Increasing fuelling capacity of hydrogen trains while minimising costs at Provincie Groningen

Designing hydrogen fuelling infrastructure in railway

Bachelor Thesis

By

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Preface

Dear reader,

You are about to read my research 'Increasing fuelling capacity of hydrogen trains while minimising costs at Provincie Groningen'. This research is executed on behalf of Provincie Groningen and in collaboration with Arriva and ProRail, as graduation assignment of the bachelor Industrial Engineering and Management at the University of Twente. This research focusses on the development of a novel model for designing hydrogen fuelling infrastructures in railway.

I would like to express my gratitude to those who contributed to the realization of this thesis. A special thanks goes to my first supervisor Alessio Trivella, whose valuable feedback and insights elevated the quality of this thesis. His support and enthusiasm have been most valuable throughout the process. I am truly fortunate to have had him as my mentor. I also extend my thanks to my second supervisor Daniela Guericke and my company supervisor Wessel Feenstra for their trust and giving me the freedom to explore, as well as their valuable input during the writing process, which spurred further enhancements.
I am thankful for the feedback and encouragement provided by my friends Ishmee de Vos, Lotte Verkerk, Feike Weijzen, Naomi Ross, and Lars Epping throughout the research journey. Lastly, I extend my appreciation to my family and loved ones for their kind support.

Enjoy reading my thesis.

Amina Balha

Management summary

Provincie Groningen (PG) is working on the implementation of hydrogen trains as a new and sustainable way of passenger railway transport. Currently the passenger time table is operated by a fleet 68 Hydrotreated Vegetable Oil (HVO) trains. PG aims to replace all HVO trains with 50 hydrogen trains by the year 2035. Consequently, resulting in the need for a new railway fuelling infrastructure. The acquisition of 50 hydrogen trains and designing the hydrogen fuelling infrastructure pose certain complexities. Currently, the primary challenge faced by PG in the project of implementing 50 hydrogen trains is the inadequacy of hydrogen fuelling capacity. The research goal aims to address the issue of insufficient fuelling capacity, as the desired norm entails a railway network sufficient of accommodating 50 hydrogen trains, while in reality there is no hydrogen fuelling infrastructure. Solving the core problem of insufficient fuelling capacity to support the desired network, while increasing the capacity is expensive.

This study is part of the Railway Network Design (RND) process, regarding the planning process of railway by Lusby, et al. (2011), due to the focus on designing a hydrogen fuelling infrastructure. The available literature on designing a railway fuelling infrastructure is scarce. Therefore, this research contributes strongly to the research field of designing a hydrogen fuelling infrastructure in railway.

This research aims to minimise costs of designing a hydrogen fuelling infrastructure while meeting the fuelling capacity requirements. The problem is formulated as an MILP, with the decision variables being the opening of shunting yards (SYs), the location of tube trailers (TTs) and Fuelling Installations (FIs) and the opening of pipelines with the assignment of the hydrogen flow. The constraints ensure that the capacity meets the required demand. Despite the treated problem sharing similarities with a Facility Location Problem (FLP), it has a multi-level decision making process: on the SY network level and the fuelling infrastructure within each SY. These levels interact, influencing the limitations and possibilities at each level. Due to the multi-level nature of the FLP in this research, the opening costs and the distance costs are calculated in both the SY network level and the fuelling infrastructure within each SY level. The goal is to minimise the overall network design costs, which includes: the train travelling and opening of the SYs costs at the first level, minimising the location costs of TTs and FIs, and the flow costs of hydrogen through the pipelines. A stylized example shows the trade-off between minimising the flow costs and the location costs at SY level. The best solution does not require the lowest possible flow costs and location cost, but the lowest total cost.

Due to the complexity of the MILP and the large problem size of the PG problem, heuristic algorithms have been created in order to solve the MILP. The heuristic algorithms on the first level minimise the travel costs of trains from their final station to the SY (heuristic H1) and minimise the opening costs of the SYs (heuristic H2). At the second level heuristic, G1 minimises the flow costs of the pipelines and heuristic G2 minimises the location costs of TTs and FIs. Heuristic algorithm G3 finds a balance between both costs components, combining heuristics G1 and G2. The heuristic algorithms can be combined across the different levels, resulting in different solving approaches that can be chosen to solve the problem. The best combination shows the lowest total costs as described by the objective function from the MILP.

Upon comparing heuristics H1 and H2, it can be concluded that heuristic H1 is a better fit to solve the first level in the PG problem. The found solution to the assignment problem in the PG case study involves dispatching 32 trains from Groningen station to SY the Vork and 18 trains from Leeuwarden station to SY Leeuwarden for overnight refuelling. The solution retrieved from heuristic G1 minimizes the flow costs, but yields higher location costs. In this solution 8 slow fuelling installations (SFI) and 3 fast fuelling installations (FFI) have been located at the Vork, supplied via 14 pipelines by 8 TT. At SY Leeuwarden 6 SFI and 3 FFI have been opened, supplied by 7 TT through 9 pipelines. Resulting in a total cost of €5 870 970. The solution from heuristic G2 minimizes the location costs, but consequently obtained higher flow costs. At SY the Vork 8 SFI and 2 FFI have been located, supplied through 14 pipelines by 8 TT. SY Leeuwarden required 7 SFI and 1 FFI, supplied by 7 TT through 10 pipelines according to heuristic G2. This yields the total costs of €5 963 662. Applying heuristic G3 yields total costs of €5 502 041 and is therefore the best found solution in this research. This hydrogen fuelling infrastructure includes locating 8 SFI and 3 FFI at SY the Vork supplied by 14 pipelines (figure I) and locating 2 SFI and 7 FF supplied by 10 pipelines at SY Leeuwarden (figure II).

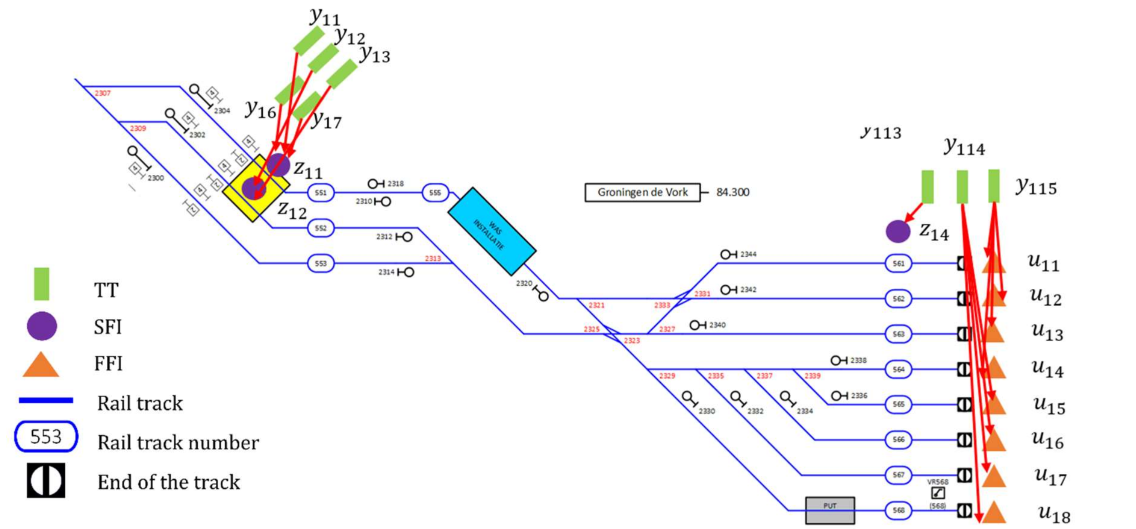

Figure I Hydrogen fuelling infrastructure at SY the Vork found by heuristic G3

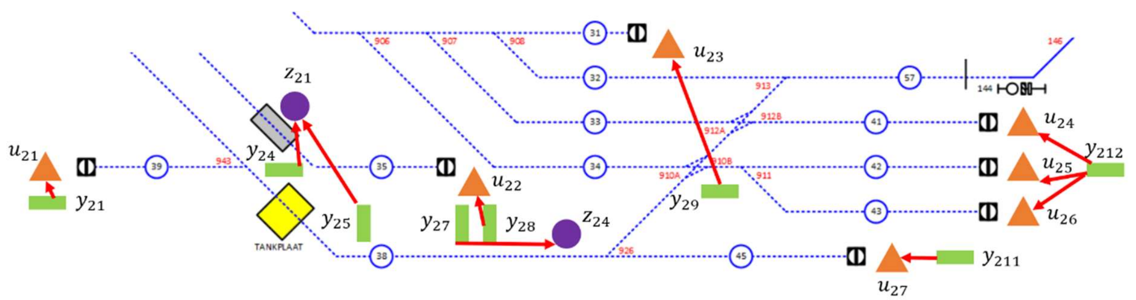

Figure II Hydrogen fuelling infrastructure at SY Leeuwarden found by heuristic G3

Through sensitivity analysis valuable insights into the fit of heuristics G1 and G2 on the costs coefficients are found. If the yearly pipeline costs are lower than €935.75 per meter, per flow, cetris paribus, applying heuristic G2 gives a better solution. Otherwise heuristic G1, cetris paribus, yields lower total costs. If the yearly FFI location costs are lower than €497 564, cetris paribus, applying heuristic G1 gives better results, than heuristic G2. Otherwise heuristic G2, cetris paribus, yields lower total costs. Any change in the SFI costs does not affect the fit of the heuristics on the total costs. The impact of the TT capacity is analysed, after which the increased capacity results in lower total costs, as long as the increased TT costs remain less than total costs difference between both capacities, is concluded. Lowering the TT capacity is not beneficial and should be avoided.

Based on the present input data and the application of heuristic H1, this study concludes that 32 hydrogen trains will be refueled at SY Vork and 18 at SY Leeuwarden. Heuristic H2 has no added value on the case study of Provincie Groningen. Therefore, according to the findings of this research heuristic H1 should be applied resulting in the asisgnment of all trains ending their timetable at station Groningen going to SY the Vork for fuelling, and all trains ending at station Leeuwarden going to SY Leeuwarden. Regarding the second level, all heuristics offer different solutions to different objectives. In case that the pipeline distance should be minimised, the solution of heuristic G1 yields the best hydrogen fuelling infrastructure. However, if the location costs should be minimised and thus the FIs should be used efficiently (reducing idle time), then heuristic G2 provides the best hydrogen fuelling infrastructure. Heuristic G3 provides the lowest total costs and should be chosen if the object of PG is to minimise the total costs. Depending on the objective of Provincie Groningen, a solution to the hydrogen fuelling infrastructure problem is provided. The main contribution of this research is an approach to design a low costs, efficient hydrogen fuelling infrastructures in railway as one of the only existing researches on designing hydrogen fuelling infrastructures in railway.

This research involves assumptions and decisions leading to discussions. Limited input data currently available should be replaced whenever available to improve accuracy. While the heuristics hold value, the solution is a guiding reference, therefore it is recommended to find a solving approach which is able to find the optimal solution. Future work includes addressing ProRail regulations, making the location sets continuous, study on the non-linear flow costs, and refining heuristic G3's applicability.

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Glossary of terms

CV	Control variable
DV	Dependent variable
FI	Fuelling installation
FFI	Fast fuelling installation
FLP	Facility Location Problem
H2	Hydrogen
HS	Hydrogen storage
HRS	Hydrogen Refuelling Station
HVO	Hydrotreated Vegetable Oil
IV	Independent variable
km	kilometre
m	metre
MILP	Mixed-Integer Linear programme
MV	Moderating variable
The fuelling infrastructure problem	The problem on designing a railway fuelling infrastructure optimally by opening shunting yards and locating fuel storages and fuelling installations, while minimising costs.
The PG problem	The problem encountered by Provincie Groningen on the insufficient fuelling capacity of 50 hydrogen powered trains.
PG	Provincie Groningen
PR	ProRail
RND	Railway Network Design
TT	Tube trailer
SFI	Slow fuelling installation
SY	Shunting yard

1. Introduction

In this chapter an introduction to the research will be provided. Section 1.1 gives a description of Provincie Groningen and the motivation behind the introduction of hydrogen in railway. Section 1.2 focusses on the problem statement and the importance of this research. Section 1.3 describes the research design and introduces the defined research questions that form the foundation of this research. Section 1.4 addresses the theoretical framework of the research, supported by the formulation of a conceptual framework.

1.1 Background

The research will be conducted on behalf of the department of Public, Smart and Green Mobility of the Provincie Groningen (PG), the problem owner. PG, functioning as the governing body for the province of Groningen, holds approximately 800 officials and is headquartered at the city centre of Groningen in the Provinciehuis. PG is responsible for various areas, including the regional infrastructure and public transport, by making sure residents can travel seamlessly across the different municipalities. Emphasizing sustainability and innovation, PG is actively working on initiatives related to hydrogen-powered trains and buses, autonomous transportation, the establishment of public charging infrastructure, and the development of other sustainable mobility frameworks.

The strategic decisions on green mobility are made by the governing board of PG, which were initially instigated by the Paris Agreement. Subsequently, the Government of the Netherlands has committed to reduce their greenhouse gas emission by 49% by 2030, with the House of Representatives being responsible for meeting the targets. To achieve this, certain goals have been set on reducing nationally the greenhouse gas emissions by the National Climate Agreement. This agreement mandates that the public transport must transition to emission-free operations by the year 2050. Provinces are required to establish their own objectives in alignment with the national targets, as part of their adherence to the Paris Agreement.

PG has set as target to offer fully emission free transport in the province, for instance by implementing hydrogen trains. Collaborating with Arriva and ProRail (PR), PG is actively engaged in the realisation of hydrogen powered public trains in Groningen. The transition from diesel-powered trains to hydrogen-powered trains, enables local emission-free mobility (Shirres, 2018). A general diesel powered train has an emission of 3.515 gram CO2 per liter (Otten et al., 2015). Currently all trains of Arriva in Groningen use Hydrotreated Vegetable Oil (HVO), which reduces the emission by 90% (Darwinkel, 2023). The introduction of hydrogen will reduce the emission to zero as hydrogen trains solely emit water vapor, thereby presenting a significantly more sustainable and green solution for the public train transportation (Logan et al., 2020). PG will start with implementing 4 hydrogen powered trains in 2027, with the ambition to expand the fleet up to 50 by the year 2035, replacing all HVO-powered trains. To ensure the successful implementation of the hydrogen train project, it is important to commence the research on the implementation and address potential bottlenecks and problems in time.

1.2 Problem Statement

The acquisition of 50 hydrogen trains and designing the hydrogen fuelling infrastructure pose certain complexity. Currently, the primary challenge faced by PG in the hydrogen train project is inadequacy of hydrogen fuelling capacity. The research goal aims to address the issue of insufficient fuelling capacity, as the desired norm entails a railway network sufficient of accommodating 50 hydrogen trains, while currently the fuelling infrastructure does not support any hydrogen trains. Consequently, PG confronts an action problem that needs to be solved: the present railway infrastructure does not support the fuelling of hydrogen powered trains, necessitating a the design of a hydrogen fuelling infrastructure to accommodate 50 hydrogen powered trains by 2035.

A problem cluster has been formulated to identify the core problem (figure 1). This problem cluster provides an overview of the scenario in 2035 in the absence of a solution to the stated action problem. The fuelling capacity cannot support the desired railway network, while increasing the capacity is expensive has been determined as core problem. This core problem results in five problems: insufficient amount of hydrogen stored, not enough fuelling employees and fuelling installations (FI), limited space available and insufficient availability of green hydrogen. The problems outlined the red boxes fall beyond the scope of this research. The availability of green hydrogen is not a problem which can be solved by PG, but by suppliers. They are responsible for delivering green hydrogen, while the only concern of PG is to have an estimate of the amount of hydrogen needed. In this research it is assumed that the supply of green hydrogen is sufficient in 2035. Also, no further research needs to be conducted on the number of employees since it can be easily calculated by the number of FI times the number of fuelling employees needed per installation. Since the information on the number of employees needed to operate a FI is not available, this research will not include the number of employees needed to support the hydrogen fuelling infrastructure. Solving the other 3 problems, by solving the core problem, will solve the stated action problem. If the problem will not be solved, it will have serious consequences leading to extra costs, disruption of the railway timetable and passenger dissatisfaction. Therefore, it is important to obtain the values for the three problems caused by the core problem, in order to upgrade the railway network to operate 50 hydrogen trains. The other determined core problem is on the number of available hydrogen trains. PG aims to gradually implement trains, increasing the fleet from 4 hydrogen trains in the year 2027, to 50 in 2035. This research does not focus on the acquisition of the hydrogen trains and assumes that in 2035 50 hydrogen trains are operating.

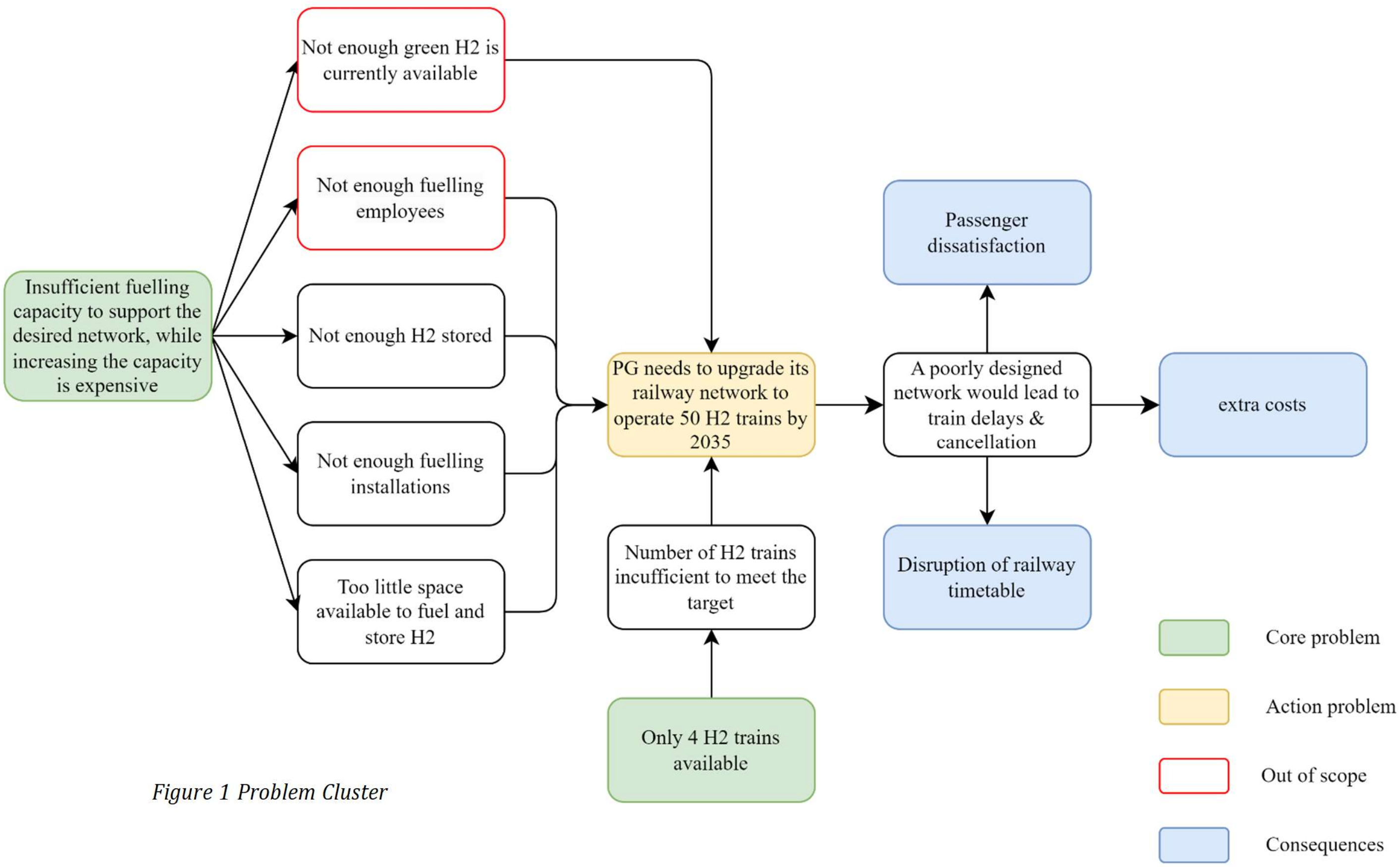


Figure 1 Problem Cluster

1.3 Research Design

The research question to solve the previously stated core problem has been defined as followed:

> **How can the fuelling capacity be increased to support the operation of 50 hydrogen powered trains while minimising costs?**

The research is found successful when it provides a fuelling infrastructure capable of fuelling 50 hydrogen powered trains, while minimising costs. This entails the description of the location and quantity of hydrogen stored and FI located at the designated shunting yards (SY).

To answer the research question, sub questions have been defined. These sub questions are structured in accordance with the Managerial Problem-Solving Method from Heerkens & van Winden (2017).

1) How is the current fuelling process and infrastructure organized?

    a) How is the current diesel fuelling process and infrastructure organized for HVO powered trains?

b) How will the hydrogen fuelling process and infrastructure be organized for 4 hydrogen powered trains?

c) How are hydrogen railway infrastructures organized at other SYs outside of PG?

The aim of the first research question is to examine the current fuelling process. This investigation studies both the analysis of the current HVO fuelling process (1.a), the hydrogen fuelling process for 4 trains (1.b) and the hydrogen railway infrastructures at other SYs (1.c). As the HVO trains will gradually be replaced by hydrogen trains, this part of the question (1.a) will focus on the current available fuelling capacity for the diesel powered trains. This analysis includes the location of the HVO storage and FI at the various the SYs. Additionally, the fuelling process for the 4 hydrogen trains will be analysed to determine the requirements for fuelling 1 hydrogen train. The purpose of this knowledge question is to identify the relevant variables, which together define the fuelling capacity. It also gives insights in the status and current way of thinking about hydrogen fuelling infrastructures. The last part of this sub question entails the hydrogen fuelling infrastructures operating at other SYs, besides PG. Addressing this sub-question provides a contextual understanding of the current situation on the current fuelling infrastructures.

2) What are existing theories in the academic literature that could be applied given the context of the PG?

   a) What are existing theories and techniques in the academic literature on fuelling hydrogen powered trains that could be applied given the context of PG?

   b) What are existing theories on railway network designs that could be applied given the context of PG?

   c) What are existing models, algorithms and other quantitative approaches on designing a railway fuelling infrastructure that could be applied?

A cross-sectional literature study acquires the relevant theoretical knowledge for the research. This study provides insights into alternative solutions to the stated problem. Conducting literature research on the railway fuelling process, capacity expansion through optimisation models and fuelling of hydrogen transport creates a comprehensive understanding of existing theories that contribute to increasing the fuelling capacity of the hydrogen powered trains. Only factual statements from established theories are utilized as foundation of this research. The identified literature is evaluated for its relevance and aligned to the criteria of the problem. The fuelling infrastructure problem can be considered a Facility Location Problem (Liu, 2009), necessitating further research on Facility Location Problems (FLP). To ensure that relevant articles can be found, research on railway network design and designing railway fuelling infrastructures is necessary.

3) How can an optimisation model be defined in order to increase the capacity while minimising costs and taking into account the practical constraints on fuelling hydrogen trains?

Based on the findings from the previously mentioned sub questions, an optimisation model will be formulated, expanding the fuelling capacity while minimising costs. The formulated Mixed-Integer Linear programme (MILP) serves as a tool to prescribe the needed capacity when fuelling 50 operating hydrogen trains. It aims to identify the optimal quantity of the hydrogen storage and fuelling installation, and their optimal locations. The optimisation model exhibits characteristics similar to an FLP, as the location of hydrogen storage and the FI plays a crucial role in the determination of the fuelling capacity. The formulated model is broadly applicable to different scenarios outside of the PG problem. A clear description of the workings of the theory will be provided by the use of a stylized example, which adds practical relevance and ensures future value to the model.

4) What is an appropriate solution method for the optimisation method, so that a good answer can be obtained?

This sub question addresses the solving method used in this research. The fuelling infrastructure problem is examined to find an appropriate solving method. The problem is decomposed into two phases, to make the problem interactable and provide a good solution to the fuelling infrastructure problem. The motivation behind the solution method and the application procedure is explained, to ensure the research validity (appendix A).

5) How do small changes in the parameters affect the found solution on fuelling infrastructure in order to meet the required fuelling capacity of PG?

This sub question aims to solve the PG problem by applying the findings from the previous sub questions. The numerical study describes the input data, after which the problem can be solved by the application of the created solving methods. The found solutions on potential fuelling infrastructures, are then compared and evaluated. The improved performance as answer to this investigation question will give value to the research, by showing the usefulness of the research to the problem owner. A sensitivity analysis will examine the impact of small changes to the PG problem. This gives valuable insights into the behaviour of the parameters and the applied solving methods.

6) How can the solution be implemented at the PG?

This last research question ensures that the found capacity requirements can be implemented correctly at PG. This part of the research will include a recommendation to PG on how to solve their problem. A visualisation of the recommended hydrogen fuelling infrastructure will be provided, containing the location for the hydrogen storage and the FI on the chosen SYL's. This chapter will also discuss the limitations and risks of the research in order to ensure the validity of the research. Currently, the PG has no in-house expertise on optimally determining the fuelling capacity. Conducting this research will solve their knowledge gap. Since the variables of the optimization model might change over time, the model will be easily adjustable to different scenarios.

A detailed overview of the research design on the sub questions can be found in appendix B.

1.4 Theoretical Framework

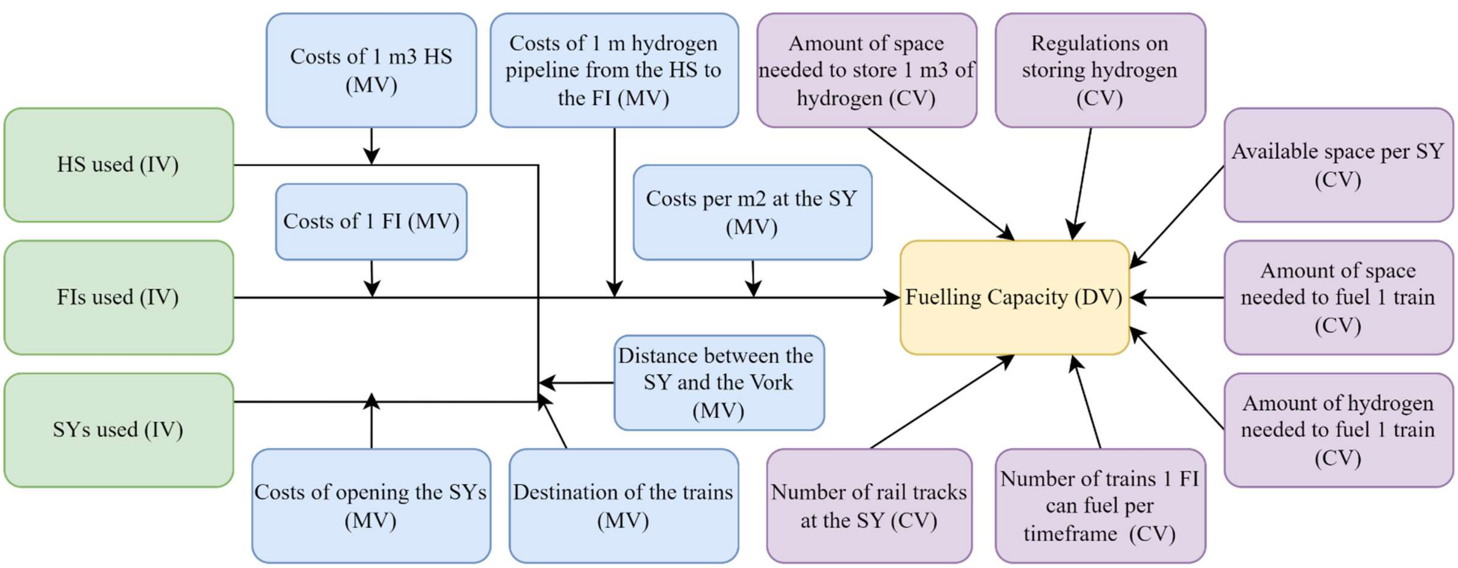


Figure 2 Conceptual framework of the fuelling capacity problem

There are many variables that together determine the total fuelling capacity. Therefore, a conceptual framework has been created which illustrates interdependencies among the relevant variables and provides a systematic understanding of the fuelling infrastructure problem (figure 2).
"A conceptual framework is a proposed set of linkages between specific variables, often along a path from input to process to outcome, with the expressed purpose of predicting or accounting for specific outcomes" (Tuckman & Harper, 2012). Therefore, the conceptual model is a tool to study all variables and their interconnections in order to observe a particular outcome. 18 different variables have been identified (appendix C) and included in the conceptual framework.

The first variables used in the conceptual framework are the Independent Variables (IV). “This variable is manipulated by the researcher, and the manipulation causes an effect on the dependent variable.”(Cooper & Schindler, 2014). There are 3 IVs that directly affect the fuelling capacity. These variables can be manipulated in order to obtain the needed fuelling capacity for the operating hydrogen trains. This research will provide the values for these 3 variables, by making use of an optimisation model. Another important variable that needs to be included within the conceptual framework is the Dependent Variable (DV). “This variable is measured, predicted, or otherwise monitored and is expected to be affected by manipulation of an independent variable.” (Cooper & Schindler, 2014). The fuelling capacity will be predicted as accurately as possible in the research. The Moderator Variable (MV) also plays an important role in the conceptual framework. The MVs affect the strength and direction of the relationship between the IV and the DV (King, 2013). Therefore, the MVs give insights on the actual effect of the IV on the DV. For instance the costs of 1 fuelling installation (MV) strongly affects the number of FI allocated, which affects the fuelling capacity. Another MV is the costs of 1 m hydrogen pipeline from the hydrogen storage (HS) to the FI. The further the storage is being allocated from the FI (and vice versa) the more expensive it will become. This affects the allocation and the number of FI the HS needs to support. The last variable that is included in the conceptual framework is the Control Variable (CV). They are variables that affect the DV, but cannot be manipulated (Tuckman & Harper, 2012). For instance, the space needed in order to fuel one train cannot be manipulated, but does constrain the fuelling capacity.

Looking at the number and location of the FI and the used SY variables, they can be described as capacitated, meaning that each fuelling installation and SY has limited capacity. These capacity limits are defined by the MV. The fixed purchasing and location costs of the FI and the hydrogen storage, and opening costs of the used SYs also affect the DV. The possible SYs are a discrete set, while the HS and the FI can be located anywhere on a line (continuous), following the rail track. The objective to minimise the costs is not included in the conceptual framework.

The relevance of this research lies in its ability to address the complexity of the problem. Due to the interconnected variables within the framework, it becomes evident that solving the problem on logic is impractical. Making the formulation of an optimisation model necessary to find a good solution.

2. Context Analysis

In this chapter the current fuelling capacity and infrastructure is analysed, giving context to the hydrogen train project of the PG. The current HVO fuelling capacity and the H2 fuelling capacity will be described in section 2.1. The analysed HVO fuelling capacity is the capacity that will become available for the hydrogen fuelling capacity by the year 2035. In section 2.2 the fuelling infrastructure of the 4 trains will be described, is the capacity which will be expanded from 4 to 50 H2 trains by the year 2035.

2.1 The HVO fuelling capacity

Currently the entire train fleet of Arriva in the province of Groningen operates on HVO fuel, necessitating a standardized fuelling process. All 68 operating trains are GTW and WINK trains, with the standard dimensions of 56 meters. In total 44 trains end their timetabling at central station Groningen, after which they go to SY the Vork during the night. The distance the trains have to travel from Groningen station to SY the Vork (figure 3, retrieved from Sporenplan) is 3.5 km. The remaining 24 trains end their timetabling at station Leeuwarden, after which they go to SY Leeuwarden (figure 4, retrieved from Sporenplan) during the night. Here, the trains travel on approximately 1.5 km. At both SYs, the trains get cleaned and fuelled. This process takes 15 minutes. Upon arrival, the train is stationed at the spill containments where meticulous parking is carried out to facilitate the proper attachment of nozzles to the fuel inlet. Subsequently, the crew undertakes the nozzle attachment process, initiating the fuelling procedure. Concurrently, additional service operations such as cleaning and fecal suction are executed. Following the completion of the fuelling process, the crew disconnects the nozzle. Finally, adhering to the Last In First Out (LIFO) principle, the train is parked by the operator at the termination point of the shunting yard. SY Groningen. At both SYs there are large HVO tanks located. At SY Groningen the 50.000 L tank is located next to the diesel tank of ProRail. At SY Leeuwarden the 40.000 L tank is also located next to diesel tank of ProRail. The HVO installations at both sited includes the tank, the pipelines and two dispensers at spill containments. The two dispensers are located next to track 551 and 552 for SY Groningen. At SY Leeuwarden there is one dispenser, located next to track 39. Currently the SY the Vork is designed for the 44 trains and SY Leeuwarden for 24 trains, defining the capacity.

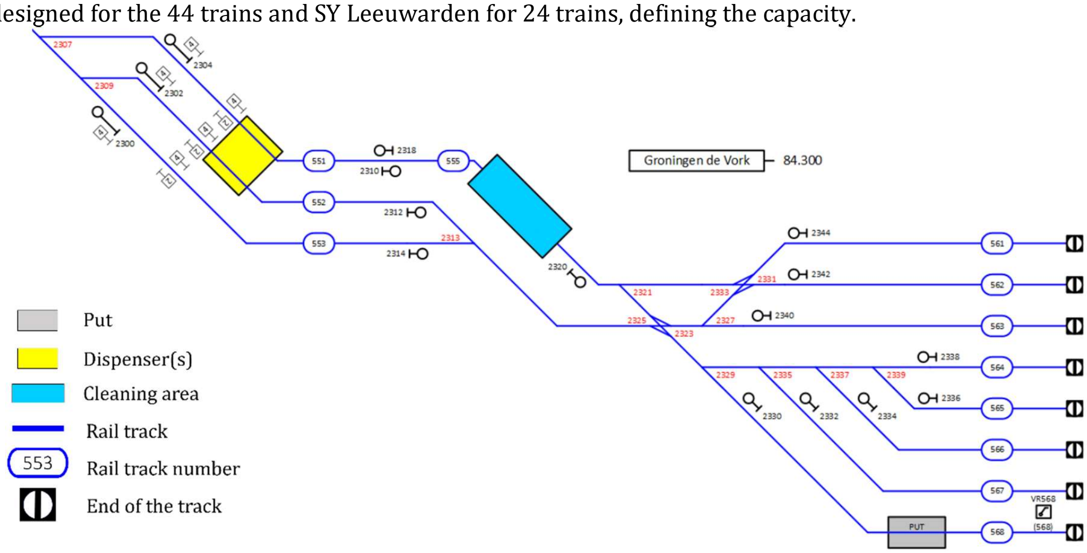


Figure 3 Shunting Yard the Vork

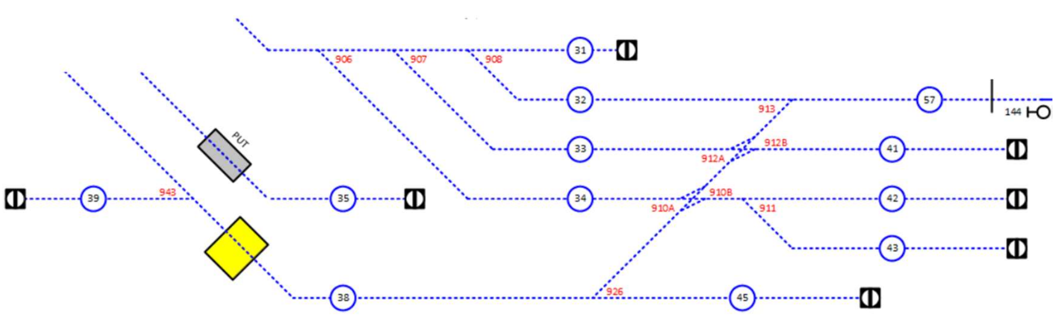


Figure 4 Shunting Yard Leeuwarden

2.2 The 4 hydrogen trains fuelling capacity

During the course of this research the PG is working on the acquisition of 4 hydrogen trains, which will operate in the year 2027. Furthermore, the acquisition process for the hydrogen storage and fuelling installations has not been finalized at the time of writing. Consequently, limited information is available regarding the details of the products. However, a general situation overview of the projected situation concerning the 4 H2 trains in the year 2027 can be provided within this section.

The estimated length of the train is comparable to the 56 meters of the current operating HVO trains. Each train will contain a tank of approximately 250 kg hydrogen, enabling it to cover distances of 1000 km. The 4 trains will operate at the route Delfzijl-Veendam, passing through Groningen. According to the timetable, the trains will go to SY the Vork, for fuelling and cleaning operations. The plan entails installing a hydrogen fuelling installation adjacent to the HVO dispenser at track 551. This fuelling installation is planned to fuel trains within 15 minutes, ensuring the compatibility with the fuelling time required for the HVO trains, that will still operating in the year 2027. The hydrogen will be stored on-site at tube trailers. Two tube trailers will be located at the SY. However, the exact location is unknown yet. There are two areas at site, in which the tube trailers can be placed in 2027. These areas are shaded red in figure 5. Each tube trailer stores 1000 kg of hydrogen at 340 bar. One tube trailer will be used to supply fuel to the trains, the other will serve as safety stock. Hydrogen storages are larger in size and require more safety regulations according to ProRail, resulting in locations further away from the fuelling installations. This limits the available space at the shunting yards.

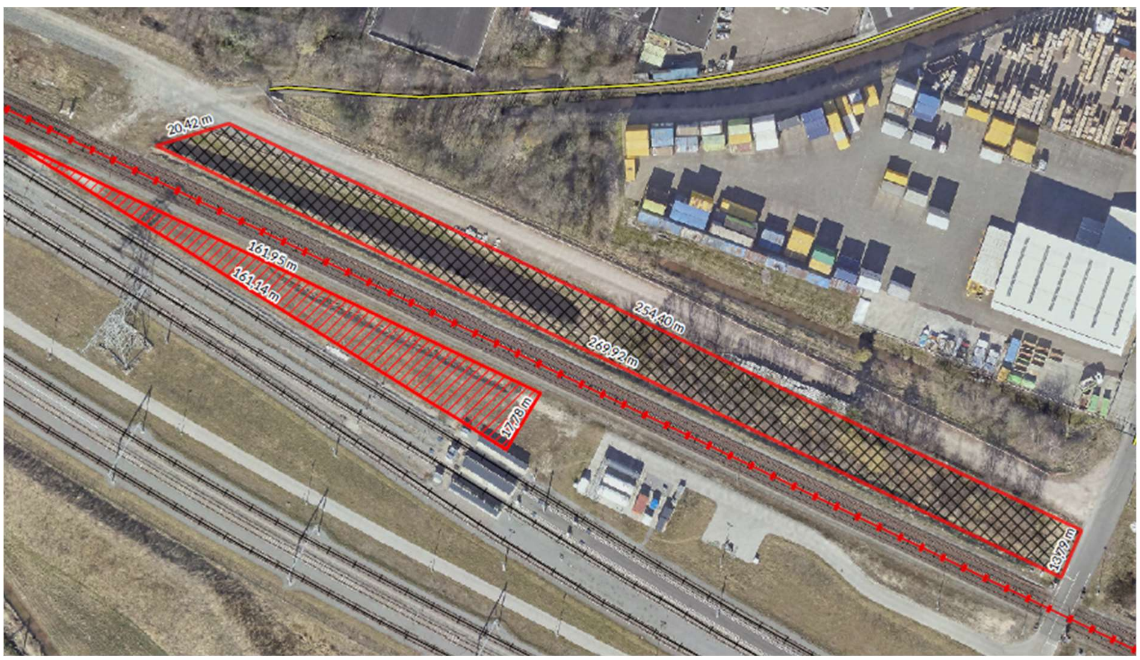


Figure 5 Aerial photo (2022) of the Vork with potential TT locations. Scale 1:1200, image by Provincie Groningen

2.3 Existing Hydrogen Refuelling Stations

Groningen will not be the first to implement hydrogen trains as regional public rail transport. In Lower Saxony, a total of 14 hydrogen Coradia iLint trains are currently operational under the management of the operator LNVG. This train model can cover a distance of 1000 km on a single tank. The construction of a dedicated filling station near Bremervörde (figure 6) was undertaken by Alstom. Linde, on the other hand, assumed responsibility for the establishment and operation of the fuelling station. According to Alexander Zörner, the project director, this station has a maximum daily refuelling capacity of 1600 kg of hydrogen.

The construction of the hydrail fuelling station required the efforts of 20 personnel from Linde, spanning a duration of one and a half year. Moreover, the long-term objective involves the production of hydrogen through wind-powered electrolysis. Currently, Linde facilitates the delivery of hydrogen from its chemical plants located in Stade to the fuelling station using trucks. On average, two or three tube trailers transport the hydrogen to the site on a daily basis. To ensure the hydrogen's arrival at the fuelling installation, it undergoes compression (3 twin IC 50/60 compressors) and is stored in constant pressure vessels before reaching the dispenser. The site holds two fuelling installations, each equipped with a dispenser. The refuelling process for the trains takes approximately 20 to 30 minutes. The Bremervörde hydrogen fuel filling station possesses a maximum daily refuelling capacity of 1600 kg H2, which is sufficient to fuel 12 Coradia iLint trains. Operating round the clock, the station ensures service throughout the entire day. Additionally, the on-site total hydrogen storage capacity amounts to a total of 4590 kg (LNVG, 2022).

Figure 6 Hydrogen Refuelling Station Bremervörde, image by Linde

2.4 Conclusion

The current fuelling infrastructure is designed for HVO fuelling and will after the implementation of 4 hydrogen trains in the year 2027, completely be replaced by the hydrogen fuelling infrastructure in the year 2035. There are some similarities between a HVO and hydrogen fuelling infrastructure, for instance the comparable dimensions of a HVO and hydrogen train. It is important to note that the fleet of 68 HVO trains will be replaced a fleet of 50 hydrogen trains. Meaning a decrease in the number of operating trains. Also, the steps of the fuelling process will stay the same. The difference that impacts the fuelling infrastructure the strongest is the location of the fuel storage. The HVO can be stored near the fuelling installation. Since hydrogen storages are larger in size and require more safety regulations, it limits the available space at the shunting yards. Resulting in need to redesign the fuelling infrastructure when implementing hydrogen trains. The hydrogen refuelling station (HRS) designed for 14 hydrogen Coradia iLint trains at Bremervörde can be used as reference for this research. The trains operating in Lower Saxony also require +/- 250 kg H2 on a daily basis, with the maximum refuelling capacity of the HRS being 1.6 tons of hydrogen. The hydrogen is being delivered by 2 tot 3 tube trailers daily. Within 1 hour, 2 trains can be fuelled by each of the 2 fuelling installations on site.

3. The state-of-the-art

3.1 Fuelling hydrogen trains in practice

Hydrogen trains operate at long ranges, provide full route flexibility, long range and require short refuelling times. Due to these characteristics, hydrogen trains are a good fit to regional passenger trains, which return to the shunting yard during night (Garrison, et al., 2019). This requires refuelling once every night for each operating train. Currently, there are three hydrogen regional passenger trains dominating the new European market. Siemens and Ballard together sell the Mireo train, Alstom the Coradia iLint and Stadler also designed hydrogen multiple unit trains. Since the PG is still in the procurement stage, all three are potential trains for the 50 hydrogen train project of the PG.

A case study of the European Union (Garrison, et al., 2019) on the region Groningen and Friesland showed a cost premium of 4% for operating hydrogen trains, compared to diesel technology. The fuel cell technology is more economical operating at longer distances and large number of fuel cell trains supplied by a central hydrogen refuelling. The research also mentioned that over-capacity of the H2 refuelling infrastructure should be avoided in order to minimize the Total Cost of Ownership (Ruf, et al., 2019*).* Therefore, it is of great important to define the refuelling infrastructure capacity. The hydrogen fuelling infrastructure facilitates the hydrogen supply to the dispenser, after which the trains can be fuelled.

The availability of green hydrogen is still scarce. According to IRENA (International Renewable Energy Agency), only 1% of the globally produced hydrogen comes from renewable energy. More common energy sources for the hydrogen production are natural gas (47%), coal (27%) and oil (4%). The PG stated that only green hydrogen will be used as fuel for the hydrogen trains. At the early stages of a hydrogen railway infrastructure, trucks will supply hydrogen tanks on a daily basis. At a later stage of the development, an on-site electrolyser system can be used in order to supply the green hydrogen. Due to the scarce availability of green hydrogen, some refuelling infrastructures found in academic literature include a Polymeric Electrolyser System (PEME). Renewable energy and deionized water will serve as input, after which the PEME transforms it into green hydrogen at site. Siemens and the Deutsche Bahn are working on a fully mobile hydrogen refuelling station in the H2goesRail project, which can be used to fuel the hydrogen trains. Another PEME that can already be found on the market is the Silyzer 300 by SIEMENS, which has been used in the study of Guerra et al (2021) to fuel 20 Coradia iLint trains. In this study, approximately 4000 kg of green hydrogen needed to be stored daily to supply the maximum capacity. The type of PEME and the number located at the shunting yard determines the number of trains which can be fuelled, and thus the fuelling capacity. The hydrogen needs to be stored at the shunting yard, to ensure an efficient supply of hydrogen to the dispenser. Hydrogen can be either stored at low pressure or high pressure. Low pressure storage has as main advantage to be less expensive, but requires more space at the shunting yard. The hydrogen needs to be compressed to 350 bar in order to be stored at high pressure to fuel the trains. Therefore, the compressor, along with high-pressure hydrogen storage is needed at the refuelling infrastructure. Lastly high flow hydrogen dispensers are needed to fuel the trains. Piraino et al. (2021) investigated a hydrogen railway facility. Detailed numerical modelling has been used in the research to implement and formalize the models. In their study a regional passenger hydrogen train consumed daily 252 kg of hydrogen. According to a study by Genovese et al. (2020) a daily operation for the hydrogen refuelling shunting yard can account for 2-10% of hydrogen losses. Therefore, 260 kg of hydrogen per train needs to be stored every day in order to support the operating trains.

The refuelling station system needs to be designed in order to support the daily operating hydrogen trains by sufficient storage, to reduce the interruption of the refuelling operations as described at figure 1. Kontaxi and Ricci (2012) identified key elements defining the capacity of tracks based on the geometrical configurations of the track:

- The Shunting yard layout
- Movement rules (for instance the minimum distance between trains)
- Maintenance and operation planning

The Railway Capacity Handbook also identifies key concepts defining capacity of Shunting Yards. One important concept is the timetable of the trains including arrival times, final destination, departure time and more. The more shunting yards are being used to fuel a fleet, the larger the fuelling capacity (van de Ven, et al, 2019). The arrival and departure time of the different train timetables, influences the assignment of the different trains to the different shunting yard locations (Kontaxi & Ricci, 2012). Also the number of rail tracks at the shunting yard and the space available at the shunting yard directly affects the amount of installations and the size of the storage which can be placed.

All these components together define the fuelling capacity as number of hydrogen trains which can be fuelled within a time period. The yard performance can be measured in processing time or monetary costs (Boysen et al., 2012). In this research the order in which trains will be stationed at the sy will not be taken into account, since the focus is on the fuelling infrastructure and not the classification of the trains.

3.2 Process of railway planning

There are three levels in the planning process of railways according to Lusby et all. (2011): Strategic level, Tactical level and the Operational level. All three levels need to be integrated in order to fully support the railway operations. However, the implementation of hydrogen trains do require some additions to the standard railway planning process. The planning process of railway with the additions to hydrogen railway is illustrated at figure 7.

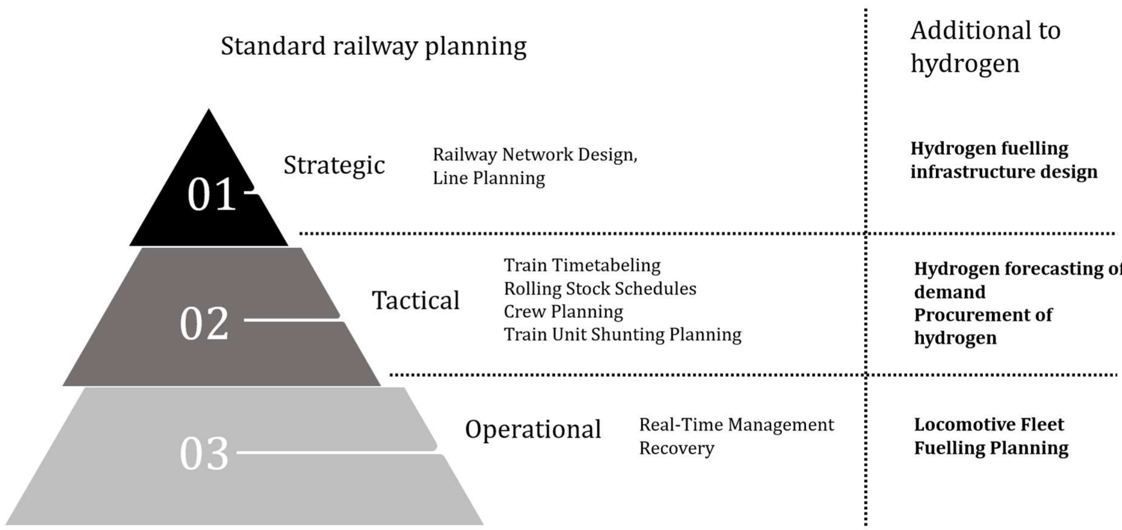


Figure 7 Stages of the Railway Planning Process

The insufficient fuelling capacity problem of the PG is on the strategic level. The Railway Network Design (RND) has to be redesigned in order to operate the hydrogen trains. This includes the physical infrastructure of the railway system, by determining the track layout, stations, SYs and other infrastructure components (Canca, et all., 2017). This research will focus on the design of the fuelling infrastructure of hydrogen trains at SYs. The available literature on designing a railway fuelling infrastructure is scarce. No research has been found on designing a hydrogen railway fuelling infrastructure. Therefore, it can be concluded that this research will contribute strongly to the research field of designing a hydrogen fuelling infrastructure in railway, since it is one of the first. This makes it difficult to compare or build on current existing theory found within literature. Almansoori and Shah (2006) studied the design and operation of a future hydrogen supply chain by formulating an MILP. This quantitative tool supports the decisions on strategic level within the hydrogen railway network. The objective of their research is to minimize the total costs spent on capital and operations of the hydrogen supply chain. In their research the candidate facility locations including production plants and storage facilities has been studied. The capital cost, the operating cost, the transportation capital cost and the transportation operating cost together make up the total costs.

Studying problems at strategic level, means solving problems on the long term. The found solution will rarely be changed over several years. This includes the opening of the SY and determining the capacity. The PG wants the fuelling infrastructure to last for approximately 15 years, due to the high investment costs. The PG problem concerns the sizing and the location of the shunting yards (facilities) within a transportation network. The objective is to minimise the sum of opening and travel costs for the SYs, the pipeline costs and the costs concerning the locating of the TTs and FIs. This problem shares similarities with a Facility Location Problem (FLP). The classic example of a FLP follows the optimisation of facility locations, meeting the demand of customers, while minimising costs. The associated costs for opening SYs, locating TTs and FIs together with the pipeline cots align with the FLP framework. Magnanti and Wong (1984) describe a method in which a facility location problem can be converted into a network design model. This can be done by adding a special node (see figure 8) to the warehouse location network (in the case of the PG project shunting yard location network). This node will serve the required flow required of the customers (trains). Special arcs from the special node to the potential shunting yard locations are added. The fixed costs of opening a potential location is given by the special arcs, while the other arcs hold transportation costs. Solving this network design problem solves the facility location problem in Magnanti and Wong (1984).

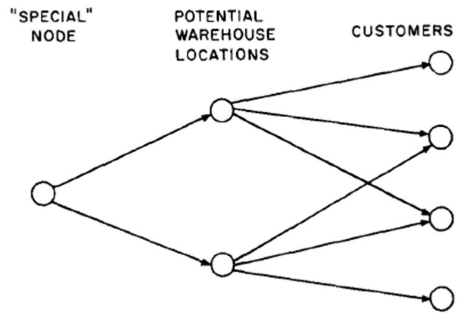


Figure 8 Plant location as an arc design problem by T. L. Magnanti and R. T. Wong

A level further within the strategic planning of shunting yards is line planning. Line planning matches transport capacity (the supply) with the passenger demand, by determining the operation zone, intermediate stations and the frequency of the trains (Lin & Ku, 2014; Fu et al., 2015). It is the process of determining the operational aspects on the lines within the rail network. The line plan will serve as base for determining the timetabling process. Changing the line plan not only requires rescheduling the rolling-stock, crew and timetable, but also requires the cooperation and coordination of several railway departments, making it expensive to change within a short period (Pu & Zhan, 2021). Commonly used methods on determining the line planning are robust and stochastic optimization. Schöbel (2012) defined two variables causing uncertainties: disturbance during service operations (e.g. accidents or maintenance may disrupt the usage of tracks) and the approximation of input parameters (incl. passenger demand, costs and traveling time). The research on the PG problem involves the assignment of trains to SYs to be fuelled. This operational aspect of the research is part of the line planning. Therefore it can be concluded that despite the research focusses mainly on the hydrogen railway network design, line planning is also part of this research. The line planning and the Railway Network Design interact.

At the tactical level, the solution to the studied problem must last for some time longer than daily. Since the diesel and HVO trains will be replaced by the hydrogen trains, the timetable must be revised and small changes might be needed. The timetabling of the trains is on the tactical level, this also includes the trains travelling to the different SYs. A common objective used for timetabling problems in railway is to minimize the number of required trains or the total travel time (Liebchen & Möhring, 2004), taking into account that the lines and shunting yard locations are given. The timetabling process interacts strongly with the line planning and thus with the PG problem as well (Fucs, et al., 2022). In order to control the complexity the assumption has been made that the transition from HVO to hydrogen trains does not affect the current timetabling. The rolling stock planning is the next step within railway planning that is part of the tactical planning. The objective of the rolling stock planning is to offer sufficient number of seats at the operating trains, while minimizing the operating costs (Thorlacius, et al., 2015). Forecasting the amount of hydrogen needed to operate the trains is also on the tactical level. The forecast is based on the timetable, infrastructure and other strategic and tactical plannings. Shunting the trains, so matching and parking, is also on the tactical level. The idle rolling stock, mostly during night, is being parked at a shunting yard. Stationing the trains is quite a challenge since the trains need to be parked according to their timetable at the shunting tracks in order to prevent the crossing of trains, resulting in disruption. This problem is also known as the Train Unit Shunting Problem (Kroon, et al., 2008). Also crew planning is an important part on the tactical level. The crew should be carefully scheduled in order to support the service operations at the shunting yards and minimize costs. All of these processes fall outside the scope of this research study.

Lastly, the operational level also plays an important role in railway planning. Real-Time Management has to be done on a daily basis. For instance the level of recovery in the delay of the timetable may be different every day. So when there is insufficient hydrogen available at the SY to fuel the train, the timetable will be disturbed, causing delay. Liebchen et al. (2009) studied the robustness of recovery in railway, by studying delay resistant timetabling. Another problem being solved at the operational level is Locomotive Fleet Fuelling Problem. Given the set of operating trains, the set of yards and the capacity, and the current hydrogen costs; this problem finds the optimal fuelling plan for the operating trains, while minimizing the fuelling cost of the locomotives (Nag & Murty, 2015). In case the PG decides to outsource the fuelling of the trains to privately owned fuelling stations, the research on the Fleet Fuelling Problem becomes relevant.

3.3 Conclusion

This research falls in the RND process and touches upon the final stage of Line Planning: from final station to SY. Within the RND it focusses on the design of the hydrogen fuelling infrastructure, while the assignment of trains is part of the Line Planning. It can be concluded that this research is cutting edge, as little research has been conducted on railway hydrogen fuelling infrastructures. Due to the lack of academic research on this topic, the availability of relevant literature is scares. Therefore the literature research has been focused on the current technology of hydrogen trains and hydrogen fuelling installations, and shunting yard planning processes on strategic, tactical and operational level. After conducting research on the strategic level, with the focus on the RND and Line Planning, it can be concluded that this research shares most similarities with a facility location problem. The problem studied in this research can be described best as a FLP, where the location of the shunting yards, the hydrogen storage, the fast fuelling installation and the slow fuelling installation needs to be determined, while minimizing the opening costs and 'connection' costs. No research could be found on a similar modification of the FLP. Therefore, it can be concluded that this research is innovative.

4. The optimisation model

4.1 Model introduction

The problem involves determining the optimal configuration of fuelling infrastructure to support the operation of hydrogen trains. The aim is to minimise costs while ensuring sufficient fuelling capacity for a fleet of hydrogen trains. In this chapter, the problem will be formulated as a Mixed-Integer Linear Programming (MILP) model. The decision variables include the opening of SYs as well as the placement of TTs and FIs at the opened SYs. These decisions form the basis of designing the optimal fuelling infrastructure. Several constraints are formulated to ensure that the fuelling capacity meets the demand. The constraints include the maximum number of trains each SY can station, the assignment of the trains and ensuring that the TTs and FIs together can fuel the assigned number of trains to every opened SY. Additionally, there are constraints on the fuelling capacity of the different FIs, the storage capacity constraint of the TTs and the assignment of the trains and controlling the flow of hydrogen through the pipelines. The assumptions made for the MILP can be found in appendix D. This MILP includes two types of FIs: the fast fuelling installation (FFI) and the slow fuelling installation (SFI). Both FIs can be used to fuel the hydrogen trains. The FFI can fuel more trains than the SFI, but is more expensive.

The problem can be classified as a FLP, due to its characteristics to determine the opening of the SYs along with the locations of the TTs and the FIs to support the fuelling of the operating hydrogen trains. It is however important to note that this problem does differ from the classic FLP, mainly because of the multi-levels of decision-making. This problem involves two levels: the SY network level and the fuelling infrastructure within each SY (figure 9). Where the first higher level focuses on deciding which SYs should be used and optimally assigning operating trains to SYs, while the second lower level provides an optimal fuelling infrastructure to support the fuelling of the assigned trains to the specific SY. This multi-level nature introduce additional complexities and interactions between the decision variables and constrains. Decisions made at one level affect the possibilities and limitations at the other level, and vice versa. The optimal configuration must consider both levels, so that it takes into account the consequences of the decisions, approaching the real-world complexities. The formulated MILP allows for the determination of the optimal fuelling infrastructure configuration. It ensures that the hydrogen train fleet requirements are met and the fuelling capacity is efficiently allocated, while minimising costs.

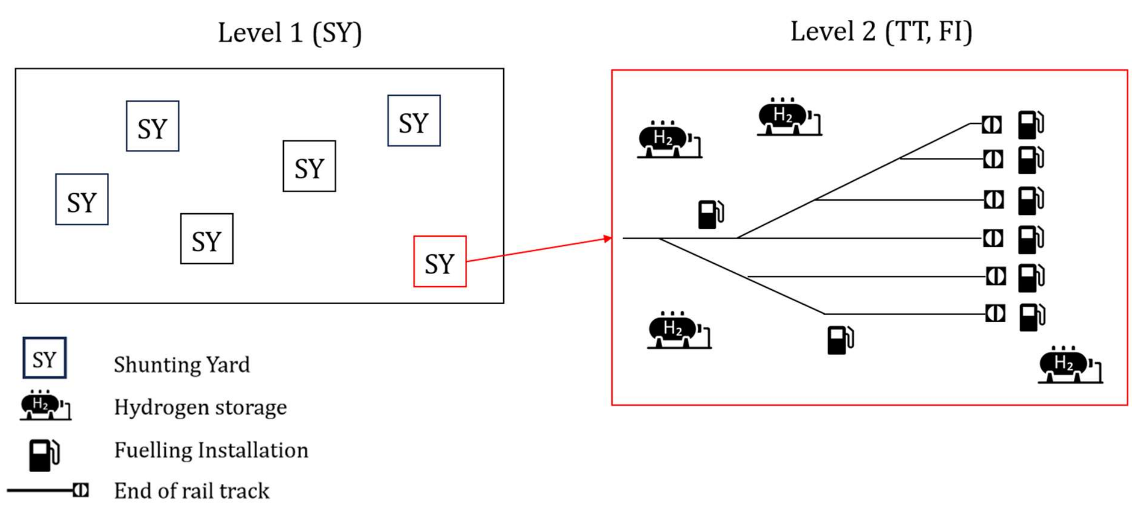


Figure 9 The multi-level nature of the fuelling infrastructure problem

4.2 Model Formulation

Sets

$$I = the\ set\ of\ SYs$$

$$J_i = The\ set\ potential\ TT\ locations\ at\ SY\ i$$

$$K_i = The\ set\ of\ potential\ FFI\ location\ at\ SY\ i$$

$$L_i = The\ set\ of\ potential\ SFI\ location\ at\ SY\ i$$

$$N = the\ set\ of\ operating\ trains$$

$$R = the\ set\ of\ final\ stations\ from\ the\ timetable$$

Parameters

$$\alpha_i = cost\ of\ opening\ SY\ i$$

$$\beta_{ij} = cost\ of\ locating\ TT\ j\ at\ SY\ i$$

$$\gamma_{ik} = cost\ of\ locating\ FFI\ k\ at\ SY\ i$$

$$\delta_{il} = cost\ of\ locating\ SFI\ l\ at\ SY\ i$$

$$\varepsilon_{ijk} = pipeline\ length\ (m)\ from\ TT\ j\ to\ FFI\ k\ at\ SY\ i$$

$$\tau_{ijk} = pipeline\ length\ (m)\ from\ TT\ j\ to\ SFI\ l\ at\ SY\ i$$

$$g = costs\ per\ meter\ pipeline\ and\ H2\ unit\ flow$$

$$\rho_{irn} = distance\ (km)\ from\ final\ station\ r\ to\ SY\ i\ travelled\ by\ train\ n$$

$$s = costs\ per\ km\ traveled\ from\ final\ station\ to\ SY\ i$$

$$d = number\ of\ trains\ which\ can\ be\ fuelled\ by\ 1\ TT$$

$$e = number\ of\ trains\ which\ can\ be\ fuelled\ by\ 1\ FFI\ per\ night$$

$$f = number\ of\ trains\ which\ can\ be\ fuelled\ by\ 1\ SFI\ per\ night$$

$$C_i = maximal\ number\ of\ trains\ that\ can\ be\ stationed\ at\ SY\ i$$

$$M = J_i + L_i + K_i\ , large\ number\ (M)$$

Decision variables

$$x_i = \begin{cases} 1 & if\ \ SY\ i\ opened \\ 0 & otherwise \end{cases}$$

$$y_{ij} = \begin{cases} 1 & if\ TT\ is\ located\ at\ j\ is\ at\ SY\ i \\ 0 & otherwise \end{cases}$$

$$z_{ik} = \begin{cases} 1 & if\ fast\ FI\ is\ located\ at\ k\ at\ SY\ i \\ 0 & otherwise \end{cases}$$

$$u_{il} = \begin{cases} 1 & if\ slow\ FI\ is\ located\ at\ l\ at\ SY\ i \\ 0 & otherwise \end{cases}$$

$$v_{in} = \begin{cases} 1 & if\ train\ n\ is\ assigned\ to\ SY\ i \\ 0 & otherwise \end{cases}$$

$$a_{ij} \quad \in [0, \dots, A], \qquad units * H2\ flow\ from\ TT\ j\ to\ FFI\ k\ at\ SY\ i$$

$$b_{ijl} \in [0, \dots, B], \qquad units\ H2\ flow\ from\ TT\ j\ to\ SFI\ l\ at\ SY\ i$$

Subject to

Maximum capacity constraint for SYs

$$\sum_{n \in N} v_{in} \leq C_i x_i \ , \qquad \forall\, i \in I$$

FI and TT can only be placed at a open SY

$$\sum_{l \in L} u_{il} + \sum_{k \in K_i} z_{ik} + \sum_{j \in J_i} y_{ij} \leq M x_i, \qquad \forall\, i \in I$$

Assignment constraint for trains

$$\sum_{i \in I} v_{in} = 1, \qquad \forall\, n \in N$$

The units H2 supplied from the TTs to the FIs through the pipelines should be equal to the number of trains at SY i. To make the model better tractable, in the constraint the units H2 supplied are equal to or greater than the number of trains. Since the model minimises the costs, the flow through the pipeline will also be minimised, resulting in the flow being equal to the number of trains.

$$\sum_{j \in J_i} \sum_{k \in K_i} a_{ijk} + \sum_{j \in J_i} \sum_{l \in L_i} b_{ijl} \geq \sum_{n \in N} v_{in}\, , \qquad \forall\, i \in I$$

Maximum fuelling capacity constraint for FFI

$$\sum_{j \in J_i} a_{ijk} \leq e z_{ik}, \qquad \forall\, i \in I, k \in K_i$$

Maximum fuelling capacity constraint for SFI

$$\sum_{j \in J_i} b_{ijl} \leq f u_{ik}, \qquad \forall\, i \in I, l \in L_i$$

Maximum storage capacity constraint for TTs

$$\sum_{k \in K_i} a_{ijk} + \sum_{l \in L_i} b_{ijl} \leq d y_{ij}, \qquad \forall\, i \in I, j \in J_i$$

Variable Domain

$$x_i, y_{ij}, z_{ik}, u_{il}, v_{in} \in \{0,1\}, \qquad \forall\, i \ \in I, j \in J_i, k \in K_i, l \in L_i, n \in N$$

Non-negativity constraint for a_{ijk} and b_{ijl} as continuous variables

$$a_{ijk}, b_{ijl} \geq 0, \qquad \forall\, i \ \in I, j \in J_i, k \in K_i, l \in L_i$$

[*] $1\ unit\ is\ the\ amount\ of\ H2\ need\ to\ fuel\ 1\ train$

Objective Function

The aim is to minimise the total cost spend on the fuelling infrastructure of N hydrogen trains, resulting in the objective function

$$MIN\ f(x_i, v_{in}, y_{ij}, z_{ik}, u_{il}, a_{ijk}, b_{ijl}) = \sum_{i\in I}(\alpha_i x_i) + \sum_{i\in I}\sum_{n\in N}\sum_{r\in R} s\rho_{irn} v_{in} + \sum_{i\in I}\sum_{j\in J_i}(\beta_{ij} y_{ij}) + \sum_{i\in I}\sum_{k\in K_i}(\gamma_{ik} z_{ik}) + \sum_{i\in I}\sum_{l\in L_i}(\delta_{il} u_{il}) + \sum_{i\in I}\sum_{j\in J_i} g\left(\sum_{k\in K_i}\varepsilon_{ijk} a_{ijk} + \sum_{l\in L_i}\tau_{ijl} b_{ijl}\right)$$

The formulation of a FLP objective consist out of two parts: the opening costs and the transportation costs. Since it is a multi-level FLP, the opening costs and the distance costs are calculated for both the SY network level and the fuelling infrastructure within each SY level. The first two term found in the objective function are respectively the opening costs of a SY and the travelling costs of trains to SYs. The following 3 terms are the location costs of the TTs, FFIs and SFIs respectively. The last term of the objective function covers the pipeline costs between the TTs and FFIs and/or SFIs. Due to the minimisation, the cost optimal solution to the fuelling infrastructure problem will be provided as output by the decision variables.

4.3 Stylized example of the sequenced model

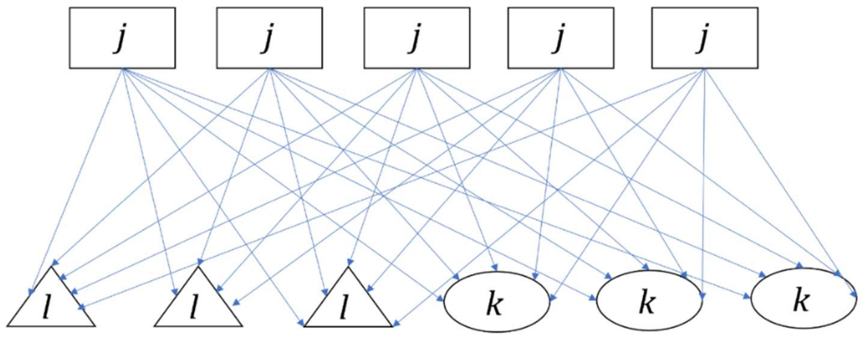


Figure 10 The potential TT-FI combinations at a SY

i = 1

d = 14

e = 12

f = 1

$J_1 = \{1, \ldots, 5\}$

$K_1 = \{1,2,3\}$

$L_1 = \{1,2,3\}$

$\sum_m v_{1m} = 14$

$$\varepsilon_{1jk} \begin{bmatrix} 13 & 17 & 20 \\ 8 & 11 & 16 \\ 2 & 9 & 12 \\ 4 & 3 & 7 \\ 7 & 6 & 3 \end{bmatrix} \; and \; \tau_{1jl} \begin{bmatrix} 2 & 3 & 7 \\ 5 & 2 & 3 \\ 9 & 6 & 3 \\ 14 & 10 & 8 \\ 18 & 13 & 11 \end{bmatrix}$$

A stylized example (see figure 10) of a fuelling infrastructure within a given SY, in section 4.3 referred to as the second level, will be provide at this section. At this SY 5 potential TT locations, 3 potential SFI location and 3 FFI locations have been determined. The pipeline lengths TTs to the FIs is given is the matrices ε_{1j} and τ_{1jk}. For instance the length from the fourth TT to the second FFI (a_{142}) is equal to 3 meters. After respecting all the constraints, the objective function can be calculated. In this scenario, 14 trains will go to SY i = 1. Therefore, the total units H2 supplied through the pipelines must be equal to at least 14. Since the costs increases with 1.4 per unit flow when suppling more hydrogen through the pipelines than necessary, the amount supplied over through the pipelines will be equal to 14. The total potential fuelling capacity of the shunting yard is 20 trains, since the 5 potential hydrogen storages together can support the fuelling of 20 trains, while the fuelling installations together can fuel 39 trains.

Lets assume that the costs of locating a hydrogen storage at a shunting yard is the same for all potential locations. Three different solutions to this situation are discussed to illustrate the problem All solutions are found without the use of a solver or other solution method. The first solution minimises the location cost, the second solution minimises the pipeline costs and the third proposes a solution with a balance between the location and flow costs.

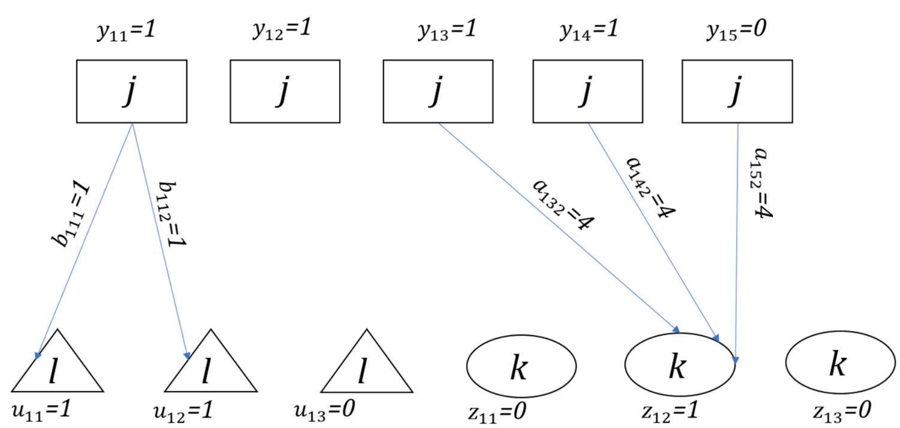


Figure 11 Solution 1 of the stylized example

In the first solution (figure 11), the SFIs will be located at position 1 and 2, and a FFI will be located at position 2. Regarding the TTs, locations 1, 3, 4 and 5 will be used to locate a TT. However, only 14 trains can be fuelled according to the supplied units H2 through the pipelines. The pipeline costs (flow costs) will be

$$\sum_{j\in J_i} g\left(\sum_{k\in K_i} \varepsilon_{ijk} a_{ijk} + \sum_{l\in L_i} \tau_{ijl} b_{ijl}\right) = 1.4((2*1) + (3*1) + (9*4 + 3*4 + 6*4)) = 107.80$$

The total costs on locating the TTs and the FIs will be equal to

$$\sum_{j\in J_i}(\beta_{ij} y_{ij}) + \sum_{k\in K_i}(\gamma_{z_{ik}} z_{ik}) + \sum_{l\in L_i}(\delta_{u_{il}} u_{il}) = 5*4 + 29*1 + 11*2 = 71$$

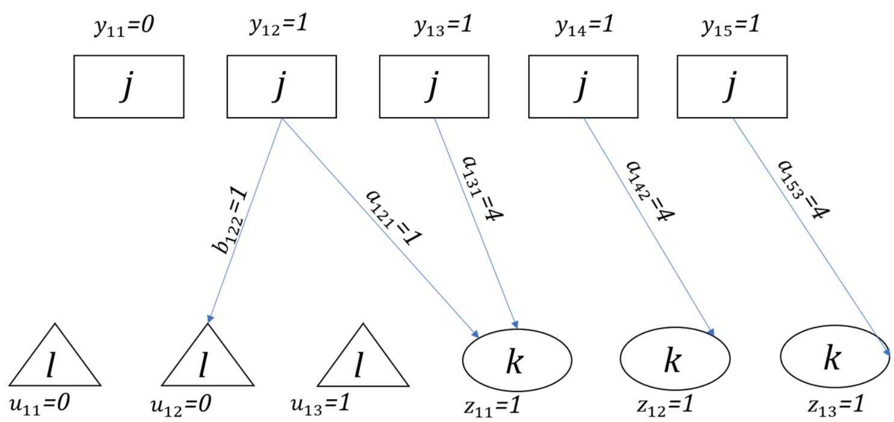


Figure 12 Solution 2 of the stylized example

The second solutions (figure 12) yields a fuelling infrastructure of 1 SFI, 3 FFI and 4 located TTs based on minimum pipeline costs, with again a total of 14 units H2 supplied through the opened pipelines. Resulting in the following flow and location costs respectively.

$$\sum_{j\in J_i} g\left(\sum_{k\in K_i} \varepsilon_{ijk} a_{ijk} + \sum_{l\in L_i} \tau_{ijl} b_{ijl}\right) = 1.4((2*1) + (8*1 + 2*4 + 3*4 + 3*4)) = 58.8$$

$$\sum_{j\in J_i}(\beta_{ij} y_{ij}) + \sum_{k\in K_i}(\gamma_{z_{ik}} z_{ik}) + \sum_{l\in L_i}(\delta_{u_{il}} u_{il}) = 5*4 + 29*3 + 11*1 = 118$$

The third solution (figure 13) opens both the third SFI, the FFIs located at 1 and 3 and TTs 2 up to 5.

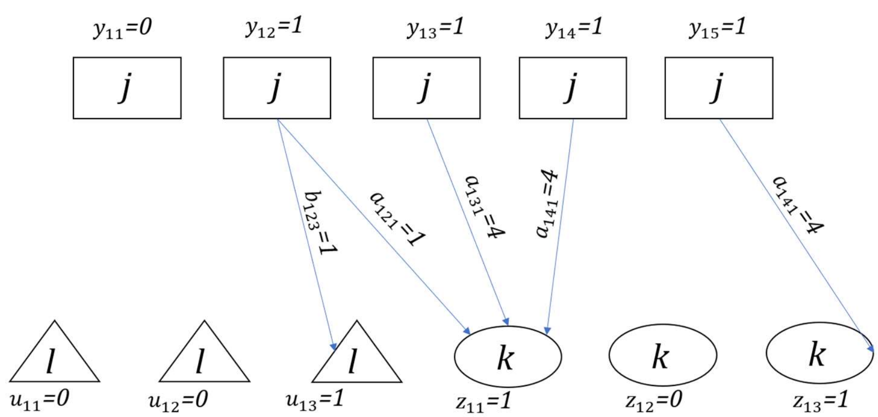


Figure 13 Solution 3 of the stylized example

$$\sum_{j\in J_i} g\left(\sum_{k\in K_i} \varepsilon_{ijk} a_{ijk} + \sum_{l\in L_i} \tau_{ijl} b_{ijl}\right) = 1.4\left((3*1) + (8*1 + 2*4 + 4*4) + (3*4)\right) = 65.8$$

$$\sum_{j\in J_i}(\beta_{ij}y_{ij}) + \sum_{k\in K_i}(\gamma_{z_{ik}}z_{ik}) + \sum_{l\in L_i}(\delta_{u_{il}}u_{il}) = (5*4) + (29*2) + (11*1) = 89$$

Now that both the flow costs and the location costs are defined, the total costs of the 3 opposed solutions can be compared in order to determine the best solution. As can be seen at table 1 solution 1 has the lowest location costs, but the highest flow costs. Solution 2 has the lowest flow costs, however, it also has the highest location costs. Solution 3 has the overall lowest total costs, even though it does not score best at the flow and location costs. Therefore, solution 3 is the best solution with a cost difference of 23 compared to both solutions.

Table 1 Comparison of the 3 opposed solutions in the stylized example

SOLUTION	FLOW COSTS	LOCATION COSTS	TOTAL COSTS
1	107,80	71,-	178,80
2	58.80	118,-	178,20
3	65.80	89,-	154,80

This is only a small part of the entire problem, since opening the shunting yard also adds costs, together with the costs of travelling from the final station to the shunting yard for each train.

4.4 Conclusion

The problem involves designing an optimal fuelling infrastructure of hydrogen trains, aiming to minimise costs while meeting the fuelling capacity requirements. The problem is formulated as a MILP, with the including decision variables being the opening of SYs, the location of TTs and FIs. The constraints ensure that the capacity meets the required demand. Due to its multi-level nature, the problem differs from the classic FLP. Strategic decisions need to be taken at the SY network level and the fuelling infrastructure within each SY needs to be designed. These levels interact, influencing the limitations and possibilities at each level. The stylized example shows the trade-off between minimising the flow costs and the location costs. The best solution does not require the lowest possible flow costs and location cost, but the lowest total cost. To find a good balance between the trade-off is difficult, since opening the shortest pipeline costs may be more expensive in the end than open longer pipeline costs but fewer FIs. Therefore, focussing on only some of the cost components may result in suboptimal solutions, as shown in the example. Resulting in the need for a heuristic algorithm approaching the balance of the cost-optimal component trade-off.

5. Solving method

5.1 Heuristic overview

In order to address the model described in section 4.2, it is necessary to develop an appropriate solving approach. The complexity of the model poses challenges in obtaining an exact solution, as it can be a time-consuming task to solve. Solvers such as Gurobi and Cplex encounter difficulties in tackling problems characterized by a high level of complexity, primarily due to the presence of a large number of binary variables and interdependencies among variables. The solver algorithms may struggle to identify the optimal solution within a reasonable timeframe when solving a model with many binary variables. Exact methods can become computationally infeasible with the presence 5 sets of binary decision variables. The total number of possible combinations of binary decisions grow exponentially with the number of variables. Furthermore, the inclusion of continuous variables further amplifies the complexity of the solving process.

A solution method for the model described in section 4.2 is a constructive heuristic algorithm. Constructive heuristics trade-off optimality for computational efficiency. This solution method approach builds a feasible solution step by step, focusing on promising region of the solution space, while exact solution methods explore the entire search space. Constructive heuristics guarantee a feasible solution, by iteratively constructing a solution by making optimal decisions locally at each step (Lai, et al., 2022). While they may not guarantee finding the optimal solution, often the find a good solution within a reasonable amount of time (Argenziano, et al., 2019). Another advantage of using constructive algorithms is that they can be tailored to create problem-specific knowledge. By incorporating problem specific insights, such as putting the focus on minimising the flow costs or the location costs, constructive heuristics can achieve better solutions according to the objective of the problem owner.

The method developed decomposes the problem into 2 levels, and applies a heuristic to each level sequentially:

I. Assigning all trains to shunting yards.
II. Determining the number and location(s) of the TT(s), FFI(s) and SFI(s), together with the hydrogen flow through the pipelines.

These levels are in line with the earlier mentioned levels in section 4.1 At each level, there are two heuristic algorithms available for consideration. The level 1 and 2 combined heuristics follow the greedy procedure. Since the objective function includes two categories of costs, namely the opening location costs and the distance costs, the formulated heuristics for both levels will aim to minimise either the opening costs associated with the locations or the distance costs.

The heuristics across the levels can be used in four different solving combinations (figure 14):

1. H1+G1
2. H1+G2
3. H2+G1
4. H2+G2

For each of the four combinations discussed above, the total costs, as defined by the objective function in section 4.2, can be computed. Subsequently, the combination resulting in the lowest total costs can be selected as the final solution to the problem. While this solving method yields a good solution, it may not guarantee an optimal solution, since the use of a heuristic may not lead to the exact optimal solution. It is a sequential approach. Even if the optimal solution at both levels have been determined, the full solution may not be optimal.

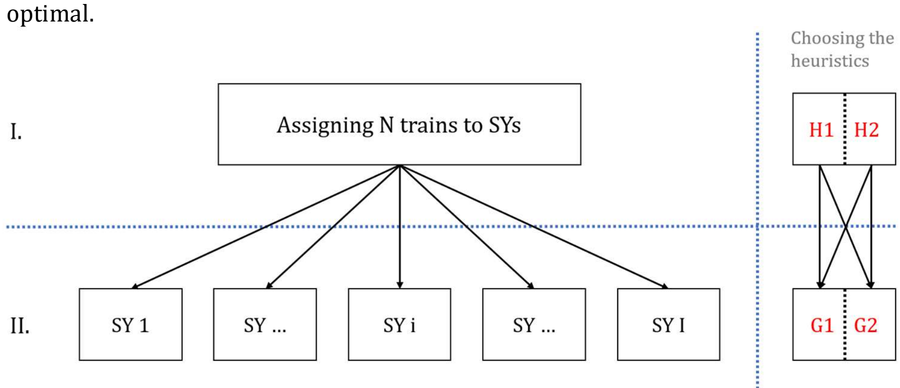


Figure 14 Multi-level problem solving approach

5.2 First-Level heuristics

For level I, one of the following heuristics can be applied:

H1. The train with the largest minimal distance (MAXMIN) from its final station to a SY will be allocated to that SY. If a station is relatively distant from an SY, priority is given to allocating the train to the SY with the smallest minimal distance. So it maximises across trains and minimises across SYs. This approach is driven by the fact that the impact on the total travelled distance of all trains is greater when a train's final destination is situated further away from the SY compared to trains with destinations closer. The heuristic proceeds by assigning the train with the largest minimal distance to an SY, followed by assigning the train with the second largest minimal distance to an SY. This process continues until all N trains have been assigned to an SY, while ensuring compliance with all model constraints. When an SY reaches its capacity, no further trains can be allocated to that particular SY.

H2. The allocation of trains will be prioritized based on the shunting yard (SY) with the lowest opening costs, until either the SY's capacity has been reached or all trains can be assigned to that particular SY. The trains with the shortest distances to this SY will be assigned. If the capacity of the SY has been reached, trains will then be allocated to the SY with the second lowest opening costs. This allocation process continues iteratively until all trains have been assigned to the SYs, while ensuring compliance with all model constraints.

When comparing the two heuristics, it becomes evident that they adopt distinct optimization approaches. H1 focuses on minimizing the travel distance of trains to the shunting yards (SYs), thereby reducing travel costs. However, this heuristic does not consider the variations in opening costs among the SYs, which may result in the selection of more expensive SYs. Conversely, the second heuristic prioritizes the minimization of opening costs but does not optimize travel costs. Opting for SYs with lower opening costs may necessitate trains to traverse longer distances, leading to higher travel costs. Hence, a trade-off exists between opening costs and travel costs in both heuristics. H1 optimizes the travel costs, while H2 optimizes the opening costs Employing both heuristics in solving the problem can offer valuable insights into both aspects of the trade-off.

5.3 Second-level heuristics

For level II the following heuristics can be used to solve the model:

G1. At an open SY, the TT-FI combination with the smallest pipeline connection will be opened. The maximum permissible hydrogen flow through the pipeline will then be determined, taking into account the relevant constraints. This entails setting the upper bound of the pipeline flow as either the maximum hydrogen capacity of the TT or the maximum number of trains that the FFI or SFI can fuel. Subsequently, the second smallest pipeline distance from a TT to an FFI or SFI will be considered, while ensuring the largest possible flow through the pipeline that adheres to the constraints. This process is repeated until the flow of hydrogen units is equivalent to the number of trains assigned to the SY. The aforementioned procedure is also applied to the other opened SY.

G2. The FI with the lowest cost (SFI or FFI) will be opened. The selected FI will then be allocated to the TT with the shortest pipeline length to that particular FI. The determination of the maximum feasible flow through the pipeline will take place, while ensuring compliance with all the constraints stipulated by the model. This flow will be directed from the opened TT to the assigned FI. If the maximum capacity of the FI to receive units of H2 has not been reached after establishing the initial connection, the second shortest pipeline length to a TT connected to this FI will be opened. This process continues until the total flow of H2 units into the FI matches the maximum allowable flow capacity of the FI. Once this maximum capacity is reached, the subsequent FI with the next lowest opening costs will be considered, following the same procedure as before. This sequence of opening TTs and FFIs/SFIs will persist until the flow of hydrogen units is equal to the number of trains assigned to the respective SY. The same procedure will be applied to any other open SYs.

There is again a trade-off which can be found between the heuristics in level 2. G1 primarily focuses on optimizing the pipeline length, without considering the location costs associated with the FFIs and SFIs. This approach of prioritizing TT-FI combinations solely based on the shortest pipeline lengths may lead to opening more fuelling installations than needed based on their maximum capacity. This may cause the TT's not supplying the maximum amount of H2 units which a FI can hold. Conversely, G2 emphasizes the location costs of the FIs by connecting TTs to the cheapest available FI until the maximum allowable H2 units capacity of the FI is reached. This ensures optimal utilization of each opened FI. However, the process of achieving this may involve opening pipelines with longer lengths, while alternative FIs with shorter pipelines could have been chosen. Consequently, this leads to higher pipeline costs but lower location costs. By computing both heuristics in the second level, valuable insights can be obtained in both directions of optimization.

5.4 Stylized example of the sequenced heuristics

The computational procedures of heuristics H1 and H2 are better to understand than those of G1 and G2. To facilitate comprehension, the utilization of G1 and G2 will be explicated through their application on the example presented in section 4.3. Furthermore, a more comprehensive exposition of heuristics H1 and H2 will be provided in the context of the PG case study, detailed in section.

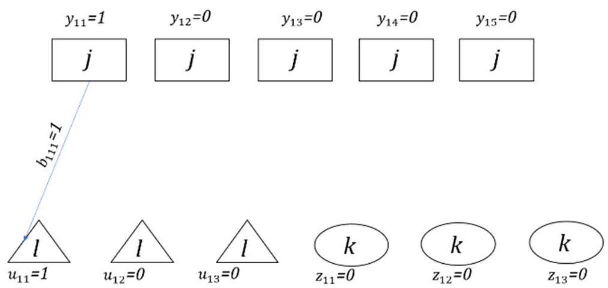


Figure 15 1st Iteration of the G1 heuristics

The shortest pipeline length is *2* over the pipeline $b_{1,1,1}$. Therefore, TT 1 (y_{11}) and SFI 1 (u_{11}=*1*) will be opened. Since the maximum flow allowed flow of a SFI is 1, TT 1 will supply $b_{1,1,1} = 1$. SFI 1 cannot receive anymore units. The total number of trains which can be fuelled now at this SY is equal to 1.

$$\tau_{1jl}\begin{bmatrix} 2 & 3 & 7 \\ 5 & 2 & 3 \\ 9 & 6 & 3 \\ 14 & 10 & 8 \\ 18 & 13 & 11 \end{bmatrix} \text{ and } \varepsilon_{1jk}\begin{bmatrix} 13 & 17 & 20 \\ 8 & 11 & 16 \\ 2 & 9 & 12 \\ 4 & 3 & 7 \\ 7 & 6 & 3 \end{bmatrix}$$

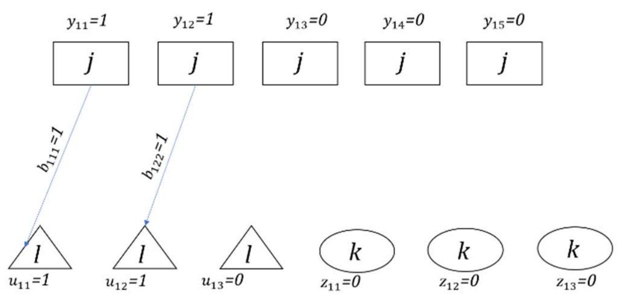


Figure 16 2nd Iteration of the G1 heuristics

The next shortest pipeline length is again 2, but now from y_{12} to u_{12}. Again the maximum allowed flow is 1 unit over b_{122}. The total number of trains which can be fuelled now is equal to 2.

$$\tau_{1jl}\begin{bmatrix} - & 3 & 7 \\ - & 2 & 3 \\ - & 6 & 3 \\ - & 10 & 8 \\ - & 13 & 11 \end{bmatrix} \text{ and } \varepsilon_{1jk}\begin{bmatrix} 13 & 17 & 20 \\ 8 & 11 & 16 \\ 2 & 9 & 12 \\ 4 & 3 & 7 \\ 7 & 6 & 3 \end{bmatrix}$$

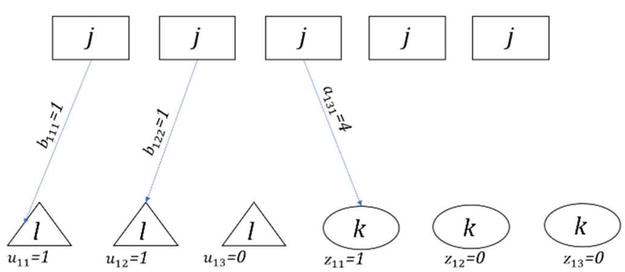


Figure 17 3rd Iteration of the G1 heuristics

In the next iteration the shortest distance is 2, from y_{13} to z_{11}, but this time the units flow over the pipeline a_{131} is equal to 4, since the maximum allowed flow from a TT (y_i) in this instance is 4, and the maximum allowed flow to enter a FFI (a_{ijk}) is 12. The total number of trains which can be fuelled now is equal to 6.

$$\tau_{1jl}\begin{bmatrix} - & - & 7 \\ - & - & 3 \\ - & - & 3 \\ - & - & 8 \\ - & - & 11 \end{bmatrix} \text{ and } \varepsilon_{1jk}\begin{bmatrix} 13 & 17 & 20 \\ 8 & 11 & 16 \\ 2 & 9 & 12 \\ 4 & 3 & 7 \\ 7 & 6 & 3 \end{bmatrix}$$

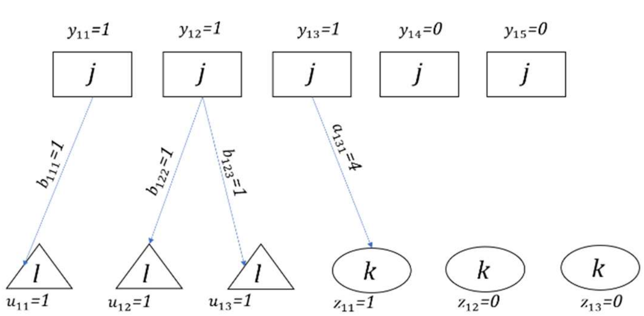


Figure 18 4th Iteration of the G1 heuristics

The next shortest distance is from y_{12} to u_{13} with a flow of 1 unit b_{123}. y_{12} Is now connected to SFI, making resulting in only 2 units left to sent away. The total number of trains which can be fuelled now is equal to 7.

$$\tau_{1jl}\begin{bmatrix} - & - & 7 \\ - & - & 3 \\ - & - & - \\ - & - & 8 \\ - & - & 11 \end{bmatrix} \text{ and } \varepsilon_{1j}\begin{bmatrix} 13 & 17 & 20 \\ 8 & 11 & 16 \\ - & - & - \\ 4 & 3 & 7 \\ 7 & 6 & 3 \end{bmatrix}$$

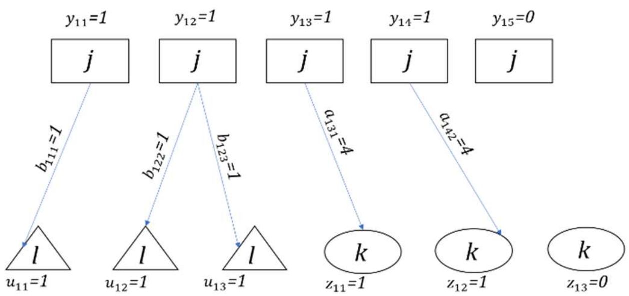


Figure 20 5th Iteration of the G1 heuristics

The next shortest distance is from y_{14} to z_{12} with a flow of 4 units from a_{142}. The total number of trains which can be fuelled now is equal to 11.

$$\tau_{1jl}\begin{bmatrix} - & - & - \\ - & - & - \\ - & - & - \\ - & - & - \\ - & - & - \end{bmatrix} \text{ and } \varepsilon_{1jk}\begin{bmatrix} 13 & 17 & 20 \\ 8 & 11 & 16 \\ - & - & - \\ 4 & 3 & 7 \\ 7 & 6 & 3 \end{bmatrix}$$

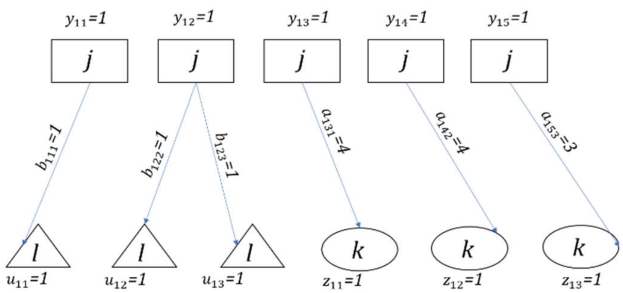


Figure 19 Final iteration of the G1 heuristics

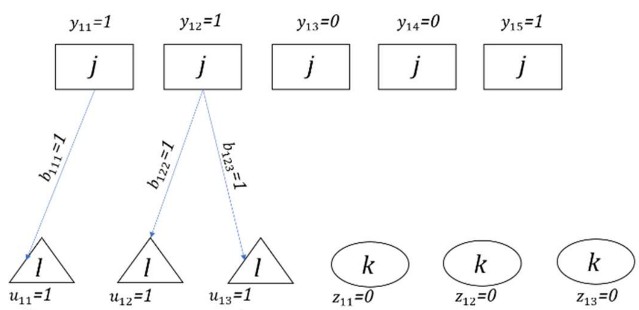
The final iteration connects y_{15} to z_{13} with a flow of 3 units over a_{153}. Only 3 units have been assigned over the pipeline, since the sum of units over all pipelines is now equal to the total number of trains that must be fuelled at this SY. Therefore, the total number of trains which can be fuelled now is equal to 14 and the final solution using heuristic G1 has been found.

$$\tau_{1jl}\begin{bmatrix} - & - & - \\ - & - & - \\ - & - & - \\ - & - & - \\ - & - & - \end{bmatrix} \text{ and } \varepsilon_{1jk}\begin{bmatrix} 13 & 17 & 20 \\ 8 & 11 & 16 \\ - & - & - \\ - & - & - \\ 7 & 6 & 3 \end{bmatrix}$$

The associated flow and location costs to this solution are:

$$\sum_{j\in J_i} g\left(\sum_{k\in K_i} \varepsilon_{ijk} a_{ijk} + \sum_{l\in L_i} \tau_{ijl} b_{ijl}\right) = 1.4\left((2*1+2*1+3*1)+(2*4+3*4+3*3)\right) = 50.4$$

$$\sum_{j\in J_i}(\beta_{ij} y_{ij}) + \sum_{k\in K_i}(\gamma_{z_{ik}} z_{ik}) + \sum_{l\in L_i}(\delta_{u_{il}} u_{il}) = 5*5+29*3+11*3 = 145$$



Heuristic G2 focusses on minimizing the location costs. Firstly all SFIs will be assigned to a TT, after which the FFIs will be opened, until the units supplied over the arcs is equal to 14. After the first three iterations all SFI have been assigned to the TTs with the smallest pipeline distance. The total number of trains which can be fuelled now is equal to 3.

$$\tau_{1jl}\begin{bmatrix} - & - & - \\ - & - & - \\ - & - & - \\ - & - & - \\ - & - & - \end{bmatrix} \text{ and } \varepsilon_{1jk}\begin{bmatrix} 13 & 17 & 20 \\ 8 & 11 & 16 \\ 2 & 9 & 12 \\ 4 & 3 & 7 \\ 7 & 6 & 3 \end{bmatrix}$$

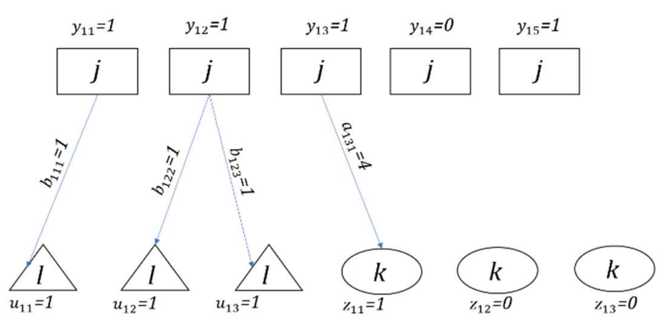


Figure 22 2nd Iteration of the G2 heuristics

Next, the first FFI will be opened and TTs with the smallest distance will be assigned until the maximum of the FFI has been reached or until the total sum of units is equal to 14. z_{11}Will first be connected to y_{13} setting the units over a_{131} equal to the maximum of 4 units. The total number of trains which can be fuelled now is equal to 7

$$\tau_{1jl}\begin{bmatrix} - & - & - \\ - & - & - \\ - & - & - \\ - & - & - \\ - & - & - \end{bmatrix} \text{ and } \varepsilon_{1jk}\begin{bmatrix} 13 & 17 & 20 \\ 8 & 11 & 16 \\ 2 & 9 & 12 \\ 4 & 3 & 7 \\ 7 & 6 & 3 \end{bmatrix}$$

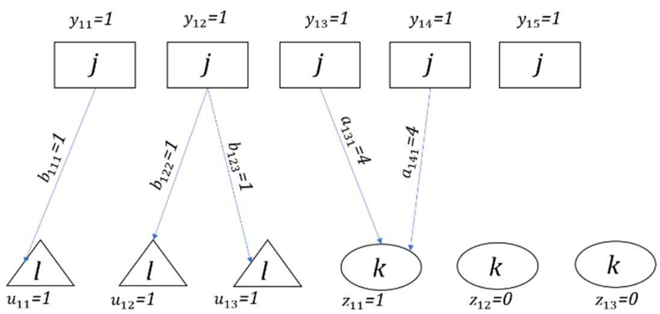


Figure 23 3rd Iteration of the G2 heuristics

The next TT which will be opened is y_{14} with unit flow of 4 over pipeline a_{141}. z_{11} now receives 8 units in total. The total number of trains which can be fuelled now is equal to 11

$$\tau_{1jl}\begin{bmatrix} - & - & - \\ - & - & - \\ - & - & - \\ - & - & - \\ - & - & - \end{bmatrix} \text{ and } \varepsilon_{1j}\begin{bmatrix} 13 & 17 & 20 \\ 8 & 11 & 16 \\ - & - & - \\ 4 & 3 & 7 \\ 7 & 6 & 3 \end{bmatrix}$$

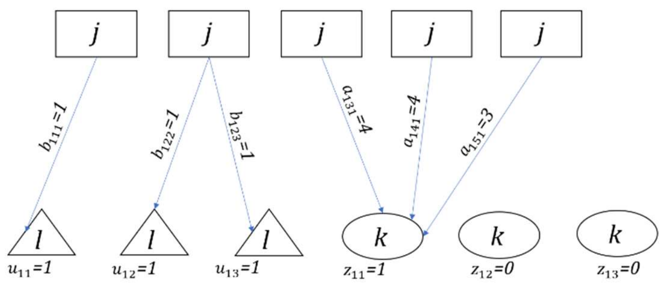


Figure 24 Final iteration of the G2 heuristics

The next and final iteration opens TT y_{15} with a supply of 3 units over pipeline a_{151}. This will put the total number of trains which can be fuelled now to 14.

$$\tau_{1jl}\begin{bmatrix} - & - & - \\ - & - & - \\ - & - & - \\ - & - & - \\ - & - & - \end{bmatrix} \text{ and } \varepsilon_{1j}\begin{bmatrix} 13 & 17 & 20 \\ 8 & 11 & 16 \\ - & - & - \\ - & - & - \\ 7 & 6 & 3 \end{bmatrix}$$

The associated flow and location costs to this solution are:

$$\sum_{j\in J_i} g\left(\sum_{k\in K_i} \varepsilon_{ijk}a_{ijk} + \sum_{l\in L_i} \tau_{ijl}b_{ijl}\right) = 1.4((2*1+2*1+3*1)+(2*4+4*4+7*3)) = 72.8$$

$$\sum_{j\in J_i}(\beta_{ij}y_{ij}) + \sum_{k\in K_i}(\gamma_{z_{ik}}z_{ik}) + \sum_{l\in L_i}(\delta_{u_{il}}u_{il}) = 5*5+29*1+11*3 = 87$$

Comparing both heuristic can be done by comparing the flow cost, the location costs and the total costs, which can be found at table 2.

Table 2 Comparison of the G1 and G2 heuristics applied on the stylized example

	Flow costs	**Location costs**	**Total costs**
G1	50.5	145	195,4
G2	72.8	87	159.8

The difference in flow costs between the solutions obtained using heuristics G1 and G2 is as expected. G1, which focuses on minimizing flow costs, tends to have higher location costs compared to G2. However, it is important to note that the total costs obtained through the heuristic G1 is significantly higher than the solutions discussed in section 4.3. Therefore, it is crucial to note that while heuristics offer a satisfactory solution, they do not provide the optimal solution. Heuristic G2 yields a better solution than G1. However, the third solution from section 4.3 still yields a better solution. Therefore, a new heuristic (G3) will be introduced in order to retrieve a better solution.

5.4 Combined Heuristic for the second-level

As mentioned before, heuristic G1 and G2 minimise either the flow costs or the pipeline costs, subsequently, but not the overall costs. Therefore, another heuristic (G3) has been created in order to find the balance between minimising flow costs and location costs at SY level. It keeps track of the already opened locations by making it more attractive to connect a new TT to an already opened FI event while taking into account the pipeline costs. The heuristic works as follows:

1. Calculate the average of the 3 smallest pipeline distances from the TT to the FFI, for each FFI.
2. Open the FI with the smallest pipeline distance to a TT. Take for the FFI the averages calculated at step 1 and for the SFI the smallest pipeline distance to a TT.
3. Assign the maximum flow through the opened pipeline.
4. Continue to the opening of the next pipeline.

a. If the next smallest distance to a TT is connected to an already opened FFI, open this new combination with a maximum possible flow through the pipeline and return to the beginning of step 4. If not continue to b.
b. If all previously opened FIs are only SFIs and the next smallest distance is from a SFI to a TT, this combination will be opened and return to the beginning of step 4. If not continue to c.
c. Calculate the following:
    i. For the already opened FFIs (calculate this for all already opened FFIs):
    FFI location costs * (currently max allowed flow through the pipelines)/max allowed flow to the FFI + smallest unopened TT distance to this FFI * max allowed flow through this pipeline * yearly costs per m, per flow pipeline
    ii. In case the smallest pipeline distance goes from a TT to an unopened FFI:
    FFI location costs + smallest unopened TT distance to this FFI * max allowed flow through this pipeline * yearly costs per m, per flow pipeline
    iii. In case the smallest pipeline distance goes from a TT to a unopened SFI:
    SFI location costs + smallest unopened TT distance to the SFI * yearly costs per m

5. Open the combination with the lowest costs from step 4.
6. Return to step 4 and continue with step 4 and 5 until the opened FFI has reached its max capacity or the total flow through all pipelines is equal to the number of trains.
7. Return to step 1 if the total flow through all pipelines is not equal to the number of trains, otherwise the final solution has been found and the total costs can be calculated by using the objective function.

At step 1 the average pipeline distance of the 3 smallest pipeline lengths of all FFI's is being calculated so that the FFI with the lowest average will be chosen over the other, which results in lower costs when using the maximal capacity of the FFI's. Step 2 ensures that the FI's with the smallest pipeline distance will be opened after which the maximum possible flow will be assigned over this pipeline (step 3). Step 4 focusses on opening a new pipeline by comparing the location costs of the FI's with the smallest pipeline costs. The location costs will be recalculated of the already opened FFI(s), by taking into account how much of the maximum capacity has been used. The closer the opened FFI is to its max capacity, the least costs will be incurred for the location costs. For instance a FFI which has receives a flow of 4 units, costs more than a FFI which receives a flow 8 units. Making it more attractive to use the already opened FFI, reducing the overall location costs. This results in minimising the opening of new FI's while other already opened FFI's have not been efficiently used. The recalculated location costs will then be added to the smallest pipeline length of this FFI's and will be compared to the sum of opening the new FFI with a smaller pipeline length. Despite the higher location costs of the new FFI, the total sum could be lower due to much lower flow costs, than the already opened FFI's. Comparing the different costs of the different decisions, results in minimising both the flow costs and the location costs. This heuristic has been tested at the PG Problem in section 6.2.

5.5 Conclusion

A Mixed Integer Linear Programming (MILP) problem has been formulated. It is a mathematical simplification of reality, based on assumptions, that captures the main features of the problem faced by PG. The objective function contains 5 sets of binary and 2 sets of continuous decision variables, with some interdependencies, making it complex to solve. Due to the complexity of the model and the large problem size of the PG problem, a solver could struggle to find the optimal solution within a reasonable timeframe. Constructive heuristics are applied, due to their characteristics of finding a good balance between the computation time, solution quality and flexibility. The problem has been split in two levels. This not only simplifies the solving, it allows for the application of different heuristics to parts of the problem, in order to find the best heuristic match. Different combinations of heuristics can be tested, after which the combination with the best solution can be chosen as final solving method. In level 1 two different heuristics could be applied. Heuristic H1 focusses on minimizing the travelling costs of the trains from the final station to shunting yard, while heuristic H2 minimizes the opening costs of the shunting yards. At level 2, heuristic G1 minimizes the pipeline length between the tube trailers and the fuelling installations. The other heuristic which can be applied at this level is heuristic G2, which minimizes over the location costs of the fuelling installations. After computing all 4 possible heuristic combinations across the levels, the combination with the lowest final costs can be chosen. A third heuristic at the second level has been introduced in order to find a balance between G1 and G2. Heuristic G3 minimises the flow and location costs by comparing different decisions on opening pipelines, deciding whether to continue with an already opened FFI or to open a new FI's.

6. Solving the PG problem

6.1 Introducing the instance

In this research, the model will be applied to the problem described by the PG at chapter 1. Therefore, the sets and parameters used in this research will be defined.

Sets

PG is considering four potential SY locations for fuelling the hydrogen trains in 2035. The potential H2 storage locations are determined in agreement with the PG and PR.

I = {1,2,3,4} = {The Vork, Leeuwarden, Onnen, Delfzijl}

The potential TT locations are determined in agreement with the PG and PR (see appendix E for the coordinates).

$$J_i = \begin{cases} i = 1: \{1, \dots, 15\} \\ i = 2: \{1, \dots, 12\} \\ i = 3: \{1, \dots, 16\} \\ i = 4: \{1, \dots, 9\} \end{cases}$$

The potential Fast Fuelling Installation locations are determined in agreement with the PG and PR (see appendix F for the coordinates).

$$K_i = \begin{cases} i = 1: \{1, \dots, 10\} \\ i = 2: \{1, \dots, 5\} \\ i = 3: \{1, \dots, 5\} \\ i = 4: \{1, \dots, 4\} \end{cases}$$

The potential Slow Fuelling Installation locations are determined in agreement with the PG and PR (see appendix G for the coordinates).

$$L_i = \begin{cases} i = 1: \{1, \dots, 8\} \\ i = 2: \{1, \dots, 7\} \\ i = 3: \{1, \dots, 5\} \\ i = 4: \{1, \dots, 4\} \end{cases}$$

The locations at the four different SY can be found at the figures below. The track layout is retrieved from Sporenplan after which the potential TT ($y_{ij,}$), FFI (z_{ik}) and SFI (u_{il}) locations have been added.

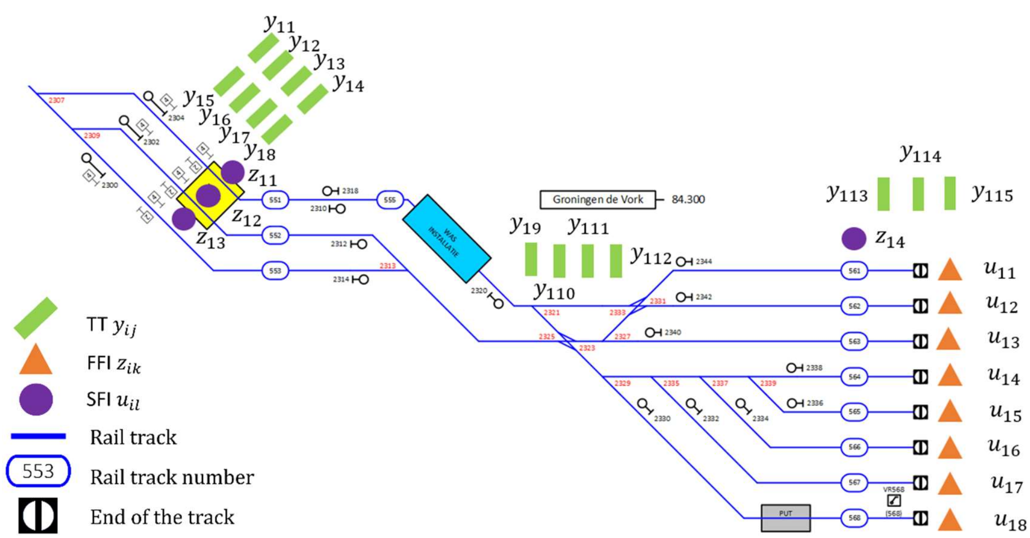


Figure 25 SY The Vork: potential TT, FFI & SFI locations

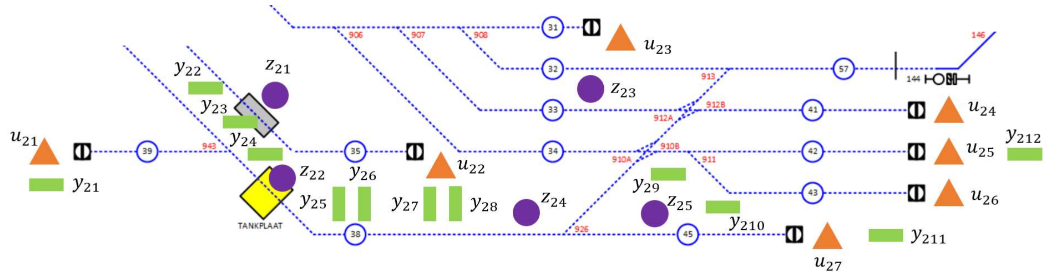


Figure 26 SY Leeuwarden: potential TT, FFI & SFI locations

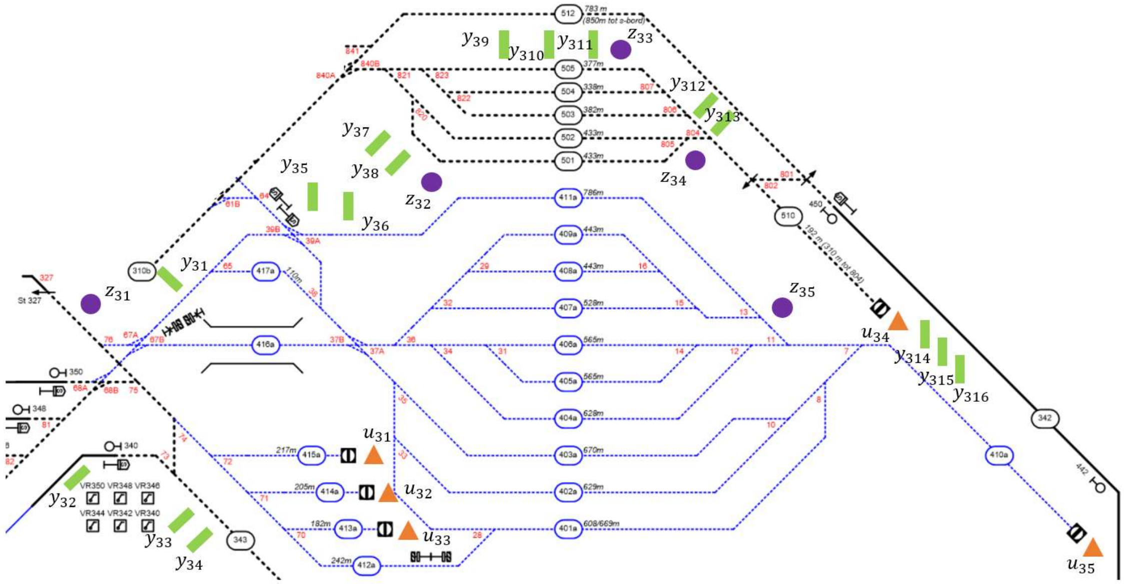


Figure 27 SY Onnen potential TT, FFI & SFI locations

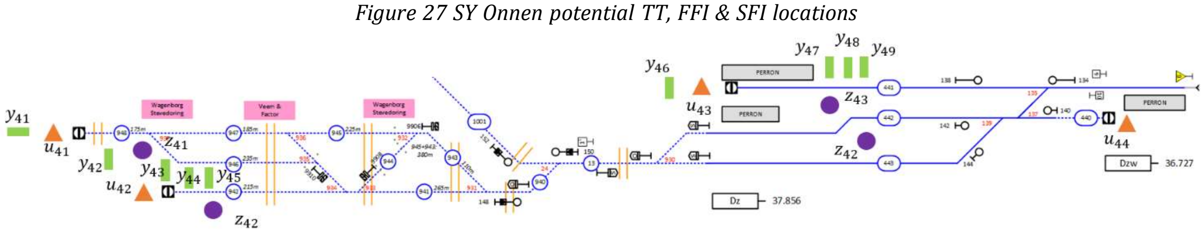


Figure 28 SY Delfzijl potential TT, FFI & SFI locations

The PG plans to have 50 operating H2 trains in the year 2035.

$$N=\{1,\ldots,50\}$$

Parameters

All costs considered in the PG problem are annualized. The investment costs (represented as the location costs in the objective function) disregard a discount rate. The fuelling infrastructure is designed for a longer period of time, than the lifespan of the fuelling installations, making the use of discount rates irrelevant in this case.

$\alpha_i = cost\ of\ opening\ SY\ i$

The cost of opening a SY is the same for all four SY owned by PR and is expressed by the following formula:

€ 0,03571 + € 0,0003462 x rail track in meters = costs per minute use of a SY.

In this case the costs per year are calculated. Assuming that all 50 trains are 4 hours a night at a SY, α_i will be equal to:

(€ 0,03571)*60*4*365 and (€ 0,0003462((56+2))*50)*60*4*365

α_i= € 3 128,20 per year per SY and € 87 948,65 per year for all 50 trains

However, the second part of the equation (€ 87 948,65) is constant. Including these fixed costs, not depended on the decisions, may affect the sensitivity analysis and will therefore be left out of the case study.

$\beta_{ij} = cost\ of\ locating\ TT\ j\ at\ SY\ i$
The primary focus of the research, as stipulated by the PG, is to examine the utilization of Tube Trailers (TT) as a means of hydrogen storage. In this context, the PG desires an agreement with the hydrogen supplier, wherein the costs associated with the TT itself are not considered. Instead, the sole expenses incurred pertain to the procurement of the required hydrogen for fuelling 50 operational trains. Consequently, if a TT has the capacity to store 4 units of hydrogen but currently holds only 1 unit, the costs accounted for would correspond to the price of the 1 unit of hydrogen. Hence, the costs attributed to the TT are contingent upon the price of hydrogen multiplied by the quantity of hydrogen required. Consequently, these costs remain unaffected by the TT's location and can be excluded from the objective function within this specific case.

$\gamma_{ik} = cost\ of\ locating\ FFI\ k\ at\ SY\ i$
The PG has provided an assumption regarding the investment cost associated with a Fast Fuelling Installation (FFI), estimating it to be € 7,000,000. Furthermore, the PG has determined the expected lifespan of the FFI to be 15 years, specifically in the year 2035. It is important to note that the locating costs of the FFI are consistent across all Shunting Yards (SYs). As a consequence, the parameter value corresponding to this assumption is as follows

$$\gamma_{ik} = \frac{7\ 000\ 000}{15} = €\ 466\ 667$$

$\delta_{il} = cost\ of\ locating\ SFI\ l\ at\ SY\ i$
The PG has made an assumption regarding the investment cost associated with a Slow Fuelling Installation (SFI), estimating it to be € 750,000. Additionally, the PG has determined the expected lifespan of the SFI to be 15 years, specifically in the year 2035. It is worth noting that the locating costs of the SFI are identical across all Shunting Yards (SYs). As a result, the parameter value derived from this assumption is as follow

$$\delta_{il} = \frac{750\ 000}{15} = €\ 50\ 000$$

$\varepsilon_{ijk} = pipeline\ length\ (m)\ from\ TT\ j\ to\ FFI\ k\ at\ SY\ i$
The pipeline lengths from the TTs to the FFIs can be found in appendix H.

$\tau_{ijk} = pipeline\ length\ (m)\ from\ TT\ j\ to\ SFI\ l\ at\ SY\ i$
The pipeline lengths from the TTs to the SFIs can be found in appendix I.

$g = costs\ per\ meter\ pipeline\ and\ H2\ unit\ flow$
The costs per unit H2 flow, per meter pipeline will be equal to €1000 per year in this case study.

$\rho_{im} = distance\ (km)\ from\ final\ station\ train\ n\ to\ SY$
According to the current timetable 44 trains end their timetable at Station Groningen and 24 end their timetable at Leeuwarden. The 50 H2 trains will replace all diesel powered trains from the current timetable by the year 2035. As the timetable for 2035 has not been established, the final destination of the H2 trains will be determined based on the current timetable, employing the same ratio of 44:24. Consequently, for the 50 trains, this ratio translates to 32 trains ending their schedule at Station Groningen and 18 trains ending their schedule at Leeuwarden. These assignments result in the following distances:

Table 3 Travel distances from final stations to the SYs

Final station\SY	Vork	Leeuwarden	Onnen	Delfzijl
Groningen i=(1,…,32)	3,8 km	65 km	8 km	31.7 km
Leeuwarden i=(33,…,50)	70 km	1.5 km	71.7 km	90.7 km

$s = costs\ per\ km\ traveled\ from\ final\ station\ to\ SY\ i$

The PG postulates that the price of hydrogen (H2) per kilogram (kg) will be €5 in the year 2035. The average fuel consumption of the hydrogen-powered (H2) trains per kilometer (km) traveled is estimated to be 0.25 kg. Consequently, the costs per kilometer traveled from the final station to the shunting yard (SY) per year can be calculated. It is assumed that the final destination of the train is also the first station it must proceed to after being fueled at the SY.

$$s = €1.25 * 365 * 2 = €912.50\ per\ km\ per\ train$$

$d = number\ of\ trains\ which\ can\ be\ fuelled\ by\ 1\ TT$

The TT observed in this case study can each hold 1000 kg of H2. The PG assumes that the trains will consume 250 kg of H2 on a daily basis on average. Therefore the number of trains which can be fuelled by 1 TT is

$$d = 4$$

$e = number\ of\ trains\ which\ can\ be\ fuelled\ by\ 1\ FFI\ per\ night$

The FFI studied in this case should be able to fuel 3 trains per hour. The period in which the trains can be fuelled is 4 hours during the night, making the number of trains which can be fuelled by 1 FFI per night

$$e = 12$$

$f = number\ of\ trains\ which\ can\ be\ fuelled\ by\ 1\ SFI\ per\ night$

The PG also wants to include the SFI as potential fuelling installation. The SFI considered in this case fuels trains throughout the 4 hours service period taking place in the night, making the number of trains which can be fuelled by 1 SFI per night

$$f = 1$$

$C = maximal\ number\ of\ trains\ that\ can\ be\ stationed\ at\ SY\ i$

The capacity of the different SYs show how many trains a SY can hold regarding the tracks and end nodes. This has been determined by the current SY capacity based on the HVO trains. Since the dimensions of the trains remain the same, it is assumed that the capacity of the SY also remains the same. Therefor the capacity is as follows:

$$C = \{44, 24, 13, 10\}$$

6.2 Solving the PG Problem

To determine a good solution, all heuristics will be tested and various combinations will be evaluated. Both excel and python have been used in the solving process. The costs calculations can be found in appendix J.

H1

Heuristic H1 focuses on the distances between the final stations of the train timetable and the potential SY locations. The C in the table represents the available capacity. The T stands for the number of trains which still needs to be assigned and the cell contains the number trains which are assigned from the final station (row) to the SY (column). Prior to the first iteration, the initial distribution is as follows:

Table 4 1st Iteration of H1 heuristic on PG problem

Final station\SY	Vork : C= 44	Leeuwarden : C=24	Onnen : C=13	Delfzijl: C=10
Groningen (1,…,32) T : 32	-	-	-	-
Leeuwarden (33,…,50) T : 18	-	-	-	-

Following the heuristic, trains will be sent to the SY with the largest minimal distance from the final station to the SY. In this case the shortest distance for the trains ending at station Groningen 3.8 km is larger than the shortest distance for the trains ending at station Leeuwarden (1.5 km). Therefore, the trains will be assigned from final station Groningen to SY the Vork until either the capacity of the SY has been reached or all trains are assigned to a SY. Since the capacity (44 trains) is greater than the number of trains (32), all 32 trains will be assigned to SY the Vork. At this point, no more trains from the final station Groningen need to be assigned, resulting in the other values in the row being set to zero. The new available capacity of SY Vork becomes 12.

Table 5 2nd Iteration of heuristic H1 on the PG problem

Final station\SY	Vork : C= 12	Leeuwarden : C=24	Onnen : C=13	Delfzijl: C=10
Groningen (1,...,32) T : 0	32	0	0	0
Leeuwarden (33,...,50) T : 18	-	-	-	-

The shortest distance is from station Leeuwarden to SY Leeuwarden. Since the capacity of SY Leeuwarden is 24 trains and only 18 trains need to be assigned, all 18 trains will be assigned to SY Leeuwarden. Now, no more trains from the final station Leeuwarden need to be assigned, resulting in the other values in the row being set to zero. The new available capacity of SY Leeuwarden becomes 6. Leading to the final distribution of trains being:

Table 6 Final iteration of heuristic H1 on the PG problem

Final station\SY	Vork : C= 12	Leeuwarden : C=6	Onnen : C=13	Delfzijl: C=10
Groningen (1,...,32) T : 32	32	0	0	0
Leeuwarden (33,...,50) T : 18	0	18	0	0

The total costs associated with opening the SYs and assigning trains to the SYs can now be calculated. This is part of the objective function as stated in section 4.2 and is computed as follows:
$\sum_{i\in I} \alpha_i x_i + \sum_{i\in I} \sum_{n\in N} \sum_{r\in R} s\rho_{ir} v_{in} = € \text{ } 3\ 128{,}20 + € \text{ } 3\ 128{,}20 + €912{,}50 * 3.5 * 32 + €912{,}50 * 1.8 * 18 =$ €138 021.4

H2

To apply the second heuristic (H2) for addressing the train assignment to SY problem, it is essential to consider distinct opening costs among the potential SYs. The SYs, namely the Vork, Leeuwarden, Onnen, and Delfzijl, are all owned by PR. The cost associated with utilizing the SYs remains uniform across all SYs, with a value of α_i= € 3 128,20 per year per SY. Consequently, since there is no variation in opening costs, the application of the second heuristic becomes irrelevant.

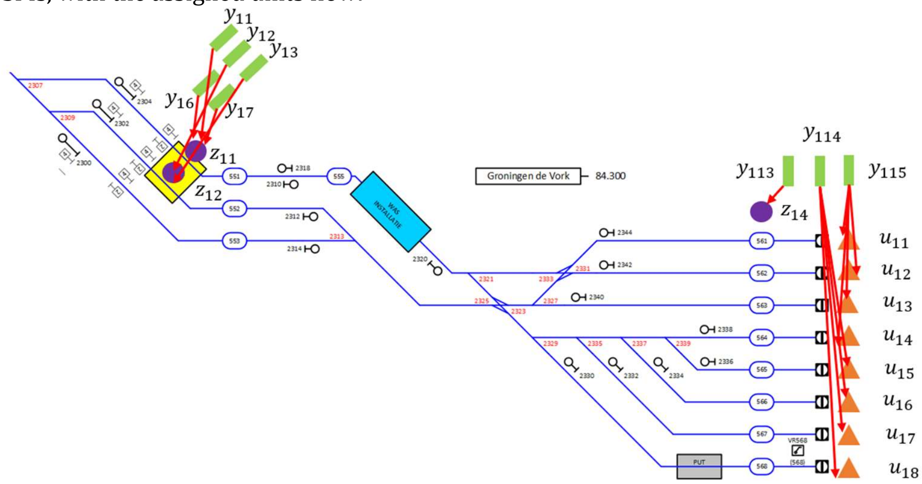
Upon comparing both heuristics for the assignment of trains to SYs, it is evident that the first heuristic H1 is a better fit to solving this specific case study. Thus, a favourable solution to the assignment problem in the PG case study involves dispatching 32 trains from Groningen station to SY the Vork and 18 trains from Leeuwarden station to SY Leeuwarden for overnight refuelling.

G1

When examining the shortest pipeline length between a TT and a FFI or SFI, the combination of TT 15 (y_{115}) supplying to SFI 1 (u_{11}) at the Vork yields 32.9 meters. According to the heuristics, the maximum amount of hydrogen units should be sent through the pipeline with the shortest length. Therefore TT 15 will be opened, together with SFI 1 with the maximum allowed flow of 1 unit through the pipeline ($b_{1151} = 1$). As TT 15 has already provided 1 unit to SFI 1, the new maximum flow that TT 15 can supply is 3 units. SFI 1 cannot be utilized in any other combination since only 1 unit can enter an SFI.

Subsequently, the combination with the second shortest pipeline length will be opened, which involves TT 6 (y_{16}) with FFI 1(z_{11}). However, the maximum allowed flow through the pipeline is now 4 units ($a_{161} = 4$), as an FFI can accommodate up to 12 units while a TT can only supply 4 units. TT 6 can no more supply units to any FI, since all possible units have been send to FFI 1. TT 6 is unable to provide any more units to any FI since all potential units have been allocated to FFI 1. It is crucial to note that only 8 units from various TTs can enter FFI 1 as it has already received 4 units and can handle a maximum of 12 units. The process of opening TTs, FFIs, and SFIs based on the shortest distance will continue until the total units through the opened pipelines equal the number of trains (24) assigned to the Vork.

This will result in the opening of the following pipelines, along with their corresponding TTs, FFIs, and SFIs, with the assigned units flow:



$b_{1,15,1} = 1$
$a_{1,6,1} = 4$
$b_{1,15,2} = 1$
$a_{1,1,1} = 4$
$b_{1,15,3} = 1$
$b_{1,15,4} = 1$
$a_{1,13,4} = 4$
$a_{1,7,1} = 4$
$a_{1,2,2} = 4$
$b_{1,14,5} = 1$
$b_{1,14,6} = 1$
$b_{1,14,7} = 1$
$b_{1,14,8} = 1$
$a_{1,3,2} = 4$

Figure 29 Fuelling infrastructure of SY the Vork retrieved by the G1 heuristic

The associated flow and location costs are respectively € 2 062 811 and € 1 800 001

For SY Leeuwarden the heuristic G1 has been applied following the same procedure as for the SY the Vork. This gives the following solution

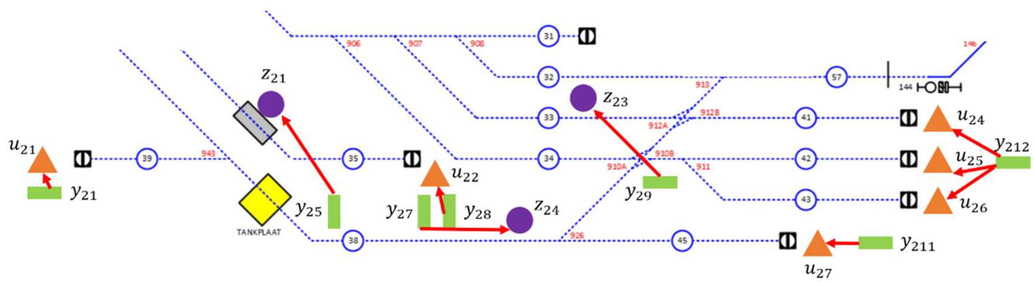


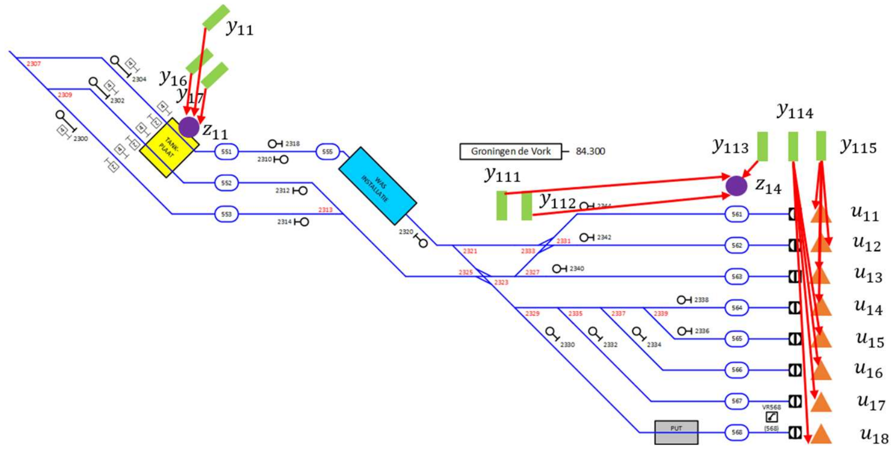
Figure 30 Fuelling infrastructure of SY Leeuwarden retrieved by the G1 heuristic

$b_{2,1,1} = 1$
$b_{2,12,5} = 1$
$b_{2,8,2} = 1$
$b_{2,12,6} = 1$
$b_{2,12,4} = 1$
$b_{2,11,7} = 1$
$a_{1,5,1} = 4$
$a_{1,7,4} = 4$
$a_{1,9,3} = 4$

The associated flow and location costs are respectively € 308 157 and € 1 700 001.

G2

Heuristic G2 in the case of the PG starts with opening the FI with the lowest cost, being the SFI. Therefore SFI 1 (u_{11}) will be supplied by the nearest TT (y_{115}). After this, the next SFI (u_{12}) will be opened, supplied by the nearest TT (y_{115}). This continues until all SFI have been opened, keeping track of the maximum possible flow from a TT being 4 units. After all SFIs have been opened, the total number of trains which now can be fuelled is 8. Now, the first FFI (z_{11}) with the shortest length to a TT (y_{16}) will be opened. Since the heuristics aims to minimize the location costs, we will keep on opening TT to supply FFI z_{11} until the maximum capacity of 12 units H2 entering the FFI has been reached. This results in opening TT y_{11} and y_{17} consecutively, after which 3 TT supply the FFI z_{11}. Now the total number of trains which can be fuelled is 20, but this needs to go to 32. Therefore, the next FFI (z_{14}) with the shortest pipeline length to an available TT (y_{113}) will be opened. After which, two more TTs supplying the same FFI will be opened, resulting in the sum of units through all pipelines being equal to the 32 trains assigned to SY the Vork. See figure 31.

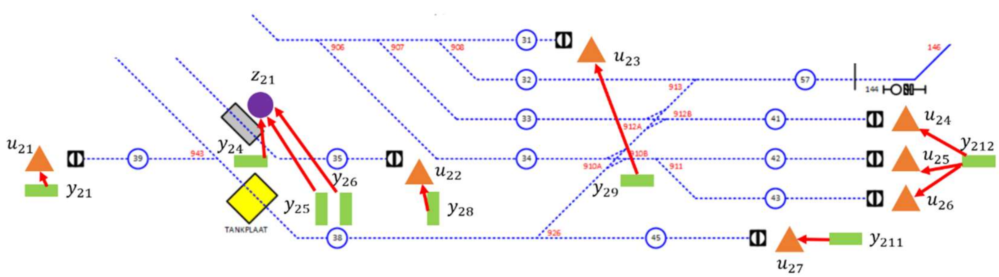


$b_{1,15,1} = 1$
$b_{1,15,2} = 1$
$b_{1,15,3} = 1$
$b_{1,15,4} = 1$
$b_{1,14,5} = 1$
$b_{1,14,6} = 1$
$b_{1,14,7} = 1$
$b_{1,14,8} = 1$
$a_{1,6,1} = 4$
$a_{1,1,1} = 4$
$a_{1,7,1} = 4$
$a_{1,13,4} = 4$
$a_{1,12,4} = 4$
$a_{1,11,4} = 4$

Figure 31 Fuelling infrastructure of SY the Vork retrieved by the G2 heuristic

The associated flow and location costs are respectively € 3 379 270 and € 1 333 334.

For SY Leeuwarden the heuristic G2 has been applied following the same procedure as for the SY the Vork. This gives the following solution:



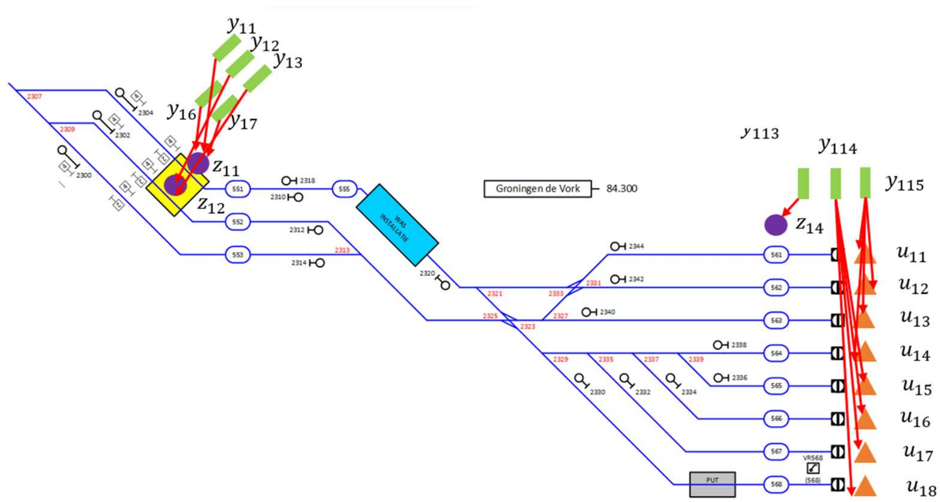
$b_{2,1,1} = 1$
$b_{2,12,5} = 1$
$b_{2,8,2} = 1$
$b_{2,12,6} = 1$
$b_{2,12,4} = 1$
$b_{2,11,7} = 1$
$b_{2,9,3} = 1$
$a_{2,5,1} = 4$
$a_{2,4,1} = 4$
$a_{2,6,1} = 3$

Figure 32 Fuelling infrastructure of SY Leeuwarden retrieved by the G2 heuristic

The associated flow and location costs are respectively € 434 391 and € 816 667.

G3

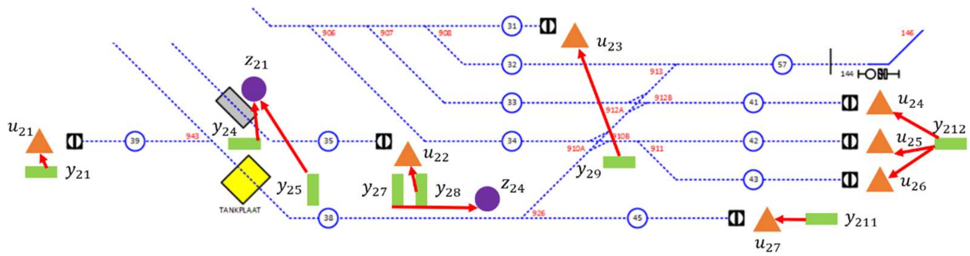
Heuristic G3 reduces both the flow costs and the location costs. After applying the heuristic, the following results are obtained.



$b_{1,15,1} = 1$
$b_{1,15,2} = 1$
$b_{1,15,3} = 1$
$a_{1,6,1} = 4$
$a_{1,1,1} = 4$
$b_{1,15,4} = 1$
$a_{1,7,1} = 4$
$b_{1,14,5} = 1$
$b_{1,14,6} = 1$
$b_{1,14,7} = 1$
$b_{1,14,8} = 1$
$a_{1,2,2} = 4$
$a_{1,13,4} = 4$
$a_{1,3,2} = 4$

Figure 33 Fuelling infrastructure of SY the Vork retrieved by the G3 heuristic

The associated flow and location costs are respectively €2 062 811 and €1 800 001.



$b_{2,1,1} = 1$
$b_{2,12,5} = 1$
$b_{2,8,2} = 1$
$b_{2,12,6} = 1$
$b_{2,12,4} = 1$
$b_{2,11,7} = 1$
$b_{2,9,3} = 1$
$a_{2,4,1} = 4$
$a_{2,5,1} = 4$
$a_{2,7,4} = 3$

The associated flow and location costs are respectively €355 895 and €1 283 334.

6.3 Comparison + discussion

After applying heuristics at the opened SYs retrieved from level 1, it is important to compare the outcomes in order to find the best solution. As expected, the flow costs of the solution found by heuristic G1 are lower than the flow costs of the solution followed by heuristic G2. The solution from G1 is approximately 38% less costs than the solution from G2. It can be concluded that G1 minimises the flow costs better than G2 in the example. However, as suspected, this does negatively impact the location costs. The location costs of the solution retrieved by G1 is 62.8% higher than the location costs from the solution of G2. Resulting in G2 minimising the location costs better than G1. A good example of G2 minimizing the location costs, but strongly increasing the flow costs is last three iterations of G2 the Vork, when FFI z_{14} needed to be opened. Since the heuristic minimizes the location costs, the opened FI needs to be connected to TTs until either the maximum capacity of the FI has been reached or the sum of units through all pipelines is equal to the number of trains. This resulted in opening the second and third TT, which had relatively large pipeline lengths, while other FFI-TT combinations had much smaller pipeline lengths. However, opening another FFI with the shorter pipeline length would lead to adding another € 466 667 costs, while continue with the already opened FFI but larger pipeline lengths would prevent the costs of opening another FFI.

The last three iterations according to the G2 heuristic resulted in the following costs

$$(53.47424853*4+219.1400622*4+289.5963432*4)*1000 = €2\,248\,843$$

If these last three iterations followed the G1 heuristic the flow costs would have been

$$(53.47424853*4+72.33896889*4+78.05101846*4)*1000 = €815\,457$$

However, now two other FFI need to be opened for the last two iterations, leading to the total costs being

$$815\,457+ 2*466\,667 = €1\,748\,791$$

	Flow costs	Location costs	Total Costs
G1	€ 2 370 968	€3 500 002	€5 870 970
G2	€3 813 661	€2 150 001	€5 963 662
difference	−€1 442 693	€1 350 001	−€92 692

Table 7 Comparison of G1 and G2 heuristic solutions on the PG problem

Comparing the total costs (table 7) of the two solutions only yield a difference of 1.55%. This means that in the end there is no big difference between the total costs of the two solutions when adding the flow and location costs at the current situation. The next chapter will discuss in which situation which heuristic yields better results.

It is a continuous trade-off between minimising the flow costs against the location costs. Heuristic G3 tries to find a balance between this trade-off. Heuristic G3 yields lower total costs compared to G1 and G2, but does not have the lowest flow and location costs as can be seen in table 8.

	Flow costs	Location costs	Total Costs
G1	€ 2 370 968	€3 500 002	€5 870 970
G2	€3 813 661	€2 150 001	€5 963 662
G3	€2 418 706	€3 083 335	€5 502 041

Table 8 Comparison of G1, G2 and G3 heuristic solutions on the PG problem

When comparing the solution of heuristic G3 with G1 of SY the Vork, it is important to note the different order in which the pipelines are opened, despite the final infrastructure and thus the costs being the same.

This shows the significant difference in the workings of both heuristics. It is also interesting to see that the solution of heuristic G3 on SY Leeuwarden is a combination of the solution of heuristic G1 and G2. The only difference between G3 and G1 and G2, is that solution G1 opened pipeline 293 and G2 has pipeline 261 opened. This shows again that G3 is a combination of both heuristics. In table 8 it can be seen that the flow cost of heuristic G3 are closer to the flow costs of heuristic G1 than G2, like the location costs. This could indicate that heuristic G3 minimises the flow costs stronger than the location costs. Approximately €400 000 can be reduced from the final costs, when applying the fuelling infrastructure from heuristic G3. Making this this solution the lowest in costs, while respecting all constraints.

7. Sensitivity analysis

When looking at the first level, the balance which has to be found is between the opening cost of the shunting yards and the traveling costs of the hydrogen trains. These costs associated are expressed in the objective function as following

$$\sum_{i\in I} \alpha_i x_i + \sum_{i\in I}\sum_{n\in N}\sum_{r\in R} s\rho_{irn} v_{in}$$

The solution for assigning 50 hydrogen operating trains is sending 32 to SY the Vork and 18 to SY Leeuwarden. These costs are equal to

$$€\,3\,128{,}20 + €\,3\,128{,}20 + €912{,}50 * 3.5 * 32 + €912{,}50 * 1.8 * 18 = €138\,021.4$$

As can be seen, the traveling costs contribute much stronger to the total costs than the opening costs of the SY. Therefore, minimizing the travel distance has a much stronger impact on reducing the total costs, than minimizing the opening costs. Besides, since the opening costs of the SYs are the same for all SY, the model will always send the trains to the SY with the smallest travel distance. Therefore, the outcome of this problem will always be to assign trains to SY the Vork and Leeuwarden. Changing the hydrogen costs does not affect the outcome, since the trains will always be sent over the smallest distance when the SY opening costs are the same. Increasing the opening costs will also not affect the outcome, since at least 2 SY need to be opened looking at the capacity.

Analysing the second level gives more valuable insights. There are location costs and flow costs expressed in the objective function as following

$$\sum_{i\in I}\sum_{k\in K_i}(\gamma_{ik} z_{ik}) + \sum_{i\in I}\sum_{l\in L_i}(\delta_{il} u_{il}) + \sum_{i\in I}\sum_{j\in J_i} g\left(\sum_{k\in K_i}\varepsilon_{ijk} a_{ijk} + \sum_{l\in L_i}\tau_{ijl} b_{ijl}\right)$$

Since the TT costs are irrelevant in the case study of the PG, these costs are left out in the sensitivity analysis. It is important to note that the objective function is linear. This means that when increasing all coefficients for instance by 10% the impact of the coefficients remains the same. One variable will not affect the final outcome stronger by this increase, than it did before in comparison to the other variables. It is also important to note that changing the cost coefficients in the objective function, does not affect the outcome heuristic G1 and G2. Heuristic G1 will always give as solution the shortest pipeline distances. These distances can be chosen independently from the pipeline costs, the FFI costs and the SFI costs. The same holds true for the outcome of G2, which minimizes the investment costs, as long as the location costs of SFI remain smaller than the FFI. In reality it will be almost always the case that SFI are less expensive than FFI, since the fuelling capacity is only 8.33% of FFIs. However, analysing the impact of the cost coefficients on the objective function, is still relevant, since the cost coefficients do affect total costs, and therefore say something about the fit of the heuristics to the problem. Since the coefficients are all estimated values for the year 2035, it is important to analyse different scenarios by changing these value, while everything else remains the same. Therefore, the variability in the cost coefficients will be analysed, in order to determine which heuristic is a better fit with which variables. The breakpoint of the heuristics in the case of PG can be tested by setting up an equality of both solutions from the PG case study, making all the cost coefficients variable. Every cost component can now be tested analytically on their sensitivity cetris paribus, giving insights in the total costs of the second-level in the PG case. The value of the decisions variables from the solutions found by heuristic G1 and G2 (section 6.2) will be used to test the sensitivity of the coefficients of the decision variables. As mentioned before, the solution from both heuristics will not change when changing the coefficients, due to the characteristics of the heuristic. Therefore the values of the decision variables will remain constant when changing the coefficients. It can now be tested which heuristic provides a better solution for which coefficients. The breakpoint can be calculated by setting both comparing both costs equations of heuristic G1 and G2, when setting the coefficients constant.

$$2370.968g + 6\gamma + 14\delta = 3813.661g + 3\gamma + 15\delta$$
$$1442.693g - 3\gamma + \delta = 0$$

The impact of the estimated costs can be analysed.

Lets first have a closer look at the estimated pipeline costs. Therefore we hold everything constant except the pipeline costs:

$$1442.693g - 3 * €466\,667 + 1 * €50\,000 = 0$$

Resulting in g being equal to €935.75 Meaning, if the costs per 1 meter hydrogen pipeline is higher than €935.75, cetris paribus, applying heuristic G1 gives a better solution than heuristic G2. If the pipeline costs are lower than €9357.51, cetris paribus, applying heuristic G2 gives a better solution. The total costs of heuristic G1 and G2 can be plotted, with the pipeline cost being variable.

$$Total\ Cost\ G1 = 2370.968g + 3500002$$
$$Total\ Cost\ G2 = 3813.661g + 2150001$$

Figure 32 shows that for all values of g smaller than €935.75 applying heuristic G2 (blue) gives lower total costs than heuristic G1 (red). However, if g is higher than €935.75, heuristic G2 gives lower costs. The plot shows how the total costs of applying heuristic G1 or G2 changes when changing the pipeline costs.

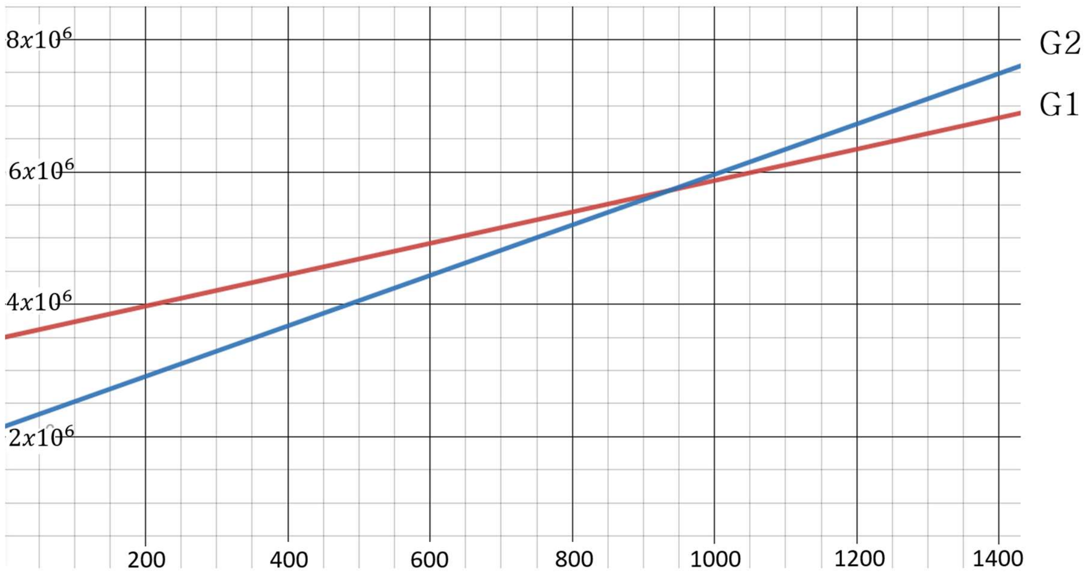


Figure 35 x-axis= the g value, y-axis= the total costs

The same can be done for the cost coefficients FFI location costs and SFI location costs. The breakpoint of the heuristics when analysing the FFI location costs can be derived by solving the following equation

$$1442.693 * 1000 - 3\gamma + 1 * €50\,000 = 0$$

If the FFI location costs are higher than €497 564 applying heuristic G2 gives better results, than heuristic G1 (figure 33). It can be concluded that heuristic G1 yields better results when the pipeline costs are relatively higher than expected. Heuristic G2 yields better results when the FFI costs are relatively lower than expected. The same can be computed for the SFI costs, cetris paribus. However, heuristic G1 always gives better results when changing SFI costs only. This concluded from analysing the total costs from both heuristics.

$$Total\ Cost\ G1 = 2370.968 * 1000 + 6 * 466\,667 + 14\delta = 5\,170\,970 + 14\delta$$
$$Total\ Cost\ G2 = 3813.661 * 1000 + 3 * 466\,667 + 15\delta = 5\,213\,662 + 15\delta$$

It can be seen in figure 34 that G2 will always give higher costs, since the SFI location costs cannot become negative and the initial value of the G2 solution is higher than the G1 solution.

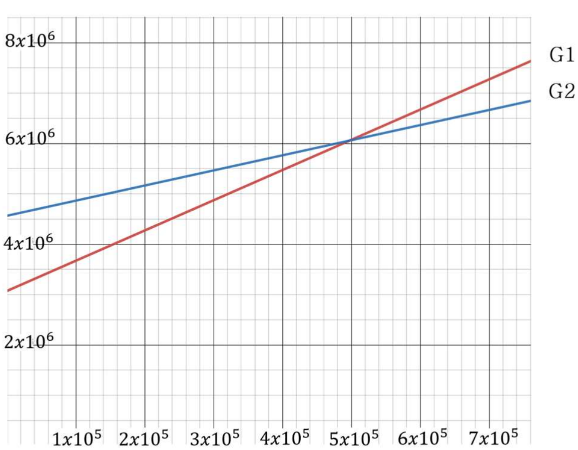


Figure 36 x-axis = SFI costs, y-axis = total costs

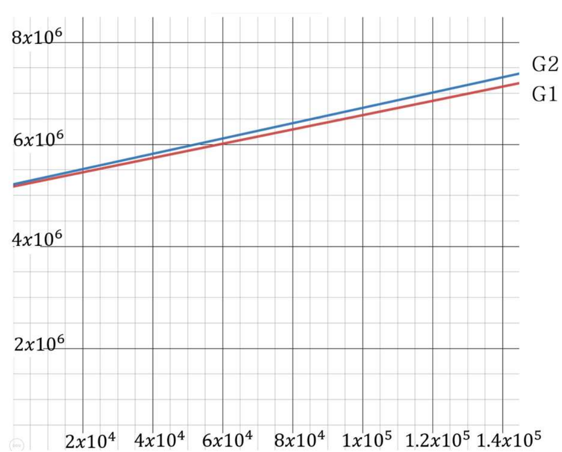
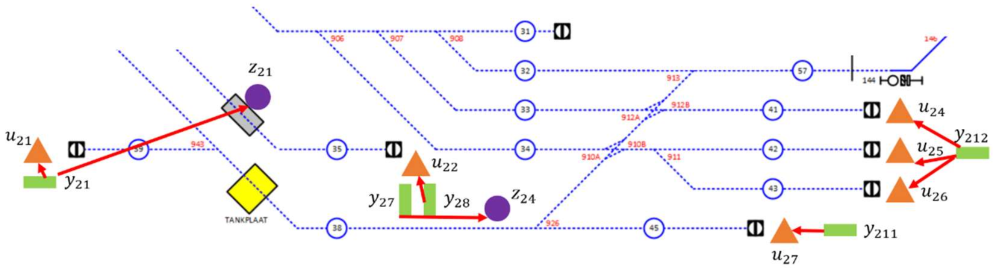


Figure 37 x-axis = FFI costs, y-axis = total costs

Lets have a closer look at the sensitivity of the coefficients, variables and constraints affecting the flow costs. The capacity of the SFI and FF are fixed and will not be further studied. The PG wants the research to be focussed on a SFI, with a fuelling capacity 1 train during the night and a FFI with a fuelling capacity of 12 trains during the night. The capacity of a TT strongly affects the total costs. Even though, the location costs are irrelevant in the PG case, it impacts the opening of the different pipelines strongly. Since the TT max capacity holds 4 H2 units, it means that at SY Leeuwarden the flow through the opened pipelines is equal to 18. This means that at least 5 pipelines need to be opened. In the case of 5 pipelines only 2 SFI can be used, which makes the location costs higher.

If the TT's capacity would have been 8, the following pipelines would have been opened according to heuristic G1:



$b_{2,1,1} = 1$
$b_{2,12,5} = 1$
$b_{2,8,2} = 1$
$b_{2,12,6} = 1$
$b_{2,12,4} = 1$
$b_{2,11,7} = 1$
$a_{1,5,1} = 7$
$a_{1,7,4} = 5$

Figure 38 G1 solution on the PG problem when the TT capacity is equal to 8

With the associated flow costs:

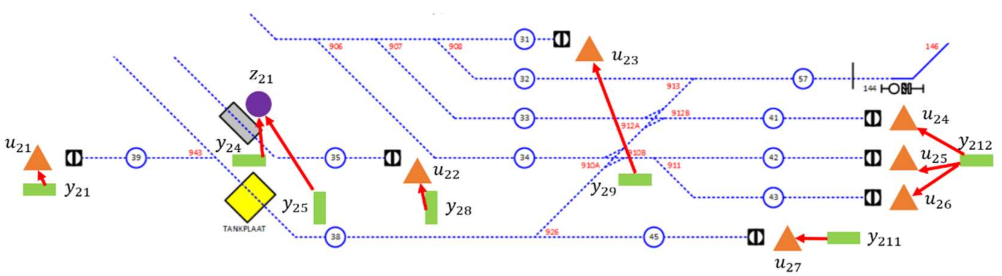
$$\sum_{i\in I}\sum_{j\in J_i} g\left(\sum_{k\in K_i}\varepsilon_{ijk}a_{ijk} + \sum_{l\in L_i}\tau_{ijl}b_{ijl}\right) =$$

(5.484649+6.710244+7.793149+8.03482+8.139527+16.99226+20.79556*7+20.95976*5)*1000= € 303 522

The associated location costs are:

$$\sum_{i\in I}\sum_{k\in K_i}(\gamma_{ik}z_{ik}) + \sum_{i\in I}\sum_{l\in L_i}(\delta_{il}u_{il}) = € \, 466\,667 * 2 + € \, 50\,000 * 6 = € \, 1\,233\,334$$

After heuristic G2 has been applied, with the capacity of the TT being 8, we get the following solution:



$b_{2,1,1} = 1$
$b_{2,12,5} = 1$
$b_{2,8,2} = 1$
$b_{2,12,6} = 1$
$b_{2,12,4} = 1$
$b_{2,11,7} = 1$
$b_{2,9,3} = 1$
$a_{1,5,1} = 8$
$a_{1,4,1} = 3$

Figure 39 G2 solution on the PG problem when the TT capacity is equal to 8

The associated flow costs of this solution are:

$$\sum_{i\in I}\sum_{j\in J_i} g\left(\sum_{k\in K_i}\varepsilon_{ijk}a_{ijk} + \sum_{l\in L_i}\tau_{ijl}b_{ijl}\right) =$$

(5.484649+6.710244+7.793149+8.03482+8.139527+16.99226+39.02272+20.79556*8+29.414*3)*1000 = € 346 784

The associated location costs however, remain the same

$$\sum_{i\in I}\sum_{k\in K_i}(\gamma_{ik}z_{ik}) + \sum_{i\in I}\sum_{l\in L_i}(\delta_{il}u_{il}) = € \, 466\,667 * 1 + € \, 50\,000 * 7 = € \, 816\,667$$

It makes sense that the impact of the TT capacity increase affects the outcome of heuristic G1 stronger. Heuristic G1 does not minimize the opening of the FFI, but only focuses on reducing the pipeline length. This results in the opening of FFI with shorter distances after the max capacity has been reached of the previously opened FFI. Increasing the capacity of the TTs to 8 units H2 flow, gives a better solution in comparison to the capacity of 4 H2 units while using G1.

Flow costs difference: $€ \, 308\,157 - € \, 303\,358 = € \, 4\,799$
Location costs difference: $€ \, 1\,700\,001 - € \, 1\,233\,334 = € \, 466\,667$

Therefore, it would be beneficial to have hydrogen storages with a higher capacity. However, TT's with a higher capacity will probably costs more than TT holding 4 H2 units max. Since 6 TTs have been used when applying G1 with the TT holding max 8 units. It can be calculated that it would only be beneficial to go for the TT with a capacity of 8, if the location costs (β_{ij}) difference between this TT and the TT with a capacity of 4 H2 units, less than €78 577.66. If the TT with a capacity of 8 H2 units cost more than €78 577.66 added to the TT with a capacity of 4 H2 units, it is better to go for the TT's with the capacity of 4 H2 units, cetris paribus. The same steps can be taken in order to calculate the value of increasing other capacities of TT's. Note that in the case of 6 TT with a capacity of 8 H2 units in total, the max capacity is equal to 48 H2 units, while only 32 H2 units are used. The opening of TT can be done more efficiently in this case.

If we decrease the TT capacity, more TT's need to be opened in order to supply the needed amount of H2 to fuel the operating trains. Subsequently, more pipelines need to be opened, which means that more units H2 need to be supplied through the pipelines with longer lengths. This will strongly affect the flow costs. Therefore, it would not be beneficial to reduce the capacity with the current locations of the TTs and FIs.

8. Conclusion

This research aims to solve the issue of insufficient hydrogen fuelling capacity to support the desired network, while increasing the capacity is expensive at Provincie Groningen. In this section the research question: 'How can the fuelling capacity be increased to support the operation of 50 hydrogen powered trains while minimizing costs?' will be answered. The conclusion and recommendations will be discussed. Solving this problem contributes to a cost-effective investment in green transport infrastructures, by contributing to the upgrade of the railway network to operate 50 H2 trains by 2035.

The transition from HVO to hydrogen fuelling infrastructure is expected to occur by 2035, driven by the implementation of four hydrogen trains in 2027. While both fuel systems share similarities in dimensions and fuelling process steps, the primary challenge lies in accommodating larger and more distantly located hydrogen storage due to safety regulations. This limitation impacts the available space at shunting yards. The Bremervörde hydrogen refuelling station serves as a valuable reference, demonstrating its capability to fuel up to 14 hydrogen Coradia iLint trains with a daily requirement of approximately 250 kg H2. The delivery of hydrogen via tube trailers and the efficient fuelling capacity of two trains per hour at each installation further highlight the operational aspects of the hydrogen infrastructure.

This research on railway hydrogen fuelling infrastructures stands at the forefront of knowledge due to the scarcity of existing studies in this field. The literature review emphasized the current state of hydrogen train technology, fuelling installations, and shunting yard planning processes. Through the examination of strategic-level considerations, it is evident that this research closely aligns with a multi-level Facility Location Problem (FLP), involving the determination of optimal locations for shunting yards, hydrogen storage, and fuelling installations while minimizing associated costs. Notably, the innovative aspect of this research lies in its unique application of the FLP framework, considering the limited presence of comparable studies.

A Mixed-Integer Linear Program (MILP) has been formulated to design fuelling infrastructures in railway optimally. It optimizes the opening of shunting yards and use and location of fuel storages and fuelling installation. In this research, the problem has not been solved exact by solving the MILP in a solver (for instance Gurobi or Cplex). The level of complexity of the MILP in combination with the large problem size of the PG problem, solving the problem within a reasonable timeframe could be challenging. Therefore, four heuristics have been defined in order to find a good solution to the problem.

The problem has been split in two levels. This not only simplifies the solving, it allows for the application of different heuristics to parts of the problem. Different combinations of heuristics can be tested, after which the combination with the best solution can be chosen as final solving method. For level 1 two different heuristics have been formulated. Heuristic H1 focusses on minimizing the travelling costs of the trains from the final station to shunting yard. While heuristic H2 minimizes the opening costs of the shunting yards. At level 2 heuristic G1 minimizes the pipeline length between the tube trailers and the fuelling installations. The other heuristic which has been defined for this level is heuristic G2, which minimizes over the location costs of the fuelling installations. After computing all 4 possible heuristic combinations across the levels, the combination that yields the lowest final costs can be chosen. A combination of heuristic G1 and G2 can be found in heuristic G3. This heuristic tries to take into account both cost components.

Currently, there is a lack of input data from the PG problem for the MILP and heuristics. Since the use of hydrogen in railway is new, at the moment of writing, the technology innovates quickly, resulting in rapid costs changes over time. Due to this new and competitive market, the companies working on hydrogen in railway do not want to share specifications and thus relevant information to this research. Due to these encountered challenges in retrieving data, most of the used parameters are expected values by the PG of the parameters in the year 2035. This makes the input data vulnerable to changes over time, and therefore the solution based on these data prone to turnout irrelevant by the year 2035. Therefore, the MILP and heuristics are of more value in this research than the actual solution.

Upon comparing heuristics H1 and H2, it can be concluded that heuristic H1 is a better fit to solve the first level in the PG problem, than heuristic H2. Thus, the found solution to the assignment problem in the PG case study involves dispatching 32 trains from Groningen station to SY the Vork and 18 trains from Leeuwarden station to SY Leeuwarden for overnight refuelling. Furthermore, it can be concluded that this is the only good solution, since all the SYs have the same opening costs and the SYs with the shortest distance to the final stations, have enough capacity to station all trains from that station. Therefore no further sensitivity analysis has been performed

The total costs of heuristics G1 and G2 do not differ much, with a cost difference of 1.55%. Therefore, both solutions can be chosen. The solution retrieved from heuristic G1 minimizes the flow costs, but yields higher location costs. In this solution 8 SFI and 3 FFI have been located at the Vork, supplied via 14 pipelines by 8 TT. At SY Leeuwarden 6 SFI and 3 FFI have been opened, supplied by 7 TT through 9 pipelines. Resulting in a total cost of €5 870 970. The solution from heuristic G2 minimizes the location costs, but consequently obtained higher flow costs. At SY the Vork 8 SFI and 2 FFI have been located, supplied through 14 pipelines by 8 TT. SY Leeuwarden required 7 SFI and 1 FFI, supplied by 7 TT through 10 pipelines according to heuristic G2. This yields the total costs of €5 963 662. Both found solutions can be chosen by the PG depending on their preference, however it is strongly recommended to use the solution found by applying heuristic G3. The solution found by this heuristic yields total costs of €5 502 041 by locating 8 SFI and 3 FFI at SY the Vork supplied by 14 pipelines and locating 2 SFI and 7 FF supplied by 10 pipelines at SY Leeuwarden.

Through sensitivity analysis valuable insights into the fit of the heuristics to the costs coefficients have retrieved. If the pipeline costs are lower than €9357.51, cetris paribus, applying heuristic G2 gives a better solution. Otherwise heuristic G1, cetris paribus, yields lower total costs. If the FFI location costs are lower than €497 564, cetris paribus, applying heuristic G1 gives better results, than heuristic G2. Otherwise heuristic G2, cetris paribus, yields lower total costs. Any change in the SFI does not affect the fit of the heuristics on the total costs. The impact of the TT capacity has been analysed, after which can be concluded that an increased capacity results in lower total costs, as long as the increased TT costs remain less than total costs difference between both capacities. Lowering the TT capacity is not beneficial and should be avoided.

9. Discussion and recommendations

Several assumptions and decisions have been made and limitations have been found throughout this research, causing points of discussion. The required input data to solve the problem is only partially available at the time of writing. This lack of information limits the research and thus the accuracy strongly. Since the actual data has been replaced by estimates of data in the year 2035, the solution is not accurate. Even though the MILP model and the heuristic remain valuable over time, the found solution should be treated as guideline only and not anything near an optimal solution. Therefore, it is strongly recommended to replace the used input data in this research by more accurate data, whenever possible.

A second point of discussion is that this research has not been able to provide the optimal solution to the PG problem. The defined heuristics in this research do provide a good solution, but there is still room for improvement. Future works on more complex heuristics could provide a better solution which approaches the optimal solution of the PG problem. Also, rewriting the MILP can maybe make it possible to find the optimal solution by the use of a solver. Future works could test modifications on the formulated MILP in solvers, so that the optimal solution to the PG problem can be found.

The third limitation in this research is that the timetabling of the trains has been left out. This research does not take into account the arrival and departure times of the trains at the SY. It also does not include the order in which the fuelled trains need to be stationed. This aspect has been out of the scope of this research, but is necessary when designing the fuelling infrastructure. For instance, if all SFL are opened, but trains arrive later than the needed time to fuel a train, then the SFI cannot fuel the train. Therefore, the trains should have been assigned to the FFI. Which then again need to be supplied by opening different TT's. Therefore, studying the timetables of the trains and including them in the MILP should be done in future works.

Future research can be done on the tactical level as discussed in section 3.2. In this research is has been regarded as out of scope, but the next steps after designing the hydrogen fuelling infrastructure, is to

Another point of discussion is the data sets used for solving the PG problem. Currently, ProRail has no regulations related to hydrogen. The TT, FFI, SFI and pipeline locations used in this research can turn out to be not possible, due to the future regulations from ProRail on hydrogen. Currently, any location at the SYs can be a potential location. However, only a few locations have been included in this research. This has been done in order to make the problem tractable. In future work it is recommended to expand the data set of the potential locations, in order to provide a more accurate answer. A heuristic should be created to handle continuous location sets. Extending the location sets from discrete to continuous will provide relevant insides, onto which better solution could be found.

Another limitation of this research concerns the pipeline costs. The pipeline costs used in this research increase linearly per meter pipeline, per unit flow. In reality however, these costs do not increase linearly (Brown, et al., 2022). It is therefore recommended to study the increase of hydrogen pipeline costs and include it in this research, to make it a better representation of reality.

Further research should be done on finding a solving method that does not require the problem to be decomposed into the two different levels as mentioned in section 5.1. This solving method should find a solution by taking into account both levels, resulting in a solution for the problem as whole and not two separate solutions that together form the solution to the problem. This new solution should give a fuelling infrastructure based on both the SY locations as the TT and FI locations. Since choices taken at one level impact the options and constraints at the other level, and vice versa. Achieving an optimal configuration necessitates a consideration of both levels, ensuring the decisions encompass the consequences and complexities of real-world scenarios.

The final point of discussion concerns heuristic G3. Heuristic G3 should be further analysed on different situations, in order to prove the usefulness of this heuristic in general and not only at the PG problem. This solving method has been created to find a balance between the different cost components in the PG case. However, no further research has been performed on the workings of the heuristic besides this case study. Studying the heuristic further should make the solving method more complete and robust. It has also been found that heuristic G3 has relatively lower flow costs than the location costs in comparison to heuristic G1 and G2. This could indicate that the heuristic G3 minimises the flow costs stronger than the location costs. It is therefore recommended to conduct further research on heuristic G3 and make adjustments in order to try and find a better balance between both costs components.

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11. Appendix

A. Research validity

In order to assure the quality of the research it is important to pay attention at the validity. The measurements should be that what has been intended to measure, in order to ensure the validity of the research. There are three key types of validity that together define the quality of the research: Internal validity, External validity and Construct validity (Cozby, 2014).

Internal validity ensures that the measuring instruments and research designs are properly formulated. 'To increase internal validity, investigators should ensure careful study planning and adequate quality control and implementation strategies-including adequate recruitment strategies, data collection, data analysis, and sample size' (Patino & Ferreira, 2018). The research design, including data collection, planning, methods to control the quality and the implementation strategy have clearly been defined in this Project Plan. This will then be reviewed by the department of Industrial Engineering and Management. The review ensures the internal validity of the research.

'External validity examines whether the findings of a study can be generalized to other contexts' (Juni, Altman & Egger, 2001). The research ensures a certain degree of external validity by specifying the data input. The model itself can be used in other contexts, the coefficients and constraints however may differ. Therefore, the results of the research are not generalized, but the study is. This is important in order to stimulate the implementation of hydrogen trains outside of the Province of Groningen. The practical relevance of this research is high, since more groups worldwide might struggle with increasing the hydrogen capacity, since it is a relatively new technology. This research should benefit to all working on the implementation of hydrogen powered trains. Since this model is easily applicable to different situations, because the number of trains to which the capacity needs to be increased is variable, it can be used for both small firms as large companies or institutes.

The last validity that needs to be identified is the construct validity. The construct validity is "an integration of any evidence that bears on the interpretation or meaning of test scores" (Messick, 1989). To increase this validity the used concepts in the research are based on scientific knowledge, coherent and properly operationalised.

The D3 (Do, Discover, Decide) from Heerkens & van Winden (2017) are part of the problem approach. Do and Discover have been discussed in the chapter 1. *Do* covers all actions that needs to be undertaken in order to solve the problem. This has been explained by the questions and research design, which clearly states all the actions that will lead to the solution to the core problem. The *Discover* part of the D3 is about everything that needs to be known when conducting this research. This has also been mentioned at the previous section. Therefore, this section will focus on the last D: *Decide*.

Decide is about the solution selection. The PG is the decision maker, while the researcher, also known as the advisor on increasing the fuelling capacity, will only advise and makes no decisions. This ensures the reliability of the research by acting independently from external interests. The researcher is not responsible for the decision and the consequences, the PG is. Another reason why the researcher should not make the final decision is that her objective might differ from the client'. This may lead to different views on what is believed to be an optimal increase of the fuelling capacity. The last reason on why the researcher will not have the final decision is that her risk assessment might differ from the client'. The output of this research will contain a normative statement, based on the objective of the PG.

Since the PG wants to know how to increase the fuelling capacity, by determining the following things:

Which SYL need to be used?

How can the fuelling installation(s) and hydrogen storage(s) optimally be allocated at the SYL(s)?

Answers to these questions give insights in the needed hydrogen fuelling capacity. The optimization model will give the optimal values on both the amount as the location of the hydrogen storage and fuelling installations. A map of the used SYL(s) and the allocation of the hydrogen storage and the fuelling capacity will be delivered at the PG, solving their problem. Along with the optimization model, coding and a model manual describing how to use and adjust the model according to new data.

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B. Research Design

Sub questions	Research method	Research population	Data gathering	Way of data processing	Activities performed
1.	Descriptive, broad, Qualitative	The Vork (fuelling location)	Fuelling process, costs per employee, time restrictions fuelling (Arriva). Location dimensions (ProRail). Fuelling stations specifications, hydrogen storage specifications (suppliers)	Map of current fuelling processes, list of constraints, requirements, data set and cost coefficient per variable	Analysis of: Current diesel fuelling process and Hydrogen fuelling process
2.	Descriptive, broad, Qualitative	-	Cross-sectional literature study	Table with found literature with characteristics of the research	Explaining reviewed literature, definition on alternative solutions and their desirability
3.	Descriptive, Quantitative	The Vork, Delfzijl, Leeuwarden (fuelling locations)	Solve the model and gather optimum values of decision variables. Apply sensitivity analysis	Code of optimization model. Table with found values of decision variables and determine the optimal solution	Formulating the optimization model, motivate choice and solve the model to find the solution to the problem
4.	Normative (Evaluative), Quantitative	The Vork, Delfzijl, Leeuwarden (fuelling locations)	Data from q.1 and 3	Table with values of decision variables of linearly increased and found capacity	Show improvement by comparing linearly increased and found capacity
5.	Normative (Prescriptive), Qualitative	The Vork, Delfzijl, Leeuwarden (fuelling locations)	Data from q.3		

C. Defining variables of the Conceptual Framework

Variable	Explanation	Value	Data retrievement
Fuelling capacity	The number of operating hydrogen trains that can be fuelled	[1,2,…,50]	*n.a.*
HS used	The dimensions (m2) that take up the hydrogen storage (HS) needed to fuel all operating hydrogen trains and the location of the hydrogen storage at the chosen shunting yard	Non-negative Rational number	Hydrogen supplier
FIs used	The number of fuelling installations (FI) allocated at the chosen shunting yard location(s) fuel all operating hydrogen trains	[1,2, …, 50]	Fuelling installation supplier
SYs used	The shunting yard location(s) used to fuel all operating hydrogen trains	[The Vork, Onnen, Delfzijl, Leeuwarden], Binary	ProRail
Costs of 1 m3 HS	The costs of storing 1 m3 of hydrogen	Non-negative Rational number	Hydrogen supplier
Costs of 1 FI	The costs of purchasing 1 fuelling installation	non-negative Rational number	Fuelling installation supplier
Costs of using the SYs	The fixed costs of using/opening a shunting yard location	Non-negative Rational number	ProRail
Destination of the trains	Distance from the location of the station the train comes from before fuelling and distance of the station destination of the train after fuelling	Non-negative Rational number	Current timetable from Arriva
Distance between the SYL and the Vork	The distance between the shunting yard location and the Vork	Non-negative Rational number	ProRail/maps
Costs of 1 m hydrogen pipeline from the storage to the installation	Costs of 1 m hydrogen pipeline in between the storage and the installation	Non-negative Rational number	Hydrogen supplier and Fuelling installation supplier
Costs per m2 at the SY	The costs for using 1 m2 at the shunting yard location	Non-negative Rational number	ProRail
# Trains 1 FI can fuel per timeframe to fuel all trains	The number of trains 1 fuelling installation can fuel within the timeframe in which all trains need to be fuelled	Non-negative Integer	Fuelling installation supplier
# Hydrogen needed to fuel 1 train	The amount of hydrogen needed to fuel 1 train, which needs to be stored	Non-negative Rational number	Train supplier
Amount of space needed to fuel 1 train	The dimensions (m2) needed to station 1 hydrogen train for fuelling	Non-negative Rational number	Train supplier, fuelling installation supplier
Available space per SY	The dimensions (m2) of the different shunting yard locations (The Vork, Onnen, Delfzijl, Leeuwarden)	Non-negative Rational number	ProRail, Provincie Groningen
Regulations on storing hydrogen	The regulations on the storage of hydrogen which are relevant for the facility location problem	Qualitative	European Union and Dutch Government (Kiwa)

Amount of space needed to store 1 m3 of hydrogen	The amount of space needed when storing 1 m3 of hydrogen	Non-negative Rational number	Hydrogen supplier
Number of rail tracks at the SY	The number of rail tracks at the shunting yard location where trains can be stationed for fuelling.	Non-negative Integer number	ProRail/maps

D. Assumptions

For the MILP

- The trains can be retrieve when needed during the operations, without moving the other trains
- The fuelling process is not affected by the other operational services
- No safety stock is necessary
- The hydrogen fuelling process runs independently of the diesel fuelling process.
- the arrival times of the trains at the FIs do not conflict with eachother
- The costs per m pipeline per unit hydrogen increase linearly
- The consumption of hydrogen is the same for every travelled km of the trains. Meaning that the cost per travelled km increase linearly per km travelled
-

For the PG problem

- 32 trains end their timetable at station Groningen and 18 trains at station Leeuwarden
- the price of hydrogen is €5 per kg hydrogen in the year 2035
- 1 TT can store enough hydrogen for 4 trains
- 1 FFI can fuel 12 trains per night
- A SFI can fuel 1 train per night
- the total yearly costs for locating a FFI € 466 667 for all potential locations at the SYs
- the total yearly costs for locating a SFI € 50 000 for all potential locations at the SYs
- the total yearly costs for locating one m pipeline is € 1 000 for all potential locations at the SYs
- The track lay-out remains the same.
- No research on the energy demand has been performed
- All trains are empty upon fuelling
- the costs per SY formulated by PR remains the same
- the chosen TT locations do meet the future regulations on storing hydrogen from PR
- No more than the cost for the hydrogen itself will be accounted for per tube trailer

E. The coordinates of the TT

SY1; The Vork

Number	Latitude	Longitude
1	53.19627	6.606967
2	53.19611	6.607531
3	53.19595	6.608099
4	53.19576	6.608677
5	53.1967	6.604743
6	53.1962	6.606191
7	53.19577	6.607467
8	53.19547	6.608418
9	53.1939	6.61268
10	53.19368	6.613366
11	53.19337	6.61436
12	53.19306	6.615285
13	53.19218	6.618995
14	53.19183	6.620145
15	53.19146	6.621264

SY2: Leeuwarden

Number	Latitude	Longitude
1	53.19449	5.780529
2	53.19467	5.781003
3	53.19472	5.782031
4	53.19472	5.783017
5	53.19475	5.78361
6	53.19477	5.784063
7	53.19486	5.78492
8	53.19498	5.785559
9	53.19499	5.786016
10	53.1951	5.78709
11	53.19519	5.78784
12	53.19545	5.789437

SY3: Onnen

Number	Latitude	Longitude
1	53.15765	6.629656
2	53.15778	6.628919
3	53.15728	6.629222
4	53.15666	6.6296
5	53.1566	6.630225
6	53.15596	6.630703
7	53.15534	6.631203
8	53.15467	6.631498
9	53.15483	6.631844
10	53.15309	6.632892
11	53.15175	6.633439
12	53.15085	6.633595

13	53.15012	6.633585
14	53.14727	6.633162
15	53.14718	6.633148
16	53.14705	6.633139

SY4: Delfzijl

Number	Latitude	Longitude
1	53.32898	6.941452
2	53.32937	6.941323
3	53.33081	6.939543
4	53.33145	6.938941
5	53.332	6.938148
6	53.33387	6.924517
7	53.33358	6.92212
8	53.33353	6.921452
9	53.33349	6.920723

F. The coordinates of the FFI

SY1: The Vork

Number	Latitude	Longitude
1	53.19598	6.606553
2	53.19592	6.606489
3	53.19587	6.60643
4	53.19214	6.618195

SY2: Leeuwarden

Number	Latitude	Longitude
1	53.19488	5.783377
2	53.19471	5.782677
3	53.19517	5.786145
4	53.19482	5.784613
5	53.19505	5.786541

SY3: Onnen

Number	Latitude	Longitude
1	53.15767	6.629518
2	53.15446	6.631607
3	53.15175	6.633406
4	53.15044	6.63327
5	53.14759	6.633109

SY4: Delfzijl

Number	Latitude	Longitude
1	53.3311	6.939052
2	53.33202	6.938189
3	53.33369	6.921374
4	53.33367	6.922056

G. The coordinates of the SFI

SY1: The Vork

Number	Latitude	Longitude
1	53.19125	6.620915
2	53.1912	6.620876
3	53.19116	6.62084
4	53.19111	6.6208
5	53.19107	6.620762
6	53.19102	6.620726
7	53.19098	6.620687
8	53.19093	6.620639

SY2: Leeuwarden

Number	Latitude	Longitude
1	53.1945	5.78045
2	53.19502	5.785656
3	53.19526	5.786384
4	53.19548	5.789328
5	53.19545	5.789337
6	53.19541	5.789341
7	53.19513	5.787611

SY3: Onnen

Number	Latitude	Longitude
1	53.15407	6.631296
2	53.15399	6.63127
3	53.15381	6.631304
4	53.14729	6.633155
5	53.1451	6.63292

SY4: Delfzijl

Number	Latitude	Longitude
1	53.32907	6.94162
2	53.33123	6.939963
3	53.33302	6.91371
4	53.33382	6.924424

H. Pipeline lengths of TTs to FFIs

Epsilon1jk

	1	2	3	4
1	42.49825063	49.74759931	57.03659014	877.402032
2	66.77272699	72.33896889	78.05101846	836.1252338
3	103.0530141	107.2824629	111.6201155	794.9410704
4	143.5865294	146.8671644	150.1849965	750.7073898
5	144.8491243	144.8231696	145.4794408	1029.430316
6	34.76760009	36.83967631	40.43751583	918.2680412
7	64.95293738	67.21189582	69.899125	820.8569343
8	136.6692129	138.2072243	139.8207382	748.7960586
9	468.7873674	469.5868944	470.1932644	416.3167777
10	520.9156178	521.7195589	522.3190823	364.1877378
11	595.472774	596.3013389	596.912998	289.5963432
12	665.9394865	666.765959	667.3660917	219.1400622
13	930.2119321	931.2957707	932.1335806	53.47424853
14	1016.219162	1017.299616	1018.129213	134.5186911
15	1101.216986	1102.278895	1103.085722	218.0797637

Epsilon2jk

	1	2	3	4	5
1	194.6135	145.1911	381.7468	274.6052	405.287
2	159.841	111.6185	347.048	241.103	371.3114
3	91.40215	43.03086	278.6384	172.3885	302.6499
4	29.414	22.70264	214.2181	106.8972	237.4857
5	20.79556	62.34425	175.1544	67.27335	197.9644
6	47.12529	92.64019	145.5127	37.01757	167.7996
7	102.8212	150.4341	88.44979	20.95976	109.8529
8	145.7533	194.2697	44.61713	65.27328	65.89498
9	176.2379	224.608	21.99526	95.26745	35.54233
10	248.6405	297.2611	63.42835	167.9532	37.14976
11	299.357	348.1132	112.9506	218.8502	88.04451
12	408.7082	457.8325	221.5208	328.8565	198.1139

Epsilon3jk

	1	2	3	4	5
1	9.533221	377.575	701.4683	836.2521	1141.869
2	41.94391	410.816	734.3096	866.0202	1167.533
3	46.99528	352.1595	675.4557	807.0138	1108.89
4	111.8946	279.2736	602.1546	733.475	1035.856
5	127.6748	255.4371	579.3903	714.0362	1020.481
6	206.0997	177.1099	501.0113	636.311	944.2191
7	281.9292	101.9434	425.4137	561.8076	871.5899

8	358.1932	24.99811	348.8727	484.8561	795.1637
9	351.354	44.55268	358.0356	497.1244	809.9846
10	556.4427	174.5338	152.7791	295.3626	612.0889
11	708.3181	325.2252	2.208125	145.3477	463.0629
12	805.3364	422.5083	101.0399	50.09488	364.2287
13	881.8303	499.9148	181.6685	41.59416	283.5484
14	1181.498	806.0422	498.701	353.1004	35.57313
15	1190.736	815.4756	508.3524	362.7442	45.10065
16	1205.053	830.0267	523.1053	377.495	59.79919

Epsilon4jk

	1	**2**	**3**	**4**
1	284.1472	401.1854	1432.569	1389.611
2	243.9045	360.2802	1409.129	1365.801
3	45.91304	161.9713	1248.489	1204.157
4	40.17737	80.29705	1192.822	1148.077
5	116.923	3.43744	1129.643	1084.631
6	1013.311	930.9832	209.5828	164.9288
7	1157.838	1081.138	51.05163	10.8677
8	1199.75	1124.13	18.56262	42.91388
9	1245.916	1171.333	48.88348	90.78513

I. Pipeline lengths of TTs to SFIs

Tau1jl

	1	2	3	4	5	6	7	8
1	1083.752611	1084.260463	1084.577787	1085.257821	1085.410618	1086.524368	1086.653344	1087.077085
2	1042.431003	1042.962638	1043.301903	1044.009625	1044.185597	1045.329892	1045.484278	1045.942924
3	1001.184322	1001.745602	1002.112043	1002.853847	1003.058201	1004.239689	1004.424891	1004.925674
4	956.927986	957.4984778	957.8743213	958.6290494	958.84503	960.042789	960.242292	960.7636827
5	1235.96884	1236.308661	1236.475097	1236.969364	1236.970487	1237.888169	1237.857844	1238.066969
6	1124.808475	1125.145063	1125.310927	1125.807325	1125.812367	1126.737855	1126.715992	1126.939362
7	1027.396799	1027.735328	1027.90529	1028.409602	1028.423299	1029.362755	1029.354373	1029.598777
8	955.3325114	955.6782915	955.8567054	956.3737943	956.3997313	957.3573076	957.3654006	957.6343733
9	622.8638317	623.1049012	623.2072081	623.6522701	623.6361793	624.5602338	624.5574673	624.8335093
10	570.7326777	570.9722893	571.0774794	571.5311942	571.5260704	572.4692202	572.4857542	572.7928755
11	496.1454257	496.4015781	496.5287658	497.0182825	497.0490224	498.0468975	498.1143325	498.4986395
12	425.683232	425.934553	426.0669658	426.5745347	426.6289113	427.6684263	427.7783469	428.2313421
13	164.4012888	165.7968189	167.0330723	168.9782867	170.2804857	172.9718948	174.5074877	176.9376187
14	82.13804754	84.80138687	87.2650259	90.76507523	93.41954419	97.76757234	100.7615927	105.1183765
15	32.89623403	38.50338011	43.51899973	49.56686882	54.48393277	60.6445688	65.63690563	72.22002014

Tau2jl

	1	2	3	4	5	6	7
1	5.484649	346.5747	399.4548	596.5261	596.3483	595.8816	477.0549
2	41.38629	312.3822	364.4973	561.9273	561.8547	561.5019	443.1014
3	108.0754	243.7619	296.2465	493.4943	493.3747	492.9766	374.4437
4	172.8075	178.7971	232.1655	428.8216	428.6021	428.1035	309.2604
5	212.3815	139.4222	193.301	389.4861	389.2188	388.6737	269.7148
6	242.6403	109.4614	163.8522	359.4706	359.1596	358.5721	239.5143
7	300.5405	51.86214	107.1176	301.6042	301.2587	300.6445	181.5669
8	344.4379	7.793149	63.47748	257.3369	257.0375	256.4832	137.6878
9	374.7648	24.14148	39.02272	227.3774	226.9848	226.3409	107.3036
10	447.4272	96.02561	50.19782	154.929	154.4231	153.6972	34.74889
11	498.2815	146.7837	97.27216	104.2829	103.6396	102.8259	16.99226
12	607.9622	256.4709	204.4478	8.139527	6.710244	8.03482	126.9413

Tau3jl

	1	2	3	4	5
1	412.1558	420.0432	440.4029	1175.082	1411.631
2	441.9816	449.4494	469.4282	1200.584	1434.967
3	382.9822	390.4418	410.4201	1141.969	1376.775
4	309.4587	316.903	336.8794	1068.971	1304.345
5	290.0935	298.0634	318.4893	1053.739	1291.102
6	213.1589	221.3489	241.894	977.5307	1215.845

7	141.3792	149.9451	170.4735	904.9532	1144.352
8	68.18776	76.99264	96.81591	828.5437	1068.426
9	92.1088	100.735	119.2281	843.3913	1084.292
10	152.4231	147.6223	132.7557	645.4211	888.2534
11	295.3481	288.6793	269.9856	496.1638	739.6819
12	389.6696	382.4405	362.8886	397.1303	640.6985
13	465.0421	457.4725	437.4875	316.3279	559.8552
14	766.5932	758.3584	737.8119	2.175689	241.4746
15	775.9497	767.705	747.1545	11.76928	231.8093
16	790.4125	782.1561	761.6013	26.5225	217.0609

Tau4jl

	1	**2**	**3**	**4**
1	15.07553	268.7434	1896.199	1252.412
2	38.74904	225.255	1877.949	1226.444
3	236.9933	54.63233	1732.997	1058.551
4	318.8161	72.28654	1684.456	999.3843
5	398.7969	147.8884	1626.695	933.6073
6	1254.814	1066.949	723.736	8.108849
7	1388.576	1213.411	561.8327	155.3704
8	1428.181	1255.666	517.1691	199.982
9	1472.049	1302.153	468.5076	248.5723

J. Calculation of the costs at the second-level

Heuristic G1

SY The Vork:
The associated flow costs are

$$\sum_{i\in I}\sum_{j\in J_i} g\left(\sum_{k\in K_i}\varepsilon_{ijk}a_{ijk} + \sum_{l\in L_i}\tau_{ijl}b_{ijl}\right) =$$

(32.89623+34.7676*4+38.50338+42.49825*4+43.519+49.56687+53.47425*4+64.95294*4+72.3389
7*4+93.41954+97.76757+100.7616+105.1184+107.2825*4)*1000= € 2 062 811

The associated location costs are

$$\sum_{i\in I}\sum_{k\in K_i}(\gamma_{ik}z_{ik}) + \sum_{i\in I}\sum_{l\in L_i}(\delta_{il}u_{il}) = € 466\,667 * 3 + € 50\,000 * 8 = € 1\,800\,001$$

SY Leeuwarden:
The associated flow costs are

$$\sum_{i\in I}\sum_{j\in J_i} g\left(\sum_{k\in K_i}\varepsilon_{ijk}a_{ijk} + \sum_{l\in L_i}\tau_{ijl}b_{ijl}\right) =$$

(5.484649+6.710244+7.793149+8.03482+8.139527+16.99226+20.79556*4+20.95976*4+21.99526*
4)*1000= € 308 157

The associated location costs are

$$\sum_{i\in I}\sum_{k\in K_i}(\gamma_{ik}z_{ik}) + \sum_{i\in I}\sum_{l\in L_i}(\delta_{il}u_{il}) = € 466\,667 * 3 + € 50\,000 * 6 = € 1\,700\,001$$

Heuristic G2

SY the Vork
The associated flow costs are

$$\sum_{i\in I}\sum_{j\in J_i} g\left(\sum_{k\in K_i}\varepsilon_{ijk}a_{ijk} + \sum_{l\in L_i}\tau_{ijl}b_{ijl}\right) =$$

(32.89623+38.50338+43.519+49.56687+93.41954+97.76757+100.7616+105.1184+34.76760009*4+42.
49825063*4+64.95293738*4+53.47424853*4+219.1400622*4+289.5963432*4)*1000= € 3 379 270

The associated location costs are

$$\sum_{i\in I}\sum_{k\in K_i}(\gamma_{ik}z_{ik}) + \sum_{i\in I}\sum_{l\in L_i}(\delta_{il}u_{il}) = € 466\,667 * 2 + € 50\,000 * 8 = € 1\,333\,334$$

SY Leeuwarden
The associated flow costs are

$$\sum_{i\in I}\sum_{j\in J_i} g\left(\sum_{k\in K_i}\varepsilon_{ijk}a_{ijk} + \sum_{l\in L_i}\tau_{ijl}b_{ijl}\right) =$$

(5.484649+6.710244+7.793149+8.03482+8.139527+16.99226+39.02272+20.79556*4+29.414*4+47.12
529*3)*1000 = € 434 391

The associated location costs are

$$\sum_{i\in I}\sum_{k\in K_i}(\gamma_{ik}z_{ik}) + \sum_{i\in I}\sum_{l\in L_i}(\delta_{il}u_{il}) = € 466\,667 * 1 + € 50\,000 * 7 = € 816\,667$$

Heuristic G3

SY the Vork
The associated flow costs are
$\sum_{i\in I}\sum_{j\in J_i} g\left(\sum_{k\in K_i}\varepsilon_{ijk}a_{ijk} + \sum_{l\in L_i}\tau_{ijl}b_{ijl}\right) =$
(32.89623+38.50338+43.519+49.56687+93.41954+97.76757+100.7616+105.1184+(34.7676+42.49825
+64.95294+72.33897+53.4742485+107.28247)*4)*1000 = 2 062 811
The associated location costs are
3*466667+8*50000= 1 800 001

SY Leeuwarden
The associated flow costs of this solution are:
$\sum_{i\in I}\sum_{j\in J_i} g\left(\sum_{k\in K_i}\varepsilon_{ijk}a_{ijk} + \sum_{l\in L_i}\tau_{ijl}b_{ijl}\right) =$
(5.484649+6.710244+7.793149+8.03482+8.139527+16.99226+39.02272+20.79556*4+29.414*4+20.95
98*3)*1000 = € 355 895

The associated location costs however are
$\sum_{i\in I}\sum_{k\in K_i}(\gamma_{ik}z_{ik}) + \sum_{i\in I}\sum_{l\in L_i}(\delta_{il}u_{il}) = €\ 466\ 667 * 2 + €\ 50\ 000 * 7 = €1\ 283\ 334$