Integrated Control in the Cryogenic Logistics of LNG and Bio-LNG: A Mixed-Integer Linear Programming Approach

A Case Study at Rolande

F.J. Boekhorst

TU Delft

ROLANDE
Fueling clean transport

Integrated Control in the Cryogenic Logistics of LNG and Bio-LNG: A Mixed-Integer Linear Programming Approach

A Case Study at Rolande

by

F.J. Boekhorst

to obtain the degree of Master of Science

at the Delft University of Technology,

to be defended publicly on Thursday December 19, 2024 at 09:00 AM.

Student number:	4694880	
Report number:	2024.TIL.9013	
Project duration:	May 6, 2024 – December 19, 2024	
Thesis committee:	Prof. dr. ir. R.R. Negenborn,	TU Delft, faculty ME (chair)
	Dr. ir. Y. Pang,	TU Delft, faculty ME
	Dr. ir. G. Correia,	TU Delft, faculty CiTG
	Ir. W. Konings,	Rolande B.V.
Cover:	Rolande, 2020	

Summary

Introduction Within the reshaping of the energy landscape, Bio-LNG has emerged as an efficient clean energy source for long-distance transportation. Liquefied Natural Gas (LNG) is a form of natural gas that is cooled to temperatures at -161°C, at which it becomes a liquid. Bio-LNG is produced from organic waste materials such as vegetable residues, sludge or manure and can also be liquefied similarly to LNG. Since LNG and Bio-LNG both have a boiling point larger than -150°C, they are called cryogenic. These fuels are transported, stored under the same cryogenic conditions. This presents a challenge for maintaining the inventory levels and managing the pressure levels due to heat leaks, and minimizing the transportation costs. The logistic network must integrate routing decisions, inventory management and pressure control. This research aims to address these complexities by developing a planning method that considers the transportation and nitrogen cooling costs. The main research question addressed is: "*How can the LNG-IRP with cryogenic temperature control be optimized considering transportation costs and nitrogen cooling costs*?"

Literature research The literature research explored the current state of research and practice, and identified gaps in the LNG IRP with pressure management. While much research focuses on maritime LNG transport, there is limited attention to inland transportation of LNG, particularly pressure management. Previous studies assumed the use of boil-off gas to control the pressure, a method that is currently prohibited in inland LNG logistics within Europe. This literature research presents three refrigeration methods to manage the pressure at the refuelling station: nitrogen cooling, offload cooling and logistic trailer cooling. Nitrogen cooling is achieved via an on-site cool tank, while offload cooling involves delivering a cold load to a station and mixing it with the warm tank inventory. The most unique type of cooling out of these three method is logistic trailer cooling, which releases warmer gas from the refuelling station's tank into the vehicle's trailer, allowing it to be offloaded at another station. Finally, the literature research identified the knowledge gap of a planning method that integrates routing, inventory and pressure decisions in LNG-IRP. This knowledge gap guided the development of planning methodology that can address this integrated control in the cryogenic logistics of LNG and Bio-LNG.

Planning methodologies Before developing the planning methodologies, the key variables and constraints were discussed, in collaboration with a planning expert and operations manager, the key performance indicators (KPIs) were identified. The KPIs are Total Costs (TC), Total Transportation Costs (TTC), Total Nitrogen Cooling Costs (TNCC) and Cost per Kilogram (CpK).

The planning methodology was developed through three steps. First, a Full Mixed-Integer Linear Programming (MILP) was created that captured all relevant constraints and variables including routing, inventory and pressure management. This model was relatively detailed and involved the waiting hours at the terminals or refuelling stations. Furthermore, the different products (LNG and Bio-LNG) were specified on product level. These details result in scalability issues for larger network, due to the model's complexity.

To address these limitations, the Full MILP was refined to a Simplified MILP model. This model reduced the complexity by making additional assumptions, such as pre-assigning vehicles to terminals, applying the products on vehicle level and eliminating the waiting hours at stations and terminals. To improve the computational efficiency of this Simplified MILP model, a rolling horizon approach was implemented that divided the planning horizon into smaller time blocks. A pre-solve process was added to identify critical stations and reduce the number of nodes in the network by considering only the critical stations. The rolling horizon approach with pre-solve process is presented in Figure 1

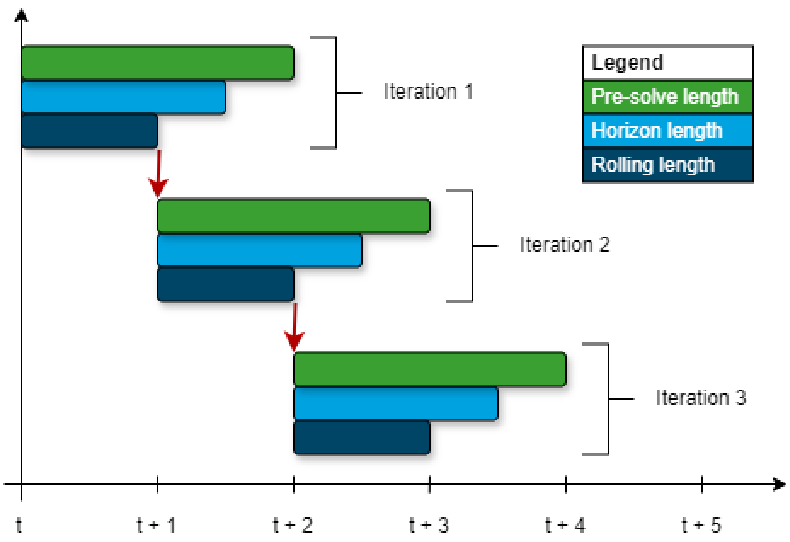


Figure 1: Overview of the rolling horizon approach with a pre-solver. The pre-solve length determines critical stations, the horizon length manages inventory and pressure levels, and the rolling length sets vehicle routing decisions. The red arrow illustrates how results from one iteration (e.g., Monday) go into the next (e.g., Tuesday), indicating the sequential nature of the rolling horizon.

Case Study Rolande The Simplified MILP with rolling horizon approach and pre-solve process was tested in a real-world case study at Rolande. Rolande is a company operating LNG and Bio-LNG refuelling stations in the Netherlands, Belgium and Germany. This research focuses on the network in the Netherlands and Belgium. A sensitivity analysis revealed that vehicle capacity was the most sensitive parameter on the feasibility and the total costs. Therefore, the pre-solve process was adjusted to include determining the required LNG supply for each day. Afterwards, the model was tested on Rolande's network of refuelling stations in the Netherlands and Belgium. The model successfully generated a feasible and cost-effective solution for a seven-day planning horizon across 19 stations and two vehicles. The model ensured that the inventory and pressure levels were within the specified bounds, preventing stockouts and critical pressure issues. While the model performed well overall, computationally times could increase on complex days that involved many critical stations and vehicles capable of performing logistic cooling. These results show the difficulty of the computational efficiency and minimizing the costs.

Conclusion This research addressed the LNG-IRP with pressure management by developing and testing a planning methodology that integrates routing, inventory and pressure management. The methodology combines the Simplified MILP model with the rolling horizon approach and the pre-solve process to solve a network of 19 refuelling stations. Despite the computational challenges on complex days, the model successfully balanced the transportation costs and nitrogen cooling, while ensuring feasibility of constraints. This study contributes to research by addressing the knowledge gap in inland LNG logistics by providing a planning methodology for real-world application.

Discussion While the methodology performs well overall, several limitations and opportunities for refinement were identified. The validation was challenging due to the lack of a benchmark in the literature. Moreover, assumptions, such as fixed logistic cooling parameters and hard inventory and pressure bounds, limit the model's flexibility. Non-linear offload cooling effect, soft constraints on inventory and pressure were not considered but could improve the model in both flexibility and model's realism.

Recommendations This research provides recommendations for the company Rolande and for future researchers. For Rolande the following recommendations are provided:

1. **Monitor outcomes**
   Dispatch vehicles according to the generated routes and monitor the inventory and pressure

levels at refuelling stations. Refine the model based on the observations.

2. **Fine-tuning offload cooling parameters**
   Track how the pressure levels change after offloads and adjust the offload cooling parameters to reflect the real-world logistics more accurately.
3. **Be aware of additional LNG in the vehicle's trailer after logistic cooling**
   When dispatching vehicles according to the generated routes, ensure that the next station after logistic cooling can accommodate for additional LNG in vehicle's trailer.
4. **Training**
   Train the logistic planner to interpret the model and adjust the model's output as needed. Furthermore, educate the software developers to add stations and constraints so the model is resilient in the future.

For future researchers, the following opportunities are recommended:

1. **Comparative analysis with existing planning methods**
   Compare the proposed planning method to a simple heuristic, such as the greedy heuristic, to evaluate the performance based on this benchmark.
2. **Evaluate the performance of the model on soft inventory and pressure bounds**
   Replace the hard inventory and pressure bounds with penalties for violations, improving the flexibility and feasibility.
3. **Non-linear offload cooling effect**
   Explore a more realistic offload cooling effect by making the offload cooling depended on the LNG temperature of the vehicle trailer, station inventory, offload quantity and LNG temperature of the station.

Contents

List of Figures

List of Tables

1 Introduction

This section describes an overview of the research framework, explaining the context in which the study is situated, the specific problem it wants to address, and the objectives it aims to achieve. In addition, the scope of the research discusses the boundaries within which the study operates. Furthermore, this section outlines the key research questions and methods that are used as a guideline throughout the research. Finally, the structure of the research report is presented to give an overview of the research approach.

1.1. Background

The transition to clean energy is reshaping the energy landscape, and Bio-LNG has emerged as an efficient clean energy source for long-distance transportation. Road transport is responsible for over 70% of the European Union's (EU) greenhouse gas (GHG) emissions, with heavy-duty vehicles accounting for more than 25% of these emissions, as depicted in Figure 1.1. Furthermore, heavy-duty vehicles contribute to over 6% of the EU's total GHG emissions (European Union, 2024). So, to meet the EU's target of reducing total emissions by at least 55% by 2030, member states must focus on making heavy road transport more environmentally friendly, and Bio-LNG offers a promising solution.

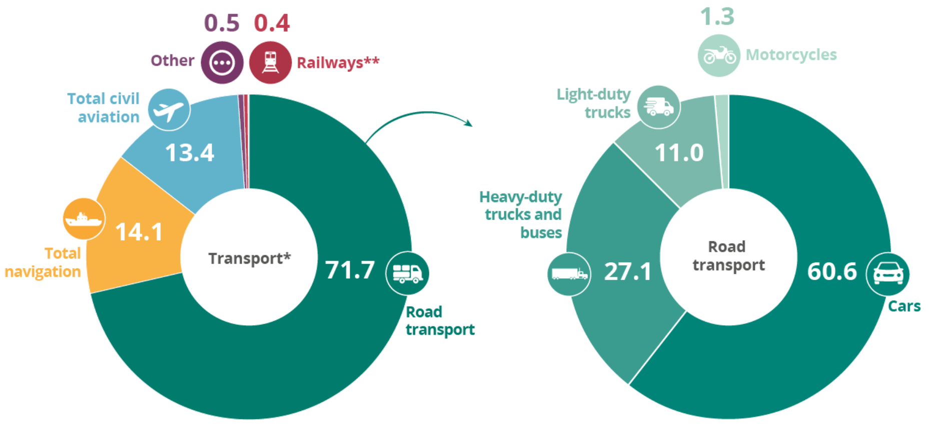


Figure 1.1: Greenhouse gas (GHG) emissions from transport in the EU (European Environment Agency, 2023), showing the distribution of emissions by different modes of transport. The left chart highlights that road transport is the largest contributor of GHG emissions. The right chart dives deeper into the modes of road transport and presents that heavy-duty trucks and buses account for 27.1% of the GHG gas emissions of road transport.

Liquefied natural gas (LNG) is a form of natural gas that is cooled to temperatures at -161°C (Volvo Trucks, n.d.). This liquefaction process significantly reduces the volume of the gas, making it easier to store and transport in large quantities (Thomas and Dawe, 2003). Bio-LNG is produced from organic waste materials such as vegetable residues, sludge or manure. In a digester, the organic material is converted to biogas and purified into a form that can be liquefied similarly to LNG. Since Bio-LNG is produced from renewable resources, it significantly reduces the carbon footprint and can play an important role in achieving carbon-neutral transport (Rolande, n.d.-a).

An important tool for comparing emissions from different transport fuels is the well-to-wheel (WtW) analysis. This analysis consist of two components: the well-to-tank (WtT) and the tank-to-wheel (TtW). WtT are the emissions in the pre-chain of the activity, for example, from extraction and production of fuels. TtW are the direct emissions from the activity, e.g. the released emissions when a vehicle drives on a fuel. A recent WtW analysis shows that Bio-LNG can significantly reduce GHG emissions in heavy-duty engines compared to fossil fuels like diesel, compressed natural gas diesel (CNG), and LNG (Alamia et al., 2016). According to this research, Bio-LNG can reduce total emissions by 43 to 67% compared to diesel, depending on the engine's efficiency. This makes Bio-LNG a promising solution for reducing GHG emissions in the heavy transport sector.

Heavy-duty vehicles can tank LNG and Bio-LNG at refuelling stations. For example, in the Netherlands, there are 25 LNG refuelling stations where LNG and Bio-LNG can be mixed and serve as fuel for heavy-duty vehicles. These refuelling stations are replenished by terminals and transporters serve as a link between the terminals and the refuelling stations. Since LNG and Bio-LNG are cryogenic products with a boiling point larger than -150°C, the pressure of the refuelling stations must be well management to prevent a pressure build-up.

1.2. Problem definition, scope, aim & objectives

The logistic distribution of LNG and Bio-LNG is a complex challenge due to the need for an integrated control of routing, inventory and pressure management. While Bio-LNG offers significant benefits in reducing emissions, its cryogenic nature requires careful handling to ensure safety. The inventory routing problem (IRP) involves distributing products from central suppliers, such as LNG terminal or Bio-LNG production plants, to customers, which are refuelling stations in this context. Each customer has its own local inventory and daily consumption rates. An overview of the key components of the integrated control in the cryogenic logistics of LNG and Bio-LNG is illustrated in Figure 1.2.

This process is even more complex because of the cryogenic characteristics of LNG and Bio-LNG, which temperature must be maintained at around -150 degrees Celsius during storage. An increase in temperature leads to a rise in pressure within the refuelling station's tank. Pressure within the refuelling stations' tanks typically fluctuate between 2.0 and 10.0 bar. If the pressure exceeds safe limits, safety protocols are activated, leading to station shutdowns. Some refuelling stations are equipped with nitrogen tanks that can be used to cool the system and lower the pressure when needed. However, not all stations have this capability, making them more vulnerable to high pressure conditions and increasing the risk of station shutdowns. Therefore, the LNG-IRP must address the routing and inventory decisions while incorporating the pressure management at the refuelling stations' tanks. According to the literature study in section 2.7, there is currently no planning method that integrates routing decisions with inventory and pressure management for LNG and Bio-LNG.

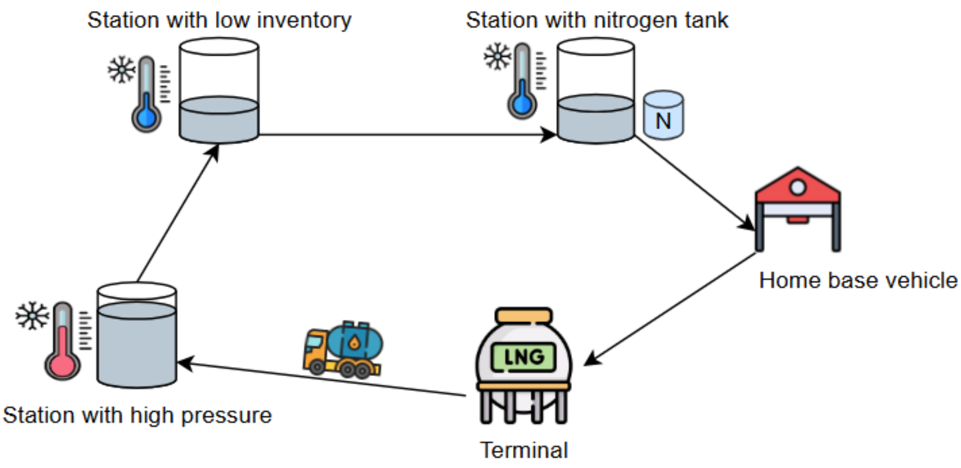


Figure 1.2: A schematic overview of integrated control in cryogenic logistics of LNG, with stations with nitrogen tanks, high pressure or low inventory, together with a terminal, a home base and vehicle routes.

In the broader supply chain of LNG, there are three main phases: upstream, midstream and downstream. The upstream phase consists of the production of natural gas. the midstream phase connects the upstream with the downstream. The liquefaction of natural gas happens in the midstream rather than in the upstream due to the requirements of downstream knowledge (Hsu and Robinson, 2019). Furthermore, the midstream phase includes the transportation to the terminals. The downstream phase is the distribution to the customers. This research focuses on the downstream phase of the supply chain, specifically the distribution from the terminal to the refuelling stations.

As outlined by Maknoon, 2024, decision-making within logistics can be categorized into four hierarchical levels: strategic, tactical, operational and real-time. Each distinguished by its temporal scope. Strategic decisions include long-term planning, while tactical decisions focus on mid-range objectives. Operational decisions relate to day-to-day management and real-time decisions are based on current, real-time data and situations. This research focuses on the operational level, as it aims for a daily integrated control of routing, inventory and pressure management of LNG and Bio-LNG.

Given the necessity to reduce emissions in heavy road transport, optimisation of the logistics of LNG is needed to improve the viability of bio-LNG as a cleaner fuel alternative. Therefore, this research aims to create a planning methodology for LNG IRP with pressure management, focusing on minimizing transportation and cooling costs. The characteristics of the planning method include multi-period, multi-depot, a heterogeneous fleet of vehicles, multi-products, split load, time windows, vendor-managed inventory and pressure management.

To achieve this research aim, a literature study will be conducted to explore the current state of research and practices related to the IRP for LNG and Bio-LNG with pressure management. The study will identify and define key performance indicators (KPIs) for evaluating the planning methodology and determine relevant constraints and variables within the context of the LNG-IRP with pressure management. A mathematical optimisation model will be developed to address the challenges, and the methodology will be evaluated through a case study at Rolande, using the defined KPIs to assess the reliability and robustness. Rolande B.V. is a provider of LNG and Bio-LNG for road transport in the Netherlands, Belgium and Germany (Rolande, n.d.-b).

Finally, this research will contribute to both science and society. The scientific contribution of this is the mathematical formulation of the LNG-IRP with pressure management, focusing on minimising transportation costs and cooling costs. This contributes to the field by combining routing, inventory and pressure management in cryogenic logistics, a topic that has currently received little attention in existing literature. The societal value of this research are the practical insights gained from the case study at Rolande. These insights contribute to a more robust and reliable supply of LNG and Bio-LNG, reducing the risks of gas shortages and supporting the heavy road transport sector in its transition to a more clean energy fuel.

1.3. Research questions and methods

The previously mentioned problem definition and objectives are transformed into the following main research question:

How can the LNG-IRP with cryogenic temperature control be optimised considering the transportation costs and nitrogen cooling costs?

Optimisation refers to the process of finding the best solution to a problem, considering the constraints and objectives. In this research, the challenge is to minimise the costs of transportation and cooling while satisfying the inventory and pressure management of LNG and Bio-LNG at refuelling stations. If this problem is not addressed it may result in high operational costs, stockout at refuelling stations and critical pressures at refuelling. To address the main research question, several sub-questions have been formulated. Furthermore, the research approach for each sub-question is shown in Table 1.1.

Table 1.1: Overview of sub-questions, methods, and corresponding chapters

Questions	Method	Ch.
1. What is the current state of research and practice regarding the LNG and Bio-LNG IRP with cryogenic temperature control?	Literature study	2
2. What KPIs are most relevant for evaluating a planning method for LNG and Bio-LNG IRP with cryogenic temperature control?	Expert opinions	3
3. What are the key constraints and variables that must be considered when designing a planning methodology for LNG and Bio-LNG IRP with cryogenic temperature control?	Conceptual model	3
4. What steps and methods are needed to develop a planning methodology for LNG and Bio-LNG IRP, with specific focus on pressure management and computational efficiency?	Mathematical optimisation	3
5. How reliable and robust is the developed LNG-IRP model, including the rolling horizon approach, within the context of Rolande's network of refuelling stations?	Case study	4

1.4. Methods and research structure

This research applies five methods to answer the sub-questions and is structured using the Double Diamond framework to answer the main research question: *How can the LNG-IRP with cryogenic temperature control be optimised considering the transportation costs and nitrogen cooling costs?*

The Double Diamond framework consists of four phases: Discover, Define, Develop and Deliver (Mahmoud et al., 2020). This framework is based on divergent thinking, where the focus is on exploring a broader problem, and convergent thinking, where targeted actions are taken to solve the problem. Figure 1.3 presents the research approach and structure by using the Double Diamond framework. The numbers in the blocks of this figure, such as *1. Introduction* or *3.4 Rolling horizon*, correspond to the chapters or sections of this thesis. Below, the four phases of the framework are explained with the related research methods used in this study.

1.4.1. Discover phase and Define phase

In the Discover phase, the goal is to explore the broader context of the LNG-IRP problem and gain knowledge about the current state of research and practice. This is achieved with a literature study that dives into Mixed-Integer Linear Programming, the rolling horizon approach, LNG-IRP, refrigeration methods and the problem characteristics. Insight from the literature is used in the Define phase. In this phase, the focus is narrowed by explaining the problem definition and research gap.

1.4.2. Develop phase

The second diamond starts with developing a conceptual model and expert opinions in Section 3.1. In collaboration with expert opinions four key performance indicators are identified that are used during the case study to evaluate the proposed planning method. The conceptual model consists of model characteristics and assumptions that need to be taken into account when developing the mathematical model. They help to formulate the key constraints and variables that must be considered when building the planning methodology for LNG and Bio-LNG.

Furthermore, potential solutions to the LNG-IRP with pressure management are developed and tested. First, a Full MILP (Section 3.2) is constructed to include all relevant constraints and variables. However, due to its computational complexity, a Simplified MILP model (Section 3.3) is created, which reduces the problem size. Finally, to deal with the challenge of multi-period planning and computational complexity a rolling horizon approach is introduced in Section 3.4. This phase concludes with a single planning methodology that is computationally efficient and will be tested in the case study.

The planning methods are developed with mathematical optimisation, more specifically Mixed-Integer Linear Programming (MILP), and implemented with the open Pulp Python Library. MILP is a mathematical optimisation technique including a maximised or minimised objective, linear constraints, and continuous and integer decision variables (Hillier and Lieberman, 2010). An example of an integer decision variables is a binary variable that has a value of one if the vehicle visits a node on a certain time step, and zero otherwise. On the other hand, an example of a continuous variable is for instance the inventory of a refuelling station on a certain time step measured in kilograms.

1.4.3. Deliver phase

In the final phase, the simplified model with the rolling horizon approach is evaluated through a case study at Rolande. The case study at Rolande consists of different elements. First, the characteristics of the case study are described. Second, a sensitivity analysis is carried out to gain insight into the robustness and reliability of the model and to identify which parameters the model is most sensitive to. Third, a pre-solver is made to determine the number of critical stations and number of Gate slots for each day. Fourth, an seven-period planning is made with historical data to check for circular patterns in the routing and the behaviour of the model. Fifth, the computational performance of the model is evaluated based on runtime for each day and the pre-solve results (specific scenario) of that day. The results provide insights into the practical applicability of the developed model in a real-world scenario.

In summary, the Double Diamond framework provides a structured approach to address the main research question. Each phase builds upon the previous one. From exploring the broader context of LNG-IRP with pressure management to defining the problem and research gap, developing a computationally efficient planning methodology and delivering practical insights through a case study. These insights contribute to the field of cryogenic logistics by combing the routing, inventory and pressure management.

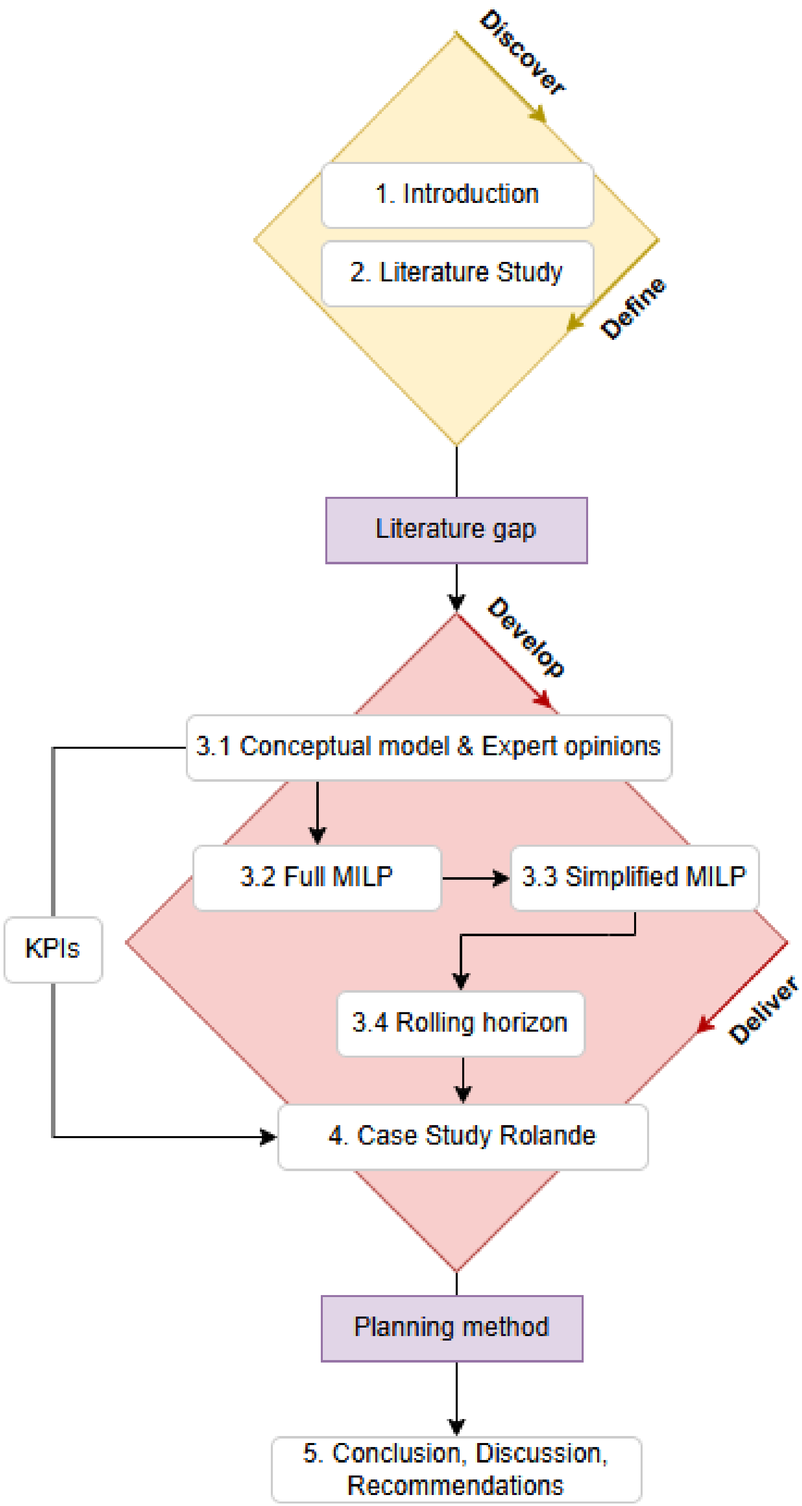


Figure 1.3: Overview of the Double Diamond framework presenting the research approach and structure. In the discover phase, literature is discussed. In the define phase the literature gap and problem are defined. The develop phase presents the conceptual model, expert opinions, Full MILP model, Simplified MILP model and rolling horizon approach. Finally, in the deliver phase the proposed planning method is evaluated through a case study at Rolande. The numbers correspond to the chapters or sections of this research.

2

Literature research

This chapter discusses the main topic, methods and terms related to the LNG IRP with pressure management. It begins by explaining the methods Mixed-Integer Linear Programming (MILP) and the rolling horizon approach. Afterwards, the LNG-IRP is described in detail, explaining the operational challenges of transporting and storing LNG in cryogenic conditions. Refrigeration methods, including nitrogen cooling, offload cooling and logistic cooling, are described as methods to manage the pressure at refuelling stations.

The chapter then presents problem characteristics, such as the inventory routing, time constraints, multi-period horizons, cooling. Next, previous case studies are reviewed to gain insights in the practice regarding LNG IRP. Finally, the research gap is identified by comparing this research with existing studies. This chapter concludes with an answer to the sub-question: ”*What is the current state of research and practice regarding the LNG and Bio-LNG IRP with cryogenic temperature control?*”

2.1. Mixed-integer linear programming

Mixed-integer linear programming (MILP) is a mathematical programming technique used in Operations Research to solve complex optimization problems. It extends on linear programming by allowing some decision variables to take only integer values, while others are continuous. This flexibility makes MILP suitable for problems that require discrete decisions, such as route selection or a binary decision of loading at a terminal (Hillier and Lieberman, 2010).

MILP problems are formulated using decision variables, an objective function, and constraints. The decision variables indicate the choices that must be made, which can be continuous, e.g. inventory levels, or discrete, e.g. binary decision for on/ off. The objective function measures the performance, for instance minimising the costs or maximising the profit, and is stated as a linear equation of the decision variables. Constraints, usually formulated by linear inequalities, limit the feasible region of the variables. An example of a common vehicle constraint is that the capacity of the vehicle limits the loading capacity of a vehicle. Constants or coefficients in the model are called parameters. Since not every parameter value can be known, some are based on a rough estimate. Therefore, it is important to analyse the sensitivity of these uncertain parameters.

MILP offers several benefits. It ensures the integration of continuous and discrete decisions, allowing it to model real-world scenarios that linear programming cannot address. Moreover, its mathematical structure is supported by solving algorithms, such as the brand-and-bound and branch-and-cut, which can be implemented in commercial solvers like Gurobi or open solvers such as Pulp. These features make MILP a versatile and widely used tool for logistics, transportation and manufacturing problems.

However, MILP also has some disadvantages. The integration of discrete decision variables in linear programming is computationally more complex, because the solution space grows exponentially with the number of variables and constraints. Large-scale MILP problems are often simplified or approximated, with heuristics or assumptions to make the model manageable.

For this research, MILP is chosen because it allows the modelling of discrete routing decisions and continuous variables like inventory and pressure levels, while allowing constraints on routing, inventory, and pressure to be defined.

2.2. Rolling horizon approach

The rolling horizon approach is a broadly used iterative method for planning and decision-making. In general terms, the main idea of the rolling horizon approach is iteratively updating schedules based on new information. The process operates as follows: the planning model is optimised for multiple periods, and only the decisions for the first period are implemented. In the subsequent period, the model is updated with new information and re-optimised. This can lead to adjustments in the previous solved planning. This re-evaluation makes the rolling horizon a dynamic approach for making decisions in uncertain environments due to the continuous adjustments to changing conditions (Sethi and Sorger, 1991). Furthermore, the method is also applied for very large problems that cannot be solved to global optimality within a reasonable period of time (Glomb et al., 2022).

However, an alternative rolling horizon approach is presented in more stable environments. In such cases, previous decisions are fixed and will not be revised or re-evaluated, under the assumption that no significant change occurs between planning periods (Swamidass, 2000). This perspective is more static and less flexible but can be more computationally efficient.

For the purpose of this research, the rolling horizon is defined as a decision-making framework that iteratively optimizes a planning model with a finite horizon, where the previous made decisions are fixed and the information for the subsequent period is updated with the refuelling station's previous period inventory and pressure levels. In this rolling horizon approach there is no re-evaluation of the previous determined decisions.

2.3. LNG-IRP

Liquefied natural gas (LNG) is the liquid form of natural gas and is a mixture of mainly methane with some residual gases of nitrogen, propane and ethane. This gas is cooled to temperatures at -161°C at which point it transforms into its liquid state (Volvo Trucks, n.d.). The volume subsequently reduced by a factor of 600 resulting in a more efficient and economically viable storage and transportation (Thomas and Dawe, 2003). The transport of LNG is temperature controlled and since it is -150°C it is called cryogenic. Besides LNG, Bio liquefied natural gas (Bio-LNG), also known liquefied biomethane (LBM) or liquefied biogas (LBG), is handled under the same cryogenic conditions as traditional LNG. Bio-LNG is biogas that has been upgraded and then liquefied, consisting of almost 100% methane. In this research biogas is always reffered to as Bio-LNG, since it shows the most obvious difference compared to LNG.

The vehicle routing problem (VRP) was first addressed by Dantzig and Ramser, 1959 in their paper titled "The Truck Dispatching Problem", which focused on the optimal routing of a fleet of gasoline delivery trucks between a terminal and service stations. Approximately 25 years later, the first integration between inventory management with vehicle routing and scheduling was established with the introduction of the vehicle routing problem (IRP) by Bell et al., 1983. Their work discussed a computer-based routing and scheduling optimizer for the distribution of industrial gases. The literature review by Coelho et al., 2014 revealed that the recent advancements in the IRP literature are on extensions of the basic IRP model and on the nature of the problem. These extensions consist of the production-routing problem, the IRP with multiple products, the IRP with direct deliveries and transshipment, and the consistent IRP. Furthermore, the focus on a more deterministic nature of the problem shifted to a more stochastic environment.

Review carried out by Alves et al., 2018 indicated that weak restrictions on time windows can be promising and that there is no benchmark for the IRP with timewindow. Most researchers use severe restrictions on time windows, however, in real situations weak restrictions on time windows can also be applicable. For instance, due to the lack of drivers, traffic times and car accidents. Furthermore, because there is no benchmark, it is difficult to compare the different IRP with time windows models, because every researcher changes the test conditions and none of them provides the code of the experiment. A recent review highlighted that the three important cost elements in the cold chain logistic vehicle routing problem are transportation, quality and environment costs (Awad et al., 2021). However, in research, there is a lack of sensitivity analyses showing each cost element's contribution to the total costs.

The reviews by Christiansen et al., 2013 and Coelho et al., 2014 indicated that a considerable amount of research has been published on transporting LNG in the maritime sector (Andersson et al., 2016; Cho et al., 2018; Fodstad et al., 2010; Grønhaug et al., 2010; Uggen et al., 2013). However, to the best of the author's knowledge, research by Ghiami et al., 2019 is the first on inland LNG inventory routing optimization. This research focused on the deteriorating inventory routing of LNG with trucks and barges over a multi-period planning horizon. Deterioration is the constant evaporation and loss of the on-hand inventory. For this research deterioration is out of context because the evaporation, boil-off gas (BOG), of LNG results in large greenhouse gas emissions and is not allowed in the inland transport of LNG in Europe. Instead of evaporating the heat out of the tank, this research focuses on refrigeration methods to lower the pressure in the tank at the refuelling stations.

2.4. Refrigeration methods

This research examines three refrigeration methods: nitrogen cooling, offload cooling and logistic trailer cooling. These methods are based on fundamental thermodynamic principles, which are briefly described here to better understand how the refrigeration methods work.

The energy level in a liquid phase is much lower than that in a vapor phase. Thermodynamic equilibrium is the state in which two objects connected by a permeable barrier do not have any heat transfer between them. Evaporation is the transition from the liquid phase to the vapor phase, while condensation is the reverse process, from vapor to liquid. A cryogenic fluid, such as LNG, is rarely at thermodynamic equilibrium due to heat leaks into the system via contact points, such as dispensers at refuelling stations. Stratification is the uneven distribution of heat in the system. In the case of an LNG tank, the top of the tank usually boils, this is a process where the liquid state changes to gaseous state (Chart Industries, 2016).

The following list describes the three refrigeration methods by means of the Figures 2.1 and 2.2.

1. **Nitrogen cooling** is a widely used method that leverages liquified nitrogen (LIN) for cooling. This method includes two approaches: *direct surface cooling* and *secondary circuit cooling*. Both approaches require a nitrogen tank on-site and have a different cooling efficiency. The cooling efficiency is also depended on the tank insulation, horizontal or vertical tank positioning and the initial LNG temperature.

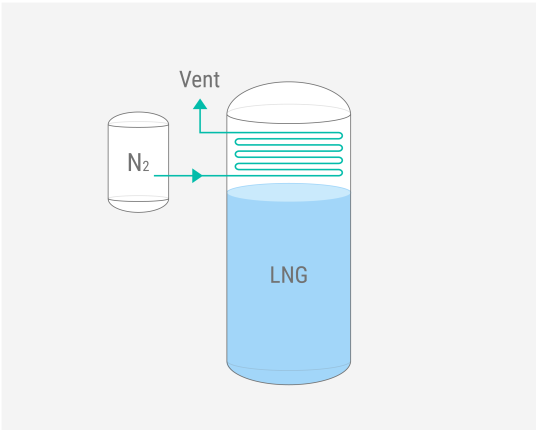
    - *Direct surface cooling*: In this approach, LIN is circulated through a coil inside the refuelling station's tank. The warm vapor at the top of the tank comes into contact with the cold coil and condenses. The condensed LNG returns to the liquid phase and falls back into the tank. During this process, the LIN evaporates as it travels through the coil and is afterwards released into the atmosphere. This process is illustrated in Figure 2.1a.

