Exploratory Simulation of Truck-Based Hydrogen Aircraft Refuelling Logistics at an Airport

Case Study at Rotterdam The Hague Airport

Gijs Ruben Janssen

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by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Friday, 20th of June at 09:30.

Student number:	4862570	
Project duration:	October 2024 – June 2025	
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TU Delft

Acknowledgements

The thesis in your hands marks the end of my academic career at the Delft University of Technology. Since 2018, I have been a proud student and resident of both Delft and Rotterdam. Even a few years of COVID could not prevent me from having the best time. My time in Delft has made me who I am today, with many great experiences, new people, and a lot of learning opportunities.

Sincere gratitude goes towards Dr. O.A. Sharpans'kykh and J. Maasland MSc. for their support during the thesis project. Your help, advice, and insights made it possible to finish this project. It was an intense learning experience, but I enjoyed doing it with you both. The same goes for all the other team members at RTHA, which made me feel at home and showed me how much fun it can be to work in the aviation sector. Thanks to this experience, I am ready for the first steps in my career.

A special thanks goes to my family, who have always been there to support me. The same goes for all my friends and housemates, old and new, who have motivated me and, most importantly, with whom I have had a lot of fun. A special thanks goes to my girlfriend, who has been a big part of my life for the last year, showed me unconditional support, and helped me through the difficult times.

I'm excited to see what the future brings!

Gijs Janssen
Delft, June 2025

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List of Abbreviations

ABM	Agent-Based Modelling
ACI	Airports Council International
AS	Average Summer scenario
ATI	Airport Technology International
AW	Average Winter scenario
BCGA	British Compressed Gas Association
BSI	British Standards Institution
CAPEX	Capital Expenditure
CO2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DES	Discrete Event Simulation
EESI	Environmental and Energy Study Institute
EHRD	ICAO code for Rotterdam The Hague Airport
EIGA	European Industrial Gases Association
EU	European Union
GH2	Gaseous Hydrogen
GSE	Ground Support Equipment
HA	Handling Agent
HRS	Hydrogen Refuelling Station
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICOM	Inputs, Controls, Outputs, Mechanisms
IDEF0	Integration Definition for Function Modelling
IEA	International Energy Agency
IQR	Interquartile Range
IRENA	International Renewable Energy Agency
Jet-A1	Kerosene
LCOE	Levelised Cost of Energy
LH2	Liquid Hydrogen
LHS	Latin Hypercube Sampling

MC	Markov Chain
NASA	National Aeronautics and Space Administration
NEO	New Engine Option
NFPA	National Fire Protection Association
NLR	Royal Netherlands Aerospace Centre
PAX	Passengers
PP	Platform Parking
PR	Penetration Rate
PRCC	Partial Rank Correlation Coefficient
PS	Peak Summer scenario
PW	Peak Winter scenario
RTHA	Rotterdam The Hague Airport
RTM	IATA code for Rotterdam The Hague Airport
SAF	Sustainable Aviation Fuel
SD	System Dynamics
TAT	Turnaround Time
TP	Trailer Parking
TRL	Technology Readiness Level
WEF	World Economic Forum

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Scientific Paper

Exploratory Simulation of Truck-Based Hydrogen Aircraft Refuelling Logistics at an Airport: Case Study at Rotterdam The Hague Airport

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Abstract

Green hydrogen is emerging as a viable alternative to kerosene for medium-range aviation, with airports playing a critical role in the distribution of liquid hydrogen (LH2). This study uses a simulation-based optimisation model to investigate hydrogen refuelling operations at Rotterdam The Hague Airport. Different analyses reveal that on-time performance and capacity are strongly influenced by hydrogen-flight penetration rate, refuelling-truck fleet size, and turnaround times. Operational efficiency depends on maintaining adequate fleet sizing and minimising LH2 refuelling durations, while factors like truck speed and trailer swap time have limited impact in compact airport layouts. Moderate integration by 2040 requires gradual investment, but high penetration by 2050 demands substantial infrastructure and vehicle expansion. As hydrogen usage grows, a second refuelling truck becomes necessary between 22% to 39% penetration, depending on the specific day and required refuelling time. Also, end-of-day and multiple close LH2 departures risk exceeding allowable departure time slots. Safety zone constraints and trailer capacity trade-offs further highlight the need for coordinated planning. These results underline that a successful transition to hydrogen aviation hinges on strategic fleet sizing, optimised processes, and phased infrastructure upgrades to ensure reliable and sustainable airport operations.

1 Introduction

Aviation drives global commerce, tourism, and cultural exchange, yet paradoxically contributes to climate change through rising carbon emissions. The International Energy Agency (2023) reports that aviation accounts for 2.5% of global CO2 emissions, with flight numbers projected to increase by 115% by 2050. Aviation's climate impact could double without intervention, as the Environmental and Energy Study Institute (2025) warned, highlighting the urgent need for emissions reductions to align with the Paris Agreement. The International Air Transport Association (2024) roadmap outlines targets to cut emissions by 48% by 2030 and reach net-zero by 2050, combining several strategies. Aircraft efficiency improvements, advanced aerodynamics, lightweight materials, and optimised operations can reduce fuel burn by 15–20%, but these gains are often outpaced by demand growth International Energy Agency (2023). Sustainable Aviation Fuels (SAF) are expected to deliver 65% of the required CO2 reductions, yet current production capacity is far below demand, requiring massive scale-up and strong policy support. Market-based mechanisms like ICAO CORSIA (2022) help limit net emissions above 2019 levels during the transition, but long-term decarbonisation depends on large-scale adoption of low-carbon fuels and propulsion. Battery-electric aircraft are emerging for short-range flights, though limited energy density restricts them to small commuter use unless breakthroughs occur.

Hydrogen propulsion offers zero-CO2 flight at the point of use, either via direct combustion in modified turbine engines or through fuel cells driving electric motors. Major aircraft manufacturers aim to field hydrogen-powered airliners by the mid-2030s, such as the Airbus (2025) project and Fokker Next Gen (2025). Recent demonstrations of regional aircraft with hydrogen fuel-cell powertrains underscore their promise. Hydrogen is widely regarded as the leading long-term technology for short- and medium-haul routes. However, many challenges remain, such as hydrogen's low volumetric energy density, which requires cryogenic storage integrated in the airframe. Besides the technological challenges, introducing hydrogen-powered aircraft imposes much more significant demands on airport infrastructure. According to the Airports Council International and Aerospace Technology Institute (2021), hydrogen fuel requires entirely new delivery, storage, and dispensing systems, meaning substantial capital investment, revised operational procedures, and updated safety protocols. For example, liquid-hydrogen transfers must be performed within tight temperature and pressure tolerances, lengthening aircraft turnaround times. The exact infrastructure footprint depends on the chosen hydrogen

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utilisation method, the daily volume of fuel required, and the design of the airport supply chain, from on-site production or import terminals to local distribution. Forecasts suggest that by 2050, up to 36% of flights at major hubs like Schiphol Amsterdam Airport could operate on hydrogen, which adds up to about fourteen to twenty-five routes (World Economic Forum (2023)). In reality, the pace of hydrogen adoption will hinge on a concerted, system-wide rollout of cryogenic storage tanks, hydrant lines, safety zones, and trained personnel across airports of varied sizes. While hydrogen's environmental benefits are clear, successfully integrating it into the aviation network will require overcoming considerable operational and infrastructural challenges.

Supplying hydrogen to aircraft involves five core stages: production, compression or liquefaction, storage, transportation, and dispensing on the airport. All of these can occur either off-site or on-site at the airport, and their combinations determine an airport's technical and economic ability to have hydrogen flights. Hydrogen arrives in two forms: compressed gas (GH2) or liquid (LH2). LH2 has higher volumetric energy density and is the leading candidate for flight refuelling, whereas GH2 already powers cars, trucks and even ground-support equipment (Schiphol Newsroom (2024)). Hydrogen can be made in multiple forms, with green hydrogen as the goal for reaching zero emissions. Green hydrogen is produced by electrolysis from renewable energy, but currently only accounts for about 1% of global supply (IRENA (2022)). Investment is scaling up: Shell (2022) is building a 200 MW electrolyser in the Port of Rotterdam (2022), and projects in Chile and Morocco promise large-scale exports (van Dijk et al. (2024)). GH2 storage options range from high-pressure tanks to underground caverns (Hoelzen et al. (2023)), while LH2 requires vacuum-insulated vessels to limit boil-off (Marksel et al. (2022)). Road transport is done by tube trailers, cryogenic tankers, or, where available, via pipelines such as those envisioned by the European Hydrogen Backbone project (Wang (2022)). Trucks are valuable for their operational flexibility and lower upfront cost. Pipelines promise lower per-kg transport costs but demand heavy initial investment (Simbeck and Chang (2002); Yang and Ogden (2007)). Dispensing hydrogen at the gate also differs from Jet-A1. Spark-free safety zones of 8–60 m diameter are required around the cryogenic connection (citeflyzero), pausing adjacent turnaround tasks unless mitigated by automation or remote refuelling points. Airports can choose between truck-based delivery and hydrant networks with bigger infrastructure upgrades.

Regardless of the upstream choice, the final distribution at the airport plays a critical role in sizing the entire chain. Most studies examine the whole conceptual supply chain of production and bulk transport to the airport, leaving a gap in the design of the airport's dispensing infrastructure. The details of fuel flow rates, refuelling vehicle logistics, spark-free safety zones, and gate assignment directly influence which delivery modes are viable for an airport. This could become increasingly relevant in scenarios where Jet-A1 and hydrogen will be used simultaneously. As hydrogen flight penetration increases, airports must anticipate how these operational constraints affect on-time performance, gate availability, and the sizing of key assets such as refuelling vehicles and trailers. This becomes critical for regional airports where infrastructure is limited and delays or inefficiencies could cascade through tightly scheduled operations. This study addresses that gap by focusing on the airport-side implications of LH2 refuelling logistics. The goal is to determine how many refuelling vehicles are needed to meet future hydrogen demand without disrupting flight operations or incurring excessive investment costs. This problem can be described with the following research question: *What is the required refuelling vehicle fleet size and associated investment costs to support hydrogen refuelling operations at an airport, considering a mixed-fuel flight schedule, different safety zone dimensions and varying refuelling characteristics?*

To answer this question, the research is structured as follows. First, Section 2 compares current Jet-A1 refuelling operations with expected future LH2 refuelling processes. Section 3 explains the research methodology, introduces the simulation-based optimisation model and Rotterdam The Hague Airport. This regional airport will be used as a case study. Next, Section 4 outlines the model inputs used to analyse the simulation model. The results of all analyses are presented in Section 5, followed by a discussion in Section 6 and conclusions and recommendations for future work in Section 7.

2 Current and Future Refuelling Operations

Current aircraft are refuelled using Jet-A1 kerosene through well-established and highly standardised procedures. Refuelling typically occurs at the gate during the turnaround process, often simultaneously with other operations like boarding, baggage handling, and catering service. Fuel is either delivered by refuelling trucks or via an underground hydrant system that connects to dispenser trucks at each stand. These systems are designed for minimal disruption, with safety zones of about 3 meters around the fuelling connection. The whole process is operated by trained personnel and generally occurs in parallel with other turnaround activities, contributing to a short and predictable turnaround time.

Refuelling with LH2 is expected to differ significantly from conventional Jet-A1 refuelling methods, both technically and operationally. Due to the cryogenic nature of LH2, which must be stored at -253°C, specialised insulated tanks, cryogenic pumps, and fuel hoses are necessary. Additionally, safety protocols need to be reassessed. Current hydrogen safety regulations require a notably larger spark-free safety zone, ranging from 8 to 60 meters in diameter, depending on local laws and the operational context. Unlike Jet-A1, which is typically dispensed using a fuel or hydrant truck with an average flow rate of approximately 15 kg/s, LH2 refuelling presents unique challenges beyond just the differences in flow rates. While LH2 is significantly lighter than Jet-A1, its lower density produces much higher volumetric requirements to deliver a similar energy content. Consequently, although a lower flow rate could theoretically yield comparable refuelling durations, the increased volume demands a larger hose diameter and distinct pumping technology, typically based on pressure-driven cryogenic pumps. These systems require special couplings and safety vents to compensate for boil-off and ensure operational integrity during transfer (Abdin et al. (2024)). Before the transfer of LH2, the hose and connector assemblies must undergo a purge to remove ambient air and then a chill-down phase to bring all metal components to cryogenic temperatures. This procedure can add several minutes to the refuelling time to prevent excessive boil-off and ensure safe operation. The Technology Readiness Level (TRL) of such LH2 refuelling systems remains relatively low. Refuelling infrastructure for the truck industry has already achieved LH2 flow rates around 7 kg/s for the LH2-powered trucks of Daimler Trucks (2024). However, these figures still fall short when considering the rapid turnaround requirements of commercial aviation.

Historically, extensive work by Boeing and NASA in the 1970s demonstrated that LH2 refuelling at 15 kg/s was technically feasible for aviation applications. More recent findings by Mangold et al. (2022) confirmed that even higher flow rates of up to 20 kg/s are achievable, provided that significantly larger fuel hoses are utilised. Nevertheless, at such high flow rates, the diameter and weight of the hose prevent manual handling, requiring the process to be fully automated. In contrast to these optimistic projections, Postman-Kurlanc et al. (2022) adopted a more conservative perspective, suggesting feasible flow rates between one and eight kg/s, depending on the specific scenario, fill time, and hose diameters. Babuder (2023) consolidated these findings into three representative flow rate scenarios: 5, 10, and 20 kg/s, to address a wide spectrum of potential developments over the coming decades. Realising this range's higher end will require stronger cryogenic pumps, advanced couplings, and comprehensive system-level innovations. As long as high flow rate systems remain under development, deploying multiple LH2 fuel trucks to a single aircraft is an alternative to maintaining acceptable turnaround times. In contrast to Jet-A1 trucks, LH2 refuelling vehicles may need to be equipped with modular refuelling arms or fixed dispensing units that operate independently from the delivery truck itself. This increased complexity reinforces the need to redesign airport-side infrastructure, vehicle integration, and turnaround coordination to accommodate the technical, spatial, and safety-specific requirements of LH2 operations. On the supply side, introducing LH2 calls for substantial upgrades to airport fuel storage and handling facilities, such as dewar tanks and cryogenic storage. Such facilities require safety systems such as pressure relief valves, emergency isolation valves, and continuous hydrogen leak detection, which must also be integrated into the airport's control centre. Depending on regional hydrogen production capacity, on-site liquefaction plants or buffer storage may also be necessary to ensure uninterrupted supply during peak traffic.

2.1 Safety

Refuelling operations at an airport must comply with risk-based safety criteria. Jet-A1's fuel safety zone distance around the refuelling is 3 meters (Postman-Kurlanc et al. (2022)). Hydrogen's low molecular weight means it can penetrate materials more easily, demanding extra precautions to prevent and detect leaks. Under normal conditions, its buoyancy causes rapid scattering, minimising local concentrations after a release (Mantzaroudis and Theotokoglou (2023)). However, when stored as cryogenic LH2 to pack enough energy for flight, its density increases, and the scattering slows. Despite these challenges, the hydrogen industry has long relied on advanced leak-detection systems and rigorous handling protocols to ensure safe storage and transfer. To ensure safe processes, an LH2 safety zone bigger than three meters is necessary to achieve equivalent risk levels, especially in the early development phase. A circular, spark-free safety zone concept is often used to ensure safety around the refuelling. Within this zone, no other aircraft may park, refuel or undergo turnaround procedures during refuelling.

3 Methodology

This research will define future scenarios to capture how flight volumes and hydrogen-powered operations might evolve. These scenarios establish the key variations in traffic demand, penetration rates, and seasonal patterns that form the basis of the study. Once the scenario framework is in place, a simulation tool will be constructed to evaluate each scenario's implications. By modelling these different traffic and penetration inputs, the research enables systematic testing of how the fleet requirements change under a range of forecasted futures. This way, the research question can be answered by comparing alternative configurations and tracing their impact on operational performance. First, the future scenarios will be determined in Section 3.1. In Section 3.2, the model will be specified, explaining the components, steps, inputs and verification. Then, in Section 3.3, the case study at Rotterdam The Hague Airport will be described, outlining the current environment and how it is translated into the model. Then, in Section 3.4, the Key Performance Indicators are specified, which are used to assess the model's outcomes. Finally, in Section 3.5, the different analyses will be introduced, which are performed to evaluate the various components in the research question.

3.1 Future Scenario Definitions

A set of future scenarios establishes the projected flight activity and hydrogen-aircraft mix that the model must accommodate. The target years 2040 and 2050 were selected to correspond with industry roadmaps and policy objectives, anticipating a significant scaling up of hydrogen flights. By 2040, manufacturers are expected to have completed their first generation of commercial hydrogen aircraft, airlines will replace a substantial portion of ageing kerosene fleets, and regulatory frameworks, such as carbon pricing and sustainable aviation fuel mandates, will exert enough pressure to drive early adoption. By setting the horizon at 2050, the model captures a period in which hydrogen propulsion is widely expected to be integrated into the sector. Aircraft turn-over cycles of 20 to 30 years mean that many of today's narrow-bodies will be due for retirement just as new hydrogen designs become economically viable.

Within these years, three hydrogen penetration-rate profiles represent the range of possible adoption values. In the low scenario, adoption is dominated by slow infrastructure roll-out and cautious airline investments. This results in hydrogen flights representing only a small part of total departures, focused on some short-haul markets. The medium scenario assumes a steady build-out of hydrogen refuelling hubs, steady technological improvements that reduce incremental capital costs, and moderate policy incentives that encourage airlines to introduce hydrogen aircraft on select routes. In the high scenario, aggressive decarbonization policies, rapid fuel-cell and storage advancements, and strong carbon pricing create an environment in which hydrogen penetration accelerates rapidly, so that by 2050, a substantial fraction of narrow-body flights operate on hydrogen.

Finally, each penetration profile is evaluated over four representative day types to ensure the model captures average operations and seasonal and peak-demand extremes. An average winter day is included to simulate low-demand conditions, when refuelling infrastructure might be underutilised. A winter peak day models the stress on hydrogen refuelling in the low season, when flight schedules have different properties, such as a larger portion of short-haul flights. A summer average weekday reflects typical high-season demand, allowing assessment of routine scheduling and refuelling requirements under normal peak loads. Lastly, a summer peak day represents the absolute operational extreme. These days, capture seasonal heterogeneity and illustrate how hydrogen infrastructure differs between quiet and busy days. Combining two key planning years, three adoption trajectories, and four operational snapshots, Figure 1 shows the twenty-four scenarios defined, which will be used in the rest of the research.

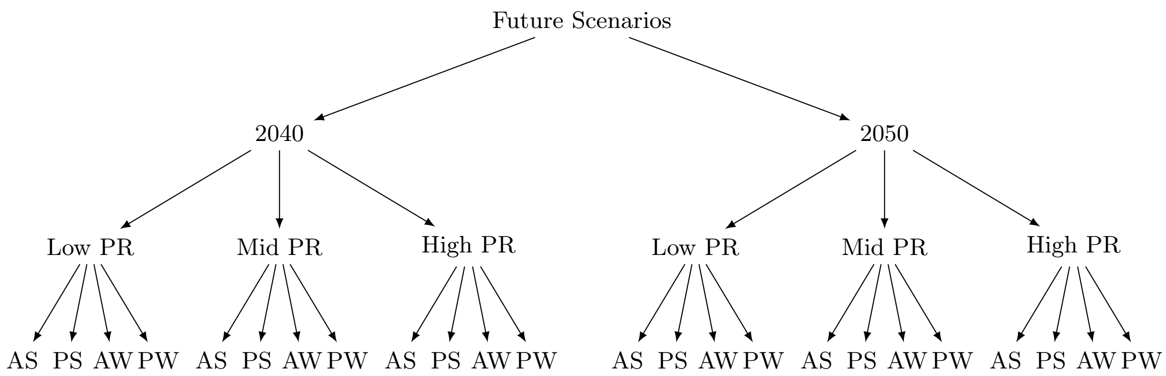


Figure 1: Tree of the 24 future scenarios by year, Penetration Rate (PR) and day type (AS: Average Summer, PS: Peak Summer, AW: Average Winter, PW: Peak Winter)

3.2 Simulation-based optimisation model

This section will explain the simulation framework to answer the research question for the future-scenario definitions, which will translate those inputs into performance metrics. A simulation-based optimisation model combines a dynamic system simulation, capable of capturing variability and operational interactions, with an optimisation layer that searches through possible configurations to identify those offering the best balance of objectives. This approach was chosen because it allows exploration of different fleet and safety-zone choices under realistic, variable conditions and systematically identifies solutions that optimise performance while accounting for uncertainty. Also, a simulation-based model can be run multiple times to assess the effects of the essential parameters in uncertain scenarios. The model's simulation utilises Discrete Event Simulation (DES) to replicate daily airport refuelling operations, evaluating whether assigned vehicle fleets service aircraft within scheduled ground times by simulating all the vehicle movements, refuelling processes and turnaround times.

This research will design the model using the Python package Salabim, which uses object-oriented DES. The model tracks truck and trailer availability, stand occupation, and aircraft refuelling status per one-minute simulation timestep. The simulation can capture dependencies between resources and time-sensitive events, where delays in one process can influence others later in the day. This model will consider no failures, maintenance or crew constraints. Additionally, different operational settings, such as the diameter of the LH2 safety zone or a different number of refuellings per trailer, can be changed to simulate technological developments of hydrogen or infrastructure changes at the airport. The model can differentiate between Jet-A1 and LH2 operations, allowing future hydrogen aircraft scenarios to be compared with the current situation. The different components in the simulation and their properties are specified in Figure 2. A detailed Swimlane diagram showing the chronological actions of these four components can be found in Supporting Work 1.2.

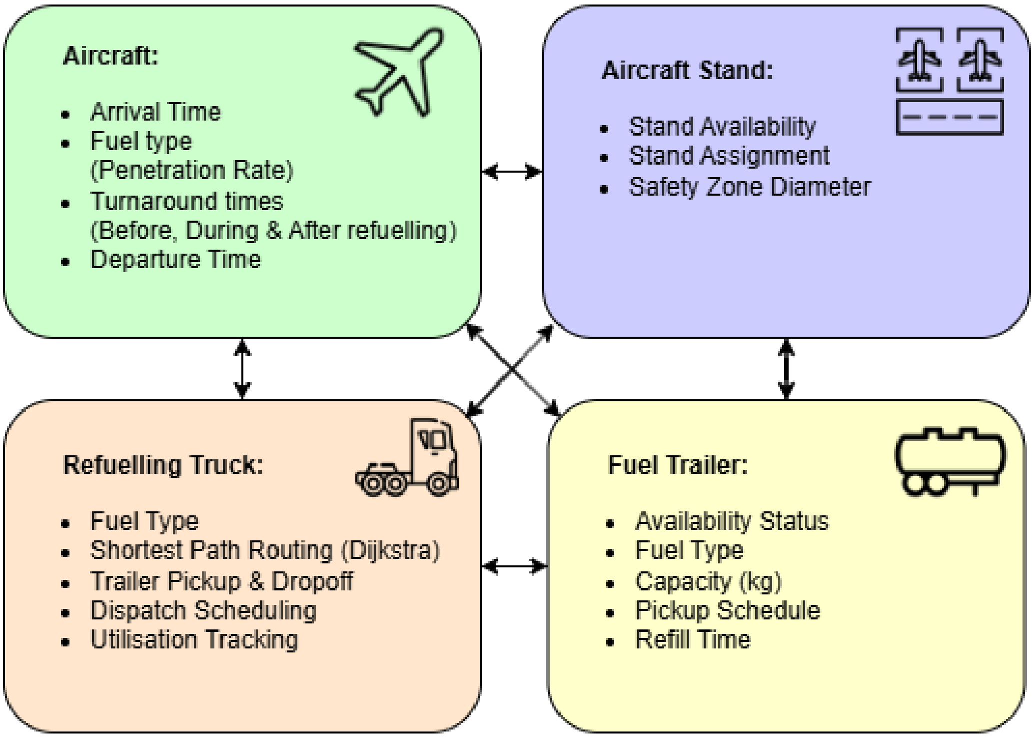


Figure 2: The different components of the simulation-based optimisation model and their functions

3.2.1 Simulation Workflow

To demonstrate the structure of the simulation, the IDEF0 methodology is adopted, a function-modelling standard that represents complex systems as a hierarchy of activities connected by arrows. Each activity box is linked to four distinct arrow types: Inputs, Controls, Outputs, and Mechanisms, collectively known as the ICOM framework. Inputs denote the data or materials consumed by a function, and controls capture the rules and procedures that govern its execution. Outputs are the products or information it generates, and finally, Mechanisms comprise the human, physical, and computational resources that carry out the work.

At the highest level, the context diagram (A0) shows the entire refuelling process as depicted in Figure 3. In our A0 block, a left-hand arrow delivers arriving aircraft gathered from the flight schedule into the simulation as the primary input. From above, a suite of operational constraints flows, such as the stand availability, individual aircraft fuel demands, trucks and trailers' current locations and availability, determined priority rules, driving distances across the airport, refuelling durations, and optional parking-stand restrictions. The right-hand arrow carries out the outputs of this function: flights have departed, records of resource consumption are produced, and the updated status of each truck and trailer is communicated back to the higher-level scheduling system. Finally, the bottom arrow lists the mechanisms that perform the refuelling: dispatch and scheduling software, human dispatchers, fuel-service vehicles and drivers, ground operators who connect and monitor the hoses, plus the monitoring and parking infrastructure on the airport.

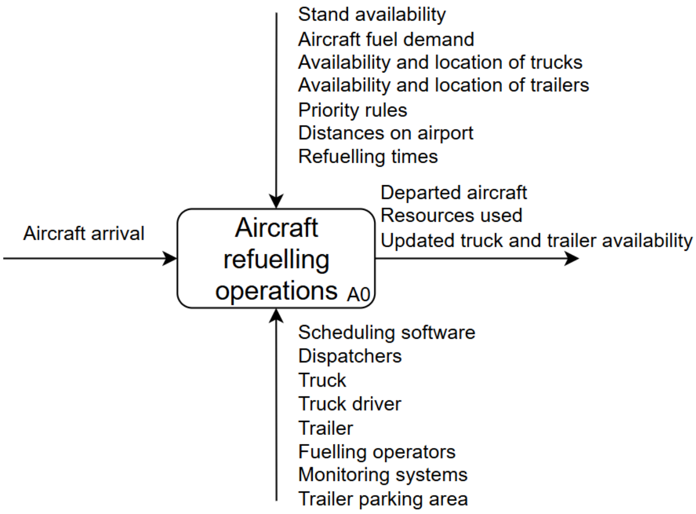


Figure 3: Building block A0 of the IDEF0 model

This process can be split into four sequential functional steps, for which all the ICOM elements of the A0 block are allocated across these sub-functions. These four steps are shown in Figure 4, corresponding to the A1 to A4 blocks in the IDEF0 model. Collectively, these four functions represent the complete operational flow of refuelling logistics within the model and support both Jet-A1 and LH2 aircraft under mixed-fleet conditions. The modular breakdown helps to clarify resource flows, identify bottlenecks, and structure the simulation logic in a traceable and interpretable way. Underneath the figure, these four blocks are further specified.

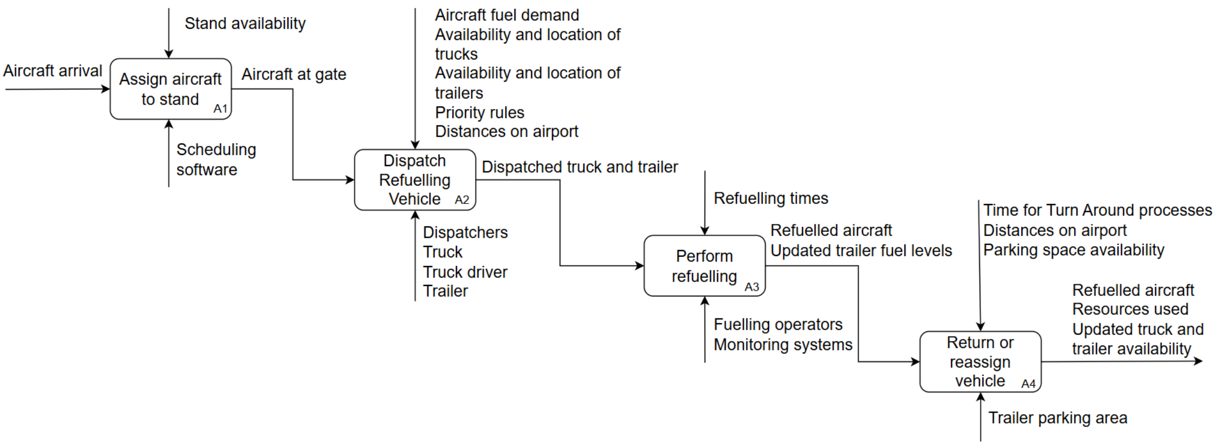


Figure 4: Building blocks A1-A4 of the IDEF0 model

Flight Arrival and Stand Assignment (A1)

An aircraft is generated when the following aircraft's arrival time in the flight schedule is reached in the simulation. Each flight is allocated randomly to any available stand. If no stand is available because other aircraft have not departed, or an active hydrogen safety zone blocks the stand, the arriving aircraft must queue on the taxiway until a stand becomes available. The stand-assignment function checks availability and delays parking until the stand capacity and the safety-zone constraints are satisfied. Each aircraft's time waiting for a stand is logged and can then be analysed for the different scenarios. By modelling stand allocation, queuing, and safety-zone blocking, the model captures how peak-period traffic and increasing LH2 penetration rates can affect on-time performance and taxiway congestion.
The aircraft then starts its pre-refuelling turnaround tasks, representing essential ground operations that must be completed before the hydrogen refuelling process begins. These include passenger disembarkation, baggage unloading, lavatory servicing, and basic maintenance checks. In the model, these tasks are not simulated individually but are instead abstracted into a single pre-refuelling delay period. The duration of this period is simulated as a uniform distribution defined by a minimum and maximum value, both of which are input parameters to the simulation. These parameter values are selected to reflect realistic variability observed in typical turnaround processes. They are included in the analysis to test their impact on truck dispatching,

queuing, and overall delay propagation. The sub-processes of the A1 block can be found in Supporting Work 1.1.

Truck and Trailer Dispatch (A2)

Once a hydrogen flight has parked and its stand is released, it is marked unavailable, and the nearest idle refuelling truck is dispatched. The truck is selected by computing the shortest-path distance via Dijkstra's algorithm from a different stand or a parking area. A compatible trailer is then attached by choosing the next one in sequence, enabling tracking of trailer utilisation. Both trucks and trailers are only valid for one of the two fuel types; no hybrid variant will be considered in this research. The truck and trailer combination moves to the assigned gate, and if the aircraft is still completing its pre-refuelling turnaround tasks, it will wait at the stand until both are ready. Otherwise, refuelling commences immediately. Connection, purging and chill-down times are incorporated within the refuelling-time parameter. The sub-processes of the A2 block can be found in Supporting Work 1.1.

Refuelling Operation (A3)

The refuelling operation is the activity in the aircraft turnaround process, where the actual fuel transfer takes place. It starts when the truck and trailer refuelling vehicle arrives at the assigned aircraft stand and establishes a connection with the aircraft. From that moment, the vehicle remains stationary, and the fuelling begins. This phase is purely operational, so no routing or scheduling decisions are involved. The duration of the refuelling depends on the type of fuel and the operational characteristics of the truck and aircraft. It is a blocking process, meaning no other ground handling activity requiring access to the fuelling area can occur during this time. Moreover, the vehicle is tied up during the entire refuelling period, making this step a significant determinant of overall resource utilisation. The output of this step is a fuelled aircraft ready for post-refuelling procedures, and a vehicle that can be reassigned or directed to refill its trailer if needed.

Redeployment and Refilling (A4)

After refuelling, the aircraft transitions into its final turnaround phase, performing the final preparation for departure. Tasks in this phase include final cabin checks, cargo loading, passenger boarding, pushback preparation, and crew readiness checks. These are all modelled within one parameter, a uniform distribution defined by a minimum and a maximum duration. While Jet-A1 and LH2 aircraft are assumed to follow similar sequencing of these activities, hydrogen-specific adjustments may affect these durations in practice. However, in this study, those variations are captured within the parameter values rather than modelled separately. Once this phase finishes, it departs at its scheduled time. If it is delayed, the difference between its actual and planned departure is logged as a delay. Simultaneously, the stand is released for the next arrival. The truck–trailer combination then checks its remaining hydrogen. It is dispatched to a queued aircraft or a designated holding area if sufficient for another complete refuelling. Otherwise, it returns to the trailer parking. The truck then remains idle until the next refuelling assignment. Idle time outside active service no longer contributes to the vehicle's utilisation metric. When a trailer is empty, it becomes unavailable during a "Trailer Refill Time," representing leaving the airport to be refilled off-site and returning to the trailer parking area. Because an unlimited supply of filled trailers is assumed to be available at the trailer parking, this refill cycle never causes additional delays to ongoing refuelling operations. Instead, the trailer refill time only affects how many trailers are required to support a full day's schedule. The sub-processes of the A4 block can be found in Supporting Work 1.1.

3.2.2 Model Inputs and Verification

The simulation-based optimisation model requires a range of input parameters that define the airport's operational characteristics, the refuelling vehicles, and the flight schedule. These inputs are grouped into four categories:

- **Turnaround Times:** These include the minimum and maximum durations for pre-refuelling and post-refuelling phases, representing the activities that occur before and after the refuelling operation within the aircraft turnaround process.
- **Refuelling Times:** These cover the minimum and maximum durations required to refuel Jet-A1 and LH2 aircraft. They capture the variability in how long the fuelling process takes, depending on fuel type and operational conditions.
- **Vehicle Parameters:** This includes the number of refuellings each trailer can perform before needing replacement, the time required to replace a trailer, and the driving speed of trucks within the airport.
- **Fleet Mix:** This refers to the penetration rate of hydrogen aircraft in the flight schedule and the number of refuelling trucks for both Jet-A1 and LH2. These parameters determine the system's demand balance and drive potential resource conflicts and delays.

The turnaround and refuelling times are modelled using input ranges to reflect uncertainty and variability in real-world operations. Within the model, these ranges are represented using uniform distributions, where each value within the specified range has an equal probability of being sampled. The uniform distributions provide a non-biased representation of uncertainty without assuming any particular central tendency. This is beneficial because many parameters depend on processes other than those within the refuelling distribution.

Once the core simulation model was designed, a systematic verification was performed to ensure that every input parameter and model output behaved as expected. Verification began with a simple, two-gate airport scenario in which manually specified arrival and departure times, truck and trailer counts, safety zone diameters, and other key inputs were then visually inspected to confirm that trailers were routed to stands as intended and that queue dynamics matched hand-calculated expectations. Then, additional complexities were introduced, such as trailer replacements, mixed Jet-A1 and LH2 fuel types, timing accuracy, and all the input variations. The simulator's event logs, time-waiting distributions, and final KPI values at each stage were compared. The complete table showing all the verification tasks is detailed in Supporting Work 2.

3.3 Case Study: Rotterdam The Hague Airport

A case study was performed at Rotterdam The Hague Airport (RTHA) to validate and test the model in a realistic scenario. RTHA is a mixed-use airport serving commercial and general aviation, along with two flight clubs; however, this research focuses solely on commercial aviation. RTHA is a small airport active in multiple hydrogen projects and is regarded as an excellent airport for testing new hydrogen technologies. This is due to the presence of all aviation types and its location; the airport is close to the Port of Rotterdam, Delft University of Technology and part of the Royal Schiphol Group. The innovation team at RTHA is investigating every facet of hydrogen at the airport, from supply-chain logistics and refuelling procedures to fire-safety protocols and small-scale validation tests. Externally, RTHA collaborates with the Port of Rotterdam to build a dedicated hydrogen delivery corridor and with Hamburg Airport to demonstrate a hydrogen-powered flight link between the two hubs in 2026.

3.3.1 RTHA Environment

A simplified version of the airport grounds is designed to use the airport in the model. The airport has one runway of 2200 meters and twelve remote aircraft stands of ICAO Size C, with a maximum allowed wingspan of 36 meters. The stands are in a 4x3 layout and are labelled with the letters 'A', 'B', 'C', 'D' for the rows and the numbers one to three for the columns. Currently, only truck and trailer fuel distribution is used, so the airport is a good environment to see the differences when hydrogen flights are integrated into the schedule. In Figure 5, a map shows the relevant part of the airport for this research. The twelve aircraft stands are indicated in blue squares. The vehicle road is displayed in the dotted black line, which the trucks use to pick up and bring the trailers to the Trailer Parking (TP). The TP is where the trailers are delivered and where the distribution at the airport starts. The Platform Parking (PP) is where the truck and trailer wait for the following arriving aircraft, when the trailer has enough capacity to refuel another flight.

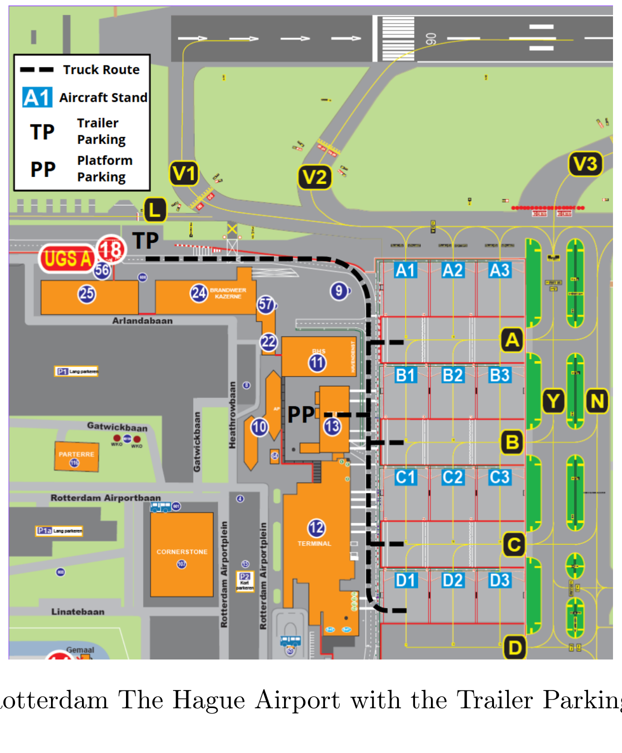


Figure 5: Airport plan of Rotterdam The Hague Airport with the Trailer Parking specified at the red arrow

A grid map is designed to simulate the airport map, which shows the key locations for the fuel distribution. These points are connected, representing the trucks' route from the trailer parking to the stands. This grid map can be seen in Figure 6, showing all the gates, TP, PP and their relative coordinates. The coordinates are also specified in the figure, with the Trailer Parking assumed to be the (0,0) coordinate. The distance between the TP and the road leading to the gates is approximately 250 meters. The distance between the gates is measured to be approximately 50 meters, so the gates are two nodes apart on the grid map. The constant velocity will be selected to include disturbances and other factors influencing the driving times. The grid map will be added to the Python code using the NetworkX package.

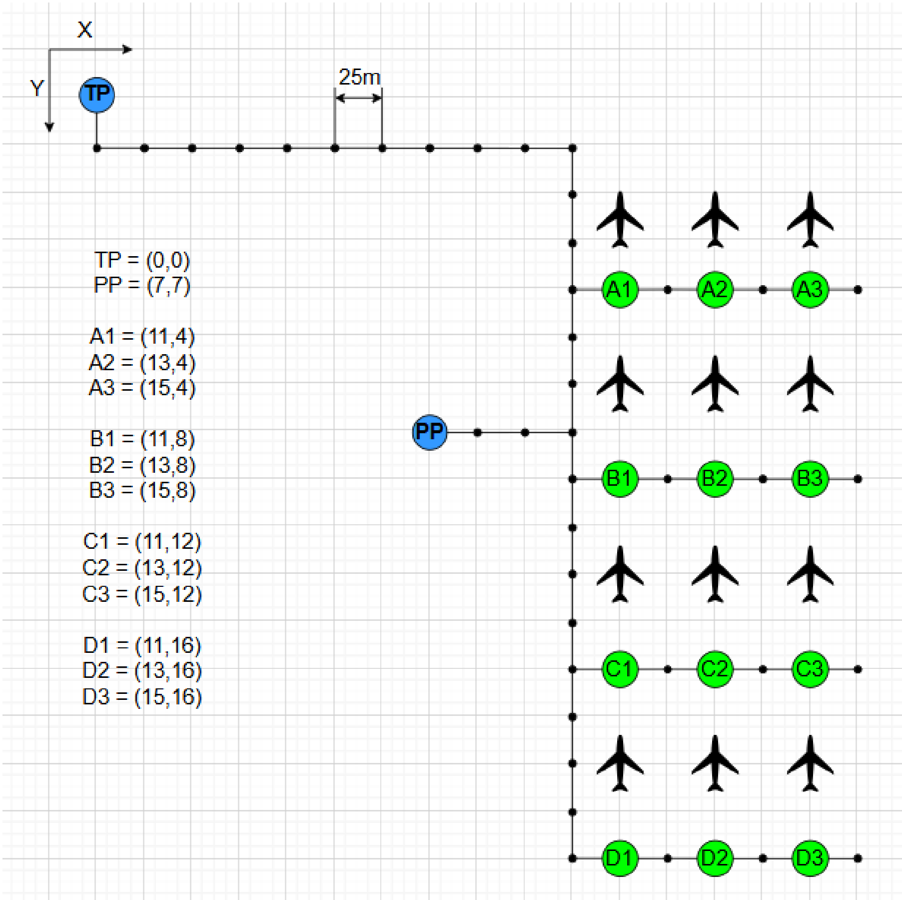


Figure 6: Grid map representation of Rotterdam The Hague Airport with the aircraft stands, Trailer Parking (TP) and Platform Parking (PP) specified

3.4 Key Performance Indicators

Five key performance indicators are defined to evaluate the model's performance against real-world operational requirements. These were selected to capture the operational reliability and logistical feasibility of hydrogen aircraft refuelling under future demand scenarios. Each indicator reflects a specific stakeholder interest and collectively ensures that the model evaluates performance across the entire process at the airport. The percentage of Delayed Flights measures the proportion of departures that miss their scheduled departure slot because of the fuelling operations. Total Average Delay quantifies the mean delay across all flights, reflecting the average duration of the delays. These on-time performance parameters are chosen to measure operational punctuality. These metrics are directly relevant to the airport, airlines and passengers, as delays can lead to increased turnaround costs, missed connections, and reduced passenger satisfaction. The combination of both metrics allows for assessing how often delays occur and how severe they are, providing a look at the system stress. Truck Utilisation records the fraction of simulated time each refuelling truck engages in driving and refuelling and is included to measure the efficiency of vehicle asset use. For the fuel service provider, high utilisation may indicate a cost-effective fleet size, while over-utilisation may signal the risk of bottlenecks or service delays. Conversely, low utilisation suggests potential over-investment in underused equipment. This KPI is critical when assessing infrastructure scaling decisions as hydrogen operations ramp up. Finally, the number of trailers refers to the trailers required to perform all the refuelling, representing logistical throughput and storage needs, capturing the total investment costs necessary to perform daily operations. The airport is also interested in this parameter because of the apron congestion management and sufficient parking space. Baseline results of simulating the current Jet-A1 distribution of these KPIs will be used to validate the model based on gathered data. These can then be used to compare the scenarios and experiments through the research.

Table 1: Key Performance Indicators and Relevant Stakeholders

KPI	Unit	Airport	Airline	Fuel Service Provider	Passengers
Delayed Flights	%	✓	✓		✓
Average Delay (all flights)	min	✓	✓		✓
Truck Utilisation	%			✓	
Number of Trailers	-	✓		✓	

3.5 Model analysis

The simulation-based optimisation model developed in this study can be applied to various scenarios and experimental setups to support decision-making for hydrogen aircraft integration. Four types of analyses are conducted to address the research question systematically. These analyses explore how operational requirements evolve across different system configurations, fuel mixes, and external constraints, enabling data-informed infrastructure planning.

This research uses a straightforward optimisation approach, which evaluates a defined set of configurations through the DES model. Each configuration represents a combination of determined key decision variables bounded by operational feasibility. By simulating these configurations individually, the model measures critical performance metrics, including average delay, on-time performance, and vehicle utilisation. This enables identifying Pareto-optimal solutions that represent efficient trade-offs between capital investment and service quality. The analyses in Figure 7 are developed to answer the different aspects of the research question. These allow for operational tuning and strategic planning, ensuring the model's outputs are actionable across different planning horizons and stakeholder interests. They will be further elaborated upon in Section 3.5.1, Section 3.5.2, Section 3.5.3 and Section 3.5.4.

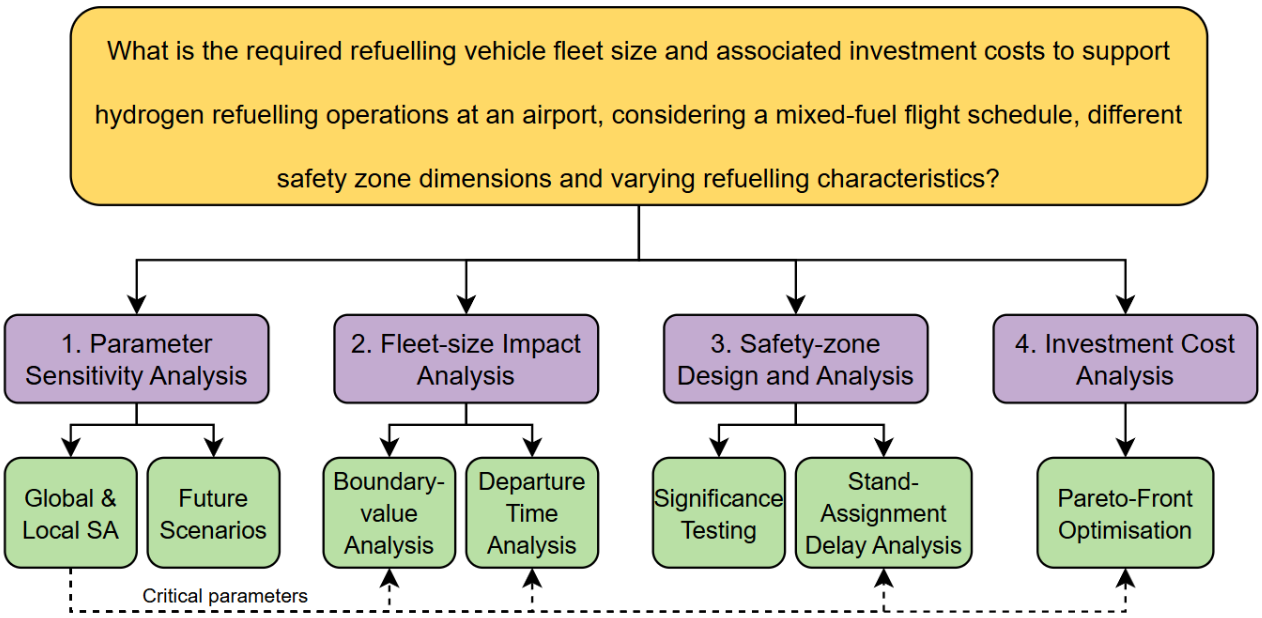


Figure 7: Diagram showing the different analyses to answer the research question

3.5.1 Parameter Sensitivity Analysis

Because the model has many uncertain parameters, an essential first step is to perform a sensitivity analysis. This will help to analyse the workings of the model, but can also lead to conclusions about the efficiency and capacity of the process at the analysed airport. This will be done by systematically varying the input parameters, evaluating their responses to changes made within the model, and determining whether essential parameters and trends can be observed concerning the on-time performance and truck utilisation rates. The sensitivity analysis consists of three parts: a global and local sensitivity analysis, and an analysis of the KPIs in the future scenarios. In the global analysis, all parameters will be varied, and a computation of the Partial Rank Correlation

Coefficient (PRCC) will first indicate which parameters influence the outputs most. The sampling method for the global analysis is Latin Hypercube Sampling (LHS), which divides each input parameter's distribution into equally probable intervals. Then it randomly samples once from each interval, resulting in a uniform, multidimensional parameter space with fewer samples than random sampling. A local sensitivity analysis will be conducted to examine how each parameter individually affects the outputs. This analysis involves assessing the slopes that result from increasing each parameter and comparing them to the corresponding outputs. These two sensitivity analyses reveal how parameters react, highlighting the most important ones for further analysis in the research. Having identified the critical parameters through global and local sensitivity analyses, the next step is to explore how those parameters evolve under projected operational conditions. This is accomplished via a future-scenario analysis, which uses the projected flight schedules for the four different day types to apply the model to analyse the KPIs for the various possible penetration rate scenarios.

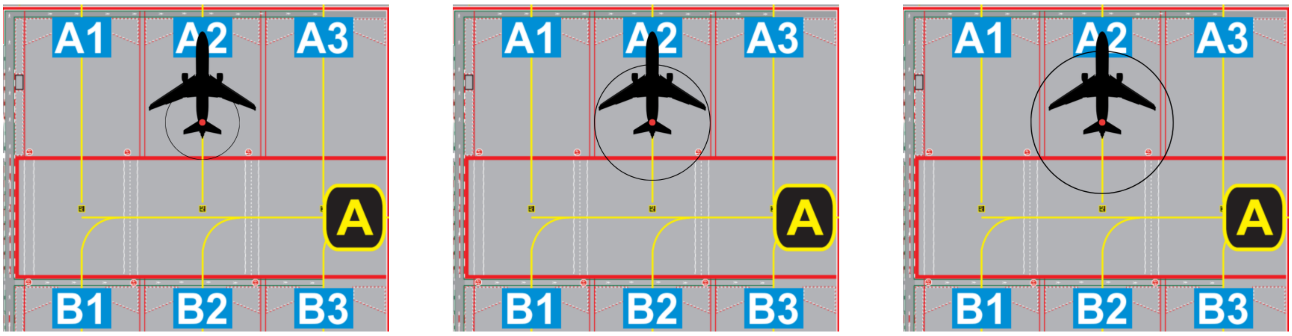
3.5.2 Fleet-size impact Analysis

The sensitivity analysis's most sensitive and impactful parameters can be further examined by assessing the fleet's capacity and how the airport's operational configuration must change to meet operational requirements. The study uses the boundary-value analysis to explore how different levels of hydrogen adoption and operational parameters affect the required refuelling fleet size and infrastructure investments. This will help address the thresholds of the key parameter values, between one and two LH2 refuelling trucks. The simulation outputs can be compared using the different truck fleet configurations. For this, a criterion must be determined, which is set to be one extra delayed flight on average for this research. To minimise delays, an additional refuelling truck must be added whenever, on average, an extra flight is delayed, as the goal is to achieve zero delays compared with the current refuelling system. From this analysis, specific breakpoints become clear, which provides direct decision support for the airports by identifying the fleet sizes at which a marginal increase in hydrogen operations would necessitate additional trucks. This is information that airport decision-makers can use when finalising budgets, procurement schedules, and infrastructure timelines.

After establishing the minimum fleet required to avoid incremental delays, the departure time analysis translates fleet-size configurations into operational consequences, focusing on the timing of aircraft departures. There are regulations near the airport that dictate the latest possible departure times for the benefit of residents. For RTHA, this limit is specified at 23:00, meaning no aircraft may depart after this time, as the airport risks incurring a fine and damaging relationships with the surrounding neighbours. Delays can create a snowball effect throughout the day, making it crucial to test whether late departures occur, in addition to the overall on-time performance. Since the model operates with a probability distribution, it can run scenarios numerous times and rerun an exact simulation using the same random seed as the outliers run. Using a distribution graph, outliers can be observed and analysed in greater depth to see how they occurred and can be prevented.

3.5.3 Safety-Zone Design and Analysis

The influence of safety-zone diameter on the stand assignment operations is evaluated in light of the research question to consider the safety aspects of the new refuelling operations. Postman-Kurlanc et al. (2022) shows research of the NFPA and NASA, which persists in using a distance of at least 30 meters to other combustible liquids. That is why three circular exclusion zones are designed with diameters of a conservative 20 meters, a medium-sized 40 meters and the extreme case of more than 40 meters centred at the aircraft's refuelling interface, most commonly expected to be located at the tail section during LH2 operations. In Figure 8, these zones are overlaid on an ICAO C-stand layout to illustrate stand availability under each scenario. At a 20-meter diameter or less, no adjacent stands fall within the exclusion area; at 40 meters, the zone overlaps taxi paths behind the gate. New LH2 arrivals cannot be assigned to stands, which blocks taxiing routes for already positioned aircraft. Aircraft that arrive later are allowed to be placed behind an LH2 aircraft because they are assumed to depart later than the refuelling time of the LH2 aircraft. For RHTA, all three stands in front of the stand are blocked for LH2 aircraft when an aircraft is on the leftmost stand. A plane on the middle column will block two stands in front, and one in front will be blocked when they are on the rightmost stand. When more than 40 meters in diameter, the safety zones also block adjacent stands, making them unavailable during refuelling. The two stands, 'C1' and 'D1', are also blocked for the extreme safety zone diameter, because of their proximity to the terminal areas.



(a) Safety zone diameter 20 m (b) Safety zone diameter 40 m (c) Safety zone diameter >40 m

Figure 8: Potential LH2 safety-zone diameters placed on the ICAO Size C stands at RTHA

These situations can be statistically compared against each other to analyse whether a significant difference between the three scenarios occurs. For this, a two-sample t-test followed by Tukey's test will be used to compare the means of the two scenarios for every combination. Tukey's test corrects for type I error, making comparisons between the scenarios more reliable. Also, an operational metric is introduced for the Stand Assignment Delay Analysis. The Stand Assignment Wait Time measures how often and for how long aircraft must wait for an available gate when different LH2 safety-zone diameters are in effect. While some gate-assignment delays may be absorbed by longer scheduled ground times, minor setbacks can result in taxiway congestion on days with tighter turnaround windows. Excessive values of the Stand Assignment Wait Time delay passenger deboarding and risks exceeding taxiway capacity, potentially forcing a reduction in daily flight movements. As LH2 safety regulations develop, monitoring this metric will be essential to ensure operational stability without decreasing the airport throughput.

3.5.4 Investment Cost Analysis

The model also tracks trailer pickups, including the schedule and the required number of trailers. This analysis investigated the total investment cost needed to maintain reliable operations. In this research, there is an endless supply of trailers, but by assigning them a unique code, the exact number of trailers required becomes evident. The same trailers will be refilled and used multiple times a day. At RTHA, this is done by driving the trucks to the port of Rotterdam to refill. For this research, a first estimation of 100 minutes is made to refill the trailer and return it to the airport. This is based on the distance to Air Products, a hydrogen supplier based in the port of Rotterdam. An analysis has been done by Hoelzen et al. (2022), which shows that it takes approximately 30 minutes to refill a trailer of four tons of LH2. It is also taken into account that the LH2 truck needs to drive a different route from Jet-A1 because LH2 trucks are not allowed to pass through tunnels as specified by the Inspectie Leefomgeving en Transport (2025), so they need to divert over the 'Van Brienenoord' bridge to reach the port of Rotterdam. Once this refilling time has passed, the trailer becomes available again and is given priority over a trailer which has not been used. In this way, the number of trailers gives a realistic count of how many trailers are used to perform the daily distribution. This value for the refill time will be varied to see the sensitivity of changing that parameter. The number of trailers is then measured for the different future scenarios. The various trucks and trailers can also be estimated to provide insights into the total capital expenditure (CAPEX) investment costs required for running the distribution. Estimations for the investment cost values are shown in Table 2.

Table 2: Investment cost estimates for Jet-A1 and LH2 trucks and trailers (MAHEPA (2019); Hoelzen et al. (2022); Beta Fueling Systems (2023))

Fuel type	Equipment	Cost (€)
Jet-A1	Truck	158 000
	Trailer	53 000
LH2	Truck	80 000
	Trailer	485 000

Another essential parameter concerning the trailer fleet size is the number of refuellings each trailer can do. As confirmed by expert opinion, this parameter currently is three refuellings for Jet-A1 trailers at RTHA. The value for LH2 depends on the trailer and aircraft fuel capacity, for which the different values can be seen in Figure 9. This figure shows how many flights can be served with a specific trailer capacity. This parameter must be chosen for specific scenarios when expecting a particular aircraft or trailer capacity. According to industry experts, current technologies for hydrogen trailers typically carry about 3000 kg of fuel. Emerging aircraft concepts target large on-board hydrogen tanks, but such high-capacity designs may prove optimistic in the early adoption phase. Also considering that most routes will not demand a full fuel load, taking three complete refuellings per trailer as a baseline scenario represents a balanced, mid-range assumption that allows an easy comparison with current Jet-A1 practices. The parameter will be tested to see the consequences on the simulation model outputs and the influence on the number of trailers. At last, a Pareto-front optimisation will be performed, showing a trade-off between the predicted CAPEX investment cost and the on-time performance.

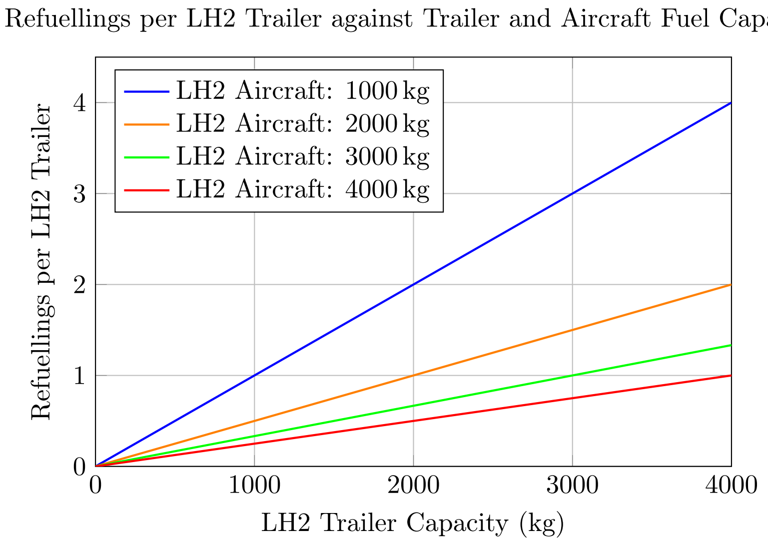


Figure 9: Number of refuellings each trailer can perform for four hydrogen aircraft sizes, as trailer capacity varies up to 4000 kg.

4 Model Input Specification

The inputs must be specified to run the optimisation model and produce reliable results. The first input is a flight schedule, which maps out demand on average and peak days in summer and winter, based on an analysis of the flight movements at RHTA in 2024. In Section 4.1, representative dates will be chosen, and it will be explained how the future flight schedules will be designed. Then, in Section 4.2, assumptions for the parameters will be made, which will be used to get baseline results. These will then be validated against the real data available.

4.1 Flight schedule

The simulation-based optimisation model uses a flight schedule as input, so representative daily flight schedules were created based on historical data from RTHA for the year 2024. Only commercial flights that arrived and departed on the same day were included, excluding aircraft with overnight stays. These aircraft depend less on the airport's busy and tightly scheduled day hours and could be refuelled overnight when no other aircraft need to be serviced. The flights were categorised into summer and winter seasons, with an average and a peak day selected for analysis. The average day was determined as the day that best corresponded to the averages for that period. The peak day was chosen as the day with the most overlapping flights, which was tested to have the most influence on the delays at the airport. If multiple dates had the same number of overlapping flights, the day with the highest total number of flights was selected, as it would most significantly spread out the effects of the peak moment throughout the rest of the day. The determination of the exact dates can be found in Supporting Work 3.

Growth estimates in passenger numbers from internal airport projections were translated into scaling factors for flight movements to predict future flight schedules. Between 2024 and 2035, passenger demand on RTHA is expected to increase by 45%. Applying this to the selected representative days, the total number of flights was scaled accordingly, as can be seen in Table 3, Table 4, Table 5 and Table 6. Overlapping flights were capped at twelve stands at the airport due to the physical constraint, and there are no plans to expand the number of stands, confirmed by experts at the airport. When creating future schedules, additional flights were inserted during the busiest periods of the day until the overlap limit was reached, and the rest of the flights were then distributed evenly to extend the peak duration and see the consequences of the accumulation of delays. Ground times of these inserted flights were based on the interquartile range (IQR) method to exclude outliers and use a suitable average. This ensured realistic turnaround durations while preventing skewness in the simulations. These representative future schedules form the basis for evaluating the impact of hydrogen aircraft integration and infrastructure scalability in the subsequent analyses.

Table 3: Predicted flights and overlaps based on passenger growth at average summer day 11-05

Year	**Max. Overlap Flights**	**Total Flights per Day**
2024	5	17
2030	6	21
2035	7	24

Table 4: Predicted flights and overlaps based on passenger growth at peak summer day 26-08

Year	**Max. Overlap Flights**	**Total Flights per Day**
2024	8	23
2030	10	29
2035	12	34

Table 5: Predicted flights and overlaps based on passenger growth at average winter day 20-02

Year	**Max. Overlap Flights**	**Total Flights per Day**
2024	4	10
2030	5	13
2035	6	15

Table 6: Predicted flights and overlaps based on passenger growth at peak winter day 31-10

Year	**Max. Overlap Flights**	**Total Flights per Day**
2024	6	16
2030	8	20
2035	10	23

Having identified four representative days, the 24 distinct scenario configurations can be specified further. Figure 10 shows the predicted development of hydrogen penetration rates for low, medium, and high cases at RTHA. These trajectories are based on the research of Hoelzen et al. (2022) and van Dijk et al. (2024). Table 7 summarises the key input parameters for each of the 24 scenarios: year, day type, penetration rate, and the corresponding daily flight count. The simulation model will be run for each case to produce comparable performance metrics.

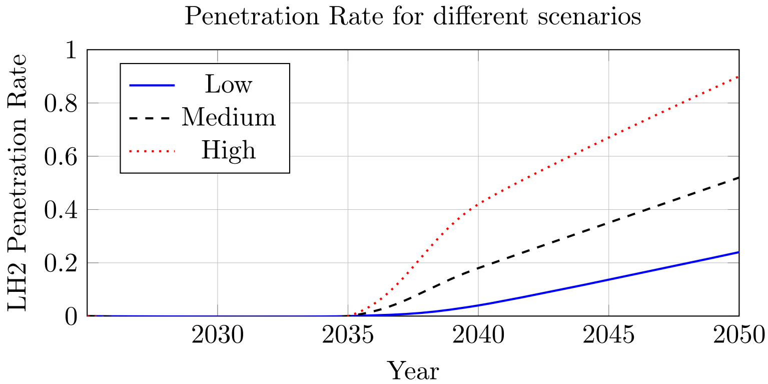


Figure 10: Penetration Rates throughout the years for three different scenarios based on Hoelzen et al. (2022) and van Dijk et al. (2024)

Table 7: Future scenarios with the input parameters

	2040						**2050**					
	Low		**Mid**		**High**		**Low**		**Mid**		**High**	
	Flights	PR	Flights	PR	Flights	PR	Flights	PR	Flights	PR	Flights	PR
Average Summer (11-05)	24	0.04	24	0.18	24	0.42	24	0.24	24	0.52	24	0.90
Peak Summer (26-08)	34	0.04	34	0.18	34	0.42	34	0.24	34	0.52	34	0.90
Average Winter (20-02)	15	0.04	15	0.18	15	0.42	15	0.24	15	0.52	15	0.90
Peak Winter (31-10)	23	0.04	23	0.18	23	0.42	23	0.24	23	0.52	23	0.90

4.2 Parametric inputs

To run the simulation model and perform the various analyses, a set of operational, technical, and scenario-based values for the input parameters must be defined, reflecting current practices at the airport. These parameters can be tested and then validated with the real operational data at the airport. The input parameters utilised for the simulation model are derived from expert consultations, direct observations, and relevant literature sources. Essential parameters such as turnaround times, refuelling durations, operational specifics, and fleet composition are outlined in Table 8. The minimum pre-refuelling turnaround time is 5 minutes, aligning with practical minimum durations for services such as water and waste management (Schmidt (2017)). The maximum pre-refuelling TAT of 12 minutes is based on typical passenger deboarding rates of the Airbus A321neo (AIRBUS (2023)). Similar reasoning applies to post-refuelling times, considering essential safety checks, system verifications, and passenger boarding processes. The Jet-A1 refuelling times vary significantly based on flight distance and fuel requirements. The minimum Jet-A1 refuelling time of 10 minutes corresponds to short-haul flights of approximately 500 kilometres, considering a typical refuelling rate and necessary hose connection time (James (2021); Joshi (2022)). The maximum refuelling time of 20 minutes reflects the longest typical routes operated from RTHA to the Canary Islands (van Dijk et al. (2024)).

Operational parameters like the number of Jet-A1 trucks, truck speeds, trailer replacement durations, and refuelling operations per trailer were based on current operations at RTHA. Two Jet-A1 trucks are currently in use to provide all the aircraft with Jet-A1 fuel, and 5 minutes is a high estimate of the multiple processes which occur during the replacement of the trailers. A high estimate is selected to contain both decoupling and coupling, and includes the additional detour required for the truck and trailer to turn around in the parking area. The assumed truck speed incorporates constraints imposed by airport speed limits and considers disturbances that could occur while driving. The fleet mix parameter, the penetration rate, was initially set at zero because of the absence of LH2-powered aircraft for the baseline year 2024. This reflects the current situation at RTHA and allows for comparison with future scenarios where LH2 aircraft become integrated into the flight schedule.

Table 8: First estimates for model parameters for the baseline output determination. All values confirmed by expert opinion at Rotterdam The Hague Airport.

	Parameter	Value	Unit	Reasoning
Turnaround Times	Before-refuelling TAT Min	5	minutes	Min. time for water/waste service (Schmidt (2017))
	Before-refuelling TAT Max	12	minutes	Deboarding A321neo: 20 pax/min → 232 pax ≈ 12 min (AIRBUS (2023))
	After-refuelling TAT Min	15	minutes	Time for system checks, fuel-quality assessments, and safety protocols
	After-refuelling TAT Max	20	minutes	Boarding A321neo: 12 pax/min → 232 pax ≈ 20 min (AIRBUS (2023))
Refuelling Times	Refuelling Time Jet-A1 Min	10	minutes	Short haul on A321neo (500 km): 1150 L/min + 4 min hose time (James (2021); Joshi (2022))
	Refuelling Time Jet-A1 Max	20	minutes	Long haul on A321neo (3200 km): 1150 L/min + 4 min hose time (James (2021); Joshi (2022); van Dijk et al. (2024))
Vehicle Parameters	Truck Velocity	15 10	km/h units/min	Gathered from expert opinion
	Trailer Replacement Time	5	minutes	Observed time to swap trailers
	Refuelings per Trailer Jet-A1	3	refuels	Current trailer usage at RTHA, confirmed by expert
Fleet Mix	Number of Jet-A1 Trucks	2	trucks	Based on current RTHA operations
	Penetration Rate	0.0	–	No LH2 aircraft in 2024

5 Results

The following section will describe the results of all the performed analyses. First, in Section 5.1, the results for the baseline model, the sensitivity analysis, and the KPIs in the future scenarios will be presented. In Section 5.2, the fleet-size impact analysis will be shown, consisting of the boundary-value and departure time analyses. Then the safety zone analysis will be shown in Section 5.3, and the investment cost analysis will be described in Section 5.4.

5.1 Baseline results and Sensitivity Analysis

The values of the input parameters are validated through simulations of baseline scenarios across the chosen dates in 2024. Results displayed in Table 9 show the KPIs in the baseline scenario 2024 with the assumed input parameters. In 2024, historical data from RTHA show that only fourteen flights experienced delays due to the fuel supplier. While not every delay is documented correctly at the airport, this still suggests refuelling operations should introduce zero delays. In our simulation for 2024, a small number of delays still appear because of the distributions in the model. The 2024 results thus serve primarily as a baseline for comparison with future scenarios rather than an exact replication of real-world delays.

Table 9: Baseline simulation results for selected 2024 dates with 95% confidence intervals (100 runs)

Metric	**Unit**	**Summer**		**Winter**	
		11-05-2024 (Avg)	**26-08-2024 (Peak)**	**20-02-2024 (Avg)**	**31-10-2024 (Peak)**
Total Flights Simulated	flights	17	23	10	16
Max Overlapping Flights	flights	5	8	4	6
Average Ground Time	hours	01:17	01:25	01:08	01:24
Simulation Outputs [95% CI]					
Delayed Flights	flights	0.22 [0.00–0.53]	0.01 [0.00–0.03]	0.14 [0.07–0.21]	0.21 [0.13–0.29]
	(% of total)	(1.29%)	(0.04%)	(1.40%)	(1.31%)
Average Delay (all flights)	minutes	0.00 [0.00–0.00]	0.00 [0.00–0.00]	0.02 [0.01–0.03]	0.03 [0.02–0.04]
Average Delay (delayed only)	minutes	0.00 [0.00–0.00]	0.01 [0.00–0.03]	0.21 [0.09–0.33]	0.42 [0.23–0.61]
Jet-A1 Truck Utilization	% busy time	73.12 [72.56–73.68]	73.82 [73.47–74.17]	66.70 [66.70–66.70]	72.89 [72.45–73.33]
Number of Jet-A1 Trailers	-	5.94 [5.86–6.02]	8.00 [8.00–8.00]	4.00 [4.00–4.00]	6.00 [6.00–6.00]
Departures After 23:00	-	0.00 [0.00–0.00]	0.00 [0.00–0.00]	0.00 [0.00–0.00]	0.00 [0.00–0.00]

5.1.1 Parameter Sensitivity Analysis

The sensitivity analysis results of the model provide insights into the key parameters and their relative importance affecting operational performance at the airport. A global sensitivity analysis has been performed for all safety zone diameter scenarios, and the results for the <20m scenario are in Figure 11. The exact values and their p-values are shown in Supporting Work 4.2. Among all the parameters tested, the number of refuelling trucks showed the highest influence on the average delay per aircraft. This result highlights the importance of optimising the fleet for hydrogen-fuelled operations, especially as the penetration rate increases. The maximum refuelling time for LH2 also indicates a strong relationship with delays, confirming that minimising the refuelling times for hydrogen turnaround operations is essential. Other time parameters, such as the maximum values for pre-refuelling and post-refuelling turnaround time, also show sensitivity, suggesting that they can absorb fluctuations but are less effective for reducing delays. Conversely, operational factors like trailer replacement time, refuellings per LH2 trailer and truck speed showed little to no significance, implying that these are less important in the case study of RTHA. The latter two also had p-values exceeding the 95% threshold, indicating high variability. This suggests that variations in those inputs produce only small, random changes, thereby having minimal impact on the simulation results. A logical explanation for this behaviour is that the distances at the airport are relatively small, but this will need to be confirmed by looking at the parameters individually.

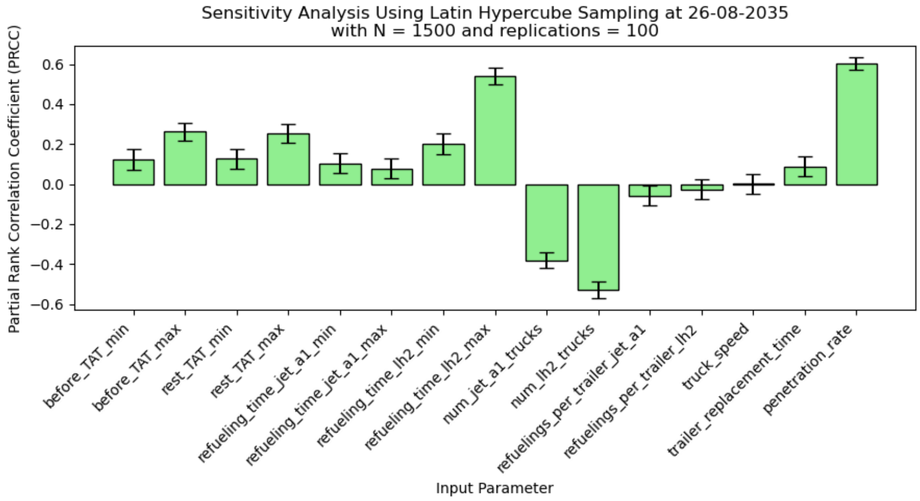


Figure 11: Global Sensitivity analysis with safety zone diameter of <20m, 1500 samples and 100 replications per sample

Tests with a 40-meter safety zone showed negligible differences from the baseline configuration. This implies that the same parameters have the most influence and are essential to focus on in that scenario. The absolute impact difference on the outputs will be elaborated upon in the safety-zone analysis in Section 5.3. However, the global sensitivity analysis results with the safety zone configuration of more than 40 meters show a significant increase in the impact of the penetration rate of LH2 aircraft on the number of delayed flights. This suggests that the number of hydrogen-powered aircraft becomes critical in operational developments in more restrictive safety configurations. While the maximum refuelling time for LH2 remains an important parameter, consistent with the baseline analysis, its influence is reduced compared to the fleet mix, indicating that constraints imposed by larger safety zones worsen scheduling conflicts more than the refuelling duration does. The rest of the parameters seem to have the same order of influence, only relatively less influential, because of the increase in importance of the penetration rate. These results imply that the focus of the further analysis should be on two fronts: exploring how truck availability scales with an increasing number of hydrogen-powered flights and understanding under what conditions the refuelling time becomes a limiting bottleneck.

The global sensitivity analysis has also been run for the Jet-A1 and LH2 truck utilisation outputs to consider the capacity requirements, shown in Supporting Work 4.2. These analyses return three critical parameters: the number of trucks for the two fuel types and the penetration rate. The fleet mix has by far the most influence, reaching scores of over 0.8. This effect is explained by the fact that a smaller fleet increases the workload per vehicle, raising utilisation rates, while a larger fleet distributes tasks more evenly, reducing individual utilisation. For the Jet-A1 case, the number of Jet-A1 trucks has more influence and vice versa for the LH2 case. The other parameters score significantly lower, so only these three are interesting. The max refuelling time, which is significant in the delay analysis, has low sensitivity concerning truck utilisation. This implies that most of the truck's active time gained by shorter refuelling times is spent driving and waiting for aircraft at the next stands.

Fleet mix and Time parameters

In the global sensitivity analysis, the number of refuelling trucks emerged as a dominant driver of performance. Analysing these parameters reveals a clear pattern: increasing the number of available trucks significantly decreases both average departure delays and the number of delayed flights. This effect is evident at lower truck counts, where the composition between Jet-A1 and LH2 trucks introduces significant variability, as can be seen by wider confidence intervals. This variability diminishes as the total truck count increases, with convergence of performance observed at five or more trucks, regardless of the fleet mix. The full results of this analysis can be found in the Supporting Work 4.2. These findings support the earlier global analysis and confirm that scaling the refuelling fleet accordingly can lower the problems introduced by a growing share of hydrogen aircraft.

When plotting the sensitivity of the time-related parameters against the average delay, the slope and the standardised slope are shown in Table 10. These values reach the same conclusions as the global sensitivity analysis results. Most notably, the LH2 maximum refuelling time emerges as the most influential parameter, with the highest standardised slope and a strong linear relationship confirming its critical role in departure delays. The other maximum turnaround times also show a steep and consistent impact, highlighting that prolonged turnaround operations at high penetration rates can significantly affect operational efficiency. The analysis also reveals that the minimum LH2 refuelling duration, which was less significant globally, has a considerable effect when explored independently across its parameter bounds. The entire timeframe of the LH2 refuelling should thus be assessed carefully. The parameters with a lower R^2 have less linear effects, mainly because they have relatively small changes resulting in more variability on a smaller scale. These values are thus also considered to have less impact on the simulation outputs. The minimum bounds for the other uniform distributions, other than the LH2 refuelling time, are confirmed to have less impact, resulting in more focus on the maximum bounds in the rest of the research.

Table 10: Slopes from linear regression of time parameters over their bounds on the 26-08-2035 schedule with 50 replications per scenario

	Parameter	Minimum Bound	Maximum Bound	Linear Regression Slope	R^2	Standardised Slope
Turnaround Times	Before Refueling Min	0	10	0.026	0.42	0.645
	Before Refueling Max	10	25	0.063	0.86	0.929
	After Refueling Min	5	15	0.037	0.56	0.752
	After Refueling Max	15	30	0.053	0.82	0.903
Refueling Times	Refueling Time Jet-A1 Min	10	20	0.014	0.12	0.339
	Refueling Time Jet-A1 Max	20	30	0.038	0.58	0.760
	Refueling Time LH_2 Min	10	30	0.040	0.82	0.903
	Refueling Time LH_2 Max	30	60	0.032	0.94	0.967

Vehicle parameters

The vehicle parameters show relatively low sensitivity in the global sensitivity analysis, suggesting that variations in these values have a limited impact on overall system performance within the explored parameter ranges compared to the other parameters. This observation is supported by the results of the individual parameter analyses, which similarly indicate a minimal effect on the key performance indicators. One reason for this limited influence is that these parameters depend on the airport layout, and in a compact airport layout like that at RTHA, they only marginally impact the model. The trailer replacement time typically occurs during non-critical periods, reducing its impact when the truck does not have a high utilisation rate. While the vehicle parameters individually score low in the global sensitivity analysis, their combined effect with other parameters can be substantial. The relationship between the LH2 refuellings per trailer and the LH2 refuelling time is interesting because both parameters are linked to the aircraft's fuel demand: higher-capacity hydrogen aircraft require longer refuelling times and consume larger volumes per turnaround, thereby reducing the number of possible refuellings per trailer. The refuellings per trailer will thus be further explored in the trailer analysis in Section 5.4.

5.1.2 Future scenarios

The results of analysing the predicted future scenarios by comparing the KPIs are presented in this section. The first set of results is shown in Figure 12, focusing on the 2040 scenario. The simulation results display minimal sensitivity in key performance indicators under the low hydrogen penetration scenario on an average summer day. The mid scenario sees a percentage of delayed flights over 8%, but the average delay is still minimal. In the high-demand scenario, a bigger increase is visible, reaching over 26%. The average delay is also reaching higher values up to 2.5%. The Jet-A1 truck utilisation lowers from around 76% in 2035 to 67% and the LH2 utilisation grows to 66%. The same trends are visible at the summer peak, but with higher values. In the high hydrogen penetration scenario, the average delay is similar, indicating, but with a higher number of delayed flights up to 31%. This suggests that the delay distribution is skewed toward a larger number of short delays rather than a few severe disruptions, and that overall schedule robustness is maintained despite increased logistical pressure. The truck utilisation also shows higher values, but is still within realistic limits. The average winter day shows fewer delayed flights but a higher average delay, suggesting longer delays occur. The high scenario also has the highest average delay of all the days, which could also result from the shorter ground times. The truck utilizations are the lowest of the four scenarios, suggesting that the difference in delay may be caused mainly by the shorter ground times and not by the fuel distribution. The peak winter day is comparable to an average summer schedule, with slightly fewer delayed flights, which could be caused by the shorter ground times in winter. None of the scenarios suggests that changes in fleet size are necessary, except that in low penetration rate scenarios, one LH2 truck may already be enough to perform the entire distribution on the day.

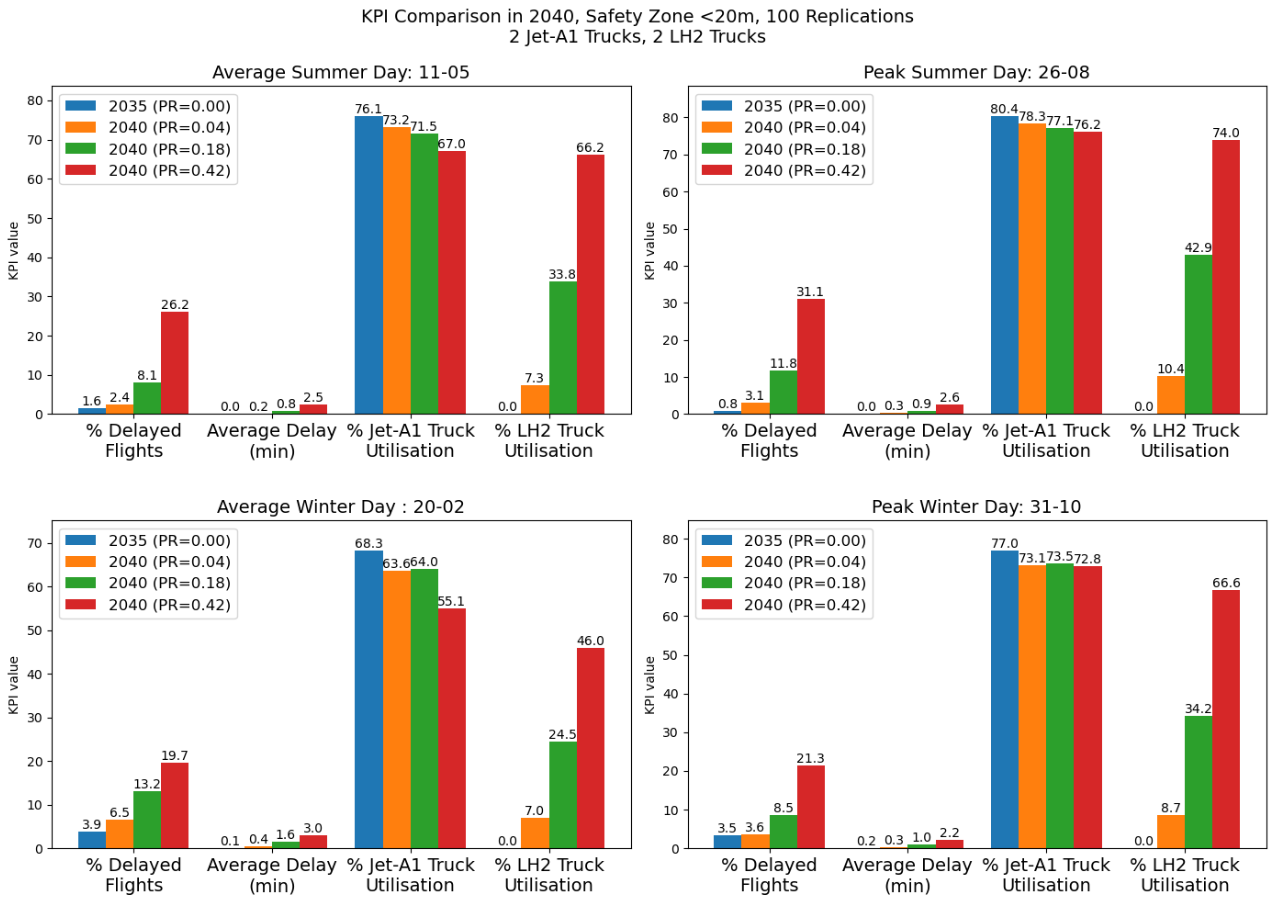


Figure 12: The KPIs for the four future scenarios in 2040 with 2 Jet-A1 and 2 LH2 trucks, a safety zone of <20m and 100 replications per scenario

The same analysis for the 2050 scenarios, displayed in Figure 13, shows that in the low-penetration case, the proportion of delayed flights climbs to nearly 15%, although average delays remain around a minute. In the mid-penetration scenario, however, delays begin to accumulate more substantially. In the high-penetration case, average departure delays on the summer peak day are around 25 minutes, signalling severe congestion. In this scenario, the summer peak is the most critical, as prolonged delays affect the most significant number of flights, leading to cascading impacts across the schedule. Truck utilizations remain within acceptable bounds except under high-penetration conditions, where LH2 trucks operate at almost 94% capacity, leaving practically no margin for unexpected circumstances. Such intense utilisation indicates that adding a third LH2 truck would be required to preserve schedule resilience under extreme hydrogen demand, which will be shown in Supporting Work 4.1.

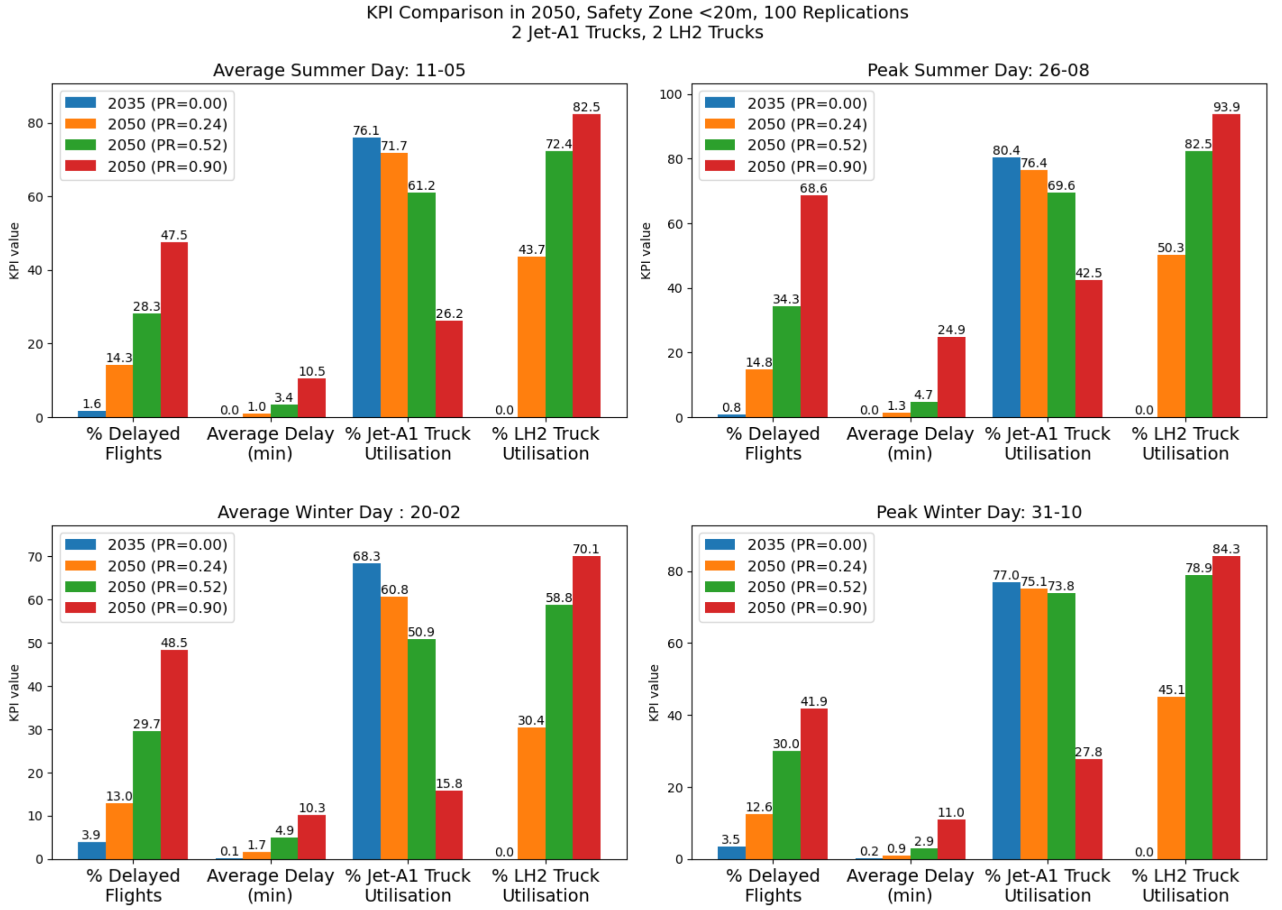


Figure 13: The KPIs for the four future scenarios in 2050 with 2 Jet-A1 and 2 LH2 trucks, a safety zone of <20m and 100 replications per scenario

5.2 Fleet-size Impact Analysis

The fleet-size impact analysis examines how the number of refuelling trucks influences key operational outcomes. First, the boundary-value analysis in Section 5.2.1 identifies the values for the critical parameters at which adding an extra LH2 refuelling truck becomes necessary to keep on-time performance. In Section 5.2.2, the departure time analysis evaluates whether the fleet configurations also satisfy real-world departure time constraints.

5.2.1 Boundary-value Analysis

After the sensitivity analyses, it became clear which parameters impacted the model's outputs most. From this, it can be determined what values will change the airport's operational configuration. Whenever hydrogen flights are integrated into the schedule, at least one LH2 truck is needed. However, it is interesting to see which critical parameter values require a second truck. This is first done for the most crucial parameter, the penetration rate. Analysis of Table 11 shows that a second LH2 refuelling truck is required when the share of hydrogen-powered flights approaches approximately 22–39% of daily operations. This threshold changes based on whether it is a peak or average day and on the assumed maximum refuelling time, because when refuelling takes longer, lower hydrogen-penetration rates require adding a second truck. Because daily traffic volumes differ between summer and winter, expressing capacity requirements as a penetration rate provides a normalised criterion for fleet sizing. The number of hydrogen flights needed to require a second truck is reduced on lower-traffic days, even though the critical percentage remains similar. Winter schedules, which are often dominated by shorter rotations, reach this one-third threshold at a lower absolute flight count than in summer. This suggests that additional LH2 assets may be required more frequently during the winter period than would initially be expected, especially considering that short- to medium-haul flights are a higher percentage of the scheduled flights in winter.
The range of maximum LH2 refuelling times significantly influences fleet sizing. Increases in the refuelling time can increase the need for additional trucks. Recognising this dependency, a complementary analysis is conducted by holding the penetration rate constant and identifying the critical refuelling-time thresholds beyond which a second LH2 truck becomes necessary.

Table 11: Boundary inputs for the Penetration Rate at which operations switch from one to two LH2 trucks

		Total Flights	Max LH2 Refuelling Time (minutes)		
			30	**45**	**60**
Summer	Average	24	0.37	0.31	0.29
	Peak	34	0.38	0.29	0.22
Winter	Average	15	0.36	0.29	0.27
	Peak	23	0.39	0.29	0.26

To complement the penetration-rate sensitivity, the analysis is inverted by fixing penetration rates at 0.2, 0.3 and 0.4 and identifying the maximum LH2 refuelling-time thresholds at which a second truck becomes necessary, which can be seen in Table 12. At a 0.2 penetration rate, no plausible refuelling-time constraint triggers the addition of a second LH2 truck. This confirms that, when hydrogen flights comprise only 20 % of operations, a single truck always provides sufficient capacity, as could also be concluded from the penetration rate analysis.

At a 0.3 penetration rate, the critical refuelling window narrows to roughly 46–56 minutes, with the peak days having the lowest boundaries. At the highest tested penetration (0.4), the threshold contracts to approximately 24–34 minutes. These results highlight a clear trade-off: as the hydrogen-flight share increases, allowable refuelling time must be shortened, or an additional truck becomes necessary. Decision-makers can use these breakpoints to right-size LH2 truck fleets for any traffic mix, once more details about the hydrogen refuelling operations are clear.

Table 12: Boundary inputs for the Maximum LH2 Refuelling Time at which operations switch from one to two LH2 trucks

		Penetration Rate		
		0.2	**0.3**	**0.4**
Summer	Average	–	56.0	29.1
	Peak	–	46.1	23.6
Winter	Average	–	45.9	23.8
	Peak	–	47.2	33.6

5.2.2 Departure Time Analysis

Building on the threshold findings, the departure time analysis then evaluates how those critical fleet configurations translate into actual departure performance under peak operational conditions. In Figure 14, the departure time for the two fuel types on a peak summer day with a 0.42 penetration rate in 2040 is shown for the different truck configurations. With this penetration rate, configurations with only one LH2 truck exceed the departure times limits and are thus deemed infeasible, as previously confirmed. A slight delay is acceptable for the airport, but departures after 23:00 are prohibited to comply with regulations in place for the surrounding neighbourhoods. Some configurations show delays after the planned departure time, which present interesting cases for further investigation. Since the model uses probability distributions, the scenario with two Jet-A1 trucks and three LH2 trucks still experienced late departures in one simulation. This occurred because the last three flights were all LH2. It could be valuable to research these scenarios further, leading to new regulations that, for example, allow LH2 flights not to be scheduled as late as Jet-A1 flights to adhere to departure time limits.

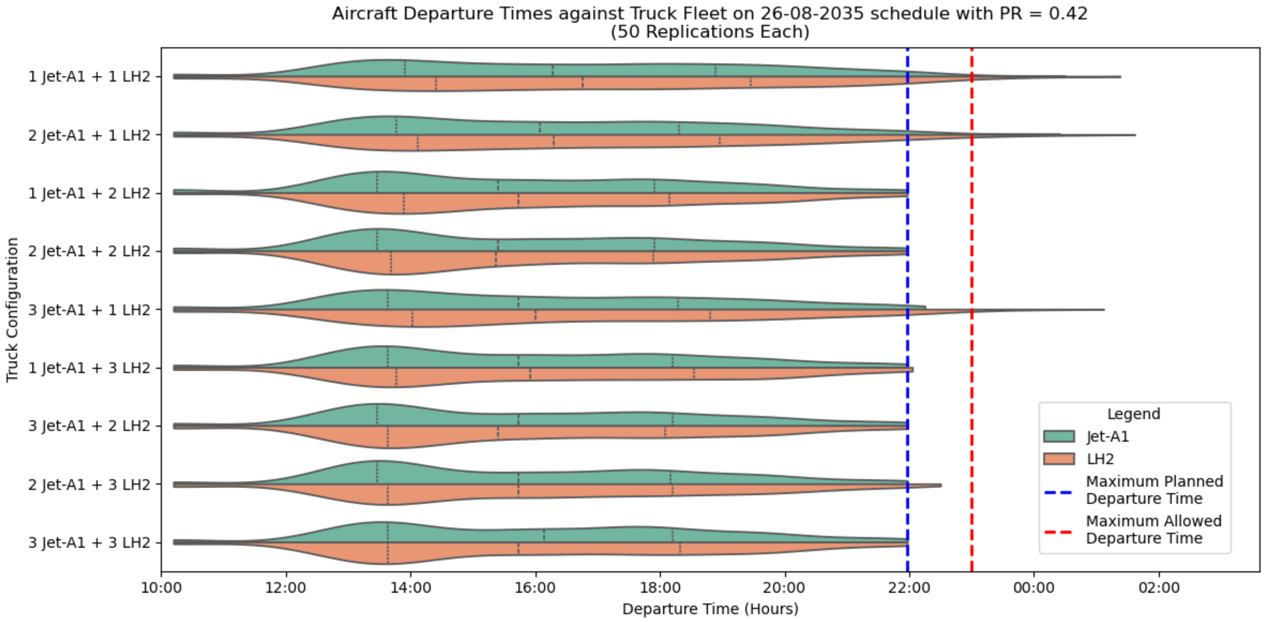


Figure 14: Violin plot of the departure times at the high penetration rate scenario with 50 replications per configuration

5.3 Safety Zones

The safety-zone analysis investigates how different safety-zone diameters affect airport throughput and aircraft delays. The first component, delay significance testing in Section 5.3.1, applies statistical tests to determine whether observed differences in delay metrics across safety-zone modes are statistically significant. The second component, stand-assignment delay analysis in Section 5.3.2, measures how safety-zone restrictions translate into concrete hold times at stands.

5.3.1 Significance Testing

The results of a two-sample t-test followed by Tukey's test between different safety zone diameters, evaluated across a range of hydrogen aircraft penetration rates with 100 replications per scenario, are shown in Table 13. At a penetration rate of 0.00, the mean differences in total average delay between safety zone diameters are minor and not statistically significant, with corresponding Vargha and Delaney A-test values close to 0.5, indicating negligible or no practical difference in delay distributions, which is as expected because the safety zones only affect hydrogen aircraft. At a penetration rate of 0.05, a statistically significant difference emerges between the safety zone bigger than 40 meters and the <20m and 20–40m groups, with A-test values of 0.437 and 0.456, respectively. These values fall below the 0.5 threshold, suggesting small but meaningful differences in delay outcomes. As the penetration rate increases further, this trend strengthens: at penetration rates of 0.10 and 0.15, the >40m safety zone leads to consistently and significantly higher delays, with A-test values decreasing to 0.431 and as low as 0.366, indicative of small to medium effects. These findings underscore that zones bigger than 40 meters begin to introduce measurable delays from even modest levels of hydrogen aircraft presence and become increasingly disruptive as penetration increases.

Table 13: Mean difference in Total Average Delay between safety-zone diameters for varying penetration rates using Tukey's HSD test and corresponding Vargha and Delaney A-test (100 replications per scenario)

Penetration Rate	Safety Zone Diameter Group 1	Safety Zone Diameter Group 2	Mean Difference	p-value	A-test value
0.00	<20 m	20-40 m	0.006	0.808	0.496
	<20 m	>40 m	–0.004	0.934	0.514
	20-40 m	>40 m	–0.010	0.592	0.518
0.05	<20 m	20-40 m	0.030	0.770	0.481
	<20 m	>40 m	0.178	0.000	0.437
	20-40 m	>40 m	0.148	0.002	0.456
0.10	<20 m	20-40 m	0.017	0.970	0.499
	<20 m	>40 m	0.452	0.000	0.431
	20-40 m	>40 m	0.435	0.000	0.431
0.15	<20 m	20-40 m	0.068	0.711	0.473
	<20 m	>40 m	0.712	0.000	0.366
	20-40 m	>40 m	0.643	0.000	0.390

5.3.2 Stand-Assignment Delay Analysis

The operational metric Total Stand Assignment Wait Time is introduced to quantify how much time aircraft spend holding on taxiways because of blocked stands. Figure 15 plots this metric alongside total departure delay as hydrogen penetration increases. Stand waits remain zero at a <20-meter zone, meaning there are enough stands for the general 2035 flight schedules. With a 20 to 40-meter diameter, a handful of aircraft wait a few minutes, but those delays fall within normal ground-time margins. By contrast, a zone bigger than 40 meters drives stand-assignment for up to 90 minutes at a 30% penetration rate, leaving aircraft idle on taxiways and keeping passengers from deboarding for a significant time. The corresponding jump in total departure delay confirms that only the largest safety zones meaningfully degrade on-time performance, confirming the statistical comparison. This means that standard turnaround buffers can absorb the limiting effects of moderate-sized safety zones. Even though the Total Stand Assignment Time can often be compensated by ground times, it is still an important metric to keep track of, because it could lead to taxiway congestion and passenger dissatisfaction. And once this reaches a certain threshold, it could lead to fewer allowed flight movements at the airport.

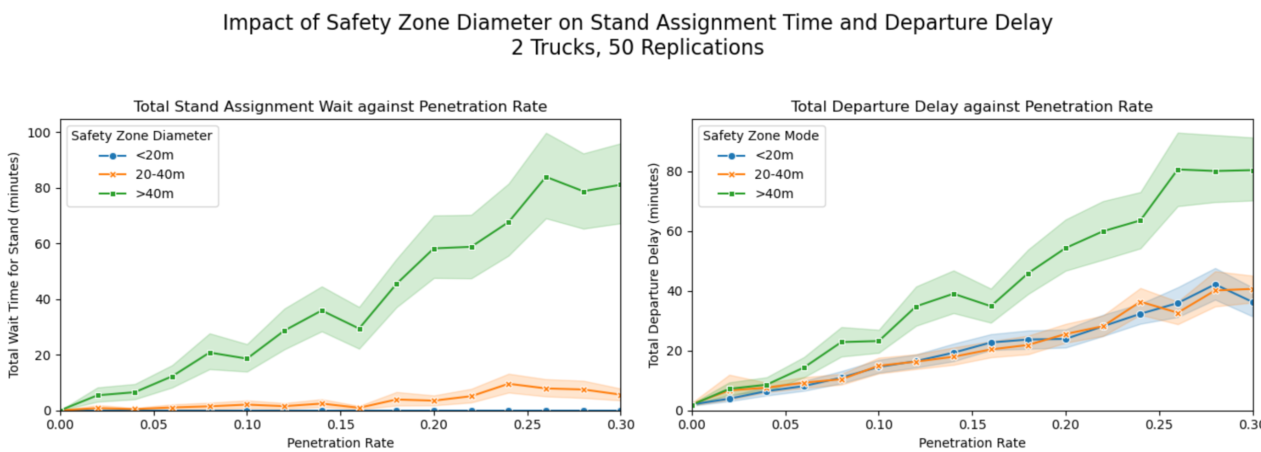


Figure 15: Total Aircraft Wait Time on an available stand for different penetration rates compared to the Total Average Delay with 50 replications per scenario

5.4 Investment Cost Analysis

The number of trailers is critical when examining the investment costs and supply to the airport. It does not influence delays and truck utilisation, but can be analysed using the simulation model. The baseline scenario involves three refuellings per LH2 trailer, with each trailer being refilled and returned to the airport in one hundred minutes, as explained in the methodology. Examining the different number of required trailers for the scenario days in Figure 16 shows the increase in the necessary total trailers when hydrogen flights are introduced. Then it levels off toward higher penetration rates, suggesting decreasing trailer needs once LH2 traffic exceeds roughly 20–30%. At low-penetration rates, virtually all trailers remain Jet-A1 types; beyond a 20% share, the LH2 portion becomes significant. The summer peak day requires the most equipment overall, whereas the winter average day has the lowest number of required trailers. The summer peak days are the only ones decreasing initially, indicating that it is currently operating at peak capacity. Once the graphs level off, Jet-A1 trailers can be linearly substituted for LH2 trailers when more hydrogen flights are present.

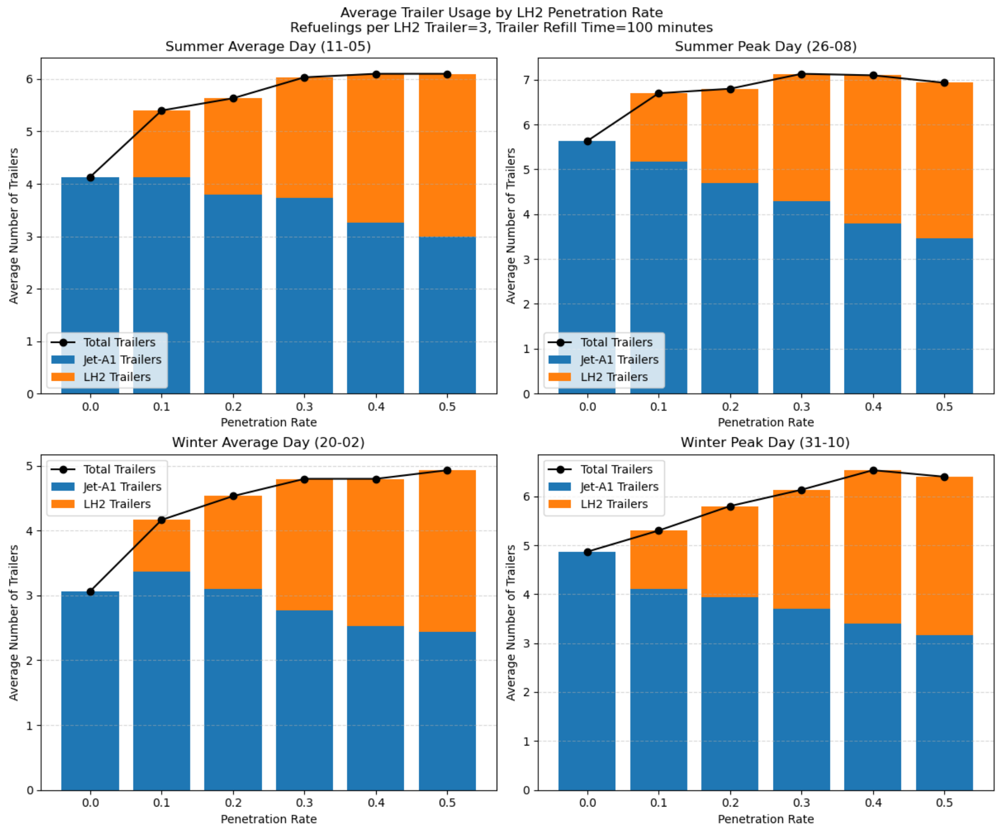


Figure 16: Baseline number of trailers for the different scenario dates for three Refuellings per LH2 Trailer, 100 minutes of Trailer Refill Time and 30 replications per scenario

The impact of varying the number of refuellings per LH2 trailer is illustrated in Figure 17. Increasing trailer capacity from one to five refuellings has a noticeable effect on the required fleet size. Specifically, the number of trailers needed decreases from approximately 6.5 when each trailer supports only one refuelling, to around 5.5 trailers when each can serve five aircraft. This represents a reduction of one trailer on average across the tested range. The most significant reduction occurs when moving from one to two refuellings per trailer. After three refuellings, the marginal reduction in trailer demand begins to plateau, suggesting diminishing returns at higher capacities. Operationally, this pattern highlights the importance of accurately estimating this parameter in practice. The lower capacity values are the most sensitive regarding impact on logistics and the most commonly assumed in early-stage planning or conservative safety estimates. Ensuring robustness in this part of the parameter space is therefore critical for efficient trailer fleet sizing and reliable LH2 refuelling logistics.

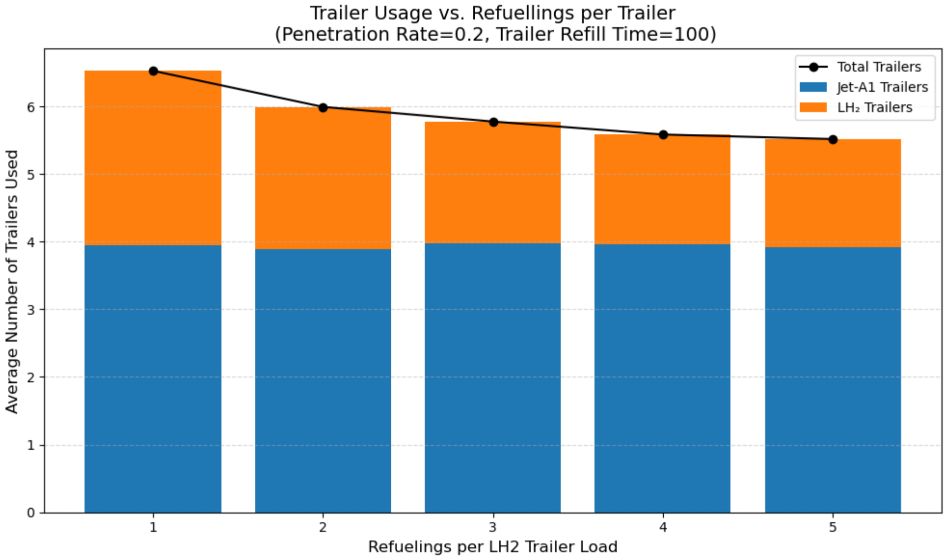


Figure 17: Number of required trailers for varying values of the Refuellings per LH2 trailer, 100 minutes of Trailer Refill Time and 30 replications per scenario

Additionally, the assumption regarding the refilling time of the trailers needs to be reviewed. If the refilling process takes longer than the assumed 100 minutes, it will also impact the number of trailers, as illustrated in Figure 18. As the refilling time for trailers increases, the overall demand for Jet-A1 and LH2 trailers rises, assuming they share an identical refilling time. At a 100-minute refill, the airport needs roughly 5.8 trailers. Pushing refill cycles out to 300 min elevates total demand to nearly 7.9 trailers. This upward trend means that longer refill times keep trailers away from the airport longer, forcing more trailers into service to maintain the same on-time performance. The values demonstrate a consistent linear effect, indicating that this parameter is relatively straightforward to monitor and predict. However, this also indicates that the effect is significant, and this parameter requires awareness and optimisation, which is recommended for future research.

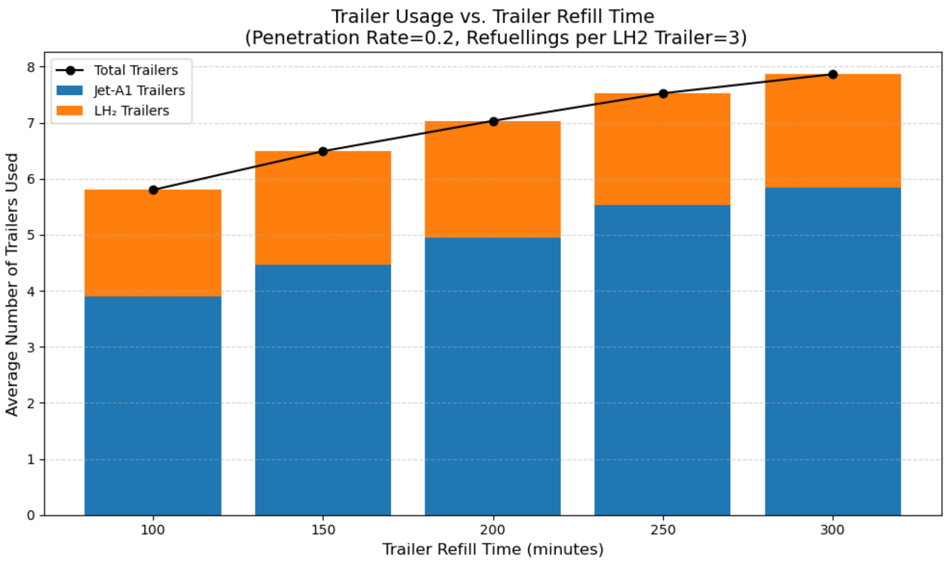


Figure 18: Number of required trailers for varying values of the Trailer Refilling Time, penetration rate of 0.2, three refuellings per LH2 trailer and 30 replications per scenario

5.4.1 Pareto Front Optimisation

With the number of trucks and trailers, a CAPEX cost estimate can be made for the different fleet sizes and scenarios. This estimate can then be compared with the on-time performance, creating a trade-off for the various scenarios throughout the years. In Figure 19, the Pareto front optimisation is shown for the three scenarios in 2040, with the values specified in Table 14. In the 2040 low-penetration case, a slight investment difference, from roughly €1.39 million to €1.46 million, pushes on-time performance from under 44% to almost 99%, showing that adding a second Jet-A1 truck is highly cost-effective at current operations and with low LH2 demand. In the middle scenario, baseline performance reaches 90% at around €1.9 million, and achieving the last few percentage points of reliability is by adding a third Jet-A1 or LH2 truck. The high-penetration fleet needs five LH2 trailers and at least two trucks of each fuel type to reach the 80% on-time performance. Adding one truck for each fuel type will increase the performance over the 90% range with an extra investment of approximately €250 thousand.

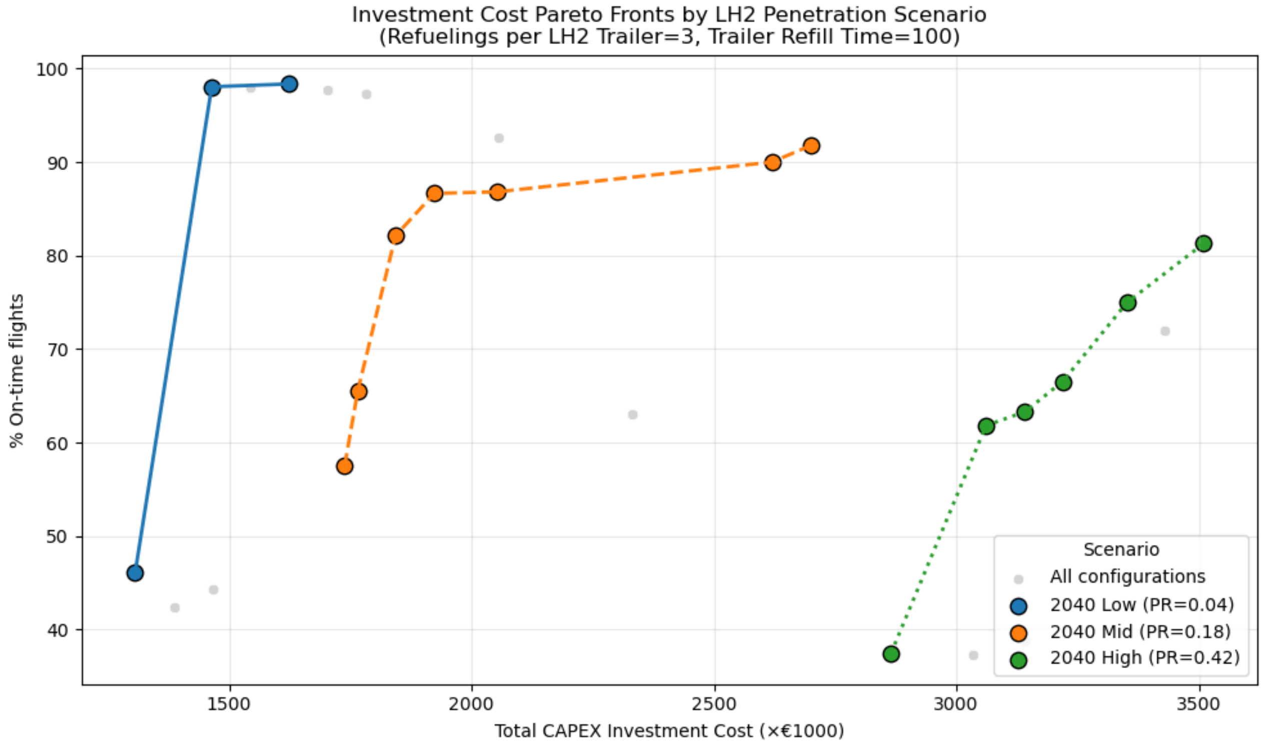


Figure 19: Pareto front optimisation for the CAPEX investment cost and the on-time performance for the different scenarios in 2040

Table 14: Pareto-optimal configurations for 2040 scenarios

Scenario	# Jet-A1 Trucks	# LH2 Trucks	# Jet-A1 Trailers	# LH2 Trailers	Total CAPEX (x€1000)	On-Time (%)
Low	1	1	11	1	1306	46.1
	2	1	11	1	1464	98.1
	3	1	11	1	1622	98.4
Mid	1	1	10	2	1738	57.5
	1	2	9	2	1765	65.5
	2	1	9	2	1843	82.1
	2	2	9	2	1923	86.6
	3	1	10	2	2054	86.8
	3	2	10	3	2619	90.0
	3	3	10	3	2699	91.8
High	3	1	7	4	2865	37.5
	1	2	6	5	3061	61.8
	1	3	6	5	3141	63.3
	2	2	6	5	3219	66.5
	2	3	7	5	3352	75.0
	3	3	7	5	3510	81.3

The same has been done for the 2050 scenarios, shown in Figure 20. In the low-penetration case, a baseline investment of about €2.17 million yields only 63% on-time performance. Adding a second Jet-A1 truck for an extra €105 thousand pushes reliability to nearly 80%, and a further €80 thousand investment in a second LH2 trailer jumps performance into the high-80s. Achieving up to 94% then requires an extra Jet-A1 trailer and LH2 truck. The improvement to 95% requires an additional LH2 trailer, making this investment substantial for a minimal increase. The mid-penetration front begins at roughly €3.09 million for just 44% on-time. Here, Jet-A1 and LH2 fleet expansions are needed. First, LH2 capacity should be increased to achieve approximately 70% and then add a Jet-A1 truck and trailer until on-time performance improves to the low 80s. This steep rise in required CAPEX highlights how moderate hydrogen uptake swiftly escalates cost requirements for acceptable service levels. Finally, in the high-penetration scenario, on-time rates remain under 15% until total spend exceeds €5.3 million, showing that high hydrogen penetration demands high upfront investment. Only after investing beyond €5.8 million does performance approach 80%. When the point of higher on-time performance is reached, trade-offs need to be made to decide whether this is worth it or if it may need to be achieved by improving other aspects to increase on-time performance. Decision-makers are advised to make a trade-off to weigh the value of additional investments against the potential for more cost-effective performance gains through operational improvements elsewhere.

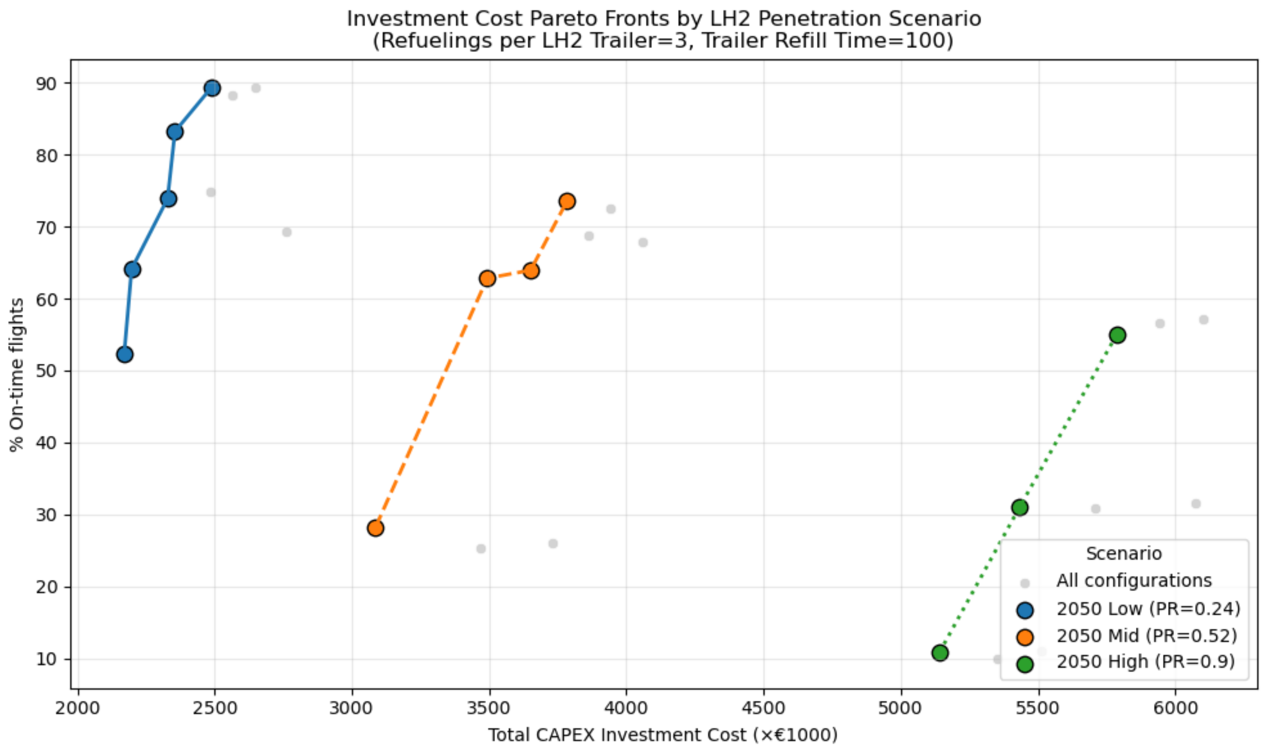


Figure 20: Pareto front optimisation for the CAPEX investment cost and the on-time performance for the different scenarios in 2050

Table 15: Pareto-optimal configurations for 2050 scenarios

Scenario	# Jet-A1 Trucks	# LH2 Trucks	# Jet-A1 Trailers	# LH2 Trailers	Total CAPEX (x€1000)	On-Time (%)
Low	1	1	9	3	2170	52.3
	1	2	8	3	2197	64.1
	2	1	9	3	2328	73.9
	2	2	8	3	2355	83.2
	2	3	9	3	2488	89.4
Mid	2	1	5	5	3086	28.2
	1	2	5	6	3493	62.8
	2	2	5	6	3651	63.9
	2	3	6	6	3784	73.6
High	1	1	1	10	5141	10.8
	2	2	2	10	5432	30.9
	1	3	1	11	5786	54.9

6 Discussion

This study provides a step toward understanding how hydrogen refuelling operations may evolve at regional airports. While the results provide clear operational insights, several broader considerations arise when placing the findings into a wider airport planning and policy context. Importantly, these considerations affect multiple stakeholders, airports, airlines, fuel service providers, and passengers, each of whom will experience different operational, logistical, and strategic impacts. Several simplifying assumptions, such as uniform fuel demand per flight and the exclusion of maintenance and crew scheduling, were made to maintain model tractability. These factors, however, can influence refuelling efficiency and delay propagation in real-world operations. Addressing such dynamics in future research would enhance the model's realism and provide more robust infrastructure and investment planning support. Finally, broader economic and regulatory uncertainties, such as hydrogen price volatility, the introduction of carbon taxation, and evolving safety legislation, could significantly affect investment priorities and operational decisions. These external factors are not explicitly modelled in this study but will play a crucial role in the feasibility and timing of hydrogen adoption in aviation. Adaptive infrastructure planning and scenario-based strategy development will be essential for stakeholders navigating the transition to hydrogen-powered flight.

Airports

For airports, the results highlight the growing importance of proactive infrastructure planning. While the study is based on Rotterdam The Hague Airport (RTHA), many of its insights are likely transferable to other regional airports with similar operational characteristics, such as compact layouts and moderate flight volumes, which limit the impact of vehicle parameters. However, larger or more complex airports will likely reach different conclusions due to increased spatial constraints, denser flight schedules, and more complicated logistics. The model demonstrates that the number of delayed flights and the size of the delay increase at higher hydrogen penetration rates if the number of trailers or refuelling trucks is insufficient. Furthermore, the analysis of safety zone diameters reveals the potential operational strain caused by restrictive layouts, which could reduce stand availability and disrupt aircraft scheduling. As a result, airports may need to consider both physical redesigns and revised procedural workflows. Since hydrogen integration will not occur alone, it must align with broader airside logistics, safety protocols, and turnaround processes, potentially involving (inter)national regulations and coordination with other airport services.

Airlines

The consequences of delayed operations will directly impact airlines. The results show that both the number of delayed flights and the average delay per flight increase as hydrogen operations grow and infrastructure remains static. This is particularly evident during high penetration rate scenarios, because hydrogen aircraft are more vulnerable to cascading delays due to expected slower refuelling operations. Airlines may therefore need to adjust scheduling strategies, potentially assigning earlier slots to LH2 flights or increasing buffer times in their timetables. These adaptations could affect slot allocation strategies and seasonal scheduling flexibility. Additionally, airlines will have to weigh the trade-offs between fleet efficiency and schedule reliability, particularly as they deploy a growing share of hydrogen-powered aircraft in the coming decades.

Fuel Service Providers

Fuel service providers play a critical role in hydrogen refuelling logistics. The research highlights truck utilisation and the number of required trailers as decisive KPIs for their operations. Efficient trailer logistics and high truck utilisation are important to avoid underinvestment and prevent downstream delays and operational inefficiencies for the airport and airlines. A single truck may suffice at low penetration rates, but a second truck becomes necessary at higher levels to maintain acceptable service levels. Service providers must therefore plan for scalability and operational flexibility, considering static capacity and dynamic refuelling demands that fluctuate with traffic peaks. Additionally, shorter trailer refill times and higher trailer capacities reduce the number of trailers needed, which could lead to significant cost savings while maintaining performance.

Passengers

Although passengers are not directly involved in operational logistics, they are sensitive to the effects of delays. The KPIs most relevant to passengers, the number of delayed flights and average delay, increase under scenarios with insufficient hydrogen infrastructure or longer refuelling durations. These disruptions can undermine trust in new hydrogen technologies and affect the travel experience. Moreover, the need for earlier turnaround buffers may reduce flight scheduling flexibility, potentially resulting in less convenient departure and arrival times for travellers. Clear communication, robust scheduling, and contingency planning will be essential to maintain passenger satisfaction during the hydrogen transition.

7 Conclusions

This research assesses the operational and logistical requirements for implementing hydrogen refuelling at airports, explicitly focusing on estimating the necessary refuelling vehicle fleet size and associated investment costs. Rotterdam The Hague Airport served as a representative case study, allowing for analysis under a realistic mixed-fuel flight schedule and varying hydrogen refuelling configurations. This was done by highlighting critical operational impacts and identifying essential parameters for future vehicle fleet sizing and infrastructure planning. Through sensitivity analyses, three primary parameters emerge as crucial determinants of the airport's on-time performance: the penetration rate, the number of refuelling trucks and the maximum LH2 refuelling time. Ensuring adequate fleet size and minimising LH2 turnaround times are crucial to maintaining operational efficiency, particularly as hydrogen penetration rates grow. Although vehicle parameters such as truck speeds and trailer replacement times showed less impact due to the airport's compact layout, the combined influence of these parameters in more extensive configurations remains relevant. The analysis of KPIs in future scenarios indicates that moderate hydrogen penetration rates until 2040 would require manageable investments to maintain efficient operations. However, by 2050, substantial infrastructure enhancements and additional resource allocations will become unavoidable. Here, operational delays and truck utilizations notably increase, indicating that achieving acceptable on-time performance may require Jet-A1 and LH2 equipment investments.

The boundary-value analysis refined these insights by pinpointing when additional LH2 trucks are required. The results demonstrate that investing in a second LH2 truck becomes essential once the number of hydrogen aircraft surpasses between 22% to 39% penetration, depending on the days and refuelling time. During winter schedules, this threshold may be reached earlier due to reduced flights and a higher proportion of short-haul operations. Furthermore, the maximum LH2 refuelling duration significantly influences fleet sizing decisions, reinforcing the need to monitor developments and optimise turnaround processes. Moreover, the analysis of departures occurring beyond the scheduled and allowable departure windows provides an understanding of how delayed LH2 refuelling operations may affect the flight planning. This boundary quantifies the potential for hydrogen-related delays to disrupt punctuality and highlights pressure points in the airport's turnaround operations. A consequence could be that LH2 flights can not be scheduled as late as Jet-A1 flights.

Exploring the safety zone constraints highlighted another critical operational challenge. While small to moderate safety zone diameters up to 40 meters pose minimal disruption, larger safety zones significantly degrade stand availability and increase delays, particularly at higher penetration rates. Airports must therefore carefully evaluate trade-offs between safety requirements and operational efficiency, possibly needing modified flight scheduling or layout changes. Lastly, analysing the number of required trailers illustrated essential trade-offs between operational performance and investment costs. Higher LH2 trailer fuel capacities and shorter trailer refill times have an impact on reducing the overall trailer fleet size requirements. Pareto optimisations demonstrate that investments could significantly enhance operational reliability, particularly at moderate hydrogen integration levels. However, at high penetration rates, the cost of maintaining high on-time performance escalates considerably, prompting airports to evaluate alternative operational improvements before committing to high infrastructure investments.

Overall, this research underlines the complexity and importance of strategic planning in transitioning to hydrogen-based aviation. Operational efficiency, resource optimisation, and proactive infrastructure investments are essential for successfully integrating hydrogen flights, ensuring that airports like RTHA remain flexible and sustainable in the future.

7.1 Recommendations for future work

The research has developed a model that considers multiple design goals and can be applied in various ways. It serves as a baseline for future work in the same area, which can be accomplished by using or extending this model. Possible extensions could be adding the processes of the other turnaround vehicles, giving insight into the effects of those on refuelling and total delays. The use of fuel could also be modelled in more detail, varying the amount of fuel each aircraft requires, resulting in different fuel volumes and a more complex assignment model. Additionally, maintenance and crew scheduling constraints provide interesting insights into the potential issues that could arise at the airport once fleet utilisation rates become high. Ultimately, it is advisable to investigate all the parameters mentioned in this research, update their values based on new developments, and revise airport requirements to prepare the entire sector for deployment once the hydrogen technology is ready.

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II

Literature Study and Research Proposal

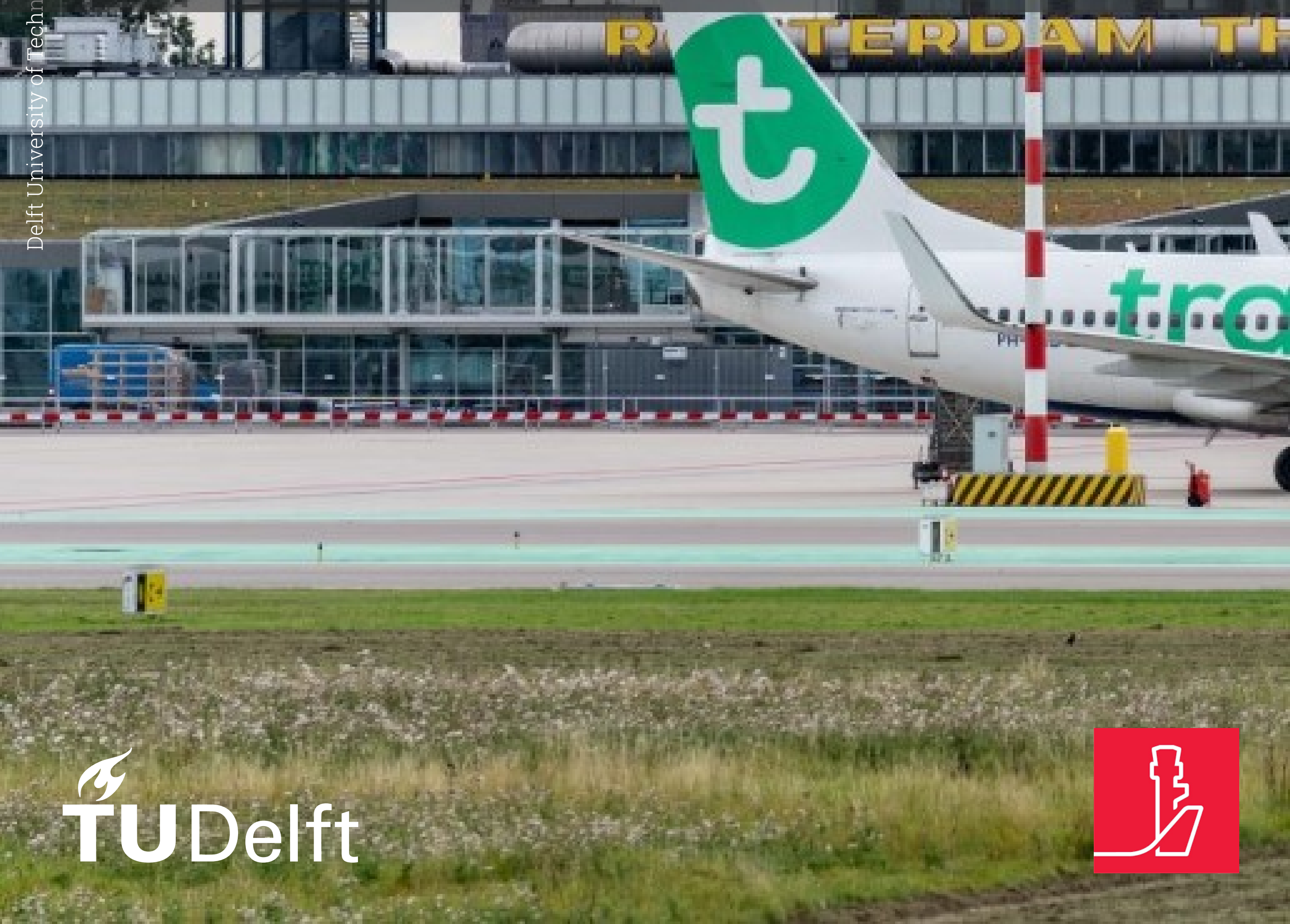
Analysis and modelling of hydrogen supply to a regional airport

Research proposal

AE5322: Thesis Control and Operations

Gijs Janssen

Delft University of Technology



TU Delft

Analysis and modelling of hydrogen supply to a regional airport

Research proposal

by

Gijs Janssen

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Cover: Rotterdam The Hague Airport

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1 Introduction

The environmental impact and ecological footprint of flying are the biggest challenges for the aviation sector. Aviation is responsible for approximately 2% of the global CO2 emissions and non-CO2 emissions, such as nitrogen oxides (NOx), contrails, and noise pollution [1]. Since the COVID-19 pandemic, the industry has already returned to the same levels as in 2019. Furthermore, the aviation sector is anticipated to resume its growth rate of 4.8% per year in passenger traffic over the next two decades [2]. This highlights the need for urgent, sustainable solutions to reduce greenhouse gas emissions as planned in global climate goals, including the European Union's target of achieving net-zero emissions by 2050.

Research into hydrogen as an aviation fuel already began in the 1970s, the focus shifted to electric propulsion and Sustainable Aviation Fuels (SAF), due to the technological and economic challenges of that time. A renewed interest in hydrogen has emerged, seeing it as a promising alternative for decarbonising aviation, potentially allowing for near-zero emissions when produced sustainably. Hydrogen-powered aircraft offer significant advantages in weight and environmental performance, but they also present complex challenges, especially concerning supply chain logistics, ground operations and required airport infrastructure.

This report aims to investigate the current situation and developments in hydrogen supply. While a lot of research has been done, a lot of advancements are still necessary to make the technique viable. If the advancements in the technological development of hydrogen aircraft bring it on the market, the rest of the sector needs to be ready for it to be implemented as quickly as possible. One crucial actor in the entire supply chain is an airport. This will be where all the developments come together, while it is already a very busy and optimised process. The airport is thus a good location to analyse the entire process of supplying hydrogen to an airport. In this study, a regional airport will be looked at, because that will probably be the first location where hydrogen aircraft will be used. Regional airports also have more space for testing innovations and introducing new techniques, compared to busy and efficient-running airports. In this research, a case study will be done at Rotterdam The Hague Airport (RTHA), the regional airport of the metropolis regions of Rotterdam and The Hague, centrally located in the Netherlands. The findings of this research can be used as a reference for other regional airports and a guideline for different-sized airports and other interested stakeholders in the hydrogen supply chain.

First, a general look at aviation's hydrogen is taken, described in chapter 2. After this, a literature study will be done on the hydrogen supply chain, from which a research gap and requirements can be drawn up for the rest of the research. This can be found in chapter 3. In the next chapter, chapter 4, the research question and its sub-questions will be drawn up, which will be used to perform the rest of the research. In chapter 5, RTHA will be described and how it will be used as a case study for the research. Finally, in chapter 6, the research methodology will be described, used to perform the rest of the study, as well as assumptions and the research planning.

2
Hydrogen in sustainable aviation

The global energy transition is a response to the urgent need to mitigate climate change. As a significant contributor to greenhouse gas emissions, the aviation sector is under increasing pressure to adopt more sustainable energy solutions. Hydrogen is one of the most promising solutions. This chapter will give a short overview of hydrogen in aviation, first looking at the history and then analysing current trends in the sector.

The aviation sector has traditionally relied on kerosene-based fuels, such as Jet-A1. Due to the high energy density required for long flights, the sector is considered one of the hardest to decarbonise. However, the industry has set targets to achieve net-zero emissions by 2050 [3]. This results in a lot of research being done on alternative fuels and technologies. Hydrogen has emerged as a promising option due to its potential for operations with zero emissions when used in fuel cells or as a combustion fuel in modified engines. In the 20th century, research began exploring liquid hydrogen (LH2) and gaseous hydrogen (GH2) as alternative fuels. In 1988, the Tupolev TU-155 flew the first successful flight on LH2 in the Soviet Union [4]. Because of the high costs, lack of infrastructure and limited resources, the fuel was not developed further until the 2000s, when the urgency to address aviation's environmental impact became more critical. Hydrogen production and storage technologies have also seen some advancements, making it a more feasible option to use as a fuel.

However, the integration into aviation presents several challenges. The production of green hydrogen, made via electrolysis, is essential to benefit from the no-emission properties of hydrogen, but for this, a lot more production and liquefaction is necessary. Even if the aviation industry managed to make flying on hydrogen feasible, there also needs to be more development in the rest of the hydrogen value chain. This 'chicken-and-egg' problem is a big struggle in all innovations. Luckily, the aviation sector is not waiting; it is already investing and researching many possibilities. In Table 2.1, current projects in designing engines and full-scale aeroplanes are shown, which are currently being developed. As can be seen, multiple active, promising projects are being developed, leading to the years when a hydrogen aircraft will become commercially available.

Table 2.1: Current Hydrogen Aircraft projects [5, 6, 7, 8, 9]

Organization	Aircraft Type	Seats	Range [km]	H_2 State	Fuel Cell [kW]	Retrofit (Y/N)	Year Into Service	Origin
ZeroAvia	Dornier-228	9-19	480	Gas	500-750	Yes	2025	UK & US
	ATR 42/72	40-80	1100	Liquid	2000-5000	Yes	2027	
Conscious Aerospace	DHC-8	30+	>750	Liquid	2100	Yes	2028	NL
		60+			4000	Yes		
H2-Fly	Dornier-238	40	2000	Liquid	TBD	Yes	2030	DE
H2GEAR / GKN Aerospace	-	19-96	1700	Liquid	2000	Yes	2035	UK
Airbus	ZEROe	<100	>1600	Liquid	1200	No	2035	FR

3
Literature study on the hydrogen supply chain

In this chapter, the different possibilities for the transport of hydrogen to and from the airport are considered. First, all the steps in the hydrogen supply chain will be described and analysed in section 3.1. After that, the entire supply chain and its possibilities are illustrated in section 3.2. From this, the research gap can be determined, which is done in section 3.3. Thereafter, in section 3.4, requirements are drawn up which bound the research within a specific scope.

3.1. Steps in the hydrogen supply chain

To consider the possibilities of the supply chain setup, first, the different steps in the supply chain need to be analysed. Multiple steps must be taken to ensure the airport's hydrogen supply is readily available. The first consideration is that two hydrogen states could be used at the airport: gaseous (GH2) and liquid (LH2) hydrogen. As the previous chapter shows, LH2 will most likely be the preferred method for refuelling aircraft. GH2 however, is now primarily used in cars so that it will be a viable solution for ground equipment at the airport. For example, Schiphol Airport already uses a hydrogen-powered GPU, as part of the TULIPS project [10]. For the airport, it could thus be beneficial to have both LH2 and GH2 available on-site. The steps that need to be taken to supply liquid hydrogen are production, liquefaction and transportation, which must happen off-site (to the airport) and on-site (to the airplane). All these steps will now be explained and analysed to determine the possible options when looking at the location in the supply chain.

3.1.1. Production

There are multiple ways to produce hydrogen, which are all mentioned in Table 3.1. To decrease carbon emissions, the goal is to create all the hydrogen as 'Green' hydrogen by electrolysis with renewable energy. But as of the end of 2021, nearly 47% of global hydrogen production came from natural gas, 27% from coal, 22% from oil (as a by-product), and only around 4% from electrolysis. With renewable sources making up about 33% of the global electricity mix in 2021, this translates to approximately 1% of global hydrogen production being derived from renewable energy [11]. However, with a lot of investments in this future technology, it is expected that when the hydrogen technology in the aviation sector is ready, the ratio of 'green' hydrogen will increase, especially when it is proven that hydrogen can be used in the aviation and other relevant sectors. An example is the new 200 MW electrolyser built in Rotterdam by Shell [12] and multiple projects in the Port of Rotterdam [13]. Production can be done locally, but can also be outsourced to locations where sustainable energy sources are more common and thus cheaper. Chile plans to build 5 GW and 25 GW of electrolysers by 2025 and 2030 to become the leader in exporting green hydrogen. This could be a solution for countries with limited renewable energy, such as the Netherlands. An example for The Netherlands could be to supply hydrogen from Morocco, where the Levelised Cost of Energy (LCOE) can be as low as €30MWh, compared to €70-80MWh in Europe [14].

Table 3.1: Comparison of Hydrogen production methods [15]

"Color"	Production method	Hydrogen feedstock	Cost [EUR/kg]	Life Cycle Emissions in kg CO_2eq/kg H_2
Brown	Gasification of coal	Coal	1.34	12
Grey	Steam reforming	Natural gas with CO_2 released into the atmosphere	2.08	8
Yellow	Electrolysis	Water with a mixture of renewable and fossil energies	3.5–6.87	1–31
Blue	Steam reforming	Natural gas with CO_2 captured and stored or processed industrially	2.27	4.8
Turquoise	Pyrolysis	Natural gas with solid carbon as co-product	1.59–1.70	4.5
Red/pink/purple	Electrolