($i \in I$)
rtp^{extra}_i	Extra refuel time for pump at Node 3 per vehicle per energy type ($i \in I$)
rp^{gry}_i	Number of refuel points for Gryphus per energy type ($i \in I$)
rp^{Node4}_{ti}	Number of refuel points for Node 4 per day ($t \in T$) per energy type ($i \in I$)
pu^{debit}_i	Pump debit in MJ/min at Node 3 per energy type ($i \in I$)
am^{pumps}	Number of pumps at Node 3
$am^{gr\_ma}_{ti}$	Has value of the lowest number of either Gryphus or Manticore vehicles per day ($t \in T$) per energy type ($i \in I$) for path C/Node 4
rt^{extra3}	Extra refuel time at Node 3 due to build/break up of supply truck
rt^{extra4}	Extra refuel time at Node 4 due to build/break up of supply truck

Emission parameters:	
ec^{4}_{ti}	CO2 equivalent emissions in kg/day ($t \in T$) for energy type ($i \in I$) at Node 4
$av^{emissions}_{ti}$	Average CO2 equivalent emissions per vehicle to drive to supply point at Node 4 per day ($t \in T$) per energy type ($i \in I$) in kg
em^{gry}_{i}	CO2 equivalent emissions of the Gryphus for energy type ($i \in I$) in kg
em^{WLS}_{i}	CO2 equivalent emissions of the WLS for energy type ($i \in I$) in kg
em^{WLS+tr}_{i}	CO2 equivalent emissions of the WLS+trailer for energy type ($i \in I$) in kg

Decision variables:	
$Sn^{4}_{ti} \in \mathbb{B}$	Binary variable whether to supply energy type ($i \in I$) at Node 4 for day ($t \in T$)
$Sn^{3}_{ti} \in \mathbb{B}$	Binary variable whether to supply energy type ($i \in I$) at Node 3 for day ($t \in T$)
$Sn^{2}_{ti} \in \mathbb{B}$	Binary variable whether to supply energy type ($i \in I$) at Node 2 for day ($t \in T$)
$Rt^{4}_{ti} \in \mathbb{B}$	Binary variable whether to supply energy type ($i \in I$) at Node 4 for day ($t \in T$) when looked at refuel time
$Rt^{3}_{ti} \in \mathbb{B}$	Binary variable whether to supply energy type ($i \in I$) at Node 4 for day ($t \in T$) when looked at refuel time
$Em_{ti} \in \mathbb{B}$	Binary variable whether to supply energy type ($i \in I$) for day ($t \in T$) when looked at CO2 equivalent emissions
$Tr^{C}_{ti} \in \mathbb{R}$	Discrete variable representing how many Gryphus trips take place at C per energy type ($i \in I$) for day ($t \in T$)
$En^{mant}_{ti} \in \mathbb{R}$	Continuous variable representing how much energy the Manticore supplies in Node 4 for energy type ($i \in I$) for day ($t \in T$)
$Fi^{mant}_{ti} \in \mathbb{R}$	Continuous variable representing with how much energy the Manticore is filled up in Node 4 for energy type ($i \in I$) for day ($t \in T$)
$Re^{mant}_{ti} \in \mathbb{R}$	Continuous variable representing with how much energy remains in the Manticores at Node 4 for energy type ($i \in I$) for day ($t \in T$)