    - *Secondary circuit LIN cooling*: Here, the cooling occurs outside of the tank. LNG is pumped out of the tank into a temperature regulator where it is cooled using liquid nitrogen. Afterwards, the cooled LNG is pumped back into the top of the tank and the evaporated LIN is released through the vent. This LNG top filling approach accelerates the condensation of vaporized LNG and restores the equilibrium more quickly. Figure 2.1b illustrates this approach.

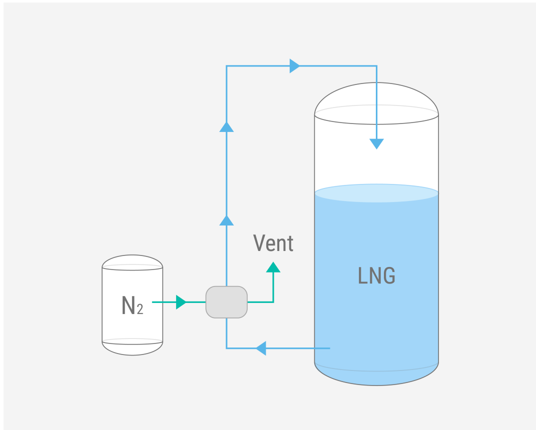
2. **Offload cooling** occurs during the delivery of cold LNG from a terminal to a refuelling station. As the cold LNG is offloaded into the station's relatively warmer tank, it cools the existing LNG,

thereby reducing the overall temperature and pressure within the tank. This process is depicted in Figure 2.2a. The temperature within the vehicle's trailer and the offload quantity have a significant effect on the offload cooling. In principle, Bio-LNG is warmer gas than grey LNG. For that reason the offload cool effect of Bio-LNG is less. In short, offload cooling is depended on a vehicle and is a practical way of managing the tank's pressure without requiring a nitrogen tank.

3. **Logistic trailer cooling** is a specialized method that relies on a vehicle trailer designed to withstand pressure of 5 to 7 bar. This method involves transferring vaporized LNG from the top of the tank into the vehicle's trailer. This transfer reduces the pressure in the refuelling station's tank while increasing the pressure in the trailer. A minimum of 8 tonnes of LNG is usually required in the vehicle's trailer for this method to work. The disadvantage of this method is that the delivery at the next station is with warmer gas so your offload cool effect is less. The process is illustrated in Figure 2.2b. Although this method does not require an on-site nitrogen tank, it does depend on a specialised vehicle trailer and a driver that is familiar with the logistic cooling process.

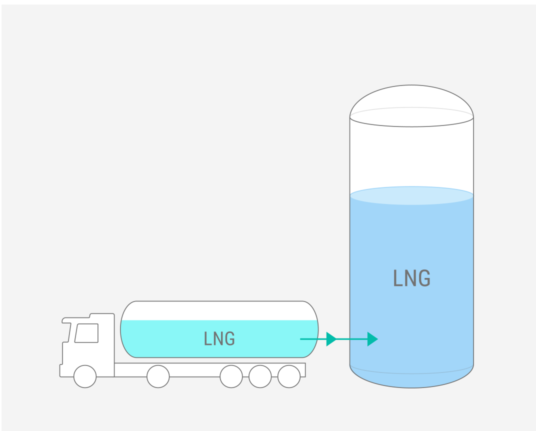


(a) Direct surface cooling (semi-indirect refrigeration). Liquefied nitrogen (LIN) is circulated through the coil inside the tank and cools down the mixture in the tank. Afterwards, the nitrogen vents into the atmosphere.

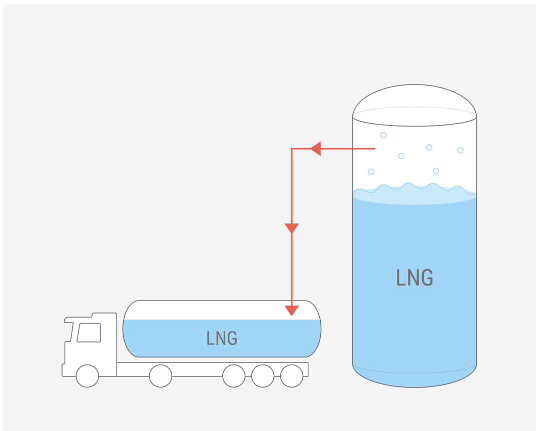


(b) Secondary circuit cooling (indirect refrigeration). LNG is pumped out of the tank into a temperature regulator where it is cooled with liquid nitrogen. Thereafter, the nitrogen evaporates through the vent and the LNG is pumped back into the tank.

Figure 2.1: The schematic drawings in Figure 2.1a and 2.1b represent nitrogen depended refrigeration methods.



(a) Offload cooling. Cooling is done by mixing the cold LNG from the terminal via a vehicle with the warmer mixture in the tank at the filling station. This cooling happens regularly, at every offload.



(b) Logistic trailer cooling. This cooling method requires a specialized vehicle that can withstand pressures of 5 to 7 bar. The warm gas from tank is transferred into trailer of the vehicle and is dropped at the next station.

Figure 2.2: The schematic drawings in Figure 2.2a and 2.2b represent vehicle depended refrigeration methods.

In practice, most refuelling stations are equipped with a nitrogen tank and use nitrogen cooling and offload cooling to control the pressure. Stations without a nitrogen tank rely on offload cooling and logistic trailer cooling. For these stations the frequency of the offload cooling relies on the demand of the stations. Stations with higher demand will empty faster, but there will also be more heat leakage during refuelling. Through regular offloading with cold LNG, you can control pressure for these types of stations. If the pressure becomes too high for these stations anyway, you can use logistic trailer cooling as a remedy. It gets logistically more complicated if you have a station with low demand and no nitrogen tank. Then the station does not run out quickly which means you can not do regular cold offloads. These stations require logistic trailer cooling on a more regular basis.

In summary, there are three methods for cooling LNG: nitrogen cooling, offload cooling and logistic trailer cooling. Each method addresses the pressure in a different way. While nitrogen cooling requires an LIN tank on-site, offload cooling uses the delivery of cold LNG and logistic trailer cooling is depended on a specialized vehicle. Additionally, the logistic trailer cooling has a negative effect on the offload cooling at the next station.

2.5. Problem characteristics

2.5.1. Inventory Routing

Integrating inventory management and routing in modelling considers the interaction between the two decision areas, ensuring that transport costs are minimised and inventory remains within safety levels (Aghezzaf et al., 2006; Coelho and Laporte, 2013). When inventory management and routing decisions are considered in the problem, it can be classified as an Inventory Routing Problem (IRP). These problems may consider that vendors monitor the inventory of the customers and that the vendors make the decisions about when and what delivery quantity should be delivered to each customer. This concept is called Vendor Managed Inventory (VMI) (Kleywegt et al., 2004).

Several studies implemented the IRP in the context of replenishing refuelling stations, each with distinct objectives. Surjandari et al., 2011 and Boers et al., 2020 focused on minimising the transportation costs. Ghiami et al., 2019 extended this by also considering holding costs in their objective function. Cornillier et al., 2008 aimed to maximize profit, defined as the revenue from the product minus the routing, regular transport time and overtime costs. Grønhaug et al., 2010 used a path flow approach to maximize the profit, considering the revenue from the product minus the transport costs and the production costs. Cho et al., 2018 also sought to maximize the profit, accounting for the revenue from the product minus routing, production, inventory holding, weather uncertainties costs and delayed delivery costs.

2.5.2. Time constraints

The Vehicle Routing Problem with Time Windows (VRPTW) is a relevant concept in optimising the replenishment of refuelling stations, which can include soft or strong restrictions on time windows (Alves et al., 2018). Cornillier et al., 2012 used a model with strong time window constraints, where the delivery truck must arrive and depart within specified intervals, and consider the driver's regular and overtime working hours. Surjandari et al., 2011 addressed the Petrol Delivery Assignment problem by utilising a tabu search algorithm to handle multi-product, multi-depot, and split deliveries with time window constraints applied exclusively at the refuelling stations. On the other hand, S. Wang et al., 2017 analysed cold chain logistics in China using a model with soft time window restrictions, incorporating penalty costs for deviations. More recently, X. Wang et al., 2023 proposed a mathematical model featuring strong time window constraints but permitted unfeasible solutions with the help of a hybrid adaptive large neighbourhood search and tabu search heuristic, leveraging penalties to manage these infeasible solutions.

2.5.3. Multi-period time horizon

Cornillier et al., 2008 introduced the Multi-Period Petrol Station Replenishment Problem (MP-PSRP). This problem decides for each day in the time horizon what the delivery quantity at each station is, and what routes the delivery vehicles you should take. Research (Moin and Salhi, 2007) on the planning horizon of inventory routing problem shows that multi-period models are more realistic in the trade-offs between the strategic and operational decisions. However, they require more computational power in comparison with a single period time horizon. For that reason, most multi-period models are considered with a deterministic demand. The second advantage of a multi-period approach is that it can better anticipate the inventory levels at the refuelling stations by taking into account future needs and delivery schedules.

2.5.4. Cooling

The transport and storage of LNG is complex due to its cryogenic nature, which requires constant cooling both during transport and while stored in the refuelling station tanks. Previous studies (Cho et al., 2018; Ghiami et al., 2019; Grønhaug et al., 2010) have examined the transportation of the cryogenic product LNG, but their mathematical models use deterioration to deal with the increasing pressure in the trailer or the refuelling station's tank.

X. Wang et al., 2023 studied a VRP with a different temperature setting in each compartment of the vehicle, but it does not look into the decision on storage temperature. The temperature settings are controlled with penalty costs. Ahmadi-Javid et al., 2023, on the other hand, reveals in their literature review that they are the first that integrate routing and temperature control at the warehouse simultaneously. However, they assume that truck temperature costs are fixed per kilometre and warehouse cooling costs are also fixed per time unit for a certain temperature level. They do not make a decision if they have to cool a station with for instance logistic trailer cooling or not.

Remarkably, there is a gap in the literature regarding the incorporation of logistic trailer cooling within the constraints of a model. Introducing refrigeration as a problem characteristic is new and adds complexity, as not only does the demand from the refuelling stations have to be met, but also pressure levels have to be managed during both transport and storage at the refuelling stations.

2.6. Previous case studies

Boers et al., 2020 could not find a feasible solution within two hours computational time for a sample case of 20 gas station in a 7 day time period with mixed integer linear programming. However, the heuristic algorithm for a petrol distributor in Denmark with one depot, 59 gas stations and 4 vehicles did found a feasible solution that showed a reduction of around 12% travel distance and around 26% average number of stops per trip.

Ghiami et al., 2019 came up with a mathematical model for LNG deteriorating inventory routing that provided the initial solution and this solution is then applied in an adaptive large neighborhood search algorithm to come up with a more efficient solution. Their proposed algorithm performed feasible with up to 100 filling stations and 14 time periods based on actual geographical distances between random selected cities in the Netherlands.

'Cho et al., 2018 experimented a two stage stochastic model for LNG carriers on historical data of the Persian Gulf. The first stage involved making decision on inventory and routing before the weather disruptions and the second stage after the occurrence of the disruptions. In the end, the model maximizes the profit taking into account the qualitative and quantitative importance of each term in the objective.
X. Wang et al., 2023 did a case study in China that involved optimizing the delivery of 30 types of perishable products from a depot to 53 stores with electric vehicles taking into account the temperature and humidity requirements of the products and charging of the batteries of the electric vehicles. The new mathematical model used a hybrid Adaptive large neighbourhood search and tabu search heuristic to minimize the travel costs.

Ahmadi-Javid et al., 2023 analysed a bi-objective case study with the objectives of minimising distribution costs and minimising energy costs for perishable products. The proposed mixed integer linear programming model was capable of optimizing to a maximum of 50 customers and 80% of the instances were solved in less than 10 minutes. Research carried out by Surjandari et al., 2011 solved the multi-product, multi-depot, split deliveries and time windows problem for an Oil and Gas company in Indonesia. This study used the tabu search algorithm to minimize the travel costs.

2.7. Research gap

This research addresses the knowledge gap concerning LNG and Bio-LNG transportation and storage, where maintaining a temperature as low as minus 150 degrees Celcius is important. In these cryogenic conditions, any rise in temperature increases pressure within the storage tank at refuelling stations. Despite the growing importance of Bio-LNG as sustainable fuel for heavy road transport, existing literature lacks optimisation studies that handle Inventory-Routing Problems specific to LNG or Bio-LNG that handle the complexities of pressure management. Previous studies (Cho et al., 2018; Ghiami et al., 2019; Grønhaug et al., 2010) incorporated boil-off gas in there models, which makes it easier to manage the pressure as discussed in Section 2.3.

As shown in Section 2.4, there are three methods for cooling the tank at the refuelling station: nitrogen cooling, offload cooling and logistic trailer cooling. Since not every LNG refuelling station consists of a nitrogen tank at the refuelling station, logistic trailer cooling becomes important. For modelling this makes it complex due to the fact that you have to make decisions when to send a vehicle to the refuelling station to cool the tank while also taking into account the storage levels and minimising the transportation and cooling costs.

Table 2.1 presents the research gap based on a comparison of the problem characteristics between the existing literature and this research. The problem characteristics are the product type, IRP, time horizon, multi-product, heterogeneous vehicle fleet, splits loads and temperature control. The comparison reveals that there is a lack of research about inland transport of LNG and Bio-LNG that takes pressure management into account, while also incorporating IRP, multi-period (M), multi-product (MP), multi-trip (MT), heterogeneous fleet of vehicles (HE), split loads (SL), time constraints (TC) and multi-depot (Multi).

Table 2.1: Research gap by comparison this study to existing studies. The studies are compared on the Product, Inventory Routing Problem (IRP), Time Horizon (TH), Multi-Product (MP), Vehicle use (VU), Vehicle Fleet (VF), Split Loads (SL), Time Constraints (TC), Time Step (TS), Depot, Case, Temperature control (Temp.). Additional abbreviations used in this table are multi-period (M), single period (S), single trip (ST), multi trip (MT), homogeneous fleet (HO), heterogeneous fleet (HE), Random Generated Data (RGD). The countries are abbreviated with Indonesia (IDN), Netherlands (NLD), Denmark (DNK), China (CHN), International (INT). The table indicates that there is a knowledge gap in inland transport of LNG and Bio-LNG that integrate routing, inventory and pressure management.

Paper	Product	IRP	TH	MP	VU	VF	SL	TC	TS	Depot	Case	Temp.
Cornillier et al., 2008	Petrol	✓	M	✓	MT	HE		✓	Day	Single	RGD	
Grønhaug et al., 2010	LNG (sea)	✓	M		MT	HE		✓	Day	Multi	INT	
Surjandari et al., 2011	Petrol	✓	S	✓	MT	HE		✓	Day	Two	IDN	
Cornillier et al., 2012	Petrol		S		MT	HE		✓	Hour	Multi	RGD	
Cho et al., 2018	LNG (sea)	✓	M		MT	HE	✓	✓	Day	Multi	Qatar	
Ghiami et al., 2019	LNG	✓	M		MT	HE	✓	✓	Day	Two	NLD	✓
Al-Hinai and Triki, 2020	Petrol		M	✓	ST	HE			Day	Single	Oman	
Boers et al., 2020	Petrol	✓	M	✓	MT	HE	✓	✓	Day	Single	DNK	
X. Wang et al., 2023	Perishable		M	✓	MT	HO		✓	Day	Single	CHN	✓
Ahmadi-Javid et al., 2023	Perishable		M		MT	HO		✓	Hour	Multi	INT	✓
This research	**(Bio)-LNG**	✓	**M**	✓	**MT**	**HE**	✓	✓	**Hour**	**Multi**	**NLD**	✓

2.8. Conclusion of literature research

This literature research dived into the main topic, methods and challenges associated with the LNG and Bio-LNG IRP with pressure management. The study identified MILP as a suitable method for modelling the LNG-IRP because it can integrate discrete and continuous decisions and handle routing, inventory and pressure constraints. Additionally, the rolling horizon approach is presented as a computationally efficient technique for tackling the complexity of multi-period planning by iteratively solving smaller manageable time blocks.

Refrigerations methods, such as nitrogen cooling, offload cooling and logistic trailer cooling, were explained and were shown schematically. Logistic trailer cooling, in particular, presents a unique modelling complexity because it requires specialized vehicles. The integration of these refrigeration methods into the LNG-IRP has not been addressed in previous literature.

The research gap is identified by comparing this research to existing studies. Previous studies explored the LNG-IRP in the maritime sector or assumed deterioration (boil-off gas) into inland transportation. However, today the evaporation of LNG is not allowed in the inland transport LNG in Europe. In addition, this study distinguished itself by focusing on multi-period scheduling, heterogeneous fleet and the integration of cooling methods such as logistic trailer cooling. The knowledge gap is the lack of LNG IRP studies that consider pressure management.

The subquestion addressed in this chapter was: "*What is the current state of research and practice regarding the LNG and Bio-LNG IRP with cryogenic temperature control?*" This literature research concludes that the existing literature provides insights into the LNG IRP and the refrigeration methods, but there is a lack of knowledge about a planning method that integrates routing decisions with inventory and pressure management for LNG and Bio-LNG.

3

Planning methodologies

This chapter presents the development of a planning methodology for LNG IRP with pressure management. The chapter answers three sub-questions, focusing on identifying the relevant KPIs, defining the key constraints and variables, and developing planning methods. The chapter starts by introducing the conceptual model and objectives. Next, constraints and variables are defined. Finally, the chapter goes through a step-by-step approach to the development of the planning methodology, starting with a Full MILP model, followed by a Simplified MILP model and ending with a rolling horizon approach. The methodology developed in this chapter is further evaluated in the next chapter Case study, where the model's robustness and applicability is tested in a real-world scenario. The mathematical models in this chapter were implemented in python and solved using the open PuLP library (version 2.9.0.). The experiments were run on a laptop with an Intel i5 processor and 8 GB of RAM.

3.1. Conceptual model and objectives

This section presents the conceptual model and the objective with the KPIs to measure the performance of the model. A conceptual model is an abstract representation of the problem, where the objective, constraints and decisions are defined and is an important step before translating the problem into mathematical equations (Hillier and Lieberman, 2010). The result of this conceptual model is an answer to sub-question: "*What are the key constraints and variables that must be considered when designing a planning methodology for LNG and Bio-LNG IRP with cryogenic temperature control?*"

3.1.1. Detailed problem description

The problem that we are solving is the integrated control of the logistics of LNG and Bio-LNG over a network of refuelling stations. Every hour the refuelling station's inventory levels decrease due to customers that tank at the stations. Furthermore, every hour the refuelling station's pressure increases due to heat leaks. If the refuelling station runs out of inventory the customers cannot tank at the station and the company loses income. If the pressure at the refuelling station gets too high the safety control starts and the station will shut down. Which will also result in income loss. For this reason, the inventory and pressure levels must be managed.

As explained in the literature in Section 2.4, the pressure can be managed by nitrogen cooling, offload cooling and logistic trailer cooling. The inventory can restocked by vehicles that deliver LNG or Bio-LNG from the terminal to the stations while taking into account the maximum inventory capacity of the station and the vehicle. The offload cooling effect depends on the terminal where the LNG or Bio-LNG is coming from. Since each terminal stores LNG or Bio-LNG at different temperatures. In addition, the logistic trailer cooling is dependent on the vehicle and the terminal from which the vehicle is coming. Not every vehicle can do logistic trailer cooling due to the pressure capacity of the vehicle's trailer. Another restriction is that logistic trailer cooling cannot be done at the last station and the vehicle's trailer must have more than 8 tons in it.

Furthermore, the vehicles must start each day at their home base. The routing should account for the vehicle's travel times since the station's demand each day can be 40% of the entire station's storage tank. Delivering at the beginning of the day or the end of a day can result in more inventory available at the station which allows for larger offloads. Routing must take into account vehicle travel times, as daily demand at the station can be up to 40% of the station's full storage capacity. Deliveries at the beginning or end of the day have a significant impact on the stock available at the station. Early deliveries provide sufficient stock to meet demand throughout the day, while late deliveries maximise available storage capacity for larger offloads. The decision about the delivery times at refuelling stations are an important component of this inventory routing problem.

3.1.2. Model characteristics

The model is designed to develop a distribution plan for LNG and Bio-LNG, coordinating deliveries from multiple terminals to a network of refuelling stations over a multi-day planning horizon. These cryogenic products, LNG and Bio-LNG, are transported by a heterogeneous fleet of vehicles differing in home base location, trailer capacity and pressure capacity. Figure 3.1 shows the conceptual model of the LNG and Bio-LNG inventory routing problem including multiple home bases and terminals. The model operates under a Vendor Managed Inventory (VMI) approach, where the vendor monitors the inventory levels at refuelling stations and determines when and what delivery quantity should be delivered to the refuelling stations. Given the cryogenic nature of the products, the vendor also knows the pressure levels at the refuelling stations.

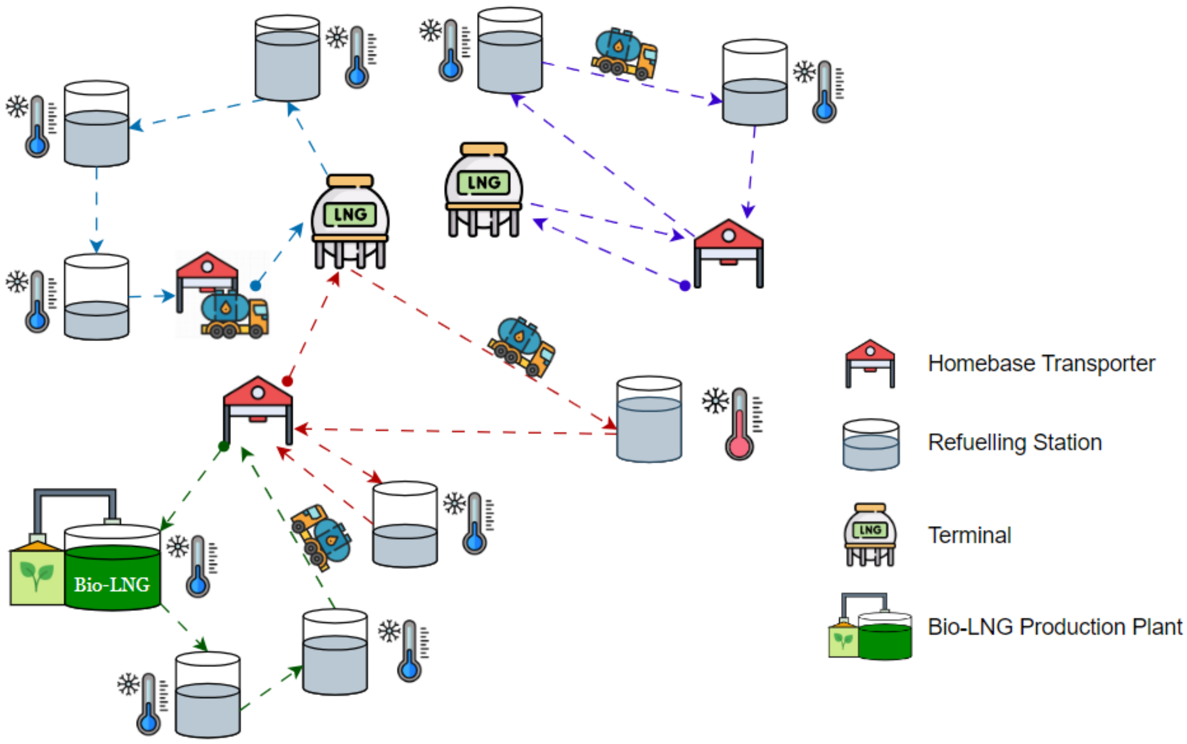


Figure 3.1: Conceptual model of LNG and Bio-LNG inventory routing problem with pressure management. The network consists of stations with low inventory or high pressure, LNG terminals, a Bio-LNG production plant, homebases of transporters and vehicle routes.

The decision to send a vehicle to a refuelling station is driven by minimum inventory thresholds and maximum allowable pressure levels. For each time step within day, in other words each hour, the decision maker determines the following decisions:

- which vehicles are used to load, offload (Bio-)LNG and logistic cool
- at what time the vehicle leaves and returns to the home base
- which and when refuelling stations need to be refuelled and/ or logistic cooled

- what terminal time slots are used to pick up load
- what the load quantity is at a terminal time slot and what product
- what the offload quantity is at a refuelling station and what product
- when do the refuelling station need to start and stop LIN cooling
- If a vehicle needs to wait at a refuelling station or terminal
- If a vehicle loads at a terminal and then waits at a homebase to offload the next day
- How many bars the vehicle has to release from the refuelling station into the vehicle

Table 3.1: Model definitions.

Term	Definition
Nodes	Locations in the distribution network i.e. home bases, terminals and refuelling stations
Edges	Link from one node to another node, defined by travel time, travel distance and toll costs
Arcs	Directed edge from one node to another node
Vehicles	Tank trucks that can load at terminals and offload at refuelling stations
Home base	Node where a vehicle starts and ends their journey and can wait for transport
Terminal	Node where a vehicle picks up (Bio-)LNG
Terminal time slots	A moment in time where a vehicle can pick up LNG or Bio-LNG at a terminal
Refuelling stations	Node where a vehicle delivers (Bio-)LNG or releases pressure with logistic cooling
Time step	The time interval between two consecutive time steps, also known as time interval
Time horizon	The total amount of time steps in the model

3.1.3. Assumptions

To create a planning methodology for LNG IRP with pressure management, several assumptions are made. These assumptions simplify the real-world challenges of cryogenic logistics. The following assumptions are made:

- The refuelling station's inventory levels are known by the decision-maker.
- The refuelling station's pressure levels are known by the decision-maker.
- The demand is deterministic, based on a forecast for each refuelling station.
- The pressure increase due to heat leaks is deterministic, based on a forecast for each refuelling station.
- At a refuelling station Bio-LNG and LNG can be mixed.
- At a terminal only one product can be loaded into the vehicle.
- The travel distance, the travel times and toll costs between the nodes are calculated with the tool TLN planner.
- Travel times are rounded, with values between 0 and 1 rounded up to 1, while all other values are rounded according to standard rounding rules.
- The fleet of vehicles are heterogeneous and differ in location of home base, inventory capacity and pressure capacity.
- All vehicles have the same travel speed, resulting in identical travel times.
- The refuelling stations can always be visited. They are open 24/7.

- The vehicles do not take into account working hours and can drive 24/7.
- The offload cooling parameter is based on the product the vehicle loads and is the same during the entire trip. It is not taken into account that the pressure in vehicles trailer increases over time and that the offload cooling effect is less at the end of the trip or when the vehicle does logistic cooling in a trip.

3.1.4. Objective and KPIs

This paragraph outlines the Key Performance Indicators (KPIs) developed to evaluate the performance of a planning methodology for integrated control in the cryogenic logistics of LNG and Bio-LNG. These KPIs were developed in collaboration with W. Konings, planning expert, and M. Ernes, operations manager, to align with the objective of minimizing the transportation costs and nitrogen cooling costs. They form the basis for addressing the main research question: *How can the LNG-IRP with cryogenic temperature control be optimised considering transportation and nitrogen cooling costs?*

The KPIs focus on the cost drivers and operational efficiency. These indicators are relevant for validating the robustness and reliability of the developed LNG-IRP planning method. The developed KPIs are listed below:

1. **Total Costs (TC) in euro**: This KPI combines the total transportation costs and nitrogen cooling costs into a single metric, providing insights into the costs and opportunities for cost savings.
2. **Total Transportation Costs (TTC) in euro**: This KPI measures the transport-related costs, including:
    - *Fuel costs in euro*: Calculated based on the total kilometres driven and a constant fuel price rate.
    - *Road toll costs in euro*: Represents the fixed costs associated with toll roads.
    - *Driver labour costs in euro*: Accounts for the working hours of the drivers based on the travel time and the service times at stations and terminals.
3. **Total Nitrogen Cooling Costs (TNCC) in euro**: This KPI measures the costs of cooling the refuelling station's storage tanks with cold nitrogen.
4. **Cost per Kilogram (CpK) in euro**: This KPI provides a normalised measure that relates the total transportation costs to the total offload quantity, and allows to compare the efficiency of delivery routes in different scenarios. The total offload quantity gives an overview of the total LNG and Bio-LNG delivered to the refuelling stations.

In summary, the four identified KPIs help to evaluate the developed planning methods. The KPIs are aligned with the research objectives and form a base for evaluating the methodology's performance.

3.1.5. Requirements

This research aims to create the planning for LNG IRP with pressure management for multiple days with the cryogenic products LNG and Bio-LNG. In collaboration with W. Konings, planning expert, and M. Ernes, operations manager, the developed requirements for the planning methodology are:

- **No stock-out or critical pressure at refuelling stations**
  This means that the inventory levels are always within the specified bounds. Furthermore, the pressure levels must not fall outside their limits. This prevents scenarios where refuelling stations have to shutdown and customers cannot refuel, leading to loss of sales.
- **The run time of the planning tool must be within four hours**
  As described in section 1.2, the scope of this research is on the operational level. Therefore, a short run time makes the planning methodology more flexible and helps in making daily planning decisions.
- **Planning output must be easy to read**
  Since the planning is send to the transporters the planning output must be understandable. The

planning shows how much drivers must load and at what terminal, the quantity to be delivered at a refuelling station, and if the driver must do logistic cooling.

3.2. Full MILP model

In this section, the Full MILP model is introduced, detailing the sets, parameters, variables, objective function, and constraints.

3.2.1. Sets, parameters and variables

Table 3.2: Notation Full MILP: sets and indices, parameters

Sets and indices		
N	Set of nodes $[N_h + N_t + N_s]$	$i, j \in N$
N_h	Subset of nodes: homebases	$N_h \subseteq N$
N_t	Subset of nodes: terminals	$N_t \subseteq N$
N_s	Subset of nodes: stations	$N_s \subseteq N$
T	Set of time steps	$t \in T$
K	Set of vehicles	$k \in K$
S	Set of terminal time slots	$s \in S$
P	Set of products	$p \in P$
Parameters		
st	Fixed service time visiting a station or terminal	[hour]
tt_{ij}	Travel time between node i and node j	[hour]
td_{ij}	Travel distance between node i and node j	[km]
c_{ij}^{toll}	Road toll costs between node i and node j	[euro]
c_{km}	Distance costs per kilometre	[euro / km]
c_{hours}	Driver costs per hour	[euro / hour]
$c_{nitrogen}$	Nitrogen cooling cost per hour	[euro]
D_{it}	Demand refuelling station i in time step t	[ton]
$I_i^{\min}$	Minimum inventory refuelling station i	[ton]
$I_i^{\max}$	Maximum inventory refuelling station i	[ton]
I_i^{initial}	Initial inventory refuelling station i	[ton]
PHL	Pressure increase due to heatleaks	[bar]
$P_i^{\min}$	Minimum pressure refuelling stations i	[bar]
$P_i^{\max}$	Maximum pressure refuelling station i	[bar]
P_i^{initial}	Initial pressure refuelling station i	[bar]
LIN_i	LIN tank available at refuelling station i	[-]
$Q_k^{\max}$	Maximum inventory capacity vehicle k	[ton]
$V_k^{\max}$	Maximum logistic cool pressure capacity vehicle k	[ton]
oc_p	Offload cooling parameter of product p	[bar / ton]
$oq_{\min}$	Fixed value for the minimum offload final station	[ton]
h_k	Home base of vehicle k	[-]

Table 3.3: Notation Full MILP: variables

Variables		
x^k_{ijt}	Binary variable, if vehicle k travels on arc (i,j) in time step t: 0 if arc (i,j) is not used 1 if arc (i,j) is used	[-]
z^k_{it}	Binary variable, if vehicle k visits node i in time step t: 0 if the vehicle does not visit 1 if the vehicle visits	[-]
L^{kp}_{it}	Binary variable, if vehicle k loads product p at terminal i in time step t: 0 if the vehicle does not load 1 if the vehicle loads	[-]
O^k_{it}	Binary variable, if vehicle k is logistic cooling or offloading at station i in time step t: 0 if the vehicle is logistic cooling 1 if the vehicle is offloading	[-]
w^k_{it}	Binary variable, if vehicle k is waiting at terminal or station i in time step t: 0 if the vehicle is not waiting 1 if the vehicle is waiting	[-]
oq^{kp}_{it}	Offload quantity of product p delivered to refuelling station i by vehicle k in time step t (float)	[ton]
lq^{kp}_{it}	Load quantity of product p loaded at terminal i by vehicle k in time step t (float)	[ton]
I_{it}	Refuelling station i's inventory level in time step t (float)	[ton]
Q^p_{kt}	Vehicle k's inventory level of product p in time step t (float)	[ton]
P_{it}	Refuelling station i's pressure level in time step t (float)	[bar]
n_{it}	LIN cooling at refuelling station i in time step t (float)	[bar]
v^k_{it}	Logistic cooling at refuelling station i in time step t by vehicle k (float)	[bar]
LC^{max}_{kt}	Pressure capacity of vehicle k in time step t (float)	[bar]

3.2.2. Objective function and constraints

Equation 3.1 defines the objective of minimizing the total costs. The total costs consists of the total transportation costs an nitrogen cooling costs. The total transportation costs are the summed costs of road toll, travel hours drivers, waiting hours drivers and fuel costs. The nitrogen cooling costs, on the other hand, are the cost number of time steps the station cools multiplied by the nitrogen cost per hour.

$$\begin{aligned} \min \quad & \sum_{t\in T}\sum_{k\in K}\sum_{\substack{ij\in N\\ i\neq j}} x^k_{ijt}c^{toll}_{ij} + \sum_{t\in T}\sum_{k\in K}\sum_{\substack{ij\in N\\ i\neq j}} x^k_{ijt}td_{ij}c_{km} + \sum_{t\in T}\sum_{k\in K}\sum_{\substack{ij\in N\\ i\neq j}} x^k_{ijt}tt_{ij}c_{hours} \\ & + \sum_{t\in T}\sum_{k\in K}\sum_{i\in N_s+N_t} w^k_{i,t}c_{hours} + \sum_{t\in T_r}\sum_{i\in N} n_{it}c_{nitrogen} \end{aligned} \tag{3.1}$$

Equation 3.2 defines the departure of vehicle k. If vehicle k travels from node i to node j in time step t ($x^k_{ijt} = 1$), then vehicle k must be at node i in time step t ($z^k_{it} = 1$).

$$z^k_{it} \geq x^k_{ijt} \quad \forall k \in K, \forall i,j \in N, i \neq j, \forall t \in T \tag{3.2}$$

Equation 3.3 defines the arrival of vehicle k. If vehicle k travels from node i to node j in time step t, then vehicle k must arrive at node j in time step $t + tt_{ij}$ (start time + travel time).

$$z^k_{j,t+tt_{ij}} \geq x^k_{ijt} \quad \forall k \in K, \forall i,j \in N, i \neq j, \forall t \in T, \text{ if } t + tt_{ij} \leq \max(T) \tag{3.3}$$

Equation 3.4 defines the flow balance constraints with incorporated travel times. If vehicle k is at node j in time step t ($z^k_{jt} = 1$), then either he must have been at node j the previous time step ($z^k_{jt-1} = 1$), or vehicle k must depart from node j in the previous time step $t-1$, or travelled to node j from node i

with travel time tt_{ij} ($x^k_{ijt-tt_{ij}}$ = 1).

$$z^k_{jt} = z^k_{j,t-1} - \sum_{\substack{i \in N \\ i \neq j}} x^k_{ji,t-1} + \sum_{\substack{i \in N \\ i \neq j \\ t-tt_{ij} \geq 0}} x^k_{ij,t-tt_{ij}} \quad \forall k \in K, \forall j \in N, \forall t \in T \setminus \{0\} \tag{3.4}$$

Equation 3.5 defines the flow balance so that for vehicle k the sum of the ingoing arcs x^k_{ijt} is the same as the outgoing arcs x^k_{jit}.

$$\sum_{\substack{i \in N \\ i \neq j \\ t \in T}} x^k_{ijt} = \sum_{\substack{i \in N \\ i \neq j \\ t \in T}} x^k_{jit} \quad \forall k \in K, \forall j \in N \tag{3.5}$$

Equation 3.6 and 3.7 define the start location of vehicle k. In time step 0 the start location of vehicle k is at home base ($z^k_{i,0} = 1$). In combination with the previous equation it ensures that every vehicle start and ends at its home base.

$$z^k_{h_k t} = 1 \quad \forall k \in K, t = 0 \tag{3.6}$$

$$z^k_{h_k t} = 0 \quad \forall k \in K, t = 0 \tag{3.7}$$

Equation 3.8 define the minimum and maximum inventory of the different stations i. The station's inventory must be above the minimum bound and below the maximum bound.

$$I^{\min}_i \leq I_{it} \leq I^{\max}_i \quad \forall i \in N_s, \forall t \in T \tag{3.8}$$

Equation 3.9 and 3.10 updates the inventory of the refuelling station in kilograms. At the time step 0 the inventory of station i is the start inventory of station i. For the rest of the time horizon station i updates the inventory depending on the previous inventory (I_{it-1}), the offload quantity (oq^k_{it}), the demand (D_i).

$$I_{it} = I^{\text{initial}}_i \quad \forall i \in N_s, t = 0 \tag{3.9}$$

$$I_{it} = I_{i,t-1} + \sum_{k \in K} \sum_{p \in P} oq^{kp}_{it} - D_i \quad \forall i \in N_s, \forall t \in T \setminus \{0\} \tag{3.10}$$

Equation 3.11 Vehicle k can only offload at node i if it visits node i.

$$oq^{kp}_{it} \leq M \cdot z^k_{it} \quad \forall k \in K, \forall i \in N_s, \forall t \in T, \forall p \in P \tag{3.11}$$

Equation 3.12 set the start inventory of the vehicle and 3.13 update the inventory of the vehicle. The vehicle's inventory for the product is updated depending on the previous inventory (Q_{kt-1}), the load quantity (lq^{kp}_{it}) and the offload quantity (oq^{kp}_{it}).

$$Q_{kt} = 0.0 \quad \forall k \in K, t = 0 \tag{3.12}$$

$$Q^p_{kt} = Q^p_{kt-1} + \sum_{i \in N_t} lq^{kp}_{it} - \sum_{i \in N_s} oq^{kp}_{it} \quad \forall k \in K, \forall t \in T \setminus \{0\}, \forall p \in P \tag{3.13}$$

Equation 3.14 defines the maximum capacity of a vehicle k.

$$\sum_{p \in P} Q^p_{kt} \leq Q^{\max}_k \quad \forall k \in K, \forall t \in T \tag{3.14}$$

Equation 3.15 and 3.16 ensure that logistic cooling (v^k_{it}) and offloading (oq^{kp}_{it}) can not occur in the same time step with the help of a binary decision variable y^k_{it} and the big M method.

$$oq^{kp}_{it} \leq M \cdot O^k_{it} \quad \forall k \in K, \forall i \in N_s, \forall t \in T, \forall p \in P \tag{3.15}$$

$$v^k_{it} \leq M \cdot (1 - O^k_{it}) \quad \forall k \in K, \forall i \in N_s, \forall t \in T \tag{3.16}$$

Equation 3.17 Vehicle k can only load at node i if it visits i.

$$L_{it}^{kp} \leq z_{it}^{k} \quad \forall k \in K, \forall i \in N_t, \forall t \in T, \forall p \in P \tag{3.17}$$

Equation 3.18 Vehicle k can only load a quantity at node i if it is allowed to load at node i.

$$lq_{it}^{kp} \leq M \cdot L_{it}^{kp} \quad \forall k \in K, \forall i \in N_t, \forall t \in T, \forall p \in P \tag{3.18}$$

Equation 3.19 Vehicle k can only load at terminal i in time step t if vehicle k is at the right terminal i at the right start time t from the available slots. Furthermore, all vehicles can not load more than the total amount of available slots.

$$\sum_{k \in K} L_{it}^{kp} \leq S_{it} \quad \forall i \in N_t, \forall t \in T, \forall p \in P \tag{3.19}$$

Equation 3.20 The pressure for refuelling stations without active cooling, no liquid nitrogen tank on site, is bounded by a minimum and maximum pressure.

$$P_i^{\min} \leq P_{it} \leq P_i^{\max} \quad \forall i \in N_s, \forall t \in T \tag{3.20}$$

Equation 3.22 Updates the refuelling station's pressure depending on the previous pressure (P_{it-1}), the pressure increase due to heat leaks (PH), logistic cooling (v_{it}^k), liquid nitrogen cooling (n_{it}) and offload cooling in bars ($oq_{it}^k \cdot Param$).

$$P_{it} = P_i^{initial} \quad i \in N_s, t = 0 \tag{3.21}$$

$$P_{it} = P_{i,t-1} + PHL - v_{it}^k - n_{it} - \sum_{k \in K} \sum_{p \in P} oq_{it}^{kp} oc_p \quad \forall i \in N_s, \forall t \in T \setminus \{0\} \tag{3.22}$$

Equation 3.23 checks if a refuelling station i has a LIN tank.

$$n_{it} \leq M \cdot LIN_i \quad \forall i \in N_s, \forall t \in T \tag{3.23}$$

Equation 3.24 Refuelling station i can not active cool, with LIN tank, (n_{it}) more than the pressure increase due to heat leaks (PH) each time step t.

$$n_{it} \leq PHL \quad \forall i \in N_s, \forall t \in T \tag{3.24}$$

Equation 3.25 Vehicle k can only reduce pressure at a refuelling station i with logistic cooling (v_{it}^k) if vehicle k visits node i.

$$v_{it}^k \leq M \cdot z_{it}^k \quad \forall k \in K, \forall i \in N_s, \forall t \in T \tag{3.25}$$

Equation 3.26 - 3.28 define the number of bar a vehicle can logistic cool. Equation 3.26 defines that at time step 0 the vehicle k is at its home base, so the LC_{kt} is set to 0. Equation 3.27 updates the LC_{kt} based on the previous LC_{kt-1}, the reset when vehicle k is loading at the terminal i ($L_{it}^k \cdot V_k^{\max}$), and minus the logistic cooling v_{it-1}^k.

$$LC_{kt} = 0 \quad \forall k \in K, t = 0 \tag{3.26}$$

$$LC_{kt} \leq LC_{kt-1} + \sum_{i \in N_t} \sum_{p \in P} L_{it}^{kp} \cdot V_k^{\max} - \sum_{i \in N_s} v_{it-1}^k \quad \forall k \in K, \forall t \in T \setminus \{0\} \tag{3.27}$$

Equation 3.28 ensures that LC_{kt} is bound by the maximum pressure capacity reduction of vehicle k ($V_k^{\max}$).

$$LC_{kt} \leq V_k^{\max} \quad \forall k \in K, \forall t \in T \tag{3.28}$$

Equation 3.29 At the final station i before the vehicle k goes back to its home base, the offload quantity (oq_{it}^k) must be more than the minimum offload quantity at the final station.

$$\sum_{p \in P} oq_{it}^{kp} \geq oq_{\min} \cdot x_{ijt}^k \quad \forall k \in K, t \in T, i \in N_s, j \in N_h \tag{3.29}$$

Equation 3.30 Vehicle k must not drive from terminal i to home base j. Otherwise the arc to the final node can not be defined.

$$x_{ijt}^k = 0 \quad \forall k \in K, t \in T, i \in N_t, j \in N_h \tag{3.30}$$

Equation 3.31 - 3.40 define the binary and continuous variables.

$$x_{ijt}^{k} \in \{0,1\} \quad \forall k \in K, \forall t \in T, \forall ij \in N, i \neq j \tag{3.31}$$

$$z_{it}^{k} \in \{0,1\} \quad \forall k \in K, \forall t \in T, \forall i \in N \tag{3.32}$$

$$L_{it}^{kp} \in \{0,1\} \quad \forall k \in K, \forall t \in T, \forall i \in N_t, \forall p \in P \tag{3.33}$$

$$O_{it}^{k} \in \{0,1\} \quad \forall k \in K, \forall t \in T, \forall i \in N_s \tag{3.34}$$

$$w_{it}^{k} \in \{0,1\} \quad \forall k \in K, \forall t \in T, \forall i \in N_s \tag{3.35}$$

$$oq_{it}^{kp} \geq 0 \quad \forall k \in K, \forall t \in T, \forall i \in N_s, \forall p \in P \tag{3.36}$$

$$lq_{it}^{kp} \geq 0 \quad \forall k \in K, \forall t \in T, \forall i \in N_t, \forall p \in P \tag{3.37}$$

$$I_{it}, P_{it}, n_{it} \geq 0 \quad \forall t \in T, \forall i \in N_s \tag{3.38}$$

$$Q_{kt}^{p} \geq 0 \quad \forall t \in T, \forall k \in K, \forall p \in P \tag{3.39}$$

$$v_{it}^{k} \geq 0 \quad \forall k \in K, \forall t \in T, \forall i \in N_s \tag{3.40}$$

$$LC_{kt} \geq 0 \quad \forall t \in T, \forall k \in K \tag{3.41}$$

3.2.3. Verification Full MILP model

Verification involves checking if the model has been built correctly by experimenting on the models behaviour in different scenarios. Seven test were performed and an overview of the results is provided in Table 3.4.

Table 3.4: Seven different verification tests applied on the Full MILP model with their description, expected behaviour, model's result and final conclusion if the expected behaviour is similar to the model's result. Pass indicates that the result is as expected.

Test	Description	Expected	Result	OK
1	Base case	km_costs > 0 hours_costs > 0 lin_costs > 0	km_costs = 282 hours_costs = 936 lin_costs = 40	Pass
2	No pressure constraints	km_costs < 282 hours_costs < 936 lin_costs = 0	km_costs = 221 hours_costs = 585 lin_costs = 0	Pass
3	No inventory constraints & pressure capacity =100	km_costs < 282 hours_costs < 936 lin_costs > 40	km_costs = 180 hours_costs = 643 lin_costs = 115	Pass
4	No offload cooling & pressure capacity = 100	km_costs = 282 hours_costs > 936 lin_costs > 40	km_costs = 282 hours_costs = 994 lin_costs = 40	Pass
5	No vehicles	Infeasible	Infeasible	Pass
6	Increase PH = 0,07	km_costs > 282 hours_costs > 936 lin_costs > 40	km_costs = 298 hours_costs = 936 lin_costs = 98	Pass
7	No service time	hours_costs < 936 lin_costs < 40	hours_costs < 468 lin_costs = 30	Pass

3.2.4. Validation Full MILP model

Validation involves evaluating whether the model can deliver realistic, practical and cost-effective solutions to the daily logistic challenges of LNG and Bio-LNG distribution.

The time-space model in Figure 3.2 presents a visual representation of the movement of a vehicle as it moves across various locations in the network over time. This graphical model takes into account the travel times of the arcs and the service times needed for certain actions that are done at each stop, such as loading or offloading. To illustrate, a single vehicle's trip is followed and afterwards the specific routing variables are highlighted.

The trip starts as the vehicle departs from the *Home base* at time step 1 and travels to the *Terminal*. According to Table 3.5, this part of the trip requires 1 hour of travel time and a 2-hour service time at the terminal, which represents the time needed for loading LNG. Therefore, by time step 4, the vehicle is ready to continue to the next destination. From the *Terminal*, the vehicle proceeds to *Station 1*. The trip to *Station 1* involves a 3-hour travel time and a 2-hour service time for offloading, resulting in a 5-hour total time at this location. After completing the service, the vehicle moves on to *Station 2.* At *Station 2*, the vehicle arrives after a 2-hour travel time and requires a 2-hour service time, totaling 4 hours at this location. Once the offloading is complete, the vehicle moves towards *Station 3*.

For the arrival at *Station 3*, the vehicle has a 1-hour travel time to this location and a 2-hour service time for further offloading, totaling 3 hours. The final end of the trip brings the vehicle back to the *Home base* after 1 hour of travel, with no additional service time needed at the *Home base*. This return travel, completes the trip. The routing variable x_{ijt}^k equals 1 if vehicle k departs from node i to node j at time step t, defining the use of an arc. For instance in this example, vehicle k departs on time 1, 4, 9, 13, 16, and $x_{ijt}^k = 1$ at these steps. The node visit variable z_{it}^k equals 1 if vehicle k is located on node i at time step t. In this example, $z_{it}^k = 1$ when the vehicle visits at time steps 0, 1, 4, 9, 13, 16, and so on, defining the times it is at specific nodes. Both these variables track the vehicle's position in the network, identifying where it departs and where it stops over time.

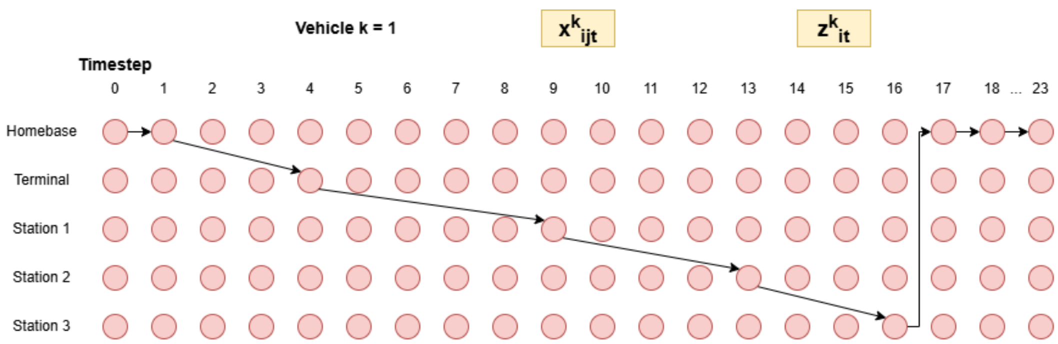


Figure 3.2: Overview of time-space model. The rows represent the nodes and the columns indicate the time steps in hours. It highlights that the service time is incorporated in the travel time and that the vehicle starts and end at its homebase.

Table 3.5: Travel time, service time and total time of arcs

Arc	Travel time	Service time	Total time
Home base - Terminal	1	2	3
Terminal - Station 1	3	2	5
Station 1 - Station 2	2	2	4
Station 2 - Station 3	1	2	3
Station 3 - Home base	1	0	1

Figure 3.3 illustrates the interaction between the vehicle load and the inventory levels of the refuelling stations over time. At time step 4, the Schenk vehicle loads 8600 kg of LNG. Subsequently, the vehicle makes its first stop at the Alkmaar station where it offloads 3000 kg of LNG. This results in a decrease in the vehicle's inventory level and an increase in the inventory of station Alkmaar, as indicated by the

red dotted line at time step 9. The vehicle then proceeds to offload 600 kg at station Geldermalsen at time step 13. The final delivery is at time step 16 with an offload of 5000 kg, leaving the vehicle's inventory empty. The upper graph in Figure 3.3 shows that all inventory levels remain within the specified bounds: Alkmaar station operates between a minimum of 1000 kg and a maximum of 20.000 kg, Geldermalsen between 2000 kg and 20.000 kg, and Tilburg between 2000 kg and 21.000 kg. Furthermore, an important point to notice is that by the end of the time horizon, time step 24, the inventory levels of Alkmaar and Geldermalsen are close to their minimum safety stock level. This suggests that implementing this route would lead to potential shortages in stocks for the next time horizon, indicating that adjustments are needed if you want sustainable planning in the future.

Figure 3.4 presents the offload cooling of the vehicles at time step 9, 13 and 16. Station Alkmaar, equipped with a nitrogen tank, maintains the pressure below the threshold of 8.0 bar. However, the offload was essential to keep the inventory above the safety stock level. The stations Geldermalsen and Tilburg, do not have a nitrogen tank onsite and rely on offload cooling or logistic cooling. In this validation scenario, offload cooling alone was sufficient to keep pressure within operational boundaries for the stations Geldermalsen and Tilburg and logistic cooling was not used.

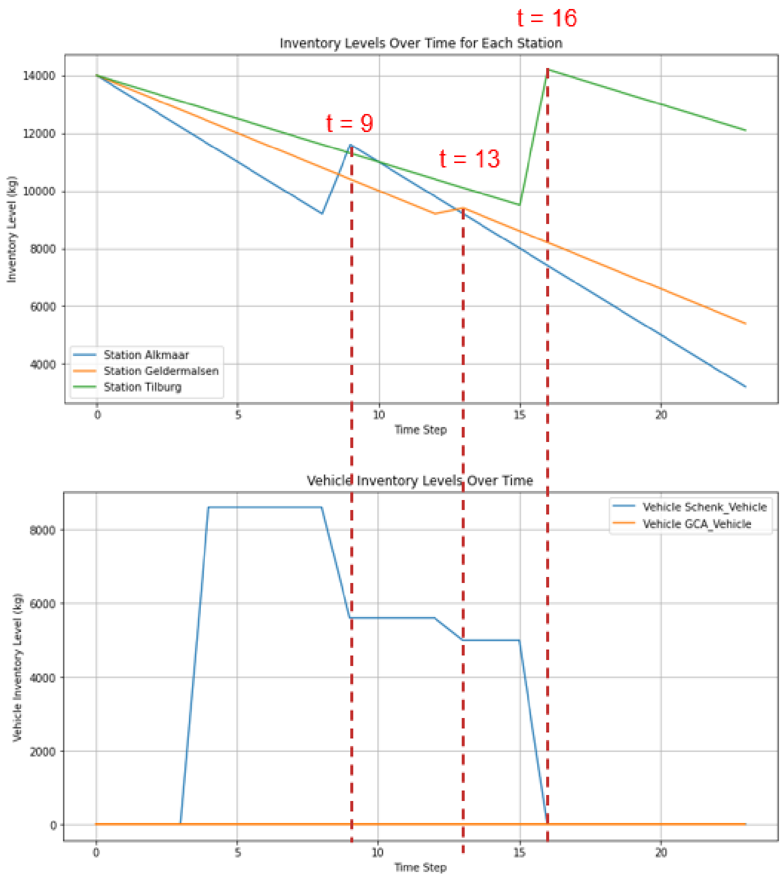


Figure 3.3: The top figure present the inventory levels over time for each station. The bottom figure presents the vehicle inventory level over time. This figure indicates that the offloads of the vehicle are reflected in the stations inventory level.

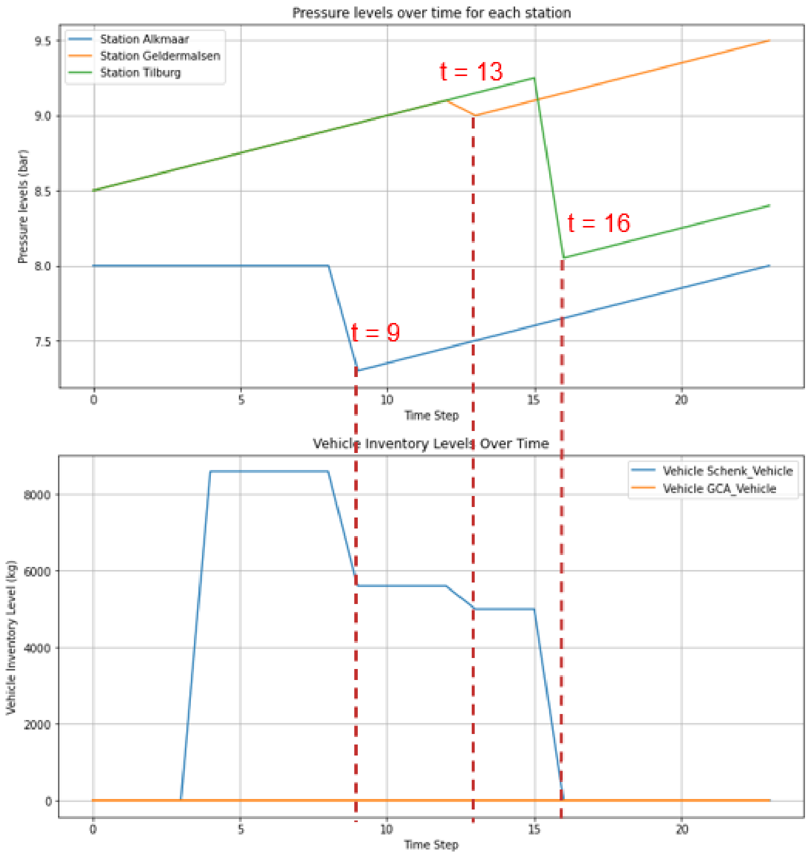


Figure 3.4: The top figure presents the pressure levels over time for each station. The bottom figure present the vehicle inventory level over time. This figure reveals that only offload cooling was required to manage the pressure in this scenario.

3.2.5. Insights Full MILP model

This subsection aims to discuss the performance and limitations of the Full MILP. By identifying its computational and practical challenges, these insights support the reason for a more computational efficient planning methodology.

The Full MILP has limitations in scalability. As the numer of nodes, vehicles and time steps increases, the model becomes computationally intensive due to the large number of variables and constraints. Additionally, the model lacks sufficent buffer considerations for inventory and pressure levels, which result in infeasible solutions on the next day. In the next Section 3.3, the model is refined by introducing additional assumptions and valid inequalities to make the model more computationally efficient.

3.3. Simplified MILP model

3.3.1. Assumptions

The assumptions are based on W. Konings, planning expert, and M. Ernes, operations manager to reduce the complexity of the model. They are the result of the Full MILP experiments. These assumptions are added on top of the previous ones formulated in Section 3.1.3, with some replacing earlier conditions and others providing additional constraints. The updated and extended assumptions are listed and explained below:

- **Vehicles must load max capacity at a terminal**
  This assumption simplifies the variable related to the quantity to be loaded at a terminal. In the simplified model there is no decision-making in the amount of LNG or Bio-LNG the vehicles loads at a terminal.
- **Vehicles must pick up load at a terminal at a specific time slot**
  This assumption restricts the routing of vehicles to specific times, limiting routing decisions over the entire time horizon. In practice, there are costs related to pickup slots at terminals and adjusting these time slots result in additional costs. Therefore, this assumption is not only practical for modelling purposes but also aligns with real-world logistical preferences.
- **Vehicles can not wait at a terminal or station**
  This allows the vehicles to only wait at a homebase and this eliminates the potential waiting times at terminals or stations. A vehicle must now start its trip from homebase to terminal to station(s) and end its trip at its homebase.
- **Vehicle can only drive to the homebase if it is empty**
  In combination with the fact that a vehicle can not wait a terminal or station, a vehicle is now also restricted to only drive home when it is empty. So it can also not wait at the homebase when there is load in the trailer of the vehicle.
- **Minimum offload at all stations is 5 ton**
  Vehicles must have more than five ton in there trailer before the system can start to offload at a refuelling station. For this reason in the Full MILP model the restriction of minimum offload was only set on the last refuelling station the vehicle visited before going to its homebase or a terminal. However, by giving a minimum offload of five ton for all stations the inventory management has a smaller solution space due to this minimum delivery quantity restriction.
- **Minimum pressure at stations is set to 2.0 bar for all stations**
  In the Full MILP model, each refuelling station had a unique minimum pressure, which varied between 3.5 to 5.5 bars. This created challenges during large offloads of cold LNG, where offloading about 12 tons could decrease the refuelling station's pressure by 3 bars. As a consequence, the refuelling station's pressure would hit the minimum pressure and the model became infeasible. By standardizing a lower minimum pressure of 2.0 bars across all station, the model is more open to larger offloads which are required for stations with high demand.
- **Vehicles are set to certain terminals**
  By fixing vehicles to certain terminals, the model avoids decisions of which vehicle to send to a terminal time slot. It reduces the routing complexity.
- **Offload cooling parameter depends on the vehicle that does the offload**
  In the Full MILP model, the loading quantity and offload quantity were specified per product type: LNG, Bio-LNG from Norway/ Sweden, Bio-LNG from the Netherlands. While all these product types could be combined within a single refuelling station, they had different effects on offload cooling. For example cold LNG reduces pressure by 1 bar for every 4 tons offloaded, while Bio-LNG from Norway/ Sweden has no offload cooling effect, and Bio-LNG from the Netherlands decreases pressure by 1 bar per 5 tons offloaded.
- **Obj function –> Minimize travel hours, km costs, road toll costs, and nitrogen cooling costs**
  The Full MILP model incorporated the waiting hours of the drivers. In the Simplified MILP there are not waiting hours for the drivers at stations or terminals. Therefore, this is not taken into account in the objective function.

- **Routing decision 24 hours, stock & pressure decision 36 hours**
  Experiments revealed that the model sometimes filled refueling stations just enough to keep them within inventory or pressure bounds by the end of the time horizon. However, this approach often led to stations running dry or reaching critical pressure levels the following day. To prevent this from happening, the duration for making inventory decisions has been extended to 36 hours. This results in a sufficient buffer at the start of each day, helping to maintain stable inventory levels over a longer time period. Furthermore, does this allow the vehicle to operate in the working hours of one day.

3.3.2. Sets, parameters and variables

Table 3.6: Notation Simplified MILP: sets and indices, parameters

Sets and indices		
N	Set of nodes $[N_h + N_t + N_s]$	$i, j \in N$
N_h	Subset of nodes: home bases	$N_h \subseteq N$
N_t	Subset of nodes: terminals	$N_t \subseteq N$
N_s	Subset of nodes: stations	$N_s \subseteq N$
T_h	Set of horizon time steps	$t \in T_h$
T_r	Set of rolling time steps	$t \in T_r$
K	Set of vehicles	$k \in K$
S	Set of terminal time slots	$s \in S$
Parameters		
st	Fixed service time visiting a station or terminal	[hour]
tt_{ij}	Travel time between node i and node j	[hour]
td_{ij}	Travel distance between node i and node j	[km]
c_{ij}^{toll}	Road toll costs between node i and node j	[euro]
c_{km}	Distance costs per kilometre	[euro / km]
c_{hours}	Driver costs per hour	[euro / hour]
$c_{nitrogen}$	Cost per hour	[euro]
D_{it}	Demand refuelling station i in time step t	[ton]
$I_i^{\min}$	Minimum inventory refuelling station i	[ton]
$I_i^{\max}$	Maximum inventory refuelling station i	[ton]
I_i^{initial}	Initial inventory refuelling station i	[ton]
PHL	Pressure increase due to heatleaks	[bar]
$P_i^{\min}$	Minimum pressure refuelling stations i	[bar]
$P_i^{\max}$	Maximum pressure refuelling station i	[bar]
P_i^{initial}	Initial pressure refuelling station i	[bar]
LIN_i	LIN tank available at refuelling station i	[-]
$Q_k^{\max}$	Maximum inventory capacity vehicle k	[ton]
$V_k^{\max}$	Maximum logistic cool pressure capacity vehicle k	[ton]
oc_k	Offload cooling parameter vehicle k	[bar / ton]
$oq_{\min}$	Fixed value for the minimum offload	[ton]
θ_k	Terminal assigned vehicle k	[-]
h_k	Home base of vehicle k	[-]

Table 3.7: Notation Simplified MILP: variables

Variables		
x_{ijt}^k	Binary variable, if vehicle k travels on arc (i,j) in time step t: 0 if arc (i,j) is not used 1 if arc (i,j) is used	[-]
z_{it}^k	Binary variable, if vehicle k visits node i in time step t: 0 if the vehicle does not visit 1 if the vehicle visits	[-]
L_{it}^k	Binary variable, if vehicle k loads at terminal i in time step t: 0 if the vehicle does not load 1 if the vehicle loads	[-]
e_{it}^k	Binary variable, if vehicle k is empty at node i in time step t: 0 if the vehicle is not empty 1 if the vehicle is empty	[-]
v_{it}^k	Binary variable, if vehicle k is logistic cooling at station i in time step t: 0 if the vehicle is not logistic cooling 1 if the vehicle is logistic cooling	[-]
O_{it}^k	Binary variable, if vehicle k is offloading at station i in time step t: 0 if the vehicle is not offloading 1 if the vehicle is offloading	[-]
oq_{it}^k	Offload quantity delivered to refuelling station i by vehicle k in time step t (float)	[ton]
I_{it}	Inventory at refuelling station i in time step t (float)	[ton]
P_{it}	Pressure of refuelling station i in time step t (float)	[bar]
n_{it}	LIN cooling at refuelling station i in time step t (float)	[bar]
Q_{kt}	Inventory of vehicle k in time step t (float)	[ton]
LC_{kt}	Logistic cooling pressure capacity of vehicle k in time step t (float)	[bar]

3.3.3. Objectives function and constraints

Objective function 3.48 consists of three terms: fuel costs, driver labor costs, road toll costs and nitrogen cooling costs. The objective is to minimize the total costs. The distance costs are calculated by the travel distance of all the used arcs multiplied by the costs per kilometre. The driver labor costs are calculated by the travel time of all the used arcs multiplied by the costs per hour of the transporter. The nitrogen cooling costs are calculated by the hours of active nitrogen cooling multiplied by the estimated costs per hour for consuming the nitrogen.

$$\min \sum_{t\in T_r}\sum_{k\in K}\sum_{ij\in N} x_{ijt}^k td_{ij} c_{km} + \sum_{t\in T_r}\sum_{k\in K}\sum_{ij\in N} x_{ijt}^k c_{ij}^{toll} + \sum_{t\in T_r}\sum_{k\in K}\sum_{ij\in N} x_{ijt}^k tt_{ij} c_{hours} + \sum_{t\in T_r}\sum_{i\in N_s} n_{it} c_{nitrogen} \tag{3.42}$$

Routing constraints

Constraint 3.49 explains the departure of vehicle k. Vehicle k can only use arc (ij), $x_{ijt}^k = 1$, if the vehicle is at node i, $z_{it}^k = 1$.

$$z_{it}^k \geq x_{ijt}^k \quad \forall k \in K, \forall i,j \in N, i \neq j, \forall t \in T_r \tag{3.43}$$

Constraint 3.50 describes the arrival of vehicle k. Vehicle k arrives at node j at time step t plus the travel time of arc (ij) if vehicle k uses arc (ij) on time step t.

$$z_{j,t+tt_{ij}}^k \geq x_{ijt}^k \quad \forall k \in K, \forall i,j \in N,\ i \neq j,\ t \in T_r,\ \text{if } t + tt_{ij} \leq \max(T_r) \tag{3.44}$$

Constraint 3.51 refers to the flow balance constraint of vehicle k. If vehicle k arrives at node j on time step t then one of the following three terms must be one: Vehicle k must have been at node j in the previous time step $t-1$, vehicle k must depart from node j in the previous time step $t-1$, or vehicle

k must use arc i,j on time step $t - tt_{ij}$

$$z_{jt}^k = z_{j,t-1}^k - \sum_{i \in N} x_{ji,t-1}^k + \sum_{\substack{i \in N \\ t-tt_{ij} \geq 0}} x_{ij,t-tt_{ij}}^k \quad \forall k \in K, \forall j \in N, i \neq j, \forall t \in T_r \setminus \{0\} \tag{3.45}$$

Constraint 3.52 defines that a vehicle must not wait at a terminal or station. Vehicle k can not visit terminal or station i in two consecutive time steps $t-1$ and t.

$$z_{it}^k + z_{i,t-1}^k \leq 1 \quad \forall k \in K, \forall i \in N \setminus N_h, \forall t \in T_r \setminus \{0\} \tag{3.46}$$

Constraint 3.53 is an often seen constraint that defines that all ingoing arcs must be equal to all outgoing arcs.

$$\sum_{i \in N} \sum_{t \in T_r} x_{ijt}^k = \sum_{i \in N} \sum_{t \in T_r} x_{jit}^k \quad \forall k \in K, \forall j \in N, i \neq j \tag{3.47}$$

Constraint 3.54 defines the start of the vehicle. Vehicle k must start and end at the home base node of vehicle k.

$$z_{h_k,t}^k = 1 \quad \forall k \in K, t \in \{0, T_r\} \tag{3.48}$$

Constraint 3.55 describes that vehicle k can not be at more than one place at the time.

$$\sum_{i \in N} z_{it}^k \leq 1 \quad \forall t \in T_r, \forall k \in K \tag{3.49}$$

Inventory station constraints

Constraint 3.56: Vehicle k can only offload oq_{it}^k at station i on time step t if vehicle k visits node i on time step t.

$$oq_{it}^k \leq M \cdot O_{it}^k \quad \forall k \in K, \forall i \in N_s, \forall t \in T_r \tag{3.50}$$

Constraint 3.57 defines the inventory of refuelling station i over the rolling time steps. The inventory of refuelling station i on time step t is the inventory at the previous time step t plus the sum of the vehicles offloads at station i on time step t minus the demand of station i on time step t.

$$I_{it} = I_{i,t-1} + \sum_{k \in K} oq_{it}^k - D_{it} \quad \forall i \in N_s, \forall t \in T_r \setminus \{0\} \tag{3.51}$$

Constraint 3.58 presents the inventory of refuelling station i in the horizon time steps from the end of the rolling till the end of the horizon time steps.

$$I_{it} = I_{i,t-1} - D_{it} \quad \forall i \in N_s, \forall t \in [T_r, T_h] \tag{3.52}$$

Constraint 3.59: The inventory of refuelling station i is bounded by the maximum capacity of refuelling station i and the minimum safety stock level of refuelling station i over the horizon time steps $[0, T_h]$.

$$I_i^{\min} \leq I_{it} \leq I_i^{\max} \quad \forall i \in N_s, \forall t \in T_h \tag{3.53}$$

Constraint 3.60: The inventory of refuelling station i on time step 0 is the initial inventory of refuelling station i.

$$I_{it} = I_i^{\text{initial}} \quad \forall i \in N_s, t = 0 \tag{3.54}$$

Constraint 3.61: Vehicle k must offload at least the minimum offload quantity if station i is visited on time step t

$$\sum_{i \in N_s} oq_{it}^k \geq oq_{\min} \cdot \sum_{i \in N_s} O_{it}^k \quad \forall k \in K, t \in T_r \tag{3.55}$$

Inventory vehicle constraints

Constraint 3.62 defines the inventory of vehicle k over the rolling horizon. The inventory of vehicle k on time step t is the previous inventory at the previous time step $t-1$ plus the loading quantity at terminal i on time step t minus the offload quantity at station i on time step t.

$$Q_{kt} = Q_{k,t-1} + \sum_{i \in N_t} L_{it}^k Q_k^{\max} - \sum_{i \in N_s} oq_{it}^k \quad \forall k \in K, \forall t \in T_r \setminus \{0\} \tag{3.56}$$

Constraint 3.63: Vehicle k must be empty at the start and end of the routing horizon.

$$Q_{kt} = 0.0 \quad \forall k \in K, t \in \{0, T_r\} \tag{3.57}$$

Constraint 3.64: Vehicle's inventory must be below the maximum capacity of vehicle k.

$$Q_{kt} \leq Q_k^{\max} \quad \forall k \in K, \forall t \in T_r \tag{3.58}$$

Constraint 3.65: Vehicle k can only offload at station i on time step t if it visits station i on time step t.

$$oq_{it}^k \leq M \cdot O_{it}^K \quad \forall k \in K, \forall i \in N_s, \forall t \in T_r \tag{3.59}$$

Constraint 3.66: Vehicle k can only load at terminal i on time step t if it visits terminal i on time step t.

$$L_{it}^k \leq z_{it}^k \quad \forall k \in K, \forall i \in N_t, \forall t \in T_r \tag{3.60}$$

Constraint 3.67: Vehicle k must load at terminal i on time step t if there is a pickup slot at terminal i on time step t.

$$\sum_{k \in K} L_{it}^k = S_{it} \quad \forall i \in N_t, \forall t \in T_r \tag{3.61}$$

Pressure constraints

Constraint 3.68 defines the pressure of station i over time. The pressure of station i on time step t is the previous pressure at the time step $t-1$ plus the pressure increase due to heatleaks PHL minus the nitrogen cooling n_{it} minus the offload cooling $\sum_{k \in K} oc_k oq_{it}^k$ depended on the offload cooling parameter for each vehicle k oc_k minus the logistic trailer cooling $\sum_{k \in K} v_{it}^k \cdot \frac{V_k^{\max}}{2}$. Vehicle k logistics cools half of the maximum pressure capacity $V_k^{\max}$.

$$P_{it} = P_{i,t-1} + \text{PHL} - n_{it} - \sum_{k \in K} oc_k oq_{it}^k + \sum_{k \in K} v_{it}^k \cdot \frac{V_k^{\max}}{2} \quad \forall i \in N_s, \forall t \in T_r \setminus \{0\} \tag{3.62}$$

Constraint 3.69 presents the pressure of refuelling station i in the horizon time steps from the end of the rolling till the end of the horizon time steps.

$$P_{it} = P_{i,t-1} + \text{PHL} \quad \forall i \in N_s, \forall t \in [T_r, T_h] \tag{3.63}$$

Constraint 3.70: The pressure of refuelling station i is bounded by the minimum pressure and the maximum pressure on each time step t over the horizon time steps $[0, T_h]$.

$$P_i^{\text{min}} \leq P_{it} \leq P_i^{\text{max}} \quad \forall i \in N_s, \forall t \in T_h \tag{3.64}$$

Constraint 3.71: The pressure of refuelling station i on time step 0 is the initial inventory of refuelling station i.

$$P_{it} = P_i^{\text{initial}} \quad \forall i \in N_s, t = 0 \tag{3.65}$$

Constraint 3.72: Nitrogen cooling n_{it} can only be activated if the station i has a nitrogen tank LIN_i.

$$n_{it} \leq M \cdot LIN_i \quad \forall i \in N_s, \forall t \in T_h \tag{3.66}$$

Constraint 3.73: Station i cannot nitrogen cool n_{it} more than the pressure increase due to heatleaks PHL on time step t.

$$n_{it} \leq \text{PHL} \quad \forall i \in N_s, \forall t \in T_h \tag{3.67}$$

Constraint 3.74: LC_{kt} monitors the logistic cooling capacity of vehicle k at each time step t. The logistic cooling capacity of the previous time step is $LC_{k,t-1}$. Furthermore, when the vehicle logistic cools ($v_{it}^k = 1$) then the capacity is reduced with $\frac{V_k^{\max}}{2}$ bar and each time the vehicle loads ($L_{it}^k = 1$) the maximum pressure capacity (V_k^{max} is added to the logistic cooling capacity.

$$LC_{kt} = LC_{k,t-1} - \sum_{i \in N_s} v_{it}^k \cdot \frac{V_k^{\max}}{2} + \sum_{i \in N_t} L_{it}^k V_k^{max} \quad \forall k \in K, \forall t \in T_r \tag{3.68}$$

Constraint 3.75: The logistic cooling capacity is bounded by the maximum pressure capacity of vehicle k.

$$LC_{kt} \leq V_k^{max} \quad \forall k \in K, \forall t \in T_r \tag{3.69}$$

Constraint 3.76: Vehicle k can only offload at station i in time step t if it visits station i in time step t.

$$O_{it}^k \leq z_{it}^k \quad \forall k \in K, \forall t \in T_r, \forall i \in N_s \tag{3.70}$$

Constraint 3.77: Vehicle k can only logistic cool at station i in time step t if it visits station i in time step t.

$$v_{it}^k \leq z_{it}^k \quad \forall k \in K, \forall t \in T_r, \forall i \in N_s \tag{3.71}$$

Constraint 3.78: If vehicle k visits station i in time step t than it must do offloading or logistic cooling or both actions at station i in time step t.

$$O_{it}^k + v_{it}^k \geq z_{it}^k \quad \forall k \in K, \forall t \in T_r, \forall i \in N_s \tag{3.72}$$

Constraint 3.79: Restricts that vehicle k can not logistic cool at the last refuelling station before travelling to home base or terminal.

$$v_{it}^k \leq 1 - x_{ijt}^k \quad \forall k \in K, \forall t \in T_r, \forall i \in N_s, \forall j \in N_s, N_h \tag{3.73}$$

Other constraints

Constraint 3.80: Vehicle k can only visit terminal i, so each vehicle is restricted to a specific terminal.

$$z_{it}^k \leq \theta_{ik} \quad \forall t \in T_r, i \in N_t, k \in K \tag{3.74}$$

Constraint 3.81: When the inventory of vehicle k is empty e_{kt} = 1, otherwise e_{kt} stays zero.

$$Q_{kt} \leq M \cdot (1 - e_{kt}) \quad \forall k \in K, \forall t \in T_r \tag{3.75}$$

Constraint 3.82: Vehicle can only drive from a station or terminal to a home base when the vehicle is empty.

$$x_{ijt}^k \leq e_{kt} \quad \forall k \in K, \forall t \in T_r, \forall i \in N \setminus N_h, j \in N_h \tag{3.76}$$

Constraint 3.83: Vehicle can only drive from a station to a terminal if the vehicle is empty.

$$x_{ijt}^k \leq e_{kt} \quad \forall k \in K, \forall t \in T_r, \forall i \in N_s, j \in N_t \tag{3.77}$$

Binary variables

$$x_{ijt}^k \in \{0,1\} \quad \forall k \in K, \forall t \in T_r, \forall ij \in N, i \neq j \tag{3.78}$$

$$z_{it}^k \in \{0,1\} \quad \forall k \in K, \forall t \in T_r, \forall i \in N \tag{3.79}$$

$$L_{it}^k \in \{0,1\} \quad \forall k \in K, \forall t \in T_r, \forall i \in N_t \tag{3.80}$$

$$e_{kt} \in \{0,1\} \quad \forall k \in K, \forall t \in T_r \tag{3.81}$$

$$O_{it}^k, v_{it}^k \in \{0,1\} \quad \forall k \in K, \forall t \in T_r, \forall i \in N_s \tag{3.82}$$

Continuous variables

$$oq_{it}^k \geq 0 \quad \forall k \in K, \forall t \in T_r, \forall i \in N_s \tag{3.83}$$

$$I_{it}, P_{it}, n_{it} \geq 0 \quad \forall t \in T_h, \forall i \in N_s \tag{3.84}$$

$$Q_{kt}, LC_{kt} \geq 0 \quad \forall t \in T_r, \forall k \in K \tag{3.85}$$

3.3.4. Valid inequalities

Valid inequalities are used to improve the performance of optimization algorithms by tightening the bounds of the solutions, making the mathematical models more efficient and reducing computation times. Bruno E. Demantova and Darvish, 2023 analysed groups of valid inequalities for mathematical models of IRP with time windows.

- Arcs that will never be used are set to 0

$$x_{ijt}^k = 0 \tag{3.86}$$

- Logistic trailer cooling is set to 0 for stations where we do not want to do logistic trailer cooling

$$v_{it}^k = 0 \tag{3.87}$$

3.3.5. Verification Simplified MILP model

Verification involves checking whether the model has been correctly built by testing if the model behaves as expected under different scenarios. Ten tests were performed to evaluate this logical coherence of the constraints and objectives. Each test is evaluated using the following key performance indicators (KPIs): Total Costs (TC), Total Transportation Costs (TTC), Total Nitrogen Cooling Costs (TNCC), Cost per Kilogram (CpK). This verification process is an important step before the validation or practical applications. The experimental setup is shown in Appendix B.

A total of ten different scenarios are evaluated. The first scenario serves as the base case, while the remaining scenarios test the logical coherence of the constraints and objectives by comparing KPIs against those of the base case. For each experiment, the expected behaviour is described by predicting how the KPIs will perform relative to the base case results. In the new scenario the KPI may be lower, higher, or remain unchanged compared to the base case scenario. An overview of the verification tests with expected behaviour and the results is show in Table 3.8.

Table 3.8: Ten different verifications tests applied on the Simplified MILP model with their description, expected behaviour, model's result ad final conclusion if the expected behaviour is similar to the model's result. Pass indicates that the result is as expected. An overview of the results is presented in Appendix C in Table C.2.

	Description	Expected	Result	OK?
1	Base case	TC > 0 TTC > 0 TNCC > 0 CpK > 0	TC = 3066 TTC = 2913 TNCC = 153 CpK = 0.0539	Pass
2	No pressure constraints	TC < 3066 TTC < 2913 TNCC = 0 CpK < 0.0539	TC = 2326 TTC = 2326 TNCC = 0 CpK = 0.0431	Pass
3	No vehicles	Infeasible	Infeasible	Pass
4	Service time is 0	TC < 3066 TTC < 2913 TNCC < 153 CpK < 0.0539	TC = 1586 TTC = 1524 TNCC = 62 CpK = 0.0282	Pass
5	Demand + 20%	TC > 3066 TTC > 2913 TNCC < 153 CpK > 0.0539	TC = 3125 TTC = 3013 TNCC = 112 CpK = 0.0558	Pass
6	No slots	Infeasible	Infeasible	Pass
7	All stations have LIN cooling	TC < 3066 TTC < 2913 TNCC < 153 CpK < 0.0539	TC = 2785 TTC = 2679 TNCC = 106 CpK = 0.0496	Pass
8	PHL + 10%	TC > 3066 TTC ≥ 2913 TNCC > 153 CpK ≥ 0.0539	TC = 3112 TTC = 2913 TNCC = 199 CpK = 0.0539	Pass
9	Maximum pressure stations + 1 bar	TC < 3066 TTC < 2913 TNCC < 153 CpK < 0.0539	TC = 2679 TTC = 2679 TNCC = 0 CpK = 0.0496	Pass
10	Maximum inventory stations + 5 ton	TC < 3066 TTC < 2913 TNCC < 153 CpK < 0.0539	TC = 2898 TTC = 2786 TNCC = 112 CpK = 0.0516	Pass

For each verification test, the reason of the expected behaviour is explained below.

- **Test 1: Base case**
  In the base case the planning horizon is three days and the network consists of five stations.
- **Test 2: No pressure constraints**
  In this test all the pressure constraints are removed, the routing decisions are guided by the inventory levels at the refuelling stations and no cooling is necessary. Therefore, the total nitrogen cooling costs is expected to be zero. In the base case scenario the vehicle must do logistic cooling in its trip to ensure that pressure does not go above the maximum pressure bound. In this scenario this stop is removed since no cooling is necessary. Therefore, the total costs, total transportation costs and cost per kilogram are expected to be lower.

- **Test 3: No vehicles**
  In this scenario, the model has no vehicles and should result in an infeasible outcome due to the demand that decreases the inventory levels of refuelling stations and heat leaks that increase the pressure levels. As a result, the minimum inventory level and maximum pressure level bound is reached.

- **Test 4: Service time is 0**
  In the base case scenario, the service time for being at a station or terminal is 2 hours. This service time accounts for the actions of logistic cooling and/ or offloading at a station or loading at a terminal. By setting the service time to zero the total costs, total transportation costs and cost per kilogram are expected to lower than the base case. Furthermore, it is more cost-effective to logistically cool instead of nitrogen cool. Therefore, the total nitrogen cooling costs are expected to be lower.

- **Test 5: Demand + 20%**
  In this scenario, the demand of LNG for all refuelling stations is increased by 20%. Refuelling stations will become more empty throughout the day. As a consequence, the offload at the refuelling stations become larger. Therefore, the total nitrogen cooling costs are expected to decrease. However, the total costs, total transportation costs and cost per kilogram are higher than the base case scenario.

- **Test 6: No slots**
  Instead of having three pick-up slots at the terminals of 52-ton LNG, this scenario has no available LNG. The hourly demand at each refuelling station decreases the inventory levels and crosses the safety stock level. Since the safety stock levels are hard bounds it is expected that the model becomes infeasible. The same can be said about the pressure levels that increase due to heat leaks. With no offload cooling or logistic cooling being done by vehicles the model will also become infeasible due to the maximum pressure level reached.

- **Test 7: All stations LIN cooling**
  In the base case scenario three out of the five stations have a liquid nitrogen tank on-site. In this scenario all the stations have a liquid nitrogen tank on-site. As a consequence, the stations can active nitrogen cooling to reduce the pressure and vehicle will not drive to stations to only do logistic cooling. It is expected than the total costs, total transportation costs, total nitrogen cooling costs, and costs per kilogram are lower than the base case scenario.

- **Test 8: PHL + 10%**
  The pressure increase due to heat leaks is increased by 10% this could be a plausible scenario, for instance during the summer. The nitrogen cooling costs are expected to increase due to more cooling needed at LIN stations and a result the total costs increase. The total transportation costs and cost per kilogram will increase if the vehicle needs to do an extra stop to do logistic cooling. Otherwise, the total transportation costs and cost per kilogram will be equal to the base scenario.

- **Test 9: Maximum pressure stations + 1 bar**
  In this scenario, the maximum pressure of all stations is increased by 1 bar. This means that refuelling stations with a LIN tank will start LIN cooling at 9.5 bar and refuelling stations without a LIN tank have their maximum pressure at 10.5 bars. The total costs, total transportation costs, total nitrogen cooling costs and cost per kilogram are expected to decrease because less nitrogen cooling or logistic cooling is required.

- **Test 10: Maximum inventory stations + 5 ton**
  In this scenario, the maximum inventory of all refuelling stations is increased by 5 tons. This means that the refuelling stations are more empty and that the vehicle can do larger offloads. The total total costs, total transportation costs, total nitrogen cooling costs, and cost per kilogram are expected to decrease since the larger offloads result in less stops and a larger offload cooling.

In conclusion, the expected behaviour of all ten verifications tests align with the results obtained. This confirms that the Simplified MILP model demonstrates logical coherence in its constraints and objectives, thereby the model is verified.

3.3.6. Validation Simplified MILP model

Validation is the process of checking whether the model is capable of providing realistic, usable and cost-effective solutions to day-to-day logistics challenges of LNG and Bio-LNG distribution. For the validation a scenario with five stations, one vehicle, and a 72 hour planning horizon is analysed. Figure 3.5 illustrates a map of the vehicle routes for each day. As depicted in the figure, a vehicle route begins at the home base, Schenk - NL, proceeds to the terminal, Gate, and then delivers LNG and/or performs logistic cooling at the stations. Finally, the vehicle ends its trip at the home base. The experimental setup is shown in Appendix B.

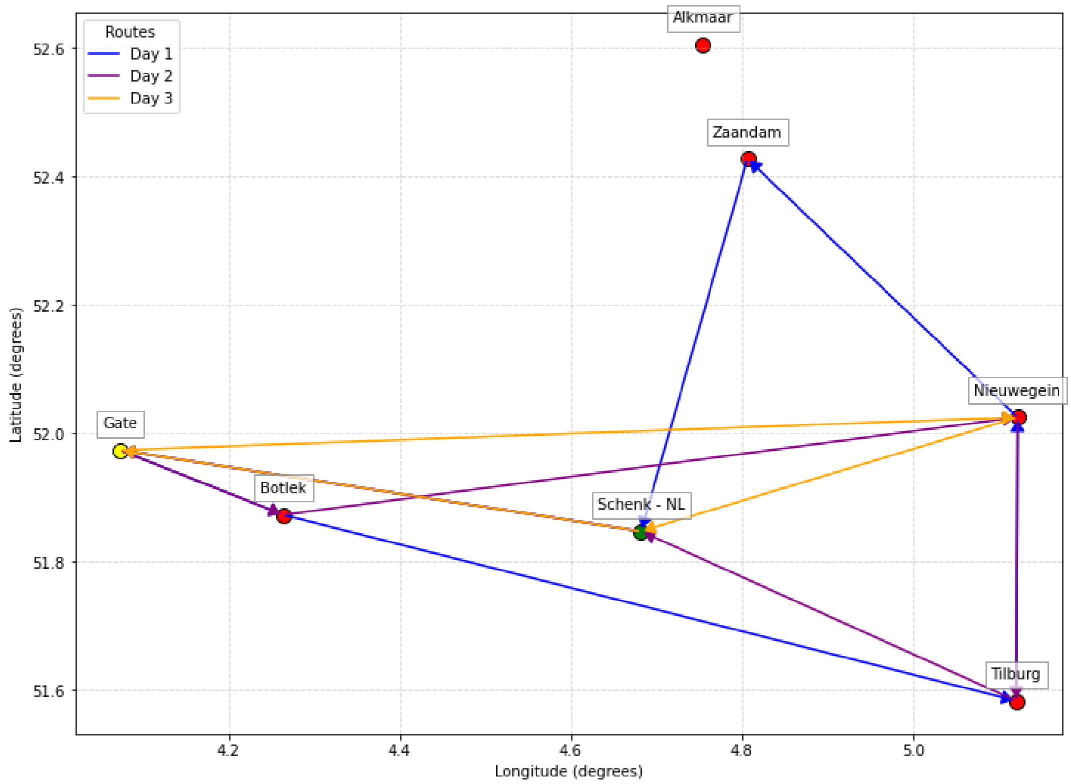


Figure 3.5: Map of vehicle routes. This map reveals that some stations (Nieuwegein and Tilburg) are visited more frequently than other (Alkmaar). Furthermore, it illustrates that the vehicles start and end at its homebase each day.

It is also evident from Figure 3.5 that certain stations are visited more frequently than others. Notable, station Alkmaar is not visited at all during the planning horizon of three days, while station Nieuwegein is visited three times. Table 3.9 presents the station stops for each day and shows how much bar is logistic cooled or how much LNG is delivered. Figure 3.6 verifies that some stations need to be replenished with LNG to stay between the inventory bounds because the inventory level is close to the safety stock level.

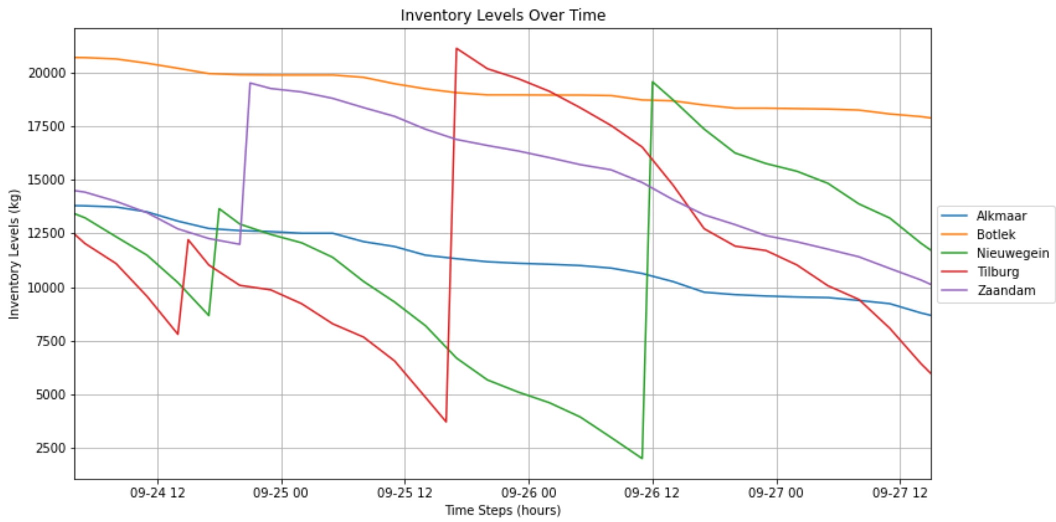


Figure 3.6: The inventory levels of the refuelling stations over time. This indicates that the model can remain the inventory level within the specified bounds and that the demand of each station is different. Furthermore, the vehicle visits from Figure 3.5 also reflect the increase in inventory levels in this figure.

Figure 3.7 presents the pressure levels of the refuelling stations over time. The stations Botlek and Tilburg do not have a LIN tank on-site and require logistic cooling or offload cooling to control the pressure in tank. It is also interesting to note that the vehicle does logistics cooling at stop 2 Nieuwegein on day 2, so that the vehicle can then offload 18 ton in Tilburg and 18 ton in Nieuwegein the next day. This shows that driving past Nieuwegein on day 2, ensures that a full load will fit in Tilburg at the end of the day and a full load can also fit in Nieuwegein the next day. This verifies that the model is capable of providing a realistic, usable and cost-effective solution for a scenario with five stations, one vehicle and 72 hour planning horizon.

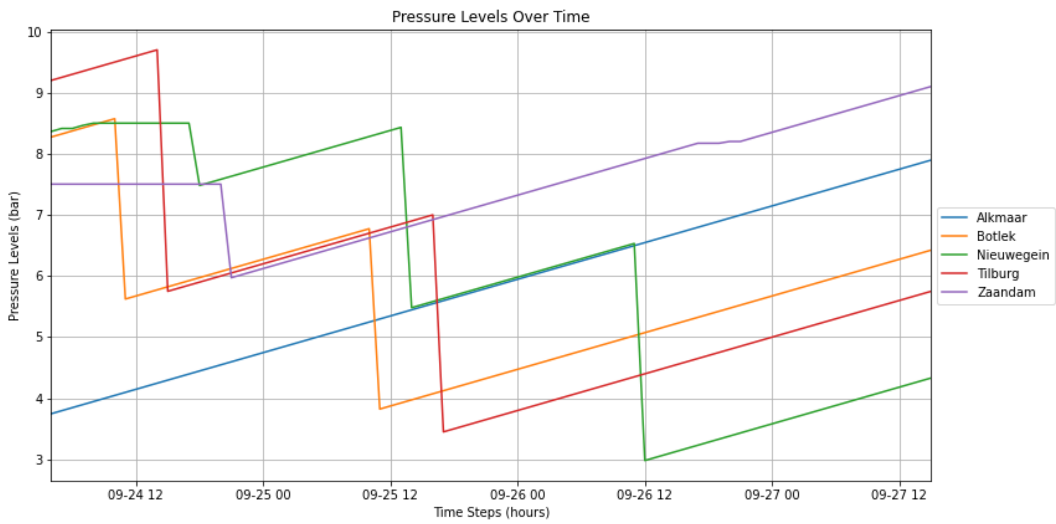


Figure 3.7: The pressure levels of the refuelling stations over time. This reveals that the model can remain the pressure levels within the specified bounds. The amount of offload and logistic cooling is reflected in the pressure levels. For instance Nieuwegein and Tilburg are visited more frequently than Alkmaar and therefore these pressures are reduced more often. Additionally, the logistic cooling at Botlek is shown twice in this figure.

Table 3.9: Planning schedule of each day. It indicates that the model does logistic cooling at Botlek twice and once at Nieuwegein and once at Tilburg. Furthermore, the offload quantity at the each station is specified.

	Stop 1	Stop 2	Stop 3	Stop 4
Day 1	Botlek: 3 bar	Tilburg: 3 bar, 5 ton	Nieuwegein: 5 ton	Zaandam: 8 ton
Day 2	Botlek: 3 bar	Nieuwegein: 3 bar	Tilburg: 18 ton	
Day 3	Nieuwegein: 18 ton			

3.3.7. Pre-solve: critical stations

The pre-solve process calculates the inventory and pressure levels for each refuelling station to determine the time step at which a station's inventory falls below the minimum inventory threshold (dry stock) or when its pressure exceeds the maximum pressure (critical pressure). This step aims to reduce the number of stations considered for routing, thereby narrowing the solution space.

The inventory level I_{it} of refuelling station i at time step t depends on the inventory level in the previous time step is $I_{i,t-1}$ and the demand of each refuelling station i in time step t is $D_{i,t}$.

$$I_{i,t} = I_{i,t-1} - D_{i,t} \tag{3.88}$$

Similarly, the pressure level P_{it} of refuelling station i at time step t depends on the pressure level in the previous time step $P_{i,t-1}$ and the pressure increase due to heat leaks PHL.

$$P_{i,t} = P_{i,t-1} + PHL \tag{3.89}$$

Figure 3.8 and 3.9 give an example of the critical points at which the inventory of a refuelling station falls below the safety stock level (dry stock) or the pressure exceeds the maximum pressure bound (critical pressure), indicated by the black dotted arrows. Based on these pre-solve results, seven out of the fourteen stations are identified as critical stations and require a visit. These stations are relevant for the routing of the vehicles, while the remaining seven stations are excluded from consideration for the first delivery day.

This reduction in the number of stations leads to a decrease in solution space and computational complexity. For all stations that do not require a visit, the following constraint holds:

$$\sum_{t \in T} \sum_{k \in K} z_{i,t}^{k} = 0 \tag{3.90}$$

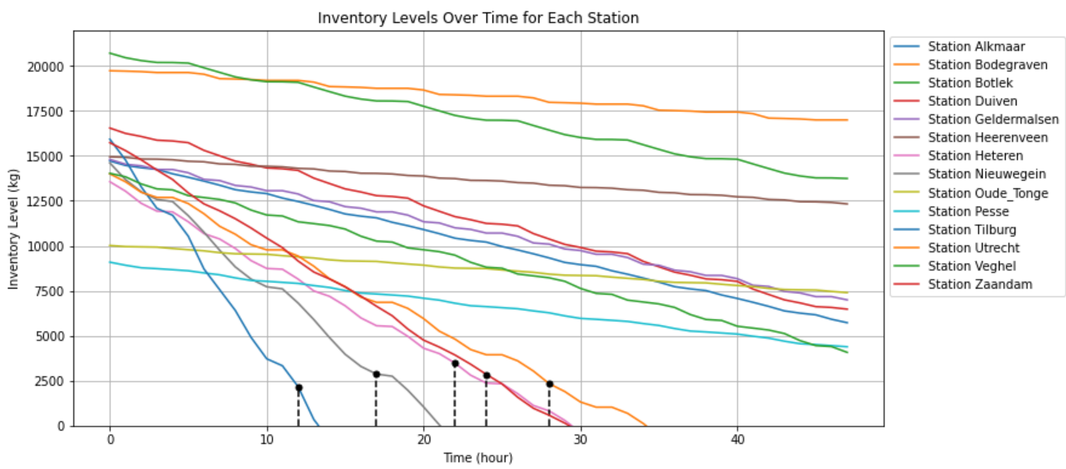


Figure 3.8: Stockout at refuelling stations. It presents the inventory levels over time for each station and the dashed lines indicate on which time step the station hits the safety stock level. In this experiment there are five critical stations based on the stockout.

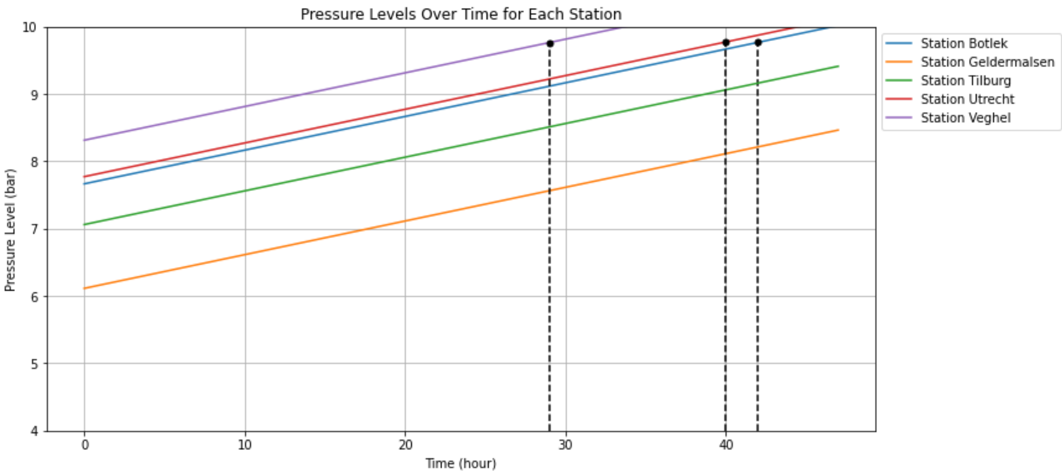


Figure 3.9: Critical pressure at refuelling stations. It shows the pressure levels of each station over time and the dashed lines indicate on which time step the station hits the critical pressure level. This experiment shows three critical stations.

3.4. Rolling horizon approach

The previously discussed MILP models solved the LNG IRP with pressure management for a small instance of nodes. However, for larger instances of nodes, vehicles and days the computational complexity increases exponentially. Therefore, the models can not be used in practice where a larger network of refuelling stations requires visitation. To deal with the computational complexity, this section introduces the rolling horizon approach. This approach offers a more efficient way of multi-period planning, allowing a more sequential way of controlling the cryogenic logistics of LNG and Bio-LNG.

3.4.1. Motivation rolling horizon approach

An important reason for implementing the rolling horizon approach in the IRP model is to prevent dry stock or critical pressures at the start of next periods. In the model daily time period, the risk of dry stock was increased because the model minimises the transportation costs and does not take into account future demand patterns. By applying the rolling horizon approach, decision can be optimised not only for the current day, but also for multiple future periods. This provides a more balanced trade-off between transportation costs and the risk of dry stock and critical pressure.

The motivation for the rolling horizon approach not only has to do with the delivery the next day but also with computational power of the model. When the amount of time steps in the model increases to plan for multiple days in one run, the model increases significantly. The amount of decision variables and constraints grow exponentially with the amount of time steps that are added. Resulting in a model that requires a large computational power to solve in a reasonable time. The rolling horizon approach does not solve the multi period all at once, but cuts the planning period into manageable blocks. In short, the rolling horizon approach does not only provide a more balanced trade off between transportation costs and inventory and pressure management, but it also makes the model more computational reasonable even if the planning period consist of the multiple periods.

3.4.2. Implementation rolling horizon approach

The rolling horizon method cuts the planning horizon into multiple periods. Instead of making decisions for one or two days, the model is solved for a series of consecutive days. This provides a broader context of optimisation making it able to plan for a whole week. In figure 3.10, the rolling horizon approach combined with the previously discussed pre-solve step from Section 3.3.7 is illustrated. In order to fully understand this approach, it is important to clarify three key terms: the pre-solve length, the horizon length, and the rolling length.

The pre-solve length refers to the number of time steps considered when determining the critical stations in the network. The horizon length is the time span during which the inventory and pressure levels at refuelling stations must remain within specified bounds. The rolling length represents the time period for which routing decisions are made. Since the rolling length is shorter than the horizon length, the vehicles must deliver sufficient LNG or Bio-LNG to ensure that the refuelling stations have enough supply for the entire horizon length. The horizon lengths acts as a kind of buffer time for the refuelling station's inventory and pressure levels.

For example, consider a planning period of three days: Monday, Tuesday, and Wednesday. In the first iteration, the pre-solver determines the critical stations for Monday and Tuesday. The results of the pre-solver then serve as inputs for the MILP model. The MILP model optimizes routing decisions and inventory/ pressure level management. In the example in figure 3.10, the horizon length is 36 hours and the rolling length is 24 hours. So, the planning for Monday is decided with foresight of Monday and Tuesday and with an additional buffer of 12 hours on Tuesday. The additional buffer is the difference between the horizon and rolling lengths.

At the end of Monday, the inventory and pressure levels at the refuelling stations are saved and these values serve as inputs for the second iteration, as indicated by the red arrow in the figure 3.10. The second iteration starts on Tuesday and begins with identifying the critical stations for Tuesday and Wednesday. The MILP uses these critical stations as inputs to determine the routing for Tuesday and ensuring the inventory and pressure levels remain within bounds for the first 12 hours of Wednesday.

In the third iterations, the inventory and pressure levels from the end of Tuesday are used as inputs for Wednesday's planning as shown by the red arrow. The pre-solver identifies the critical stations for Wednesday and Thursday, which serve as inputs by the MILP model to determine the routing for Wednesday, with again a buffer extending into the first 12 hours of Thursday. Overall, this approach results in a schedule for Monday, Tuesday and Wednesday, developed using the rolling horizon methodology with a 48-hour look ahead for the solution, a 24-hour rolling length for routing decisions and a 12-hour buffer for the following day, guaranteed by the length of the horizon.

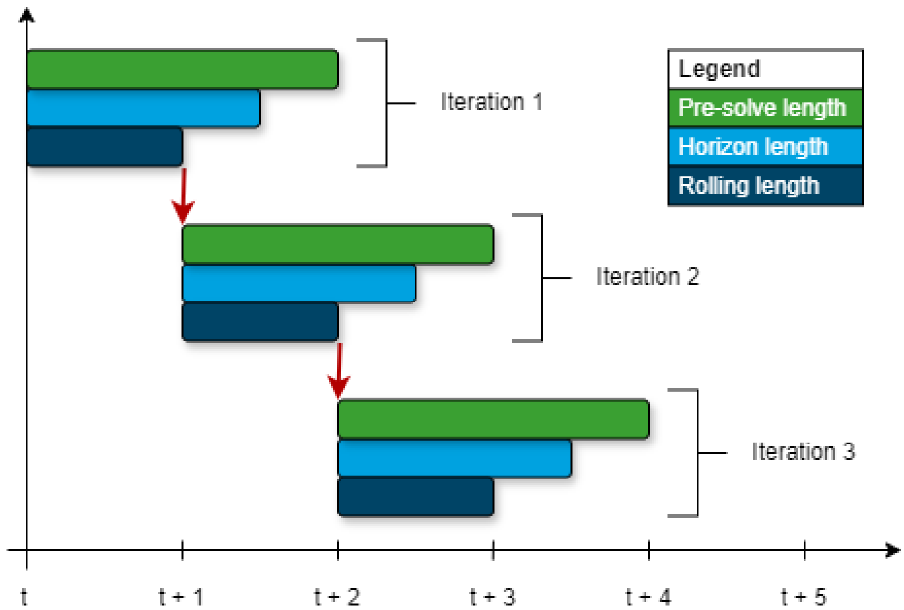


Figure 3.10: Overview of the rolling horizon approach with the incorporation of the pre-solver. The pre-solve length refers to the number of time steps when determining the critical stations in the network. The horizon length represents the time during which the inventory and pressure levels must be managed. The rolling length is the time period for which the vehicle routing decisions are made. The red arrow indicates that the results, inventory and pressure levels, from the first iteration (Monday) at the end of the rolling length are used as input for the second iteration (Tuesday). This shows the sequential approach of the rolling horizon.

3.4.3. Evaluating the rolling horizon approach vs. the static approach

In this experiment, the rolling horizon approach and static approach are compared on their runtime and the KPIs: total costs (TC), total transportation costs (TTC), total nitrogen cooling costs (TNCC). This experiment aims to validate that the rolling horizon approach is a more efficient multi-period planning method than the static approach. The static approach in this experiment refers to the simplified MILP model as described in Section 3.3. This approach solves the entire multi-period planning problem at once. In contrast, the rolling horizon approach breaks down the problem into smaller manageable time blocks and solves them sequentially. The experimental setup is shown in Appendix B.

An overview of the results of this experiment is presented in Table 3.10. First, the runtime of the rolling horizon approach is lower than the static approach, especially for problems that require more planning days. For example, for a 3-day planning horizon, find an optimal solution in 15 seconds compared to 434 seconds for the static approach. For 5 days and beyond, the static approach either reaches the time limit (7200 seconds) or becomes infeasible, whereas the rolling horizon remains efficient with runtime below 40 seconds. As illustrated in Figure 3.11, the runtime of the rolling horizon approach shows a linear growth as the number of planning days increases. In contrast, the static approach indicates an exponential growth in runtime, making it less applicable for larger planning periods. This highlights that the rolling horizon approach is computationally more efficient than the static approach.

Table 3.10: Static and rolling horizon approach are compared in seven different experiment for a planning horizon of one to seven days. Both approaches are compared on their runtime, status, gap, Total Costs (TC), Total Transportation Costs (TCC) and Total Nitrogen Cooling Costs (TNCC). Overall, the rolling horizon approach appears to be more computationally efficient. An overview of the results is presented in Appendix C in the Tables C.1 and C.3.

Planning (day)	**Approach**	**Runtime** (sec)	**Status**	**Gap**	**TC** (euro)	**TTC** (euro)	**TNCC** (euro)
1	Static	4	Optimal		1105	1038	67
	Rolling	5	Optimal		1105	1038	67
2	Static	57	Optimal		2062	1875	187
	Rolling	10	Optimal		2062	1875	187
3	Static	434	Optimal		3066	2913	153
	Rolling	15	Optimal		3182	2875	307
4	Static	614	Optimal		3959	3717	242
	Rolling	20	Optimal		3970	3613	357
5	Static	7200	Time limit	0.19	5467	5335	132
	Rolling	22	Optimal		4926	4450	467
6	Static	7200	Infeasible				
	Rolling	34	Optimal		6140	5614	526
7	Static	7200	Infeasible				
	Rolling	37	Optimal		7141	6525	616

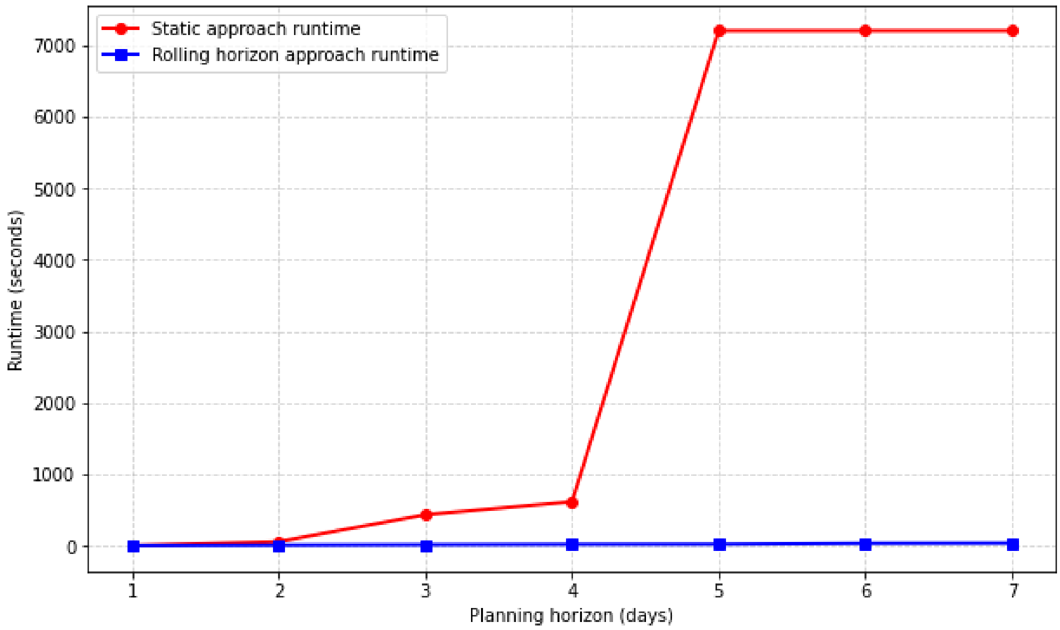


Figure 3.11: Runtime comparison static vs rolling horizon approach. The runtime of the static approach increases exponentially as the number of planning days rise, while the rolling horizon approach remains linear.

Second, the results in Table 3.10 indicate that the cost differences between the static and rolling horizon approaches are small, especially for the shorter planning horizons. For 1 and 2 days, the four KPIs are identical between the two approaches. For 3 and 4 days, the rolling horizon approach achieves slightly higher costs (€3182 vs. €3066 for 3 days and €3970 vs. €3959 for 4 days). These small variations suggest that the rolling horizon approach remains competitive in terms of costs. For 5 days, the static approach could not find an optimal solution because of the set time limit. Therefore, the total costs of the static approach are higher than the rolling horizon approach and this is the reason for the unexpected outcome

The small variation in total costs is mainly explained by the nitrogen cooling costs. It can be seen that nitrogen cooling costs are generally lower for the static approach. This can be explained by the fact that the static approach solves the entire multi-period planning problem at once and the rolling horizon approach breaks the problem into different time blocks and solves them sequentially. Due to the nature of the static approach, it can account for nitrogen cooling costs at the end of the planning horizon.

In short, the comparison reveals that the rolling horizon approach is computationally more efficient than the static approach, as it shows a linear runtime growth compared to the exponential runtime growth of the static approach. While cost differences are minimal for shorter horizon, the rolling horizon shows slightly higher nitrogen cooling costs for 3 and 4 days due to its sequential nature. However, for 5 days and beyond, the rolling horizon approach outperforms the static approach, because it exceeds the set time limit or becomes infeasible. Overall, the rolling horizon approach offers a more practical and scalable solution with similar costs.

3.4.4. Sensitivity analysis on horizon length

This experiment evaluates how different horizon lengths impact the performance of the rolling horizon approach for the Simplified MILP model considering the number of feasible days and the KPIs: total costs (TC), total transportation costs (TTC), total nitrogen cooling costs (TNCC). The horizon length refers to the time span during which the inventory and pressure at refuelling stations must remain within the specified bounds. It serves as a buffer beyond the rolling length that makes the planning robust and forward-looking.

A horizon length that is too short may lead to decisions that do not have foresight and neglect future demand and pressure increase due to heat leaks. This could result in frequent stockouts or critical pressure levels. On the other hand, an excessively long horizon length will put too much focus on maintaining the inventory and pressure constraints in the future. This could lead to inefficient routes or unnecessary deliveries to maintain large buffers at refuelling stations. Therefore, this experiment aims to identify the sweet spot that has robust planning across days and avoids unnecessary routing inefficiencies.

The horizon lengths are scanned for the number of feasible days to determine which horizon lengths need deeper investigation. In the scan horizon lengths with a range of 0 to 36 hours are included. A horizon length of 0 means that the inventory and pressure levels only need to be satisfied within the rolling window of 24 hours. A horizon length of 36 hours indicates that the inventory and pressure requirements must be met for the 24-hour rolling window plus an additional 36 hours. The first test assesses how many days the model can develop a feasible solution, with each horizon length tested over a planning horizon of 28 days. As shown in Figure 3.12, shorter horizon lengths (0-7 hours) fail to make robust planning, with no more than six feasible days out of 28. This suggests that the constraints are insufficiently forward-looking, leading to unsustainable outcomes.

Horizon lengths of 8 to 25 hours, however, indicate feasible solutions for the entire 28-day planning horizon. These horizon lengths show robust planning, as the model consistently finds solutions that satisfy the constraints. Horizon lengths within this range offer sufficient buffer to remain between the inventory and pressure bounds. Beyond 25 hours, the number of feasible days gradually decreases. This occurs because longer horizon lengths require the model to maintain larger buffers for inventory and pressure levels far into the future. Given the fixed supply available in each time period, these larger buffer requirements can not be met. Finally, The results suggest that the optimal horizon length lies between 8 to 25 hours horizon length. The next analysis will dive into the costs associated with these horizon lengths.

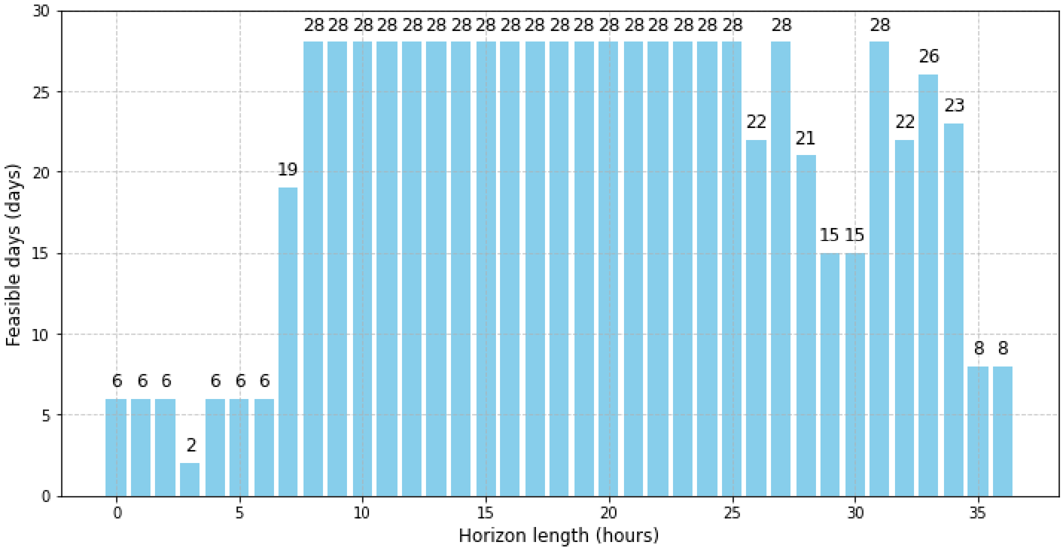


Figure 3.12: Number of feasible days per horizon length between 0 to 36 hours. It indicates that the horizon lengths 8 to 25 hours are more robust in different scenarios.

Figure 3.13 presents the total costs associated with the horizon lengths between 8 to 25 hours. The red trend line indicates that as the horizon length increases, the total costs also tend to rise. This trend can be explained by the fact that the model must maintain larger buffers at refuelling stations for longer horizon lengths and therefore the transportation costs increase. The lowest total costs (€27901) can be observed at a horizon length of 14 hours, indicating that this is the best balance between robust planning and cost efficiency. Short horizon length (8 to 10 hours) result in slightly higher costs because the planning lacks sufficient foresight of future demand and pressure increase due to heat leaks.

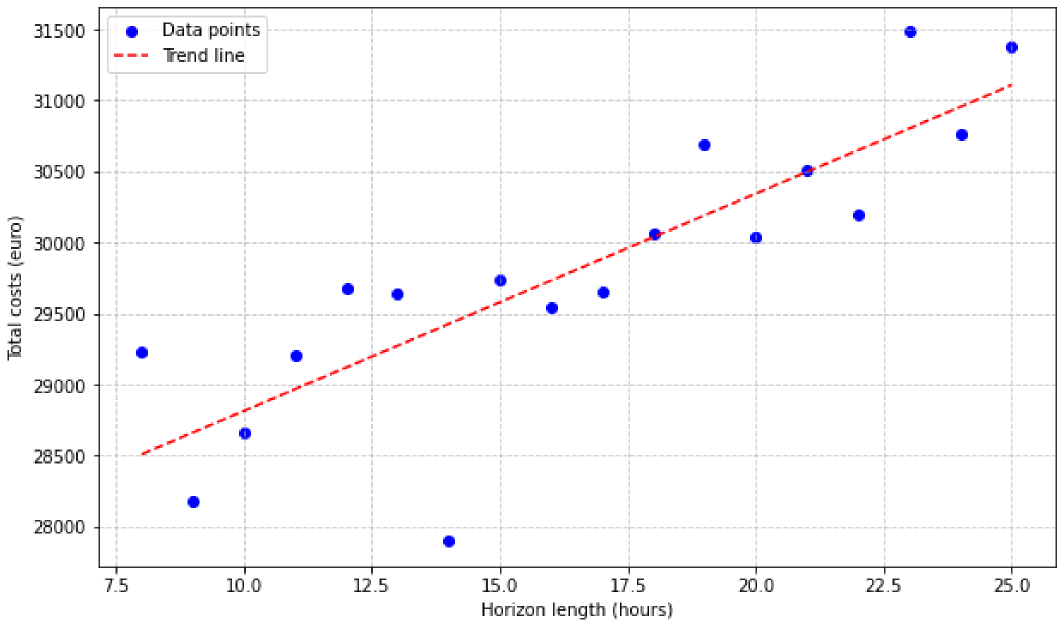


Figure 3.13: Total costs per horizon length between 8 to 25 hours. A general trend is shown that indicates that the total costs tend to rise as the horizon length in hours increases.

A complete overview of the results of the horizon lengths between 8 to 25 hours is shown in Appendix C. Table 3.11 provides a summary of the key results for select horizon lengths (8, 9, 10, 14, and 20 hours). Horizon length of 9 hours has the lowest transportation costs (€24451), but has the highest nitrogen cooling costs (€2995). Longer horizons, like 20 hours, result in increased total costs (€30033) due to higher transportation costs. However, the longer horizons have the lowest nitrogen cooling costs (€2735).

Table 3.11: Overview of the results for the horizon lengths 8, 9, 10, 14 and 20 hours based on the Total Costs (TC), Total Transportation Costs (TTC) and Total Nitrogen Cooling Costs (TNCC). It reveals that the horizon length of 14 hours has the lowest TC. In Appendix C in Table C.5 the horizon lengths results are shown.

Horizon length	TC	TTC	TNCC
8	29226	25842	3384
9	28177	24451	3726
10	28663	25634	3029
14	27901	24906	2995
20	30033	27298	2735

Overall, the horizon length of 14 hours provides the best balance between cost-efficiency and robust planning, However, horizon lengths between 8 and 10 hours also deliver good results, balancing relatively low total costs with robust planning for 28 days. The main insight from this experiment is that the horizon lengths can not be too short, as they lack sufficient buffer, making the model less robust and not applicable in different scenarios. Additionally, excessively long horizon lengths focus too much on keeping reserves, resulting in routing inefficiencies and higher total costs.

3.5. Conclusion of planning methodologies

This chapter answers three sub-questions that support the aim of creating a planning methodology for LNG IRP with pressure management.

- **SQ2: What KPIs are most relevant for evaluating a planning method for LNG and Bio-LNG IRP with cryogenic temperature control?**
  In Section 3.1.4, the KPIs relevant for evaluating a planning method for LNG and Bio-LNG with cryogenic temperature control have been identified as Total Costs (TC), the Total Transportation Costs (TTC), the Total Nitrogen Cooling Costs (TNCC) and the Cost per Kilogram (CpK). These KPIs were determined in collaboration with a planning expert and an operations manager. The KPIs focus on the planning method's cost drivers and operational efficiency. TTC measures the costs of the vehicle routes. TNCC focuses on the costs required to control the pressure. CpK indicates the transportation costs per kilogram delivered. Finally, TC gives an overview of the overall costs of transportation and pressure control costs.
- **SQ3: What are the key constraints and variables that must be considered when designing a planning methodology for LNG and Bio-LNG IRP with cryogenic temperature control?**
  Several constraints and variables must be considered. Inventory levels at refuelling stations must stay above minimum thresholds to avoid stockout and below maximum storage capacity. Pressure levels, which increase due to heat leaks, must remain below maximum pressure bound to prevent station shutdowns. Vehicle constraints, such as inventory capacity, pressure capacity, home base location, have an effect on the routing decisions. Time constraints, including travel and service time, must be accounted to coordinate the deliveries, logistic cooling and terminal loading time slots. The methodology must also incorporate the cooling methods: logistic cooling, nitrogen cooling and offload cooling. Each cooling method has specific restrictions. The key variables include routing decisions, (off)loading operations, inventory and pressure levels at refuelling stations, as well as LIN cooling and logistic cooling activities.
- **SQ4: What steps and methods are needed to develop a planning methodology for LNG and Bio-LNG IRP, with specific focus on pressure management and computational efficiency?**
  To develop a planning methodology for LNG and Bio-LNG IRP with cryogenic temperature con-

trol, the process began with constructing a Full MILP model in Section 3.2. This detailed model included all relevant constraints and variables. However, due to the high computational complexity of solving the Full MILP model for larger instances, the approach was refined by developing a Simplified MILP model in Section 3.3. To improve computational efficiency and handle multi-period planning, a rolling horizon approach was applied in Section 3.4. This approach splits the planning horizon into smaller, manageable time blocks that are solved sequentially.

In conclusion, this chapter has set up a framework for LNG and Bio-LNG IRP with cryogenic temperature control by defining the relevant KPIs, identifying key constraints and variables, and developing planning methods. The Simplified MILP model combined with the rolling horizon approach serves as a robust, computationally efficient planning methodology. While, this methodology has not been fully validated in a real-world scenario, initial tests indicate that the model can solve a robust planning over a time period of 28 days when considering the impact of the horizon length. The next chapter applies the Simplified MILP model in combination with the rolling horizon approach in a real-world case study, where the model is tested on Rolande's network of refuelling stations.

4 Case study Rolande

In this chapter, the developed LNG-IRP model, including a rolling horizon approach, is experimented in a real-world case study involving Rolande's network of refuelling stations. Rolande's logistic operations focus on efficient inventory routing solutions that consider transportation costs and nitrogen cooling costs. However, the practical use of this model depends not only on reducing costs, but also on its applicability under different operational conditions. By analysing the model's robustness and resilience in response to demand fluctuations, pressure heat leaks fluctuations and different safety stock levels, this chapter aims to assess its applicability for sustained use in Rolande's network. The focus in this case study is the following question: *How reliable and robust is the developed LNG-IRP model, including the rolling horizon approach, within the context of Rolande's network of refuelling stations?*.

The mathematical models in this chapter were implemented in python and solved using the open PuLP library (version 2.9.0.). The experiments were run on a laptop with an Intel i5 processor and 8 GB of RAM.

4.1. Company description Rolande

Rolande B.V. is a leading provider of LNG and Bio-LNG for Dutch and European road transport. They develop, build and operate their own network of LNG refuelling stations in the Netherlands, Belgium and Germany. This case study analysis their network in the Netherlands and Belgium. Figure 4.1 shows a map of stations (red), terminals (yellow) and homebases (green) that are included in this research. In July 2024 Rolande started their own production plant of Bio-LNG. This Bio-LNG is locally produced fuel extracted from biogas from waste streams such as organic household, waste, sludge, manure or agricultural waste. Afterwards, the biogas is upgraded and then liquefied into Bio-LNG, consisting of 100% methane and contributing to a circular economy (Rolande, n.d.-a).

Rolande believes in 100% clean road transport and is optimistic and forward-looking. Its core values ambitious, enterprising, knowledgeable and committed underpin everything that Rolande does to make transport green and sustainable while ensuring profitability. Currently, at Rolande the ratio between grey LNG and Bio-LNG is around 80-20%. However, with the new introduction of their own Bio-LNG production plant, Rolande will be able to switch to primarily Bio-LNG. This will allow heavy road transport to move towards sustainable transport by 2030.

In the Netherlands, Rolande and Shell are the two largest providers of LNG for heavy road transport. While both companies hold a large market share, their visions for managing the logistic system differs greatly. At Shell, all LNG refuelling stations are equipped with nitrogen tanks. This setup results in less uncertainties for the pressure management of the cryogenic tanks at the refuelling stations. However, the operational costs are high due to extensive use of nitrogen. A logistics planner involved in Shell's stations supplies said that Shell pays little attention to the high cooling costs because LNG is not their core business. These additional costs are easily absorbed within the company's broader operations.

Rolande, on the other hand, utilizes a different approach. Instead of installing nitrogen tanks at every station, Rolande makes strategic decisions about which stations to equip with a nitrogen tank. Their vision is that you do not require a nitrogen tank if the demand of the station is high, as pressure can be managed through offload cooling or logistic cooling. This view asks for more tailored logistic decisions that consider inventory and pressure management.

Figure 4.1: Geographical map of Rolande's refuelling stations and depots. The three letter abbreviations of the refuelling stations are defined in Appendix D.

4.2. Case study characteristics

The refuelling stations of Rolande are supplied by LNG and Bio-LNG. The LNG and Bio-LNG is loaded at three different terminals: Gent, Gate and Luttelgeest. At Gent only warm Bio-LNG, originally from Norway or Sweden, is picked up at a specific time slot and delivered to stations. At Gate cold LNG is loaded at a specific time slot and delivered to the stations. Lastly, at Luttelgeest, Rolande has its own

Bio-LNG production plant where they must load Bio-LNG once a day and deliver it to the stations. The geographical location of the terminals is marked with yellow indicators in Figure 4.1.

The network in the Netherlands and Belgium are distributed by three different transporters: Schenk, GCA, Nijman. Each transporters has different trailers with different characteristics such as maximum pressure in the trailer and the inventory capacity. The maximum pressure in the trailer has an influence on the amount of times it can release the pressure. In their fleet there are 7 bar, 5 bar and 3 bar trailers. A 7 bar trailer can release the pressure twice, a 5 bar trailer can release the pressure once and a 3 bar trailer can not release the pressure.

In Europe, the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) regulates the transportation of dangerous goods by road. This ADR framework sets guidelines and safety measures for transporting dangerous goods such as the cryogenic products LNG and Bio-LNG. Furthermore, the ADR framework sets different maximum weight limits for trailers in each country. For example, the maximum capacity in the Netherlands is 22 tons and in Belgium 20 tons.

In the Netherlands, Rolande operates fourteen refuelling stations of which ten stations have a nitrogen tank on site. These ten stations can cool the station with nitrogen cooling, offload cooling and logistic trailer cooling. The other four stations do not have a nitrogen tank, so they rely on only offload cooling and logistic trailer cooling to reduce the pressure at the station. The transporter GCA cannot offload at the refuelling stations Alkmaar, Veghel and Heerenveen due to their nozzle. This is the connecting piece between the vehicles trailer and the LNG storage tank at the refuelling station.

For the routing, you have to take into account the inventory and pressure levels. In addition, logistic trailer cooling can be done at certain stations. The offload cooling parameter differs per product that is offloaded due to the different temperatures at the terminals. For instance, LNG from Gate is loaded at around two bars. It is assumed that it reduces the pressure at a station by 0.25 bar per ton LNG. On the other hand, warm Bio-LNG from Gent is loaded at around six bars. So it is assumed that you reduce the pressure by 0.1 bar per ton Bio-LNG. Finally, Bio-LNG from Luttelgeest is loaded at around four bars and it is assumed that you can reduce the pressure at a station by 0.2 bar per ton of Bio-LNG. Due to these different offload cooling parameters, Rolande does not deliver warm Bio-LNG from Gent to Botlek, Veghel and Utrecht because the offload cooling effect is too low. It does offload at refuelling station Tilburg because the demand at this station is so high that it must almost be replenished daily.

In Belgium, Rolande operates five refuelling stations and all stations are equipped with a nitrogen tank. In addition, only cold LNG from the terminal Gate is delivered to Belgium. Logistic trailer cooling can be an option to reduce the pressure at refuelling stations but it is not mandatory since every station has a liquid nitrogen tank on site. The travel distance to refuelling stations in Belgium can be far so it is important to notice that a refuelling station becomes critical in time. In short, the case study characteristics of Rolande's network in the Netherlands and Belgium have been described. Consequently, three constraints are added to the Simplified MILP model to account for i. the transporter GCA being unable to offload at every station, ii. no Bio-LNG must be delivered to Belgium and iii. Bio-LNG from Gent should not go to Botlek, Veghel and Utrecht.

When vehicle k is operated by GCA and station i is restricted (i.e., Alkmaar, Veghel, or Heerenveen), the variable $z_{i,t}^{k}$, indicating vehicle k's presence at station i at time t, must satisfy

$$z_{i,t}^{k} = 0, \quad \forall t \in T_r \tag{4.1}$$

When vehicle k is assigned to terminal Gent or Luttelgeest, as specified by the parameter θ_{ik}, the vehicle is restricted from visiting any station i located in Belgium. Therefore, the variable $z_{i,t}^{k}$, indicating vehicle k's presence at station i at time t, must satisfy

$$z_{i,t}^{k} = 0, \quad \forall t \in T_r \tag{4.2}$$

When vehicle k is assigned to terminal Gent, as specified by the parameter θ_{ik}, the vehicle is not allowed station Botlek, Veghel and Utrecht. Therefore, the variable $z_{i,t}^{k}$, indicating vehicle k's presence at station i at time t, must satisfy

$$z_{i,t}^{k} = 0, \quad \forall t \in T_r \tag{4.3}$$

4.3. Sensitivity analysis

The sensitivity analysis aims to analyse how the performance of the model is affected by different parameters. This provides insight into the robustness and reliability of the model and identifies which parameters the model is most sensitive to. In this sensitivity analysis, the following parameters are analysed:

- Cost per kilometre and cost per hour (costkmhour)
- Cost nitrogen cooling (costN)
- Demand and vehicle inventory capacity (Demand&cap)
- Offload cooling parameter (offloadcooling)
- Pressure increase due to heat leaks (PHL)
- Vehicle inventory capacity (Vehiclecap)
- Minimum inventory level station (Imin)
- Travel distance and travel time (Traveldistime)
- Vehicle pressure capacity (Vehicleprescap)

A variation of $\pm$20% from the baseline values was applied for each parameter. The model's performance is measured by the total cost (TC). Furthermore, one key requirement from Section 3.1.5 must be satisfied: No stock-out or critical pressure at refuelling stations. This means that the solution must be feasible.

The results of the sensitivity analysis, presented in Table 4.1 and Figure 4.2, show that the model is most sensitive to the vehicle inventory capacity (Vehiclecap). A reduction of 20% in vehicle capacity makes the model infeasible, indicating that the model relies on sufficient vehicle capacity to deliver LNG and Bio-LNG to refuelling stations. On the other hand, a 20% increase in vehicle capacity results in a 19% increase in total costs, because the vehicles must take detours so the offloads occur later that day, when the stations are more empty.

Other parameters with significant impact on the performance are cost per kilometre and cost per hour (costkmhour), pressure increase due to heat leaks (PHL) and travel distance and travel time (Traveldistime). Fluctuations in these parameters can cause the total costs to vary by up to 18% for costkmhour and 11% for both PHL and Traveldistime.

In contrast, parameters such as minimum inventory level (Imin) and vehicle pressure capacity (Vehicleprescap) have a low impact on the total costs, with fluctuations of only 1-2%. This suggests that the model is robust to changes in these parameters within the range tested.

Table 4.1: Sensitivity analysis results with changes in parameters (TC = Total Costs in euro). A variation of ±20% was applied on the parameters.

Parameter	TC (80%)	Δ	TC (100%)	Δ	TC (120%)
costkmhour	5825	-18%	7141	18%	8446
costN	6791	-5%	7141	7%	7651
Demand&cap	7401	4%	7141	1%	7198
Imin	7141	0%	7141	-1%	7047
Offloadcooling	7546	6%	7141	0%	7161
PHL	6623	-7%	7141	11%	7911
Traveldistime	6654	-7%	7141	11%	7893
Vehiclecap	Infeasible	–	7141	19%	8482
Vehicleprescap	6974	-2%	7141	-1%	7075

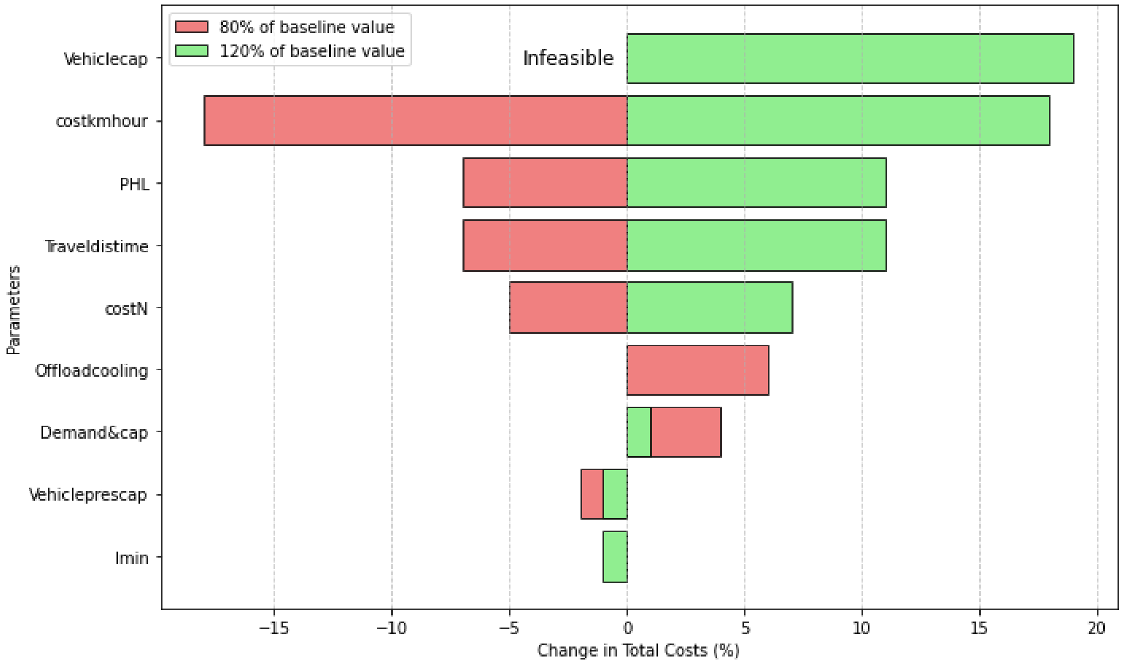


Figure 4.2: Tornado diagram that presents the most sensitive parameter on top and least sensitive parameter at the bottom. It reveals that the vehicle capacity is the most sensitive parameter and that the model becomes infeasible if the vehicle capacity is reduced by 20%.

The sensitivity analysis identified vehicle capacity as the critical parameter for the performance on the total costs and the feasibility of the model. The model's reliance on sufficient vehicle capacity showed the importance of determining the required LNG supply in advance. This is because vehicle capacity is directly linked to LNG supply: each vehicle must load its maximum vehicle capacity at terminal pickup slots. This motivates the adjustment of the pre-solve process from Section 3.3.7 with determining how much supply is required each day. By addressing this challenge upfront, the pre-solver makes the daily planning feasible. The following section introduces the pre-solve process.

4.4. Pre-solve: critical stations and Gate slots

This section elaborates on Section 3.3.7 by adding the required LNG supply in the pre-solve. In Section 4.2, the characteristics of terminals Gent, Luttelgeest and Gate are described. At Luttelgeest and Gent, Bio-LNG is picked up, while LNG is picked up at Gate. For Rolande, the Bio-LNG pickup slots at Luttelgeest and Gent are known in advance, whereas the slots at Gate are more flexible. The goal of the new pre-solve process is to identify which stations are critical and should be included in the daily planning and to determine if additional Gate slots are needed beyond those at Luttelgeest and Gent.

If extra Gate slots are required, the pre-solve process determines the quantity of Gate slots that are necessary. Figure 4.3 presents a flowchart illustrating the decision-making process within the pre-solve.

In Figure 4.3 the solid lines represents the flow of the decision-making process of the pre-solver. The dashed line are the feedback loops that are required to add stations to the critical stations list. The pickup slots of Gent and Luttelgeest, and the refuelling station's inventory and pressure forecast are the inputs of the pre-solver, shown by the blue parallelograms. The yellow rounded rectangles are the general operations within the decision making process, the grey rounded rectangles are operations dealing with the critical stations list, and the green rounded rectangles are operations that have to do with the determination of Gate slots.

The pre-solver starts with identifying the stockout stations and the critical pressure stations. Stock out stations are refuelling stations that exceed the safety stock level in the pre-solver's time horizon. The critical pressure stations are refuelling stations that exceed the maximum pressure level within the same time horizon. The stockout stations and critical pressure stations form the initial list of critical stations. Thereafter, the available inventory for each station in the list of critical stations is calculated on 09:00 a.m. on that specific day. This time is selected because it typically marks the first pickup slot of the day. Then a decision is made if the refuelling station is located in the Netherlands or Belgium. The total available inventory of the critical refuelling stations in the Netherlands is calculated and it is compared to the total supply of the Gent and Luttelgeest slots. If the demand in the Netherlands is less than the supply, the station with the most available inventory in Netherlands is added to the list of critical stations, shown by the dashed feedback loop. If the demand in the Netherlands is more than the supply continue with determining the amount of Gate slots needed to satisfy the demand surplus in the Netherlands. If the available inventory of the critical station is located in the Belgium. The total available inventory of the critical refuelling stations in Belgium is calculated and this helps in determining the Gate slots required for satisfying the demand of the refuelling stations in Belgium. Lastly, after identifying critical pressure stations a flow goes to the determination of Gate slots due to logistic cooling. The operations dealing with the determination of the Gate slots are described below:

- **Determine Gate slots due to demand surplus NL**
  The total demand of the critical stations in the Netherlands minus the supply of the terminal pick up slots of Luttelgeest and Gent is the demand surplus. The demand surplus in the Netherlands divided by the Gate slot capacity in kilograms is the amount of Gate slots that the pre-solver would recommend to satisfy the demand surplus in the Netherlands for the critical stations.
- **Determine Gate slots due to Belgium stations**
  The total demand of the critical stations in Belgium divided by the Gate slot capacity in kilograms is the amount of Gate slots that the pre-solver suggests to satisfy the stock out of the Belgium stations.
- **Determine Gate slots due to logistic cooling**
  First, the critical pressure stations with less than five tons of available inventory are counted. If more than two stations meet this criterion, two Gate slots are recommended. If only one or two stations satisfy this requirement, one single Gate slot is recommended.
- **Determine amount of Gate slots**
  The recommended number of Gate slots for each issue, namely demand surplus in the Netherlands, Belgium stations and logistic cooling, are the input for the defining the final number of Gate slots needed for a specific day. If the recommended number for each of these issues is one, the final number of Gate slots will be two. Otherwise, the final number is the maximum of the three recommended values. Additionally, the total number of Gate slots on any given day must be at least two. If this requirement is not satisfied, the final number of Gate slots will be two minus the number of slots of Gent and Luttelgeest for that day.

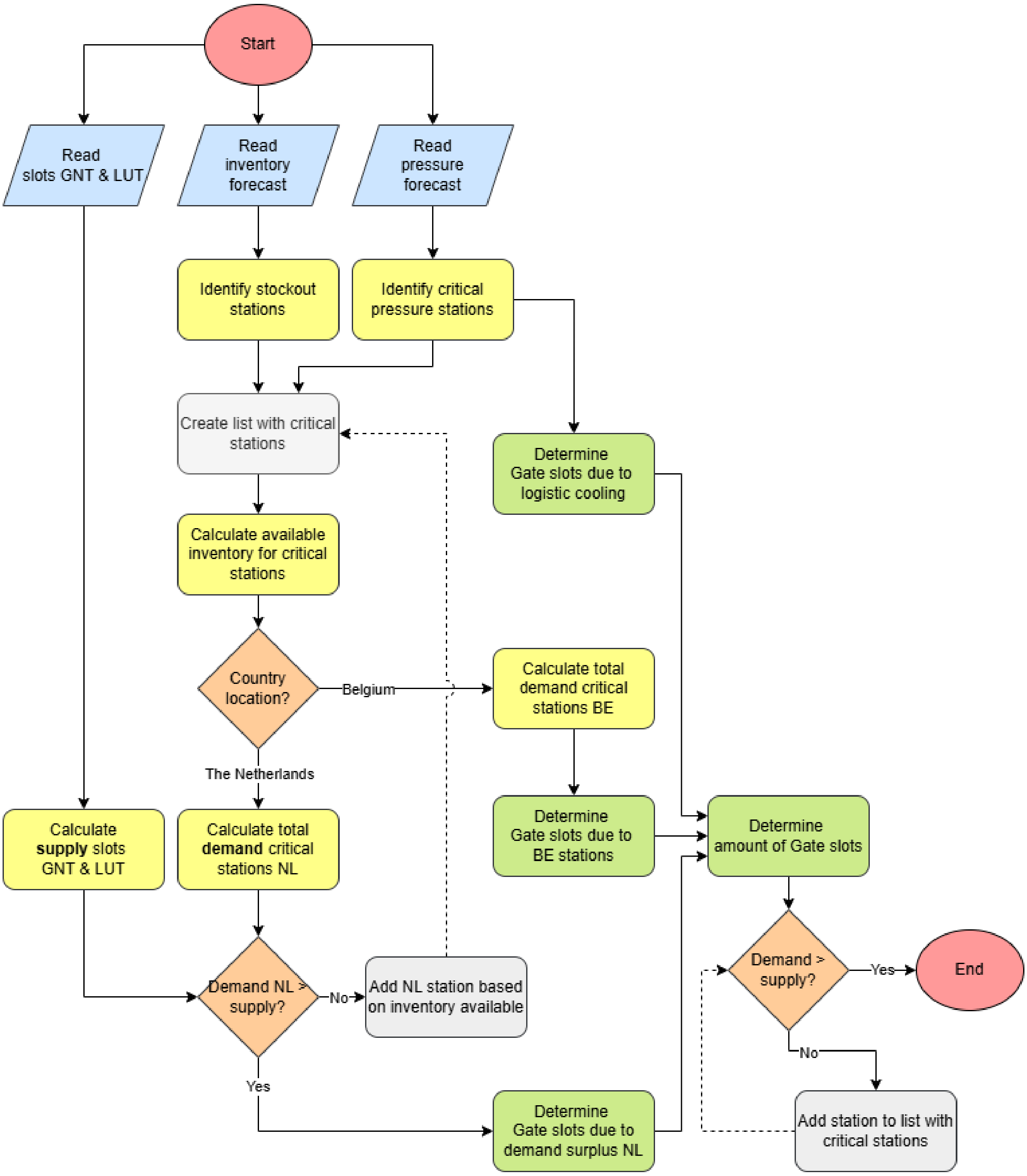


Figure 4.3: Pre-solve phase flow chart of case study at Rolande. The red oval forms indicate that start and end of the flow chart. The blue parallelograms are the inputs of the pre-solve process. The yellow blocks are calculations. Grey blocks are moments in the flow chart where critical stations are added to the list. The orange diamonds represent the decisions in the flow chart. Finally, the green blocks refer to the determining Gate slots.

4.5. Simplified MILP model with rolling horizon approach in practice

The objective of this experiment is to test the simplified MILP with rolling horizon with the historical data from the company Rolande. The start time of the planning is Monday 9 September 2024 at 04:00. The planning horizon covers a period of seven days. Furthermore, the experimental setup is shown in Appendix E.

In figure 4.4 the planning of seven days is shown. On the rows you have for each day the routes of the vehicles. On the columns you have four different block: Terminal, 1st stop, 2nd stop, 3rd stop and 4th stop. The terminal block shows the arrival time, load quantity and location of the terminal. The stop blocks give the arrival time, action that needs to be taken and stop location. The action that needs to be taken is offloading shown in tons and/ or logistic cooling shown in bars.

	Terminal			1st stop			2nd stop			3rd stop			4th stop		
	Arrival	Load	Location	Arrival	Action	Location	Arrival	Action	Location	Arrival	Action	Location	Arrival	Action	Location
Day 1															
Vehicle 1	3	17 ton	Gate	8	5 ton, 2 bar	Veghel	11	12 ton	Heteren						
Vehicle 2	10	15 ton	Luttelgeest	14	15 ton	Tilburg									
Day 2															
Vehicle 1															
Vehicle 2	34	15 ton	Luttelgeest	38	6.5 ton	Nieuwegein	41	2 bar	Botlek	44	8.5 ton	Utrecht			
Day 3															
Vehicle 1	51	17 ton	Gate	54	2 bar	Botlek	57	2 bar	Utrecht	60	12 ton	Tilburg	63	5 ton	Meer
Vehicle 2	58	15 ton	Luttelgeest	62	15 ton	Zaandam									
Day 4															
Vehicle 1	75	17 ton	Gate	79	9.3 ton	Antwerpen	82	7.7 ton	Tilburg						
Vehicle 2	82	15 ton	Luttelgeest	86	10 ton	Nieuwegein	89	2 bar	Veghel	92	5 ton	Utrecht			
Day 5															
Vehicle 1	99	17 ton	Gate	102	2 bar	Botlek	108	17 ton	Waregem						
Vehicle 2	106	15 ton	Luttelgeest	110	6.6 ton	Geldermalsen	113	8.4 ton	Tilburg						
Day 6															
Vehicle 1	123	17 ton	Gate	127	11.6 ton	Meer	130	2 bar	Veghel	133	5.4 ton	Heteren			
Vehicle 2	130	15 ton	Luttelgeest	134	6.7 ton	Alkmaar	137	8.3	Utrecht						
Day 7															
Vehicle 1															
Vehicle 2	154	15 ton	Luttelgeest	158	10 ton	Nieuwegein	161	2 bar	Botlek	165	5 ton	Tilburg			

Figure 4.4: Planning output of seven days. It reveals that the Simplified MILP model with rolling horizon approach and pre-solve process can solve a multi-period planning of seven days and provide an output that is easy to read and this confirms the requirement in Section 3.1.5.

Figures 4.5 and 4.6 present the inventory and pressure levels of the multi period planning of seven days. This proves that the simplified MILP model performs well in real life logistics for a network of nineteen refuelling stations, two terminals and two vehicles. The model succesfully maintains the inventory levels across the refuelling stations within the specified bounds, showing that there are no inventory stock outs and the demand is met. The pressure levels also indicate that the model can deal with the pressure increase due to heat leaks and find solutions with offload cooling, nitrogen cooling and logistic trailer cooling to manage the pressure levels. These results provide proof of the model's ability to solve the multi-period IRP for LNG and Bio-LNG with cryogenic temperature control in practice.

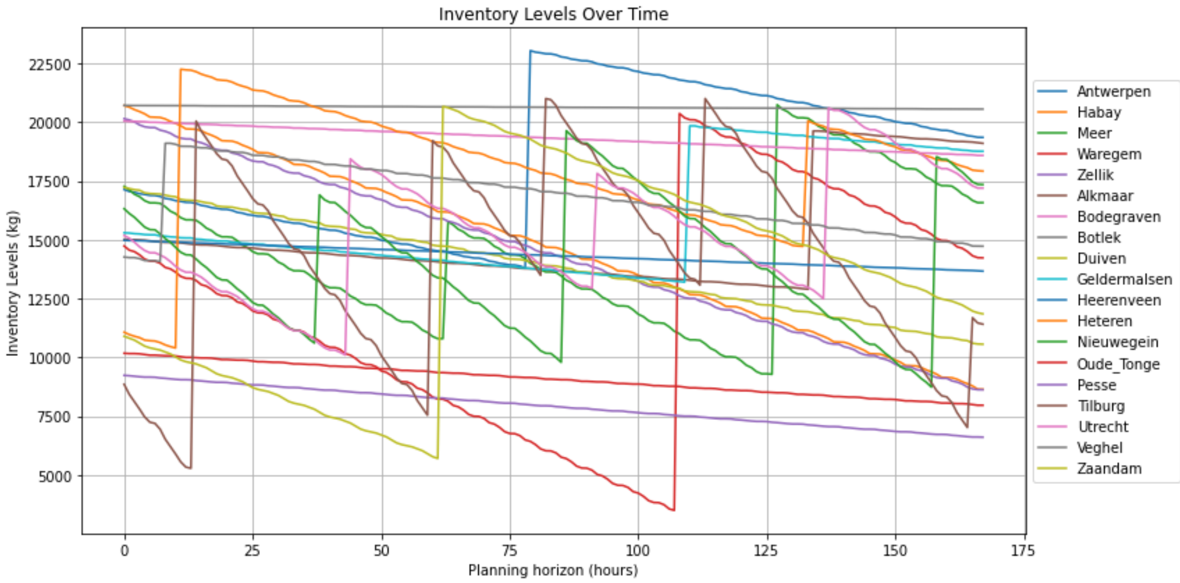


Figure 4.5: The inventory levels of each station over time. This indicates that the model can produce a feasible solution that keeps the inventory between the specified bounds.

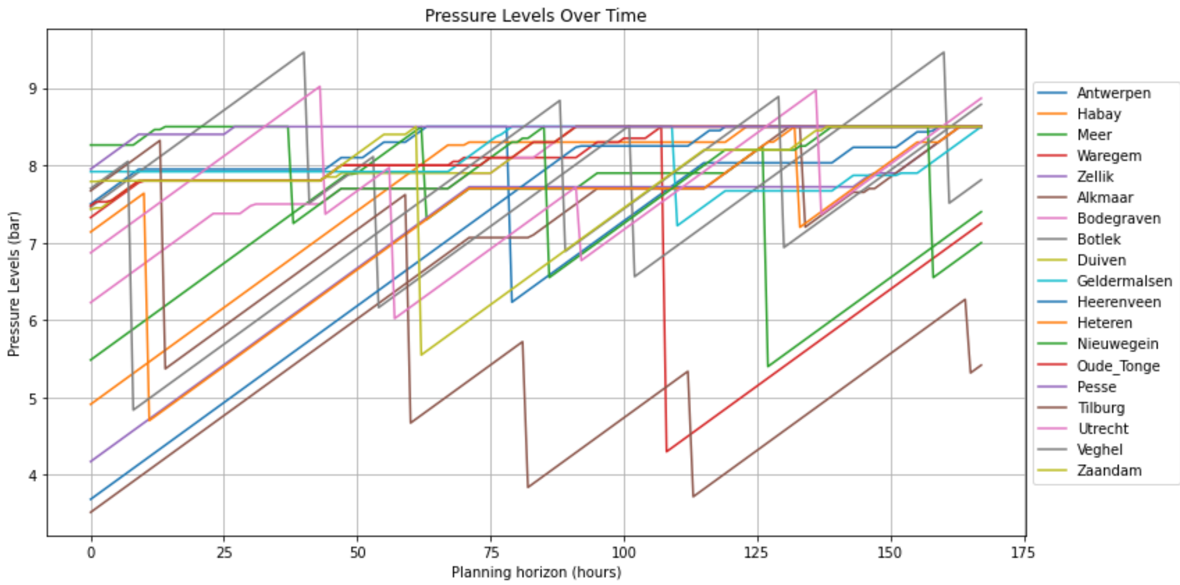
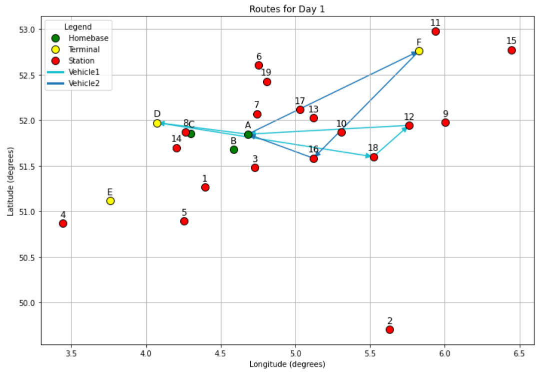


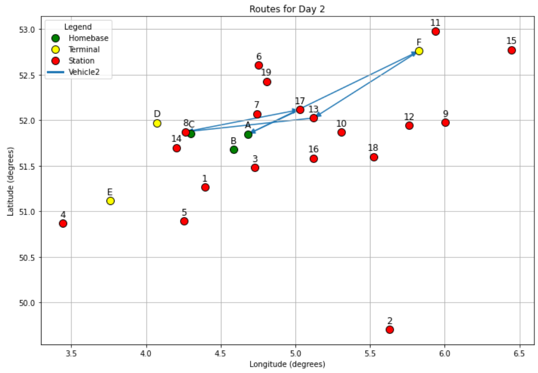
Figure 4.6: The pressure levels of each station over time. This gives insights that the model is able to solve a seven day planning for Rolande and that it can remain the pressure levels within the specified bounds.

Figure 4.7 shows a geographical view of the vehicle's route over the seven-day planning period. Each sub figure (Figures 4.7a - 4.7g) presents the specific route for each day, pointing out the refuelling station and terminals visited by the vehicles. The map is based on latitude and longitude coordinates of home bases, stations and terminals in Rolande's network. Table 4.2 serves as a support for reading the geographical view where the stations are represented by numbers and the home bases and terminals by alphabetic letters.

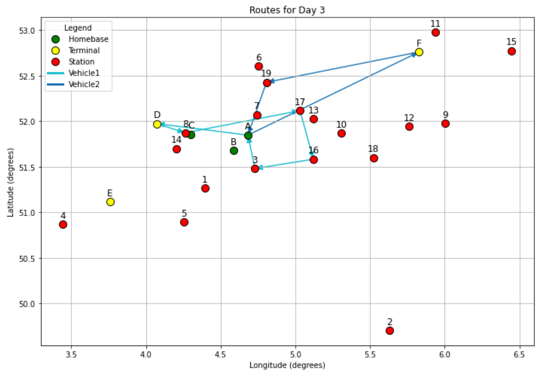
It is noticeable that most routes in the geographical representation are circular in nature, with each route having a closed start and end point at the vehicle's home base. Nevertheless, figure 4.7d for Day 4's route does have a linear route back and forth. The vehicle travels from Nieuwegein (13) - Veghel (18) - Utrecht (17). However, this linear route can be explained by the logistic cooling in Veghel (18) and the constraint that you cannot do logistic cooling at the final station before travelling back to the home base. Overall, due to the circular nature of the vehicle routes it can be stated that the simplified model including the rolling horizon approach effectively optimizes the travel distance and travel times while taking the constraint into account.



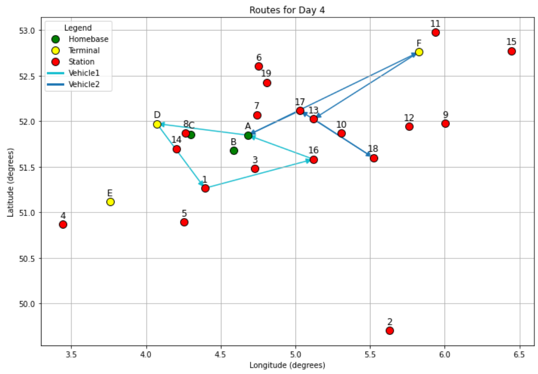
(a) Routes for day 1



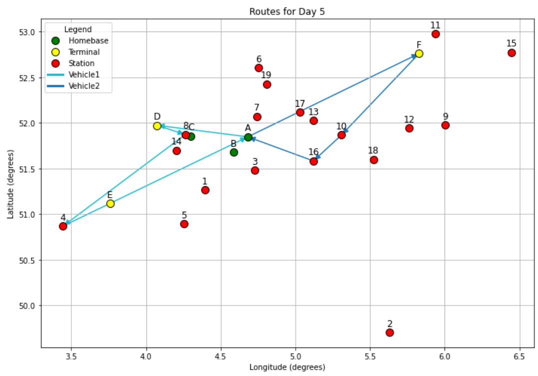
(b) Routes for day 2



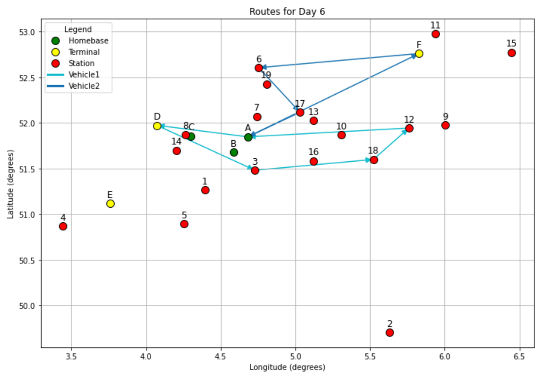
(c) Routes for day 3



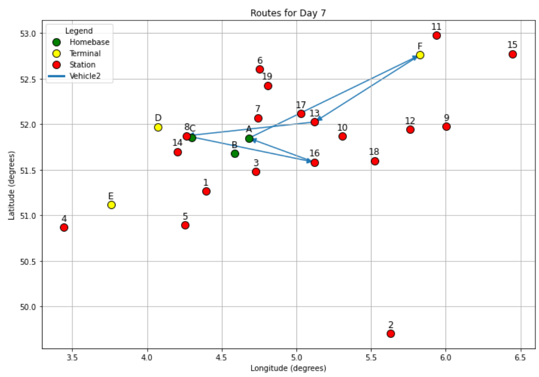
(d) Routes for day 4



(e) Routes for day 5



(f) Routes for day 6



(g) Routes for day 7

Figure 4.7: Geographical presentation of the routes. It reveals that the vehicles start and end at its home base each day. Furthermore, it shows that a vehicle start its trip by picking up LNG at a terminal and then delivers it to the refuelling stations.

Table 4.2: Overview of the routing of each vehicle for each day. The letters refer to the terminals and the numbers correspond to the stations in Figure 4.7.

Day	Vehicle ID	Routing
1	Vehicle1	Gate (D) - Veghel (18) - Heteren (12)
	Vehicle2	Luttelgeest (F) - Tilburg (16)
2	Vehicle1	N/A
	Vehicle2	Luttelgeest (F) - Nieuwegein (13) - Botlek (8) - Utrecht (17)
3	Vehicle1	Gate (D) - Botlek (8) - Utrecht (17) - Tilburg (16) - Meer (3)
	Vehicle2	Luttelgeest (F) - Zaandam (19)
4	Vehicle1	Gate (D) - Antwerpen (1) - Tilburg (16)
	Vehicle2	Luttelgeest (F) - Nieuwegein (13) - Veghel (18) - Utrecht (17)
5	Vehicle1	Gate (D) - Botlek (8) - Waregem (4)
	Vehicle2	Luttelgeest (F) - Geldermalsen (10) - Tilburg (16)
6	Vehicle1	Gate (D) - Meer (3) - Veghel (18) - Heteren (12)
	Vehicle2	Luttelgeest (F) - Alkmaar (6) - Utrecht (17)
7	Vehicle1	N/A
	Vehicle2	Luttelgeest (F) - Nieuwegein (13) - Botlek (8) - Tilburg (16)

In summary, the simplified MILP model with the rolling horizon approach and preliminary pre-solve process is tested to solve the planning for Monday 9 September 2024 04:00 till Monday 16 September 2024 04:00. The results proof that the model is able to solve the multi-period IRP for LNG and Bio-LNG with cryogenic temperature control in this scenario. However, it does not indicate that this model is generalisable to other networks, as this is still open for future researchers. The circular nature of the vehicles routes indicate that the model effectively optimizes the travel distances and travel times while taking the constraint into account.

4.6. Evaluation of solver computational time

This experiment analyses the computational performance and objective values produced by the Simplified MILP model with the rolling horizon approach and preliminary pre-solve process. The experiment focuses on a planning horizon of seven days. The aim of this experiment is to understand the computational challenges that can occur on specific days, and analyse the evolution of the objective value versus the best possible bound. This analysis is important because Section 3.1.5 requires that the computation time of the planning must be within four hours.

The computational time bar chart, in Figure 4.8, shows that most days require a relatively short computational time of under 150 seconds. However, on Day 4 the computational time increased to 5052 seconds, indicating a challenging problem or more complex constraints that the solver needs to handle on that day. The same happens on Day 7, where an unusually long computational time of 8063 seconds is required. Such spikes suggest that the planning is harder to solve for these days due to more constraints and variables.

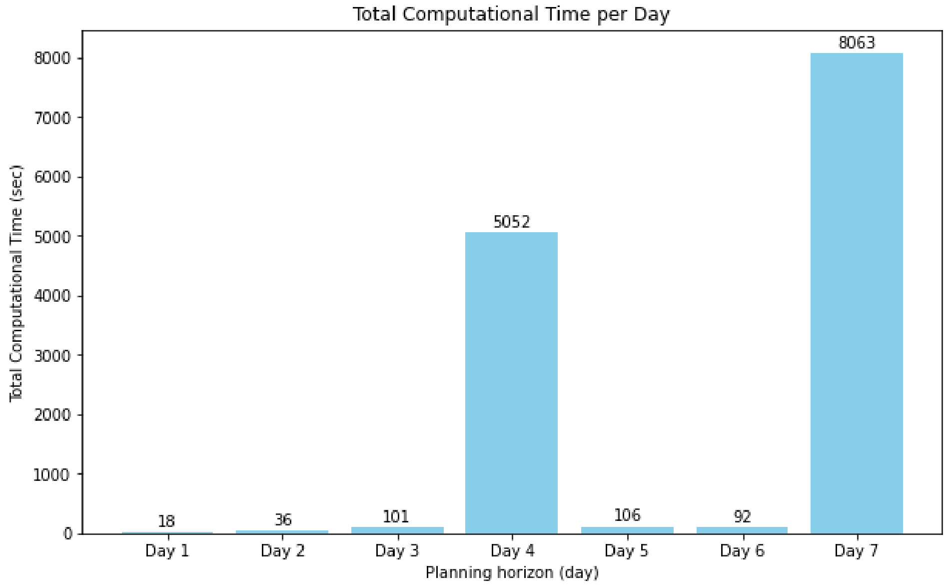


Figure 4.8: The total computational time for each day in the planning horizon. Day 4 and 7 are identified as complex days where the runtime increases significantly.

To further analyse the factors contributing to the complexity on these specific days, Table 4.3 provides an overview of the different scenarios for each day. This table may offer insights into the underlying factors driving these computational challenges. The number of pressure, stock out, additional and critical stations are determined during the pre-solve phase for each day, as described in the previous subsection. The number of no-cooled vehicles corresponds to the amount of slots from Gent or Luttelgeest on that specific day and is given as input to the model. The number of cool vehicles represents the number of slots from Gate, which is also determined in the pre-solve phase for each day. Finally, the stops per vehicle indicate the amount of stations stops per vehicle and the amount of bar logistic cooled is defined as the total pressure reduction achieved by logistic trailer cooling on that day.

The pre-solve phase provides the total amount of critical stations as input to the Simplified MILP model. A higher amount of critical stations offers more options for the vehicle routing. Additionally, because only cool vehicles can perform logistic trailer cooling, the presence of these vehicles introduce many additional constraints to the model. Consequently, it is expected that the scenarios or days with a high number of critical and especially pressure stations, combined with a large number of cool vehicles will require longer computational times.

From this perspective, the high runtime on Day 7 can be explained by the presence of eight critical stations, two cool vehicles and one no-cool vehicle. However, the long runtime Day 4 is more difficult to explain. Day 4 has three pressure stations, six critical stations and two cool vehicles, whereas Day 2 has two pressure stations, seven critical stations and one cool vehicle and one no-cool vehicle. Given these new insights, the runtime on Day 4 exceeds that of Day 2, suggesting that the combination of cool vehicles and pressure stations may significantly impact the runtime.

Table 4.3: Overview of the results of the computational performance experiment. The different indicators (rows) provide information about the specific scenario of that day (columns). A scenario with a high number of cool vehicles and a high number of critical stations is defined as complex.

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Number of pressure stations (#)	2	2	0	3	1	2	1
Number of stock out stations (#)	3	3	4	3	3	4	7
Number of additional stations (#)	1	2	0	0	1	0	0
Total critical stations (#)	6	7	4	6	5	6	8
Number of cool vehicles (#)	1	1	2	2	2	1	2
Number of no-cool vehicles (#)	1	1	0	0	0	1	1
Stops per vehicle (#)	2	3	1.5	2.5	1.5	2	2.3
Amount of bar logistic cooled (bar)	0	6	0	3	0	3	3
Total computational time (sec)	18	36	101	5052	106	92	8063

Figure 4.9, presents how the solver refines the solution over time. In the first second, the MILP solver finds an objective value with linear relaxation, by removing the requirement of integer variables. Then, the initial best possible bound is found after 550 seconds, represented by the start of the red dashed line. Furthermore, the first integer objective value is found after 600 seconds, this is the start of the blue line. The objective value starts with high total costs and gradually improves towards the best possible bound. On day 4 the convergence towards an optimal solution appears to be slower and more iterative than usual since there is a larger gap between the objective value and the best bound. The gap is narrowed down after significant computational time, showing the solver's effort to close in the gap. It is noteworthy that the best possible bound does not improve for 50 minutes after finding the initial best possible bound.

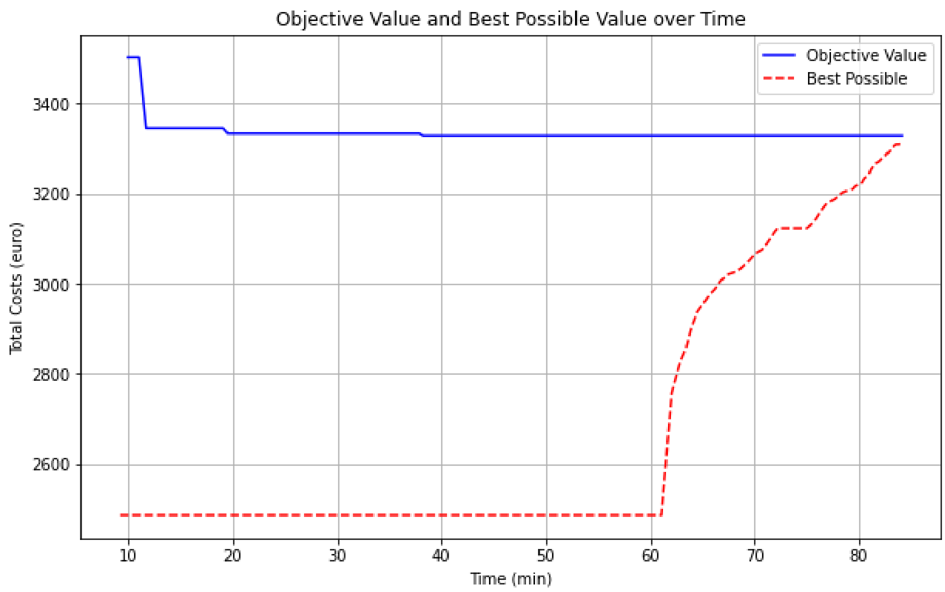


Figure 4.9: Objective value versus the best possible bound over time. It present the developement of the branch and bound solving process.

Overall, this analysis demonstrates the computational performance of the Simplified MILP model and specifically the performance on day 4 in the context of the rolling horizon. Especially when the model has to handle a complex day it requires significantly longer solution times. A complex day is defined as one a day with a high number of critical stations, cool vehicles and total vehicles.

4.7. Conclusion case study Rolande

This case study evaluated the developed Simplified MILP model with the rolling horizon approach in the context of Rolande's network of refuelling stations. The model balanced the transportation costs, nitrogen cooling costs, while satisfying the constraints regarding inventory and pressure management.

The sensitivity analysis revealed that model's most sensitive parameter is the vehicle, because it has a large impact on the total costs and the feasibility. Therefore, the pre-solve process was extended with not only determining the critical stations but also the required Gate slots for each day.

The Simplified MILP model with the rolling horizon approach successfully solved a multi-period planning horizon of seven days, while managing the inventory and pressure levels. This result confirmed that the model can maintain the refuelling stations inventory and pressure levels between the specified bounds, preventing stockout and critical pressure levels.

In terms of computational performance, the analysis revealed that most days required manageable solution times. However, certain days can be more complex than other. A complex day is defined as a day when the number of critical stations and the number of cooling vehicles capable of performing logistic cooling is high. The convergence of the objective value towards the best possible bound showed that the model can eventually handle these complex days.

While the model proved to find a solution for a seven-day planning for nineteen stations and two vehicles, its generalisably to other networks and scenarios remains untested. Testing the model under a broader range of scenarios would provide additional certainty in its robustness and applicability.

Despite these limitations, the Simplified MILP model with the rolling horizon approach and preliminary pre-solve process offers a practical solution for LNG and Bio-LNG IRP with pressure management in Rolande's network refuelling stations. Further validation in more diverse scenarios can give more certainty about the robustness for real-world use.

5 Conclusion, discussion & recommendations

5.1. Conclusion

The main research question addressed was: "*How can the LNG-IRP with cryogenic temperature control be optimised considering the transportation costs and nitrogen cooling costs?*". To answer this question, this research explored the current state of research and practice regarding the LNG-IRP with pressure management, identified relevant KPIs, refined planning methodologies, and tested the model's reliability and robustness through a case study at a distributor with its own network of LNG and Bio-LNG refuelling stations.

The literature research revealed the limitations in existing studies, which either focuses on maritime LNG transportation or incorporated boil-off gas as a method for pressure management. Refrigeration methods that are identified in the literature research are nitrogen cooling, offload cooling and logistic trailer cooling. Nitrogen cooling is achieved via an on-site cool tank, while offload cooling involves delivering a cold load to a station and mixing it with the warm tank inventory. The most unique method is logistic trailer cooling, which releases warmer gas from the refuelling station's tank into the vehicle's trailer, allowing it to be offloaded at another station. By integrating these refrigeration methods, this research addressed the knowledge gap of a planning method that integrates routing, inventory and pressure management for inland transportation of LNG.

At the beginning of the Planning methodologies chapter, the key constraints and variables related to inventory routing, pressure management, and refrigeration methods are discussed. Afterwards, the key performance indicators, Total Costs, Total Transportation Costs, Total Nitrogen Cooling Costs and Cost per Kilogram, are identified. The planning methodologies chapter presented the development of the Full MILP model, the Simplified MILP model and the rolling horizon approach. The Full MILP model determined how much load each vehicle should pick up at the terminal, waiting times at stations or terminals, which terminals the vehicles would use and the offload cooling effect was set at the product level. However, this model resulted in complications such as a lack of buffer stock for the following day and large computational times for larger instances of nodes, vehicles and time steps. To address this, the Simplified MILP was introduced. This model removed waiting times at stations or terminals, assigned vehicles to specific terminals, applied the offload cooling effect at the vehicle level and set different horizons for vehicle and station variables.

The computational time of the Simplified MILP model increases when the planning horizon exceeded four days within a scenario of five refuelling stations. To address this, a rolling horizon approach was introduced, including a pre-solve length, rolling length and horizon length. Given that vehicles operate within set working hours, the rolling length is constant and set to 24 hours. A sensitivity analysis on the horizon length revealed that as the horizon length increases, the Total Costs rise. On the other hand, too small a horizon length may result in unfeasible solutions for longer planning horizons. Therefore, an optimal horizon length must be determined to balance transportation costs and nitrogen cooling costs. The Simplified MILP model with rolling horizon approach and pre-solve process for determining the critical stations is experimented in the case study.

In the case study, the model was applied to Rolande's network of refuelling stations in the Netherlands and Belgium, confirming that the model is able to generate feasible and cost-effective solutions fo a seven-day planning horizon. The sensitivity analysis revealed that the vehicle capacity is the most sensitive parameter. Therefore, the pre-solve process is extended with not only determining the critical stations but also the number of Gate slots. While the model performs well in maintaining the inventory and pressure levels within the specified bounds, the computational time at complex days can be longer. Testing the Simplified MILP model with rolling horizon approach and pre-solve process in more scenarios may provide more certain on its robustness and reliability in other LNG networks.

Despite computational challenges on complex days, the model successfully solved a seven-day planning for 19 stations and two vehicle, proving its ability to handle multi-period LNG IRP with pressure management. This research contributes to the field of cryogenic LNG logistics by providing a planning method that integrates routing, inventory and pressure management decisions.

5.2. Discussion

This research explored the LNG-IRP with pressure management by proposing a planning methodology that integrates routing, inventory and pressure management. While the results show the potential of the Simplified MILP model with a rolling horizon approach and pre-solve process, several limitations are identified.

Proving the validity of this research was challenging, due to the lack of a baseline scenario for comparison. In the existing literature, there are no models developed for the LNG IRP with cryogenic temperature control, making it difficult to benchmark the model. Moreover, a cost comparison with human operators is complex because planners often take into account factors beyond cost minimisation, such as maintenance test schedules, weekend costs, waiting hours and terminal slot prices. These factors are not included in the model and make the model perform better compared to a human operator.

The variability in LNG supply also posed a challenge for validation. Different LNG types, such as Bio-LNG from Gent, Bio-LNG from Luttelgeest and LNG from Gate, have different offload cooling parameters and they significantly impact performance of the model. Despite these challenges, the model's validity is supported by the close collaboration with the company's planning experts. Different meetings were scheduled to check whether the proposed planning output/ routes were realistic and applicable in the network of Rolande's refuelling stations. Moreover, the circular structure, in geographical routing plots, and the cost per kilogram KPI, which is the same order of magnitude as the company's current costs, provide additional support for the validity of the model.

Several limitations are identified during this research and are discussed below:

1. The logistic cooling parameter is fixed for each time of this action, which does not reflect the variability in real life.
2. The offload load cooling parameter is fixed per vehicle. In real-life, the offload cooling effect would reduce after each offload, because the vehicles trailer's temperature increases to heat leaks while offloading. This effect is not accounted for in this research.
3. The logistic cooling does not account for the additional LNG in kilograms that is added to the vehicle trailer. This extra LNG must be able to be unloaded at the next station. In practice, this assumption may lead to situations where the vehicle is unable to unload the extra LNG at the next station. However, this additional LNG is a small quantity, not more than 500 kilograms, and is captured by fact that a vehicle can not do logistic cooling at the final station.
4. The minimum and maximum inventory and pressure are set as hard bounds. This rigidity may

lead to infeasibility where soft bounds would not. An example of such a scenario is that a refuelling station starts with an inventory level close to the safety stock level and the model has no time to reach this station in time.

5. The computational performance of the model presents an additional area for improvement in typical scenarios. While most scenarios were solved within reasonable time frames, complex days with high number of vehicles that can logistically cool and a high number of critical stations require longer runtimes.

In summary, while the Simplified MILP model with rolling horizon approach and pre-solve process is able to solve a LNG-IRP with pressure management, its validation is limited by the absence of a baseline in the literature. The next sections will provide different recommendations for the company and future researchers.

5.3. Recommendations Rolande

Given that the Simplified MILP model with rolling horizon approach and pre-solve process is already integrated with Rolande's database, including the inventory and pressure levels, the next step is to monitor the performance in real-world scenarios. Appendix F presents the integrated planning tool in Rolande's system. This research provides the following recommendations for Rolande:

1. **Monitor outcomes**
   Test the routes generated by the model in actual operations. Dispatch vehicles according to the planning schedule and observe if the inventory and pressure levels remain within the specified bounds. By consistently monitoring the planning schedule, observations can identify challenges where the model lacks compared to reality.
2. **Fine-tuning offload cooling parameters**
   Track how the pressure levels change at the refuelling stations after offloads. If the pressure drops faster or slower than that modelled, adjust the offload cooling parameter to better reflect the real-world impact of offloading.
3. **Be aware of additional LNG in the trailer of the vehicle after logistic cooling**
   Logistic cooling results in additional LNG in the vehicle's trailer and this not incorporated in the model. Ensure that the next station after logistic cooling has sufficient available inventory to deal with this additional LNG.
4. **Training**
   Provide a training to logistic planners on interpreting the model's output. This includes understanding and recognizing when manual adjustments in the parameters or general settings are required. Furthermore, it is important for the software developers at the company to know how to add stations or additional constraints to the model.

By implementing these recommendations, Rolande can utilize the Simplified MILP model with rolling horizon approach and pre-solve process effectively. Monitoring the model's performance and fine-tuning the offload cooling parameters will support the applicability in the real-world. Furthermore, training planners and developers makes the planning tool adaptive to future changes in the network.

5.4. Recommendations future researchers

This research is the first planning method that integrates routing, inventory and pressure management decisions in the context of LNG and Bio-LNG transportation. As a result, this research offers several new opportunities for follow-up research. The following recommendations are introduced to future researchers:

1. **Comparative analysis with existing planning methods**
   Future studies should validate the proposed planning methodology by comparing it with a baseline scenario. This baseline scenario could be made with a greedy heuristic. Where at each step in the journey you visit the closest stations first while taking the inventory and pressure constraints into account. This comparison could highlight the strengths on computational and cost efficiency of the proposed planning method.

2. **Evaluate the performance of the model on soft inventory and pressure bounds**
   Future research should explore the use of soft inventory and pressure bounds constraints. This would help the model to become more practical if the starting conditions of the inventory and pressure levels of the refuelling stations create infeasibilities.

3. **Non-linear offload cooling effect**
   Future studies should analyse the effect of a non-linear offload cooling effect. Currently, the model applies a fixed efficiency parameter to represent the cooling effect of offloading LNG or Bio-LNG into the station's tank. In real-world scenarios the offload cooling effect is influenced by several factors, such as initial temperature and inventory level of station's tank mixture, temperature of LNG in the vehicle's trailer, and the volume of LNG offloaded. The current linear assumption in the model may lead to inaccuracies of the cool effect. Especially, for stations with high demands where large offloads are scheduled this linear effect is overestimated.

By exploring these new areas in research, the cryogenic logistics of LNG and Bio-LNG will gain more insights into the efficiency of the proposed planning method, the model's performance on soft bound constraints and incorporating a more realistic approach for the offload cooling effect. This will result in a stronger foundation for optimising cryogenic logistics in real-world scenarios.

Bibliography

Aghezzaf, E., Raa, B., & Landeghem, H. (2006). Modeling inventory routing problems in supply chains of high consumption products. *European Journal of Operational Research*, *169*, 1048–1063. https://doi.org/10.1016/j.ejor.2005.02.008

Ahmadi-Javid, A., Mansourfar, M., Lee, C.-G., & Liu, L. (2023). Optimal distribution of perishable foods with storage temperature control and quality requirements: An integrated vehicle routing problem. *Computers & Industrial Engineering*, *182*, 109215. https://doi.org/https://doi.org/10.1016/j.cie.2023.109215

Alamia, A., Magnusson, I., Johnsson, F., & Thunman, H. (2016). Well-to-wheel analysis of bio-methane via gasification, in heavy duty engines within the transport sector of the european union. *Applied Energy*, *170*, 445–454. https://doi.org/https://doi.org/10.1016/j.apenergy.2016.02.001

Al-Hinai, N., & Triki, C. (2020). A two-level evolutionary algorithm for solving the petrol station replenishment problem with periodicity constraints and service choice. *Annals of Operations Research*, *286*(1), 325–350.

Alves, P. Y. A. L., Delgado, K. V., & Silva, V. F. (2018). Inventory routing problem with time windows: A systematic review of the literature. *Proceedings of the XIV Brazilian Symposium on Information Systems*. https://doi.org/10.1145/3229345.3229376

Andersson, H., Christiansen, M., & Desaulniers, G. (2016). A new decomposition algorithm for a liquefied natural gas inventory routing problem. *International Journal of Production Research*, *54*, 564–578. https://doi.org/10.1080/00207543.2015.1037024

Awad, M., Ndiaye, M., & Osman, A. (2021). Vehicle routing in cold food supply chain logistics: A literature review. *The International Journal of Logistics Management*, *32*(2), 592–617.

Bell, W. J., Dalberto, L. M., Fisher, M. L., Greenfield, A. J., Jaikumar, R., Kedia, P., Mack, R. G., & Prutzman, P. J. (1983). Improving the distribution of industrial gases with an on-line computerized routing and scheduling optimizer. *Interfaces*, *13*(6), 4–23.

Boers, L., Atasoy, B., Correia, G., & Negenborn, R. R. (2020). The multi-period petrol station replenishment problem: Formulation and solution methods. *Computational Logistics: 11th International Conference, ICCL 2020, Enschede, The Netherlands, September 28–30, 2020, Proceedings 11*, 600–615.

Bruno E. Demantova, L. C. C., Cassius T. Scarpin, & Darvish, M. (2023). An improved model and exact algorithm using local branching for the inventory-routing problem with time windows. *International Journal of Production Research*, *61*(1), 49–64. https://doi.org/10.1080/00207543.2021.1998696

Chart Industries. (2016, October). Intro to cryogenics [video]. https://www.youtube.com/watch?v=T-6R5exBUCo

Cho, J., Lim, G. J., Kim, S. J., & Biobaku, T. (2018). Liquefied natural gas inventory routing problem under uncertain weather conditions. *International Journal of Production Economics*, *204*, 18–29. https://doi.org/https://doi.org/10.1016/j.ijpe.2018.07.014

Christiansen, M., Fagerholt, K., Nygreen, B., & Ronen, D. (2013). Ship routing and scheduling in the new millennium. *European Journal of Operational Research*, *228*(3), 467–483.

Coelho, L. C., Cordeau, J., & Laporte, G. (2014). Thirty years of inventory routing. *Transport Science*, *48*, 1–19. https://doi.org/10.1287/trsc.2013.0472

Coelho, L. C., & Laporte, G. (2013). The exact solution of several classes of inventory-routing problems. *Computers & Operations Research*, *40*(2), 558–565. https://doi.org/https://doi.org/10.1016/j.cor.2012.08.012

Cornillier, F., Boctor, F., & Renaud, J. (2012). Heuristics for the multi-depot petrol station replenishment problem with time windows. *European Journal of Operational Research*, *220*(2), 361–369.

Cornillier, F., Boctor, F. F., Laporte, G., & Renaud, J. (2008). A heuristic for the multi-period petrol station replenishment problem. *European Journal of Operational Research*, *191*(2), 295–305. https://doi.org/https://doi.org/10.1016/j.ejor.2007.08.016

Dantzig, G. B., & Ramser, J. H. (1959). The truck dispatching problem. *Management science*, *6*(1), 80–91.

European Environment Agency. (2023). Greenhouse gas emissions from transport in the EU. https://www.eea.europa.eu/signals-archived/signals-2022/infographics/greenhouse-gas-emissions-from-transport/view

European Union. (2024). Reducing CO_2 Emissions from Heavy-Duty Vehicles. https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles/reducing-co2-emissions-heavy-duty-vehicles%5C_en

Fodstad, M., Uggen, K. T., Rømo, F., Lium, A.-G., Stremersch, G., & Hecq, S. (2010). Lngscheduler: A rich model for coordinating vessel routing, inventories and trade in the liquefied natural gas supply chain. *Journal of Energy Markets*, *3*(4), 31–64.

Ghiami, Y., Demir, E., Van Woensel, T., Christiansen, M., & Laporte, G. (2019). A deteriorating inventory routing problem for an inland liquefied natural gas distribution network. *Transportation Research Part B: Methodological*, *126*, 45–67. https://doi.org/10.1016/j.trb.2019.05.014

Glomb, L., Liers, F., & Rösel, F. (2022). A rolling-horizon approach for multi-period optimization. *European Journal of Operational Research*, *300*(1), 189–206. https://doi.org/https://doi.org/10.1016/j.ejor.2021.07.043

Grønhaug, R., Christiansen, M., Desaulniers, G., & Desrosiers, J. (2010). A branch-and-price method for a liquefied natural gas inventory routing problem. *Transportation Science*, *44*(5), 400–415. https://doi.org/10.1287/trsc.1100.0317

Hillier, F. S., & Lieberman, G. J. (2010). *Introduction to operations research* (9th). McGraw-Hill.

Hsu, C. S., & Robinson, P. (2019). Midstream transportation, storage, and processing. *Petroleum Science and Technology*. https://doi.org/10.1007/978-3-030-16275-7_17

Kleywegt, A., Nori, V., & Savelsbergh, M. (2004). Dynamic programming approximations for a stochastic inventory routing problem. *Transportation Science*, *38*, 42–70. https://doi.org/10.1287/trsc.1030.0041

Mahmoud, E. S., Elekyaby, Sadek, M., & Hassan, S. (2020). Double diamond strategy saves time of the design process. *International Design Journal*. https://doi.org/10.21608/IDJ.2020.96345

Maknoon, Y. (2024). Fundamentals of multimodal transportation.

Moin, N. H., & Salhi, S. (2007). Inventory routing problems: A logistical overview. *Journal of the Operational Research Society*, *58*, 1185–1194. https://doi.org/10.1057/palgrave.jors.2602264

Rolande. (n.d.-a). BIO-LNG-Duurzaam transport.

Rolande. (n.d.-b). Over Rolande.

Rolande. (2020). Tankstation uhlm [Image is from intern image database of Rolande].

Sethi, S., & Sorger, G. (1991). A theory of rolling horizon decision making. *Annals of Operations Research*, *29*, 387–415. https://doi.org/10.1007/BF02283607

Surjandari, I., Rachman, A., Dianawati, F., & Wibowo, R. (2011). Petrol delivery assignment with multi-product, multi-depot, split deliveries and time windows. *International Journal of Modeling and Optimization*, *1*(5), 375.

Swamidass, P. M. (2000). Rolling horizonrolling horizon. In P. M. Swamidass (Ed.), *Encyclopedia of production and manufacturing management* (pp. 653–654). Springer US. https://doi.org/10.1007/1-4020-0612-8_827

Thomas, S., & Dawe, R. A. (2003). Review of ways to transport natural gas energy from countries which do not need the gas for domestic use. *Energy*, *28*(14), 1461–1477. https://doi.org/https://doi.org/10.1016/S0360-5442(03)00124-5

Uggen, K. T., Fodstad, M., & Nørstebø, V. S. (2013). Using and extending fix-and-relax to solve maritime inventory routing problems. *Top*, *21*, 355–377.

Volvo Trucks. (n.d.). Wat is lng? [Geraadpleegd op 10 december 2024]. https://www.volvotrucks.nl/nl-nl/news/kennisbank/transportbegrippen/lng-motor-tank-tankstations.html

Wang, S., Tao, F., Shi, Y., & Wen, H. (2017). Optimization of vehicle routing problem with time windows for cold chain logistics based on carbon tax. *Sustainability*, *9*(5), 694.

Wang, X., Liang, Y., Tang, X., & Jiang, X. (2023). A multi-compartment electric vehicle routing problem with time windows and temperature and humidity settings for perishable product delivery. *Expert Systems with Applications*, *233*, 120974. https://doi.org/https://doi.org/10.1016/j.eswa.2023.120974

A

Scientific paper

LNG Inventory Routing Problem with Pressure Management

Flip Boekhorst (Delft University of Technology, Delft, Netherlands)

Keywords: IRP, Pressure Management, LNG, Rolling Horizon Approach

The distribution of LNG and Bio-LNG presents a complex challenge due to pressure management at the refuelling stations. This research introduces an Inventory Routing Problem with pressure management to optimize LNG and Bio-LNG distribution by minimizing transportation and nitrogen cooling costs. Using a Mixed-Integer Linear Programming (MILP) formulation integrated with a rolling horizon approach, the model integrates routing, inventory and pressure decisions. The model was tested on a real-world network of LNG and Bio-LNG refuelling stations in the Netherlands and Belgium. Results show that the model can maintain the inventory and pressure levels within the specified bounds while minimizing the total costs for a seven-day planning horizon of a network nineteen refuelling stations. A sensitivity analysis revealed the vehicle capacity as the most critical factor influencing the total costs and feasibility. These finding reveal the potential to optimize cryogenic logistics while maintain the inventory and pressure levels. Future research can refine the offload cooling parameters to improve the model's realism.

1 Introduction

This research introduces a new variant of the Inventory Routing Problem (IRP) that optimises the distribution of liquefied natural gas (LNG) and liquefied biogas (Bio-LNG) to a network of refuelling stations over a multi-period planning horizon with specific consideration for cryogenic temperature management. LNG and Bio-LNG can be mixed at the cryogenic storage tanks of refuelling stations. These storage tanks are designed to keep liquid gases at extremely low temperatures, around -162 °C, so that they remain in liquid form and reduce in volume (Thomas & Dawe, 2003). Furthermore, the cryogenic temperature of the mixture is managed by on-site nitrogen cooling and vehicles that may do offload cooling and logistic trailer cooling. The vehicles are heterogeneous and are equipped with flow meters, allowing each vehicle to distribute the trailer's volume across multiple refuelling stations. At the refuelling stations, the inventory must be maintained between the safety stock level and the station's maximum capacity. Moreover, the cryogenic temperature is controlled between the minimum pressure level and the maximum pressure level. If the maximum pressure level is exceeded, the refuelling stations' safety protocol will be activated, potentially resulting in a station shutdown. The objective is to optimize vehicle routing by considering the transportation costs and nitrogen cooling costs. The transportation costs consist of road toll costs, fuel costs and driver labor costs. An overview of the problem is shown in Figure 1.

In this research, the supplier has access to the refuelling stations' inventory levels and pressure levels, also known as the Vendor Managed Inventory (VMI) concept (Kleywegt et al., 2004). For each time step the supplier has to determine:

- Routing decisions of the vehicles
- Offload quantity depending on the station's inventory and pressure levels
- For each station if a vehicle needs to do logistics trailer cooling
- For each station when to activate the nitrogen cooling
- When the vehicle starts and returns to the home base

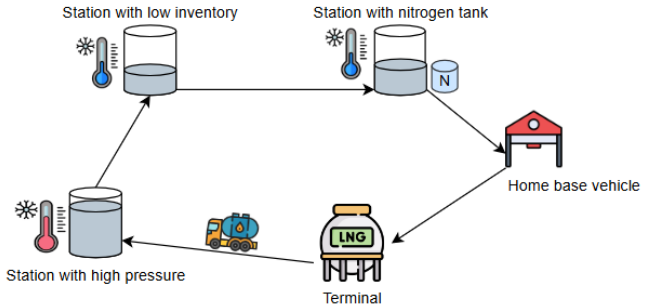


Figure 1: A schematic overview of integrated control in cryogenic logistics of LNG, with stations with nitrogen tanks, high pressure or low inventory, together with a terminal, a home base and vehicle routes.

The supplier integrates the routing, inventory and pressure management decisions at the downstream phase of the supply chain, i.e. from the terminal to refuelling stations (Hsu & Robinson, 2019). Furthermore, this research focuses on the operational level (Maknoon, 2024). Operational decisions relate to the day-to-day management based on current data and situations.

The problem is formulated with the help of a Mixed Integer Linear Programming model. Due to the computational complexity of the model, a rolling horizon approach is applied to find an exact solution for the Multi-period IRP with Cryogenic Temperature Management. The developed planning method was tested on a network of refuelling stations in the Netherlands and Belgium

This research is structured as follows. Section 2 gives an overview of the relevant literature and culminates into the research gap, Table 6. Section 3 presents the mathematical MILP formulation with the rolling horizon approach. Section 4 presents the results of the case study. Section 5 answers the research question and proposes recommendations for future research.

2 Literature

Liquefied natural gas (LNG) is the liquid form of natural gas and is a mixture of mainly methane with some residual gases of nitrogen, propane and ethane. This gas is cooled to temperatures to minus 162 degrees Celsius at which point it transforms into its liquid state. The volume subsequently reduced by a factor of 600 resulting in a more efficient and economically viable storage and transportation (Thomas & Dawe, 2003). The transport of LNG is temperature controlled and since it is minus 150 degrees Celsius it is called cryogenic. Besides LNG, Bio liquefied natural gas (Bio-LNG), also known liquefied biomethane (LBM) or liquefied biogas (LBG), is handled under the same cryogenic conditions as traditional LNG. Bio-LNG is biogas that has been upgraded and then liquefied, consisting of almost 100% methane. In this research biogas is always reffered to as Bio-LNG, since it shows the most obvious difference compared to LNG.

There are three types of refrigerated vehicles in temperature controlled transport the mechanical refrigeration, the cold storage plate cooling and the liquefied gas refrigeration (S. Wang et al., 2017). LNG and Bio-LNG are both cooled with liquefied gas refrigeration with liquid nitrogen. Liquid nitrogen adsorbs heat from the cargo, effectively cooling it down. This type of refrigeration method is the most rapid among the three methods because of the high latent heat of vaporization, meaning it adsorbs a significant amount of heat as it evaporates into a gas (Chart Industries, 2016). More information about the refrigeration methods will discussed later on the literature study.

2.1 LNG replenishment

The vehicle routing problem (VRP) was first addressed by Dantzig and Ramser (1959) in their paper titled "The Truck Dispatching Problem", which focused on the optimal routing of a fleet of gasoline delivery trucks between a terminal and service stations. Approximately 25 years later, the first integration between inventory management with vehicle routing and scheduling was established with the introduction of the vehicle routing problem (IRP) by Bell et al. (1983). Their work discussed the a computer-based routing and scheduling optimizer for the distribution of industrial gases.

The literature review by Coelho et al. (2014) revealed that the recent advancements in the IRP literature are on extensions of the basic IRP model and on the nature of the problem. These extensions consist of the production-routing problem, the IRP with multiple products, the IRP with direct deliveries and transshipment and the consistent IRP. Furthermore, the focus on a more deterministic nature of the problem shifted to a more stochastic environment.

Review carried out by Alves et al. (2018) indicated that weak restrictions on time windows can be promising and that there is no benchmark for the IRP with timewindow. Most researchers use severe restrictions on time windows, however, in real situations weak restrictions on time windows can also be applicable. For instance, due to the lack of drivers, traffic times and car accidents. Furthermore, because there is no benchmark, it is difficult to compare the different IRP with time windows models, because every researcher changes the test conditions and no of them provides the code of the experiment.

A recent review highlighted that the three important cost elements in the cold chain logistic vehicle routing problem are transportation, quality and environment costs (Awad et al., 2021). However, in research, there is a lack of sensitivity analyses showing each cost element's contribution to the total costs.

The reviews by Christiansen et al. (2013) and Coelho et al. (2014) indicated that a considerable amount of research has been published on transporting LNG in the maritime sector (Andersson et al., 2016; Cho et al., 2018; Fodstad et al., 2010; Grønhaug et al., 2010; Uggen et al., 2013). However, to the best of the author's knowledge, research by Ghiami et al. (2019) is the first on inland LNG inventory routing optimization. This research focused on the deteriorating inventory routing of LNG with trucks and barges over a multi-period planning horizon. Deterioration is the constant evaporation and loss of the on-hand inventory. For this research deterioration is out of context because the evaporation, boil-off gas (BOG), of LNG results in large greenhouse gas emissions and is not allowed in the inland transport of LNG in Europe. Instead of evaporating the heat out of the trailer, this research focuses on refrigeration methods to lower the pressure in the tank at the refuelling stations or in the trailer of the vehicles.

2.2 Refrigeration methods

As previously described in the context of LNG handling, LNG is cooled with the refrigeration of nitrogen, but logistic trailer cooling is also an option. This research examines three methods of nitrogen cooling. To provide a foundation for these methods, a few thermodynamic principles need to be clarified. The energy level in a liquid phase is much lower than that in a vapor phase. Thermodynamic equilibrium is the state in which two objects connected by a permeable barrier do not have any heat transfer between them. Evaporation is the transition from the liquid phase to the vapor phase, while condensation is the transition from the vapor phase to the liquid phase. A cryogenic fluid is rarely at thermodynamic equilibrium, because heat leaks into the system via contact points. Stratification is the uneven distribution of heat in the system. In the case of an LNG tank, the top of the tank usually boils, this is a process where the liquid state changes to a gaseous state (Chart Industries, 2016).

This research includes three refrigeration methods: nitrogen cooling, offload cooling and logistic trailer cooling.

1. **Nitrogen cooling** is a widely used method that leverages liquified nitrogen (LIN) for cooling. This method includes two approaches: *direct surface cooling* and *secondary circuit cooling*. Both approaches require a nitrogen tank on-site and have a different cooling efficiency. The cooling efficiency is also depended on the tank insulation, horizontal or vertical tank positioning and the initial LNG temperature.
    - *Direct surface cooling*: In this approach, LIN is circulated through a coil inside the refuelling station's tank. The warm vapor at the top of the tank comes into contact with the cold coil and condenses. The

condensed LNG returns to the liquid phase and falls back into the tank. During this process, the LIN evaporates as it travels through the coil and is afterwards released into the atmosphere. This process is illustrated in Figure 2.

- *Secondary circuit LIN cooling*: Here, the cooling occurs outside of the tank. LNG is pumped out of the tank into a temperature regulator where it is cooled using liquid nitrogen. Afterwards, the cooled LNG is pumped back into the top of the tank and the evaporated LIN is released through the vent. This LNG top filling approach accelerates the condensation of vaporized LNG and restores the equilibrium more quickly. Figure 3 illustrates this approach.

2. **Offload cooling** occurs during the delivery of cold LNG from a terminal to a refuelling station. As the cold LNG is offloaded into the station's relatively warmer tank, it cools the existing LNG, thereby reducing the overall temperature and pressure within the tank. This process is depicted in Figure 4. The temperature within the vehicle's trailer and the offload quantity have a significant effect on the offload cooling. In principle, Bio-LNG is warmer gas than grey LNG. For that reason the offload cool effect of Bio-LNG is less. In short, offload cooling is depended on a vehicle and is a practical way of managing the tank's pressure without requiring a nitrogen tank.
3. **Logistic trailer cooling** is a specialized method that relies on a vehicle trailer designed to withstand pressure of 5 to 7 bar. This method involves transferring vaporized LNG from the top of the tank into the vehicle's trailer. This transfer reduces the pressure in the refuelling station's tank while increasing the pressure in the trailer. A minimum of 8 tonnes of LNG is usually required in the vehicle's trailer for this method to work. The disadvantage of this method is that the delivery at the next station is with warmer gas so your offload cool effect is less. The process is illustrated in Figure 5. Although this method does not require an on-site nitrogen tank, it does depend on a specialised vehicle trailer and a driver that is familiar with the logistic cooling process.

In summary, while all three methods aim to cool LNG, they vary in their efficiency. Semi-indirect cooling is the most efficient method out of the three and logistic trailer cooling seems to be the least efficient. This analysis provides a foundation for selecting the most appropriate refrigeration method based on the operational requirements and will be a decision to be made during the distribution of LNG across the network of refuelling stations.

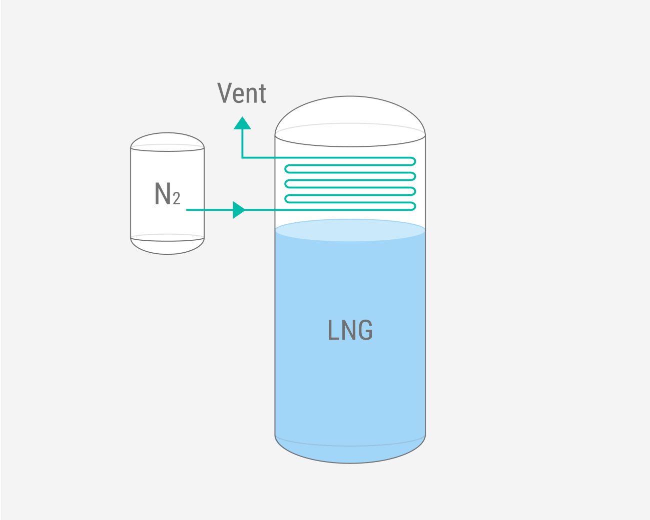


Figure 2: Direct surface cooling (semi-indirect refrigeration). Liquefied nitrogen (LIN) is circulated through the coil inside the tank and cools down the mixture in the tank. Afterwards, the nitrogen vents into the atmosphere.

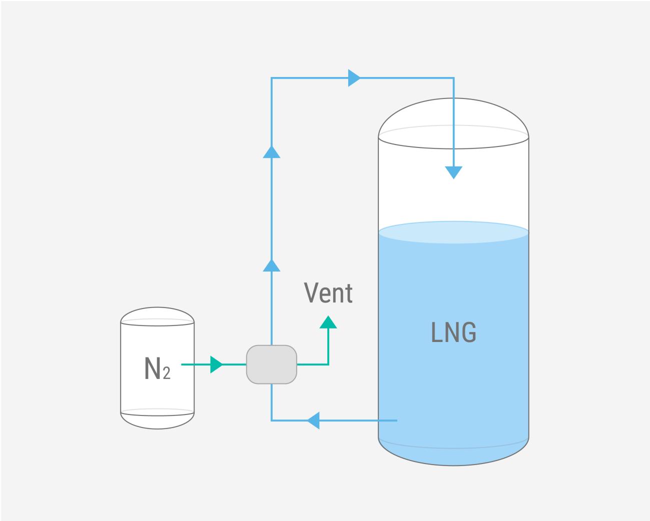


Figure 3: Secondary circuit cooling (indirect refrigeration). LNG is pumped out of the tank into a temperature regulator where it is cooled with liquid nitrogen. Thereafter, the nitrogen evaporates through the vent and the LNG is pumped back into the tank.

2.3 Problem characteristics

2.3.1 Inventory Routing

Integrating inventory management and routing in modelling considers the interaction between the two decision areas, ensuring that transport costs are minimised and inventory remains within safety levels (Aghezzaf et al., 2006; Coelho & Laporte, 2013). When inventory management and routing decisions are considered in the problem, it can be classified as an Inventory Routing Problem (IRP). These problems may consider that vendors monitor the inventory of the customers and that the vendors make the decisions about when and what delivery quantity should be delivered to each customer. This concept is called Vendor Managed Inventory (VMI) (Kley-

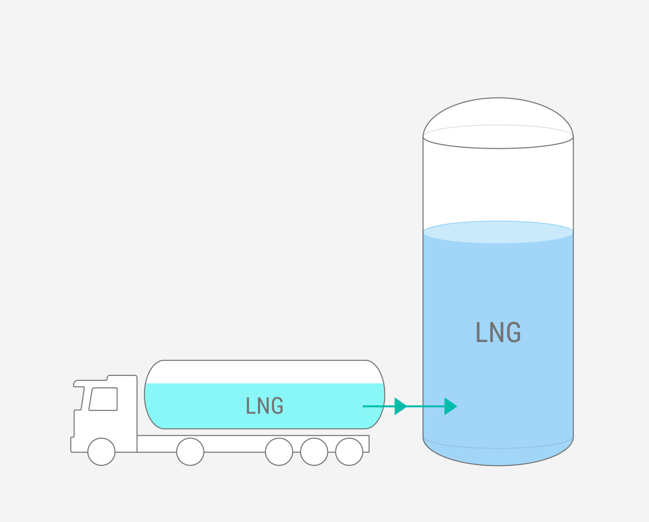


Figure 4: Offload cooling. Cooling is done by mixing the cold LNG from the terminal via a vehicle with the warmer mixture in the tank at the filling station. This cooling happens regularly, at every offload.

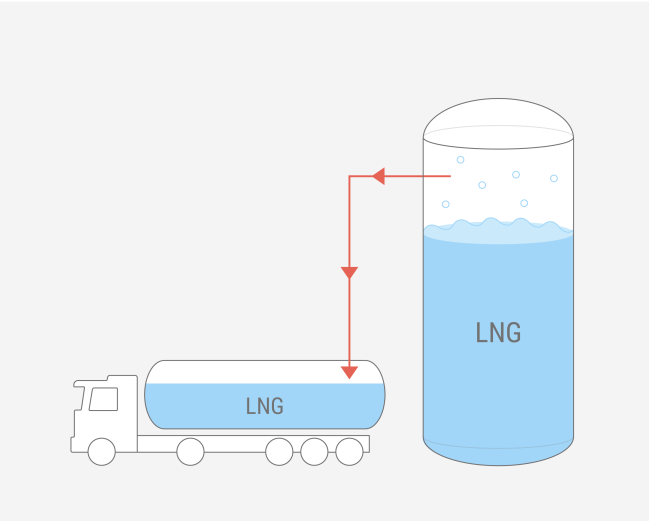


Figure 5: Logistic trailer cooling. This cooling method requires a specialized vehicle that can withstand pressures of 5 to 7 bar. The warm gas from tank is transferred into trailer of the vehicle and is dropped at the next station.

wegt et al., 2004).

Several studies implemented the IRP in the context of replenishing refuelling stations, each with distinct objectives. Surjandari et al. (2011) and Boers et al. (2020) focused on minimising the transportation costs. Ghiami et al. (2019) extended this by also considering holding costs in their objective function. Cornillier et al. (2008) aimed to maximize profit, defined as the revenue from the product minus the routing, regular transport time and overtime costs. Grønhaug et al. (2010) used a path flow approach to maximize the profit, considering the revenue from the product minus the transport costs and the production costs. Cho et al. (2018) also sought to maximize the profit, accounting for the revenue from the product minus routing, production, inventory holding, weather uncertainties costs and delayed delivery costs.

2.3.2 Time constraints

The Vehicle Routing Problem with Time Windows (VRPTW) is a relevant concept in optimising the replenishment of refuelling stations, which can include soft or strong restrictions on time windows (Alves et al., 2018). Cornillier et al. (2012) used a model with strong time window constraints, where the delivery truck must arrive and depart within specified intervals, and consider the driver's regular and overtime working hours. Surjandari et al. (2011) addressed the Petrol Delivery Assignment problem by utilising a tabu search algorithm to handle multi-product, multi-depot, and split deliveries with time window constraints applied exclusively at the refuelling stations. On the other hand, S. Wang et al. (2017) analysed cold chain logistics in China using a model with soft time window restrictions, incorporating penalty costs for deviations. More recently, X. Wang et al. (2023) proposed a mathematical model featuring strong time window constraints but permitted unfeasible solutions with the help of a hybrid adaptive large neighbourhood search and tabu search heuristic, leveraging penalties to manage these infeasible solutions.

2.3.3 Multi-period time horizon

(Cornillier et al., 2008) introduced the Multi-Period Petrol Station Replenishment Problem (MP-PSRP). This problem decides for each day in the time horizon what the delivery quantity at each station is, and what routes the delivery vehicles you should take. Research (Moin & Salhi, 2007) on the planning horizon of inventory routing problem shows that multi-period models are more realistic in the trade-offs between the strategic and operational decisions. However, they require more computational power in comparison with a single period time horizon. For that reason, most multi-period models are considered with a deterministic demand. The second advantage of a multi-period approach is that it can better anticipate the inventory levels at the refuelling stations by taking into account future needs and delivery schedules.

2.3.4 Cooling

The transport and storage of LNG is complex due to its cryogenic nature, which requires constant cooling both during transport and while stored in the refuelling station tanks. Previous studies (Cho et al., 2018; Ghiami et al., 2019; Grønhaug et al., 2010) have examined the transportation of the cryogenic product LNG, but their mathematical models use deterioration to deal with the increasing pressure in the trailer or the refuelling station's tank.

X. Wang et al. (2023) studied a VRP with a different temperature setting in each compartment of the vehicle, but it does not look into the decision on storage temperature. The temperature settings are controlled with penalty costs. Ahmadi-Javid et al. (2023), on the other hand, reveals in their literature review that they are the first that integrate routing and temperature control at the warehouse simultaneously. However, they assume that truck temperature costs are fixed per kilometre and warehouse cooling costs are also fixed per time unit for a certain temperature level. They do not make a decision if they have to cool a station with for instance logistic trailer cooling or not.

Remarkably, there is a gap in the literature regarding the incorporation of logistic trailer cooling within the constraints of a model. Introducing refrigeration as a problem characteristic is new and adds complexity, as not only does the demand from the refuelling stations have to be met, but also pressure levels have to be managed during both transport and storage at the refuelling stations.

2.4 Previous case studies

Boers et al. (2020) could not find a feasible solution within two hours computational time for a sample case of 20 gas station in a 7 day time period with mixed integer linear programming. However, the heuristic algorithm for a petrol distributor in Denmark with one depot, 59 gas stations and 4 vehicles did found a feasible solution that showed a reduction of around 12% travel distance and around 26% average number of stops per trip.

Ghiami et al. (2019) came up with a mathematical model for LNG deteriorating inventory routing that provided the initial solution and this solution is then applied in an adaptive large neighborhood search algorithm to come up with a more efficient solution. Their proposed algorithm performed feasible with up to 100 filling stations and 14 time periods based on actual geographical distances between random selected cities in the Netherlands.

Cho et al. (2018) experimented a two stage stochastic model for LNG carriers on historical data of the Persian Gulf. The first stage involved making decision on inventory and routing before the weather disruptions and the second stage after the occurrence of the disruptions. In the end, the model maximizes the profit taking into account the qualitative and quantitative importance of each term in the objective.

X. Wang et al. (2023) did a case study in China that involved optimizing the delivery of 30 types of perishable products from a depot to 53 stores with electric vehicles taking into account the temperature and humidity requirements of the products and charging of the batteries of the electric vehicles. The new mathematical model used a hybrid Adaptive large neighbourhood search and tabu search heuristic to minimize the travel costs.

Ahmadi-Javid et al. (2023) analysed a bi-objective case study with the objectives of minimising distribution costs and minimising energy costs for perishable products. The proposed mixed integer linear programming model was capable of optimizing to a maximum of 50 customers and 80% of the instances were solved in less than 10 minutes.

Research carried out by Surjandari et al. (2011) solved the multi-product, multi-depot, split deliveries and time windows problem for an Oil and Gas company in Indonesia. This study used the tabu search algorithm to minimize the travel costs.

2.5 Research gap

This research addresses the knowledge gap concerning LNG and Bio-LNG transportation and storage, where maintaining a temperature as low as minus 150 degrees Celcius is important. In these cryogenic conditions, any rise in temperature increases pressure within the storage tank at refuelling stations. Despite the growing importance of these fuels, existing literature lacks optimisation studies that handle Inventory-Routing Problems specific to LNG or Bio-LNG, considering the complexities of temperature control during transport and storage on land. The studies (Cho et al., 2018; Ghiami et al., 2019; Grønhaug et al., 2010) take boil-off gas into account, which makes it easier to maintain the temperature at the right level. As shown before, there are three methods for cooling the tank at the refuelling station: semi-indirect cooling, indirect cooling and logistic trailer cooling. Since not every LNG refuelling station consists of a cooling instrument at the refuelling station, logistic trailer cooling becomes important. For modelling this makes it complex due to the fact that you have to make decisions when to send a vehicle to the refuelling station to cool the tank while also taking into account the storage levels and minimising the transportation and cooling costs. Table 6 gives a comparison based on the problem characteristics between the existing literature and this research.

3 Methodology

Set of nodes consists of home bases (N_h), terminals (N_t) and stations (N_s). The indices $i, j \in N$ refer to an arc in the network. The set of horizon time steps is T_h, where t is an element of T_h. The set of rolling time steps is T_r, where t is an element of T_r. The set of vehicles is K, where k is an element of K. The set of terminal time slots is S, where s is an element of S.

c_{km} is the cost per kilometre, c_{hours} is the costs per hours, c_{ij}^{toll} is road toll costs of arc i, j. The travel distance of arc i, j is indicated by td_{ij} and the travel time presented by tt_{ij}. The terminal time slot parameters are the terminal location and the pickup slot start time. The minimum offload quantity is oq_{min}

The station parameters are the initial inventory level of that day I_{i0}. The minimum and maximum inventory level I_i^{min} and I_i^{max}. The initial pressure level of that day P_{i0}. The minimum and maximum pressure level bound P_i^{min} and P_i^{max}. The pressure increase due to heatleaks PH_i. If a liquid nitrogen LIN) refrigeration tank is available on-site LIN_i. If the logistic trailer cooling is an option to reduce the pressure V_i and nitrogen cooling costs per bar $c_{i,nitrogen}$. The demand is represented by D_{it}.

The vehicle parameters are the maximum capacity Q_k^{max}, the maximum logistic pressure cooling V_k^{max}. The designated terminal θ_k. The home base of the vehicle h_k. The offload cooling parameter oc_k.

The arc routing variable is x_{ijt}^k and is 1 if vehicle k travels on arc ij on time step t. The node visit variable is shown by z_{it}^k. L_{it}^k determines if vehicle k loads at terminal i in time step

Figure 6: Research gap, with time horizon (TH), single period (S), multi-period (M), multi-product (MP), vehicle use (VU), single trip (ST), multi-trip (MT), vehicle fleet (VF), homogeneous (HO), heterogeneous (HE), split load (SL), time constraints (TC), time step (TS), temperature control (Temp.)

Paper	Product	IRP	TH	MP	VU	VF	SL	TC	TS	Depot	Case	Temp.
(Cornillier et al., 2008)	Petrol	✓	M	✓	MT	HE		✓	Day	Single	Random Generated Data	
(Grønhaug et al., 2010)	LNG (sea)	✓	M		MT	HE		✓	Day	Multi	International	
(Surjandari et al., 2011)	Petrol	✓	S	✓	MT	HE		✓	Day	Two	Indonesia	
(Cornillier et al., 2012)	Petrol		S		MT	HE		✓	Hour	Multi	Random Generated Data	
(Cho et al., 2018)	LNG (sea)	✓	M		MT	HE	✓	✓	Day	Multi	Qatar	
(Ghiami et al., 2019)	LNG	✓	M		MT	HE	✓	✓	Day	Two	Netherlands	✓
(Al-Hinai & Triki, 2020)	Petrol		M	✓	ST	HE			Day	Single	Oman	
(Boers et al., 2020)	Petrol	✓	M	✓	MT	HE	✓	✓	Day	Single	Denmark	
(X. Wang et al., 2023)	Perishable		M	✓	MT	HO		✓	Day	Single	China	✓
(Ahmadi-Javid et al., 2023)	Perishable		M		MT	HO		✓	Hour	Multi	International	✓
This research	**(Bio)-LNG**	✓	**M**	✓	**MT**	**HE**	✓	✓	**Hour**	**Multi**	**Netherlands**	✓

t. The variable e_{it}^{k} determines if vehicle k is empty at node i in time step t. The logistic cooling of vehicle k at station i in time step t is determined by v_{it}^{k}. O_{it}^{k} determines if vehicle k is offloading at station i in time step t. The offload quantity is presented by oq_{it}^{k}. The station's inventory level is monitored by $I_i t$. The station's pressure level is tracked by the P_{it}. n_{it} determines the nitrogen cooling at station i in time step t. The inventory of vehicle k in time step t is determined by $Q_k t$. Finally, the logistic cooling pressure capacity is determined by LC_{kt}.

3.1 MILP formulation

Equation 1 refers to the objective function and consists of three terms: fuel costs, driver labor costs, road toll costs and nitrogen cooling costs. The distance costs are calculated by the travel distance of all the used arcs multiplied by the costs per kilometre. The driver labor costs are calculated by the travel time of all the used arcs multiplied by the costs per hour of the transporter. The nitrogen cooling costs are calculated by the hours of active nitrogen cooling multiplied by the estimated costs per hour for consuming the nitrogen.

Equation 2-5 represent the routing constraints of the vehicle during the rolling time steps. Equation 6 is the flow balance constraint. Equation 7 ensures that the vehicle starts and ends at its home base. Furthermore, Equation 8 states that a vehicle can only be at one place at the same time. Equation 9 - 12 indicate the tracking of the station's inventory level. Where the demand continues after the rolling time steps till the horizon time steps. Furthermore, the station's inventory levels are bounded by the minimum and maximum inventory level. Equation 13 and 14 indicate the offload of the vehicle.

The vehicle's inventory level is tracked by Equation 15 - 17. Equation 18 - 19 represent the loading of the vehicle k and determines that a vehicle must pick up load if a terminal slot is present. Equation 20 - 23 formulate the station's pressure levels and the specific minimum and maximum bound. The pressure level can increase due to the heat leaks and decreases by nitrogen cooling, offload cooling and logistic trailer cooling. Equation 24 and 25 present he nitrogen cooling if a LIN refrigeration tank is available at station i. The logistic cooling pressure capacity is outlined by equation 27 - 28. Each time the vehicle loads at a terminal the logistic cooling pressure capacity resets.

Equation 29 - 32 ensure that a vehicle can only logistic cool or offload if it is a the station and a vehicle must always do one of the two or both if it visits a station. Furthermore, it the vehicle restricted to logistic cool at the final station before driving to the home base or the terminal. Equation 33 assigns a vehicle to its designated terminal. Equation 34 - 36 determine when a vehicle is empty that it can only drive to its home base or to its terminal when it is empty. Finally, the variables are described in Equation 37 - 44.

$$\text{Min} \quad \sum_{t\in T_r}\sum_{k\in K}\sum_{ij\in N} x^k_{ijt} td_{ij} c_{km} + \sum_{t\in T_r}\sum_{k\in K}\sum_{ij\in N} x^k_{ijt} c^{toll}_{ij} + \sum_{t\in T_r}\sum_{k\in K}\sum_{ij\in N} x^k_{ijt} tt_{ij} c_{hours} + \sum_{t\in T_r}\sum_{i\in N_s} n_{it} c_{nitrogen} \quad (1)$$

S.t.

$$z^k_{it} \geq x^k_{ijt} \quad \forall k \in K, \forall i,j \in N, i \neq j, \forall t \in T_r \quad (2)$$

$$z^k_{j,t+tt_{ij}} \geq x^k_{ijt} \quad \forall k \in K, \forall i,j \in N,\ i \neq j,\ t \in T_r \quad (3)$$

$$z^k_{jt} = z^k_{j,t-1} - \sum_{i\in N} x^k_{ji,t-1} + \sum_{\substack{i\in N\\ t-tt_{ij}\geq 0}} x^k_{ij,t-tt_{ij}} \quad \forall k \in K, \forall j \in N, i \neq j, \forall t \in T_r \setminus \{0\} \quad (4)$$

$$z^k_{it} + z^k_{i,t-1} \leq 1 \quad \forall k \in K, \forall i \in N \setminus N_h, \forall t \in T_r \setminus \{0\} \quad (5)$$

$$\sum_{i\in N}\sum_{t\in T_r} x^k_{ijt} = \sum_{i\in N}\sum_{t\in T_r} x^k_{jit} \quad \forall k \in K, \forall j \in N, i \neq j \quad (6)$$

$$z^k_{h_k,t} = 1 \quad \forall k \in K, t \in \{0, T_r\} \quad (7)$$

$$\sum_{i\in N} z^k_{it} \leq 1 \quad \forall t \in T_r, \forall k \in K \quad (8)$$

$$I_{it} = I_{i,t-1} + \sum_{k\in K} oq^k_{it} - D_{it} \quad \forall i \in N_s, \forall t \in T_r \setminus \{0\} \quad (9)$$

$$I_{it} = I_{i,t-1} - D_{it} \quad \forall i \in N_s, \forall t \in [T_r, T_h] \quad (10)$$

$$I^{\min}_i \leq I_{it} \leq I^{\max}_i \quad \forall i \in N_s, \forall t \in T_h \quad (11)$$

$$I_{it} = I^{\text{initial}}_i \quad \forall i \in N_s, t = 0 \quad (12)$$

$$\sum_{i\in N_s} oq^k_{it} \geq oq_{\min} \cdot \sum_{i\in N_s} O^k_{it} \quad \forall k \in K, t \in T_r \quad (13)$$

$$oq^k_{it} \leq M \cdot O^k_{it} \quad \forall k \in K, \forall i \in N_s, \forall t \in T_r \quad (14)$$

$$Q_{kt} = Q_{k,t-1} + \sum_{i\in N_t} L^k_{it} Q^{\max}_k - \sum_{i\in N_s} oq^k_{it} \quad \forall k \in K, \forall t \in T_r \setminus \{0\} \quad (15)$$

$$Q_{kt} = 0.0 \quad \forall k \in K, t \in \{0, T_r\} \quad (16)$$

$$Q_{kt} \leq Q^{\max}_k \quad \forall k \in K, \forall t \in T_r \quad (17)$$

$$L^k_{it} \leq z^k_{it} \quad \forall k \in K, \forall i \in N_t, \forall t \in T_r \quad (18)$$

$$\sum_{k\in K} L^k_{it} = S_{it} \quad \forall i \in N_t, \forall t \in T_r \quad (19)$$

$$P_{it} = P_{i,t-1} + \text{PHL} - n_{it} - \sum_{k\in K} oc_k oq^k_{it} + \sum_{k\in K} v^k_{it} \cdot \frac{V^{\max}_k}{2} \quad \forall i \in N_s, \forall t \in T_r \setminus \{0\} \quad (20)$$

$$P_{it} = P_{i,t-1} + \text{PHL} \quad \forall i \in N_s, \forall t \in [T_r, T_h] \quad (21)$$

$$P^{\min}_i \leq P_{it} \leq P^{\max}_i \quad \forall i \in N_s, \forall t \in T_h \quad (22)$$

$$P_{it} = P^{\text{initial}}_i \quad \forall i \in N_s, t = 0 \quad (23)$$

$$n_{it} \leq M \cdot LIN_i \quad \forall i \in N_s, \forall t \in T_h \quad (24)$$

$$n_{it} \leq \text{PHL} \quad \forall i \in N_s, \forall t \in T_h \quad (25)$$

$$(26)$$

$$LC_{kt} = LC_{k,t-1} - \sum_{i\in N_s} v^k_{it} \cdot \frac{V^{\max}_k}{2} + \sum_{i\in N_t} L^k_{it} V^{max}_k \quad \forall k \in K, \forall t \in T_r \quad (27)$$

$$LC_{kt} \leq V^{max}_k \quad \forall k \in K, \forall t \in T_r \quad (28)$$

$$O^k_{it} \leq z^k_{it} \quad \forall k \in K, \forall t \in T_r, \forall i \in N_s \quad (29)$$

$$v^k_{it} \leq z^k_{it} \quad \forall k \in K, \forall t \in T_r, \forall i \in N_s \quad (30)$$

$$O^k_{it} + v^k_{it} \geq z^k_{it} \quad \forall k \in K, \forall t \in T_r, \forall i \in N_s \quad (31)$$

$$v^k_{it} \leq 1 - x^k_{ijt} \quad \forall k \in K, \forall t \in T_r, \forall i \in N_s, \forall j \in N_s, N_h \quad (32)$$

$$z^k_{it} \leq \theta_{ik} \quad \forall t \in T_r, i \in N_t, k \in K \quad (33)$$

$$Q_{kt} \leq M \cdot (1 - e_{kt}) \quad \forall k \in K, \forall t \in T_r \quad (34)$$

$$x^k_{ijt} \leq e_{kt} \quad \forall k \in K, \forall t \in T_r, \forall i \in N \setminus N_h, j \in N_h \quad (35)$$

$$x^k_{ijt} \leq e_{kt} \quad \forall k \in K, \forall t \in T_r, \forall i \in N_s, j \in N_t \quad (36)$$

$$x^k_{ijt} \in \{0,1\} \quad \forall k \in K, \forall t \in T_r, \forall ij \in N, i \neq j \quad (37)$$

$$z^k_{it} \in \{0,1\} \quad \forall k \in K, \forall t \in T_r, \forall i \in N \quad (38)$$

$$L^k_{it} \in \{0,1\} \quad \forall k \in K, \forall t \in T_r, \forall i \in N_t \quad (39)$$

$$e_{kt} \in \{0,1\} \quad \forall k \in K, \forall t \in T_r \quad (40)$$

$$O^k_{it}, v^k_{it} \in \{0,1\} \quad \forall k \in K, \forall t \in T_r, \forall i \in N_s \quad (41)$$

$$oq^k_{it} \geq 0 \quad \forall k \in K, \forall t \in T_r, \forall i \in N_s \quad (42)$$

$$I_{it}, P_{it}, n_{it} \geq 0 \quad \forall t \in T_h, \forall i \in N_s \quad (43)$$

$$Q_{kt}, LC_{kt} \geq 0 \quad \forall t \in T_r, \forall k \in K \quad (44)$$

3.2 Pre-solve: determine critical stations

In the pre-solve the inventory and pressure levels for each station are calculated with the aim of determining the time step at which the inventory of a refuelling station is below the minimum inventory/ dry stock or when the pressure of a refuelling station is above the maximum pressure/ critical.

The inventory level of refuelling station i in time step t is $I_{i,t}$. The inventory level of the previous time step is $I_{i,t-1}$ and the demand of each refuelling station i in time step t is $D_{i,t}$.

$$I_{i,t} = I_{i,t-1} - D_{i,t} \quad (45)$$

The pressure level of refuelling station i in time step t is $P_{i,t}$. The pressure level of the previous time step is $P_{i,t-1}$ and the parameter PHL is the pressure increase due to heat leaks.

$$P_{i,t} = P_{i,t-1} + PHL \quad (46)$$

As a result of the pre-solve, critical stations are identified and for all stations that must not be visited the following constraint holds:

$$\sum_{t\in T_r}\sum_{k\in K} z^k_{i,t} = 0 \quad (47)$$

3.3 Multi-period planning

In the previously discussed MILP model, the IRP problem was solved with a day-to-day planning. This involved optimising inventory levels, pressure levels and deliveries separately for each period. However, in practice, this approach lacks foresight due to the risks of dry stock and/ or critical pressure of refuelling stations the next period. Resulting, in infeasible solutions the next period because the vehicles could not arrive at the refuelling stations in time. In reality, this will result in revenue loss, because you can not sell your product and additional costs are maybe necessary to reduce the pressure at the refuelling station. To deal with this problem, a rolling horizon approach will be introduced in this subsection. This approach offers a more robust and efficient way of multi-period planning, allowing continuous optimisation of inventory and routing decisions based on current and predictive data.

3.3.1 Motivation rolling horizon approach

An important reason for implementing the rolling horizon approach in the IRP model is to prevent dry stock or critical pressures at the start of next periods. In the model daily time period, the risk of dry stock was increased because the model minimises the transportation costs and does not take into account future demand patterns. By applying the rolling horizon approach, decision can be optimised not only for the current day, but also for multiple future periods. This provides a more balanced trade-off between transportation costs and the risk of dry stock and critical pressure.

The motivation for the rolling horizon approach not only has to do with the delivery the next day but also with computational power of the model. When the amount of time steps in the model increases to plan for multiple days in one run, the model increases significantly. The amount of decision variables and constraints grow exponentially with the amount of time steps that are added. Resulting in a model that requires a large computational power to solve in a reasonable time. The rolling horizon approach does not solve the multi period all at once, but cuts the planning period into manageable blocks. In short, the rolling horizon approach does not only provide a more balanced trade off between transportation costs and inventory and pressure management, but it also makes the model more computational reasonable even if the planning period consist of the multiple periods.

3.3.2 Implementation rolling horizon approach

The rolling horizon method cuts the planning horizon into multiple periods. In stead of making decisions for one or two days, the model is solved for a series of consecutive days. This provides a broader context of optimisation making it able to plan for a whole week. In figure 7, the rolling horizon approach, combined with the previous discussed pre-solving method, is illustrated. In order to fully understand this approach, it is important to clarify three key terms: the pre-solve length, the horizon length, and the rolling length.

The pre-solve length refers to the number of time steps considered when determining the critical stations in the network. The horizon length is the time span during which the inventory and pressure levels at refuelling stations must remain within specified bounds. The rolling length represents the time period for which routing decisions are made. Since the rolling length is shorter than the horizon length, the vehicles must deliver sufficient LNG or Bio-LNG to ensure that the refuelling stations have enough supply for the entire horizon length.

For example, consider a planning period of three days: Monday, Tuesday, and Wednesday. In the first iteration, the pre-solver determines the critical stations for Monday and Tuesday. The results of the pre-solver then serve as inputs for the MILP model. The MILP model optimizes routing decisions and inventory/ pressure level management. In the example in figure 7, the horizon length is 36 hours and the rolling length is 24 hours. So, the planning for Monday is decided with foresight of Monday and Tuesday and with an additional buffer of 12 hours on Tuesday. The additional buffer is the difference between the horizon and rolling lengths.

At the end of Monday, the inventory and pressure levels at the refuelling stations are saved and these values serve as inputs for the second iteration, as indicated by the red arrow in the figure 7. The second iteration starts on Tuesday and begins with identifying the critical stations for Tuesday and Wednesday. The MILP uses these critical stations as inputs to determine the routing for Tuesday and ensuring the inventory and pressure levels remain within bounds for the first 12 hours of Wednesday. In the third iterations, the inventory and pressure levels from the end of Tuesday are used as inputs for Wednesday's planning as shown by the red arrow. The pre-solver identifies the critical stations for Wednesday and Thursday, which serve as inputs by the MILP model to determine the routing for Wednesday, with again a buffer extending into the first 12 hours of Thursday. Overall, this approach results in a schedule for Monday, Tuesday and Wednesday, developed using the rolling horizon methodology with a 48-hour look ahead for the solution, a 24-hour rolling length for routing decisions and a 12-hour buffer for the following day, guaranteed by the length of the horizon.

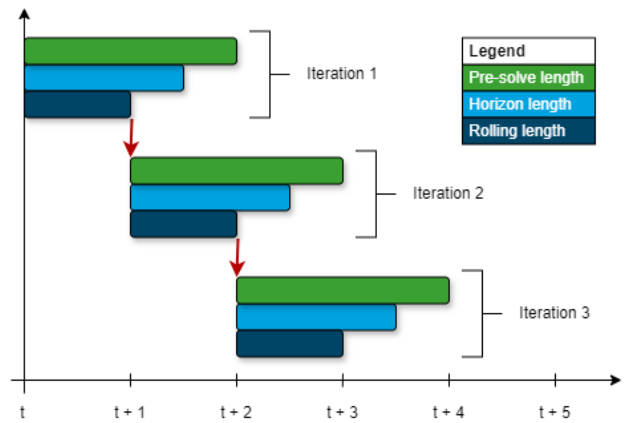


Figure 7: Overview of the rolling horizon approach with a pre-solver. The pre-solve length determines critical stations, the horizon length manages inventory and pressure levels, and the rolling length sets vehicle routing decisions. The red arrow illustrates how results from one iteration (e.g., Monday) go into the next (e.g., Tuesday), indicating the sequential nature of the rolling horizon.

4 Results

4.1 Evaluating the rolling horizon approach vs. the static horizon approach

In this experiment the rolling horizon versus the static horizon approach are tested on their runtime, and the KPIs: total transportation costs (TTC), total nitrogen cooling costs (TNC) and cost per kilogram (CpK).

Table 1 present the results of the experiment. The rolling horizon approach has a shorter runtime in most planning horizons, whereas in the static approach the runtime increases exponentially and even hits the maximum runtime limit, 7200 seconds, without reaching optimality for the planning horizons 5-7 days. For the planning horizon of five and six days the model did find a feasible solution, however, the seven-days planning horizon could not find a solution in the maximum time limit. This shows that rolling horizon approach has computational efficiency advantage over the static approach. Furthermore, the comparison of the total transportation costs show that the rolling horizon approach has lower TTC than the static approach, especially the planning horizon of five and six days where the static approach did not find a optimal solution. On the other hand, the total nitrogen costs are lower with the static approach, TNC is often zero. Additionally, the CkG is around constant for the rolling horizon approach over most planning horizons. However, in the static approach experiments the CkG increases significantly on the planning horizons five and six days, due to the non optimal solutions.

Table 1: Comparison of rolling horizon and static approach

	Rolling approach			Static approach		
Planning (day)	**TTC** (euro)	**TNC** (euro)	**CpK** (euro)	**TTC** (euro)	**TNC** (euro)	**CpK** (euro))
1	795	0	0.05303	795	0	0.05303
2	1495	75	0.04984	1622	0	0.05408
3	2418	120	0.05373	2524	0	0.05610
4	3118	269	0.05196	3521	54	0.05868
5	4073	548	0.05431	5397	0	0.07196
6	4977	821	0.05530	7181	0	0.07979
7	5591	1096	0.05325	-	-	-

The total costs of the rolling and the static approach are shown in Figure 8. It is noticeable that for the rolling horizon approach the TNC has a larger proportion in total costs compared to the static approach. Furthermore, exponential growth of the runtime for the static approach relative to the linear growth of runtime for the rolling approach is presented in Figure 9.

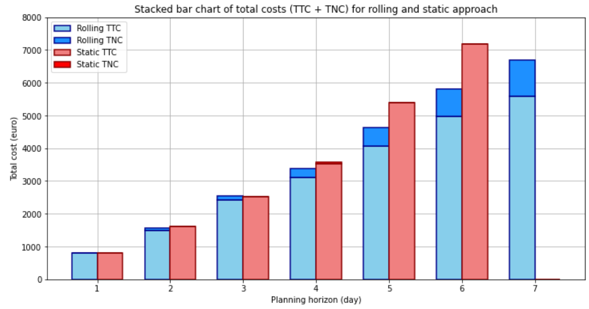


Figure 8: Cost comparison rolling vs. static approach

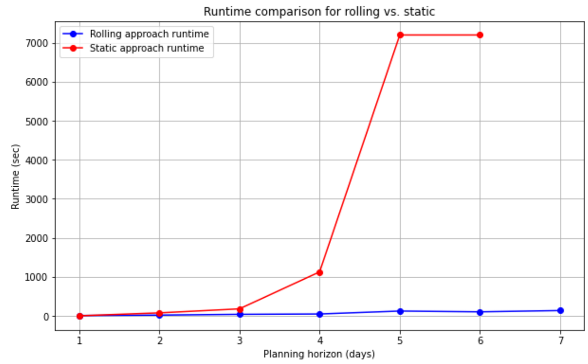


Figure 9: Run time comparison rolling vs static approach

In short, the static and rolling approach are evaluated on the computational time and the total transportation costs, total nitrogen cooling costs, and cost per kilogram. The rolling horizon approach performs significantly stronger for longer planning horizons. However, due to the short horizon foresight the total nitrogen cooling costs have a greater share in the total costs compared to the static approach. Overall, the rolling horizon approach seems to be more computational efficient.

4.2 Rolling horizon in context of nineteen stations

The objective of this experiment is to test the simplified MILP with rolling horizon with the historical data from the company Rolande. The start time of the planning is Monday 9 September 2024 at 04:00. The planning horizon covers a period of seven days.

Figures 10 and 11 present the inventory and pressure levels of the multi period planning of seven days. This proves that the simplified MILP model performs well in real life logistics for a network of nineteen refuelling stations, two terminals and two vehicles. The model succesfully maintains the inventory levels across the refuelling stations within the specified bounds, showing that there are no inventory stock outs and the demand is met. The pressure levels also indicate that the model can deal with the pressure increase due to heat leaks and find solutions with offload cooling, nitrogen cooling and logistic trailer cooling to manage the pressure levels. These results provide proof of the model's ability to solve the multi-period IRP for LNG and Bio-LNG with cryogenic temperature control in practice.

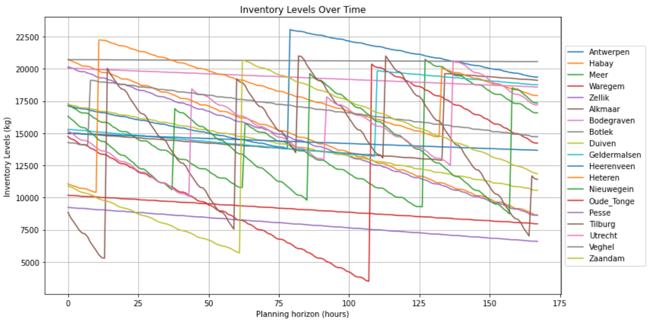


Figure 10: The inventory levels of each station over time. This indicates that the model can produce a feasible solution that keeps the inventory between the specified bounds.

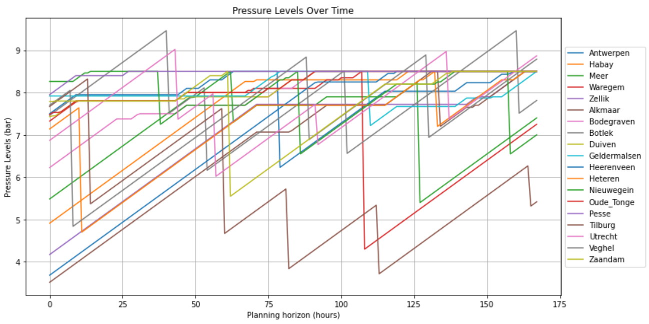
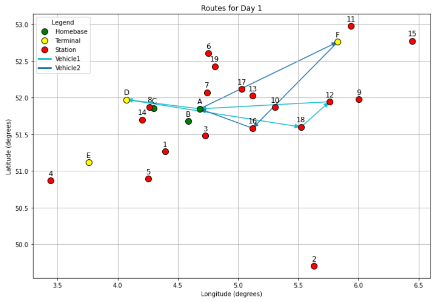


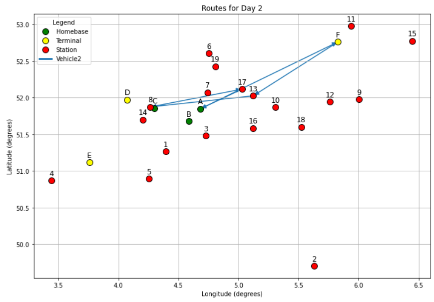
Figure 11: The pressure levels of each station over time. This gives insights that the model is able to solve a seven day planning for Rolande and that it can remain the pressure levels within the specified bounds.

Figure 12 shows a geographical view of the vehicle's route over the seven-day planning period. Each sub figure (Figures 12a - 12g) presents the specific route for each day, pointing out the refuelling station and terminals visited by the vehicles. The map is based on latitude and longitude coordinates of home bases, stations and terminals in Rolande's network.

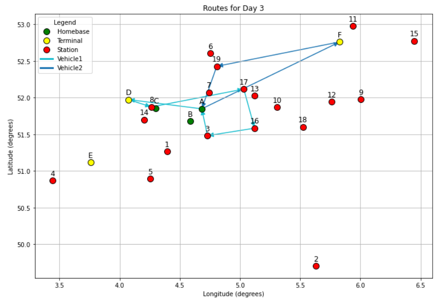
It is noticeable that most routes in the geographical representation are circular in nature, with each route having a closed start and end point at the vehicle's home base. Nevertheless, figure 12d for Day 4's route does have a linear route back and forth. The vehicle travels from Nieuwegein (13) - Veghel (18) - Utrecht (17). However, this linear route can be explained by the logistic cooling in Veghel (18) and the constraint that you cannot do logistic cooling at the final station before travelling back to the home base. Overall, due to the circular nature of the vehicle routes it can be stated that the simplified model including the rolling horizon approach effectively optimizes the travel distance and travel times while taking the constraint into account.



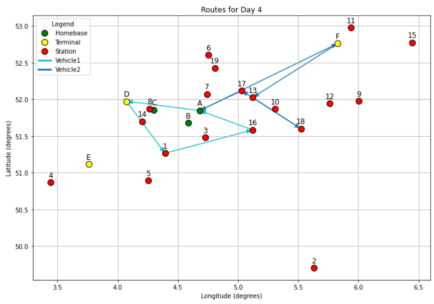
(a) Routes for day 1



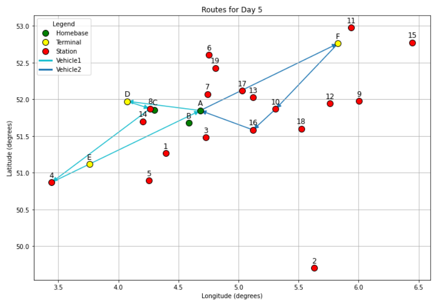
(b) Routes for day 2



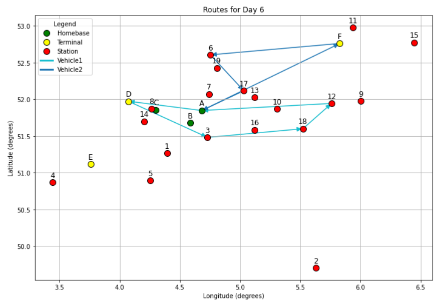
(c) Routes for day 3



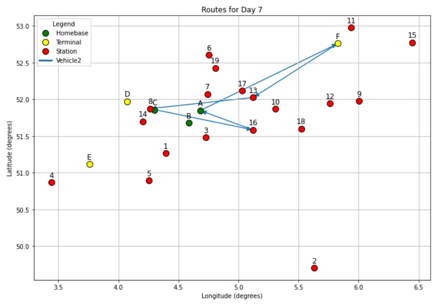
(d) Routes for day 4



(e) Routes for day 5



(f) Routes for day 6



(g) Routes for day 7

Figure 12: Geographical presentation of the routes. It reveals that the vehicles start and end at its home base each day. Furthermore, it shows that a vehicle start its trip by picking up LNG at a terminal and then delivers it to the refuelling stations.

In summary, the simplified MILP model with the rolling horizon approach is tested to solve the planning for Monday 9 September 2024 04:00 till Monday 16 September 2024 04:00. The results proof that the model is able to solve this multi-period IRP for LNG and Bio-LNG with cryogenic temperature control. Furthermore, does the circular nature of the vehicles routes indicate that the model effectively optimizes the travel distances and travel times while taking the constraint into account.

5 Conclusion and recommendations

In this paper a planning method for LNG IRP with pressure management was developed. The multi-period horizon was addressed with the rolling horizon approach. The rolling horizon approach is more computational efficient for planning horizons exceeding four days in a scenario of five refuelling stations. Moreover, the model successfully solved a seven-day planning for 19 stations and two vehicle, proving its ability to handle multi-period LNG IRP with pressure management. The circular nature of the vehicle routes indicate that the model effectively optimizes the travel distances and travel times while taking the constraint into account. This research contributes to the field of cryogenic LNG logistics by providing a planning method that integrates routing, inventory and pressure management decisions.

Future research should focus on validating the planning method by conducting a comparative anal- ysis to an existing planning method in terms of costs and efficiency. In addition, it would interesting to investigate a more realistic approach for the offload cooling. In the proposed planning method, the offload cooling parameter is a fixed value for each vehicle, resulting in a linear cooling effect. However, in real life, offload cooling depends on more factors such as the temperature of the mixture at the refuelling station and the temperature within the vehicle's trailer.

References

Aghezzaf, E., Raa, B., & Landeghem, H. (2006). Modeling inventory routing problems in supply chains of high consumption products. *European Journal of Operational Research*, *169*, 1048–1063. https://doi.org/10.1016/j.ejor.2005.02.008

Ahmadi-Javid, A., Mansourfar, M., Lee, C.-G., & Liu, L. (2023). Optimal distribution of perishable foods with storage temperature control and quality requirements: An integrated vehicle routing problem. *Computers & Industrial Engineering*, *182*, 109215. https://doi.org/https://doi.org/10.1016/j.cie.2023.109215

Al-Hinai, N., & Triki, C. (2020). A two-level evolutionary algorithm for solving the petrol station replenishment problem with periodicity constraints and service choice. *Annals of Operations Research*, *286*(1), 325–350.

Alves, P. Y. A. L., Delgado, K. V., & Silva, V. F. (2018). Inventory routing problem with time windows: A systematic review of the literature. *Proceedings of the XIV Brazilian Symposium on Information Systems*. https://doi.org/10.1145/3229345.3229376

Andersson, H., Christiansen, M., & Desaulniers, G. (2016). A new decomposition algorithm for a liquefied natural gas inventory routing problem. *International Journal of Production Research*, *54*, 564–578. https://doi.org/10.1080/00207543.2015.1037024

Awad, M., Ndiaye, M., & Osman, A. (2021). Vehicle routing in cold food supply chain logistics: A literature review. *The International Journal of Logistics Management*, *32*(2), 592–617.

Bell, W. J., Dalberto, L. M., Fisher, M. L., Greenfield, A. J., Jaikumar, R., Kedia, P., Mack, R. G., & Prutzman, P. J. (1983). Improving the distribution of industrial gases with an on-line computerized routing and scheduling optimizer. *Interfaces*, *13*(6), 4–23.

Boers, L., Atasoy, B., Correia, G., & Negenborn, R. R. (2020). The multi-period petrol station replenishment problem: Formulation and solution methods. *Computational Logistics: 11th International Conference, ICCL 2020, Enschede, The Netherlands, September 28–30, 2020, Proceedings 11*, 600–615.

Chart Industries. (2016, October). Intro to cryogenics [video]. https://www.youtube.com/watch?v=T-6R5exBUCo

Cho, J., Lim, G. J., Kim, S. J., & Biobaku, T. (2018). Liquefied natural gas inventory routing problem under uncertain weather conditions. *International Journal of Production Economics*, *204*, 18–29. https://doi.org/https://doi.org/10.1016/j.ijpe.2018.07.014

Christiansen, M., Fagerholt, K., Nygreen, B., & Ronen, D. (2013). Ship routing and scheduling in the new millennium. *European Journal of Operational Research*, *228*(3), 467–483.

Coelho, L. C., Cordeau, J., & Laporte, G. (2014). Thirty years of inventory routing. *Transport Science*, *48*, 1–19. https://doi.org/10.1287/trsc.2013.0472

Coelho, L. C., & Laporte, G. (2013). The exact solution of several classes of inventory-routing problems. *Computers & Operations Research*, *40*(2), 558–565. https://doi.org/https://doi.org/10.1016/j.cor.2012.08.012

Cornillier, F., Boctor, F., & Renaud, J. (2012). Heuristics for the multi-depot petrol station replenishment problem with time windows. *European Journal of Operational Research*, *220*(2), 361–369.

Cornillier, F., Boctor, F. F., Laporte, G., & Renaud, J. (2008). A heuristic for the multi-period petrol station replenishment problem. *European Journal of Operational Research*, *191*(2), 295–305. https://doi.org/https://doi.org/10.1016/j.ejor.2007.08.016

Dantzig, G. B., & Ramser, J. H. (1959). The truck dispatching problem. *Management science*, *6*(1), 80–91.

Fodstad, M., Uggen, K. T., Rømo, F., Lium, A.-G., Stremersch, G., & Hecq, S. (2010). Lngscheduler: A rich model for coordinating vessel routing, inventories and trade in the liquefied natural gas supply chain. *Journal of Energy Markets*, *3*(4), 31–64.

Ghiami, Y., Demir, E., Van Woensel, T., Christiansen, M., & Laporte, G. (2019). A deteriorating inventory routing problem for an inland liquefied natural gas distribution network. *Transportation Research Part B: Methodological*, *126*, 45–67. https://doi.org/10.1016/j.trb.2019.05.014

Grønhaug, R., Christiansen, M., Desaulniers, G., & Desrosiers, J. (2010). A branch-and-price method for a liquefied natural gas inventory routing problem. *Transportation Science*, *44*(5), 400–415. https://doi.org/10.1287/trsc.1100.0317

Hsu, C. S., & Robinson, P. (2019). Midstream transportation, storage, and processing. *Petroleum Science and Technology*. https://doi.org/10.1007/978-3-030-16275-7_17

Kleywegt, A., Nori, V., & Savelsbergh, M. (2004). Dynamic programming approximations for a stochastic inventory routing problem. *Transportation Science*, *38*, 42–70. https://doi.org/10.1287/trsc.1030.0041

Maknoon, Y. (2024). Fundamentals of multimodal transportation.

Moin, N. H., & Salhi, S. (2007). Inventory routing problems: A logistical overview. *Journal of the Operational Research Society*, *58*, 1185–1194. https://doi.org/10.1057/palgrave.jors.2602264

Surjandari, I., Rachman, A., Dianawati, F., & Wibowo, R. (2011). Petrol delivery assignment with multi-product, multi-depot, split deliveries and time windows. *International Journal of Modeling and Optimization*, *1*(5), 375.

Thomas, S., & Dawe, R. A. (2003). Review of ways to transport natural gas energy from countries which do not need the gas for domestic use. *Energy*, *28*(14), 1461–1477. https://doi.org/https://doi.org/10.1016/S0360-5442(03)00124-5

Uggen, K. T., Fodstad, M., & Nørstebø, V. S. (2013). Using and extending fix-and-relax to solve maritime inventory routing problems. *Top*, *21*, 355–377.

Wang, S., Tao, F., Shi, Y., & Wen, H. (2017). Optimization of vehicle routing problem with time windows for cold chain logistics based on carbon tax. *Sustainability*, *9*(5), 694.

Wang, X., Liang, Y., Tang, X., & Jiang, X. (2023). A multi-compartment electric vehicle routing problem with time windows and temperature and humidity settings for perishable product delivery. *Expert Systems with*

Applications, *233*, 120974. https://doi.org/https://doi.org/10.1016/j.eswa.2023.120974

Flip Boekhorst is a student of MSc Transport, Infrastructure and Logistics at Delft University of Technology in Delft, the Netherlands.

B

Experimental setup: Validation and verification

Table B.1: Model characteristics

Model parameters	Value
c_{km} (euro)	0.594
c_{hours} (euro)	58.49
Service time (hour)	2
c_{ij}^{tax} (euro)	0.0
oq_{min} (kg)	5000

Table B.2: Station characteristics

Station ID	I_0	I_{min}	I_{max}	P_0	P_{min}	P_{max}	PH	LIN	V	$c_{nitrogen}$
Alkmaar	12658	2000	22000	4.29	2.0	8.5	1.2	1	1	100
Botlek	20721	2000	22000	6.65	2.0	9.75	1.2	0	1	100
Nieuwegein	14746	2000	22000	6.83	2.0	8.5	1.2	1	1	100
Tilburg	15471	2000	22000	7.90	2.0	9.75	1.2	0	1	100
Zaandam	14835	2000	22000	7.5	2.0	8.5	1.2	1	1	100

Table B.3: Vehicle characteristics

Vehicle ID	Q_{max}	V_{max}	θ	h	oc
GAT0	19000	6.0	Gate	Schenk NL	0.25

Table B.4: Slot characteristics

Slot ID	Terminal	Start time
01	Gate	4

Table B.5: Travel times including service time (in hours) and distances (in kilometers)

From/ to	Schenk NL		Gate		Alkmaar		Botlek		Nieuwegein		Tilburg		Utrecht	
	Time	Dist	Time	Dist	Time	Dist	Time	Dist	Time	Dist	Time	Dist	Time	Dist
Schenk NL	0	0	3	68	4	132	3	32	3	48	3	67	3	59
Gate	1	68	0	0	5	172	3	38	4	123	5	157	4	119
Alkmaar	2	132	5	172	0	0	4	156	4	93	4	153	3	75
Botlek	1	32	3	38	4	156	0	0	3	87	4	147	3	84
Nieuwegein	1	48	4	123	4	93	3	87	0	0	3	68	3	21
Tilburg	1	67	5	157	4	153	4	147	3	68	0	0	3	80
Zaandam	1	59	4	119	3	75	3	84	3	21	3	80	0	0

C Results

Table C.1: Results simplified MILP static approach

ID	Experiment	TC	Runtime	Status	Gap	TTC	TNCC	CpK	OQ	Bio slots	Grey slots
R24-S5	1 Day	1105	4	Optimal		1038	67	0.0577	18000	0	1
R48-S5	2 Days	2062	57	Optimal		1875	187	0.0521	36000	0	2
R72-S5	3 Days	3066	153	Optimal		2913	153	0.0539	54000	0	3
R96-S5	4 Days	3959	614	Optimal		3717	242	0.0516	72000	0	4
R120-S5	5 Days	5467	7200	Timelimit	0.19	5335	132	0.0593	90000	0	5
R144-S5	6 Days		7200	Infeasible						0	6
R168-S5	7 Days		7200	Infeasible						0	7

Table C.2: Results simplified MILP verification tests

ID	TC	Runtime	Status	Gap	TTC	TNCC	CpK	OQ	Bio slots	Grey slots
V1-R72-S5	3066	434	Optimal		2913	153	0.0539	54000	0	3
V2-R72-S5	2326	120	Optimal		2326	0	0.0431	54000	0	3
V3-R72-S5		1	Infeasible							
V4-R72-S5	1586	1192	Optimal		1524	62	0.0282	54000	0	3
V5-R72-S5	3125	2026	Optimal		3013	112	0.0558	54000	0	3
V6-R72-S5		1	Infeasible							
V7-R72-S5	2785	196	Optimal		2679	106	0.0496	54000	0	3
V8-R72-S5	3112	301	Optimal		2913	199	0.0539	54000	0	3
V9-R72-S5	2679	408	Optimal		2679	0	0.0496	54000	0	3
V10-R72-S5	2898	426	Optimal		2786	112	0.0516	54000	0	3

Table C.3: Results rolling horizon

Experiment ID	Total costs	Runtime	Status	Gap	TTC	TNCC	CpK	OQ	Bio slots	Grey slots
S5-D1	1105	5	Optimal		1038	67	0.0577	18000	0	1
S5-D2	2062	10	Optimal		1875	187	0.0521	36000	0	2
S5-D3	3182	15	Optimal		2875	307	0.0532	54000	0	3
S5-D4	3970	20	Optimal		3613	357	0.0502	72000	0	4
S5-D5	4926	22	Optimal		4450	467	0.0494	90000	0	5
S5-D6	6140	34	Optimal		5614	526	0.052	108000	0	6
S5-D7	7141	37	Optimal		6525	616	0.0518	126000	0	7

Table C.4: Overview of sensitivity analysis results

Experiment ID	TC	Runtime	Status	TTC	TNCC	CpK	OQ	Bio slots	Grey slots
Base	7141	31	Optimal	6525	616	0.0518	126000	0	7
Costkmhour0.8	5825	38	Optimal	5281	544	0.0419	126000	0	7
Costkmhour1.2	8446	37	Optimal	7830	616	0.0621	126000	0	7
CostN0.8	6791	37	Optimal	6483	308	0.0515	126000	0	7
CostN1.2	7651	31	Optimal	6629	1022	0.0526	126000	0	7
Demand0.8C14400	7401	41	Optimal	6421	980	0.0637	100800	0	7
Demand1.2C21600	7198	38	Optimal	6539	659	0.0432	151200	0	7
I_min0.8	7141	34	Optimal	6525	616	0.0518	126000	0	7
I_min1.2	7047	38	Optimal	6451	596	0.0512	126000	0	7
Offloadcooling0.8	7546	46	Optimal	6857	689	0.0544	126000	0	7
Offloadcooling1.2	7161	38	Optimal	6872	289	0.0545	126000	0	7
PHL0.8	6623	39	Optimal	6623	359	0.0497	126000	0	7
PHL1.2	7911	40	Optimal	7058	853	0.056	126000	0	7
Service time 1	5589	48	Optimal	5023	566	0.0399	126000	0	7
Service time 3	8431	21	Optimal	7680	751	0.061	126000	0	7
Traveldistime 0.8	6654	40	Optimal	6123	531	0.0486	126000	0	7
Traveldistime 1.2	7893	31	Optimal	7172	721	0.0569	126000	0	7
Vehiclecapacity 0.8			Inf day 7					0	7
Vehiclecapacity 1.2	8482	45	Optimal	8028	454	0.0531	151200	0	7
Vehiclepressurecap0.8	6974	35	Optimal	6388	586	0.0507	126000	0	7
Vehiclepressurecap1.2	7075	39	Optimal	6369	706	0.0505	126000	0	7

Table C.5: Overview of horizon lengths 8 to 25 hours experiment

Horizon length	TC	TTC	TNCC
8	29226	25842	3384
9	28177	24451	3726
10	28663	25634	3029
11	29211	26058	3153
12	29681	25911	3770
13	29639	25938	3701
14	27901	24906	2995
15	29735	26436	3299
16	29538	26141	3397
17	29656	27227	2429
18	30060	26780	3280
19	30696	27616	3080
20	30033	27298	2735
21	30506	27129	3377
22	30202	27301	2901
23	31483	27967	3516
24	30763	27686	3077
25	31379	27830	3549

D

Station abbreviations

Table D.1: Three letter abbreviations of the refuelling stations of Rolande and the corresponding country

Station	Abbreviation	Country
Antwerpen	Ant	Belgium
Habay	Hab	Belgium
Meer	Mee	Belgium
Waregem	War	Belgium
Zellik	Zel	Belgium
Alkmaar	Alk	Netherlands
Bodegraven	Bod	Netherlands
Botlek	Bot	Netherlands
Duiven	Dui	Netherlands
Geldermalsen	Gel	Netherlands
Heerenveen	Hee	Netherlands
Heteren	Het	Netherlands
Nieuwegein	Nie	Netherlands
Oude Tonge	Oud	Netherlands
Pesse	Pes	Netherlands
Tilburg	Til	Netherlands
Utrecht	Utr	Netherlands
Veghel	Veg	Netherlands
Zaandam	Zaa	Netherlands
TsPernis	TsP	Netherlands

E

Experimental setup: simplified MILP with rolling horizon approach in practice

- **Demand forecast**: data of the expected hourly demand at each refuelling station for the planning horizon.
- **Starting inventory and pressure levels**: Starting inventory and pressure levels of the refuelling stations at the time.
- **Heat leaks**: Assumption of pressure rise due to heat leaks per time step.
- **Travel times and distances**: Data of travel times, travel distances and road toll costs are based on the TLN planner that includes ADR routes. As each arc had to be entered manually in this TLN planner and there were more than 1,500 arcs in the network, it was decided to assume that the travel distance, travel time and toll costs are the same from A to B as from B to A.
- **Characteristics of Rolande's refuelling stations**:
  - Minimum and maximum inventory capacity
  - Minimum and maximum pressure capacity
  - If LIN tank available
  - If logistic trailer cooling can be done
  - Country
  - Address
  - Coordinates
- **Characteristics of transport vehicles**:
  - Identifier
  - Max capacity in kilogram
  - Logistic pressure capacity in bars
  - Transport company
  - Terminals
  - Offload cooling parameter
- **Characteristics terminal pick-up slots**
  - start time pick up slot

- end time pick up slot
- Location
- Product

- **Characteristics terminals**
  - Name
  - Address
  - Coordinates
- **Characteristics homebase**
  - Name
  - Transport company
  - Address
  - Coordinates

F Integrated planning tool in Rolande's system

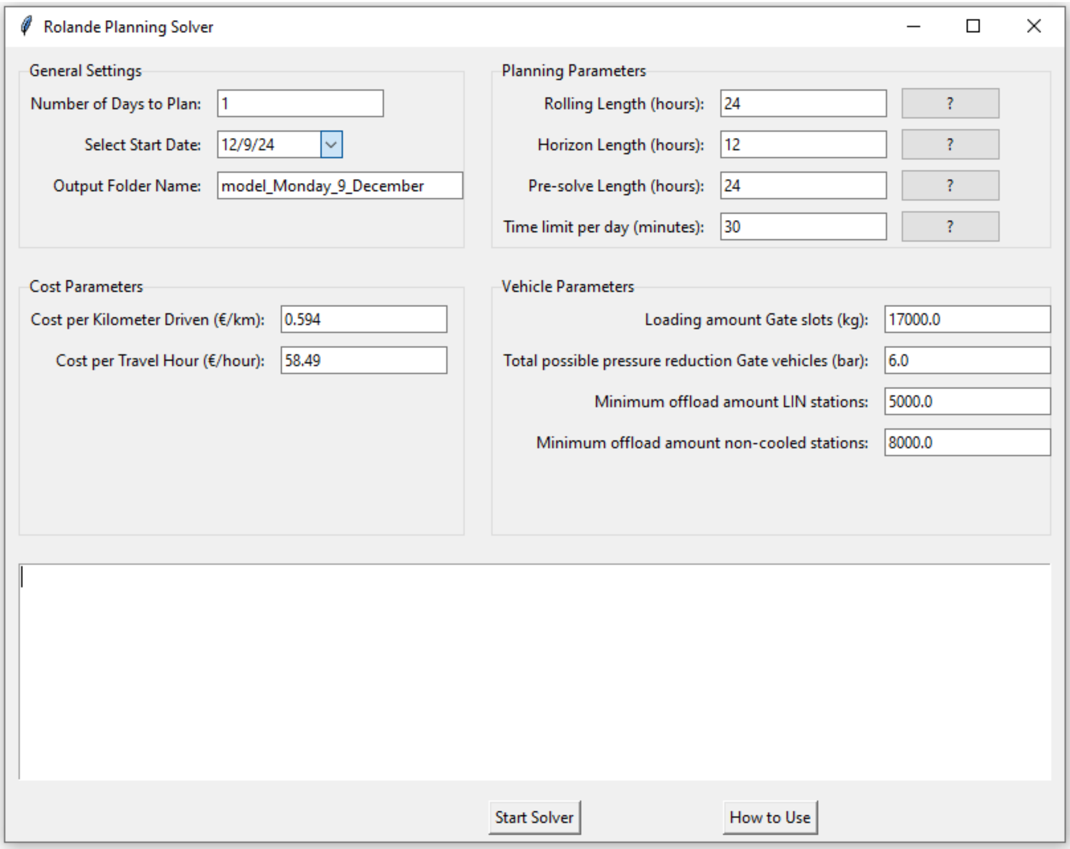


Figure F.1: Integrated the planning method in Rolande's system in collaboration with W. Konings, software developer at Rolande. This planning tool uses the required data from the Planning Excel file as input. Furthermore, the General Setting, Costs Parameters, Planning Parameters and Vehicle Parameters can be manually adjusted in this application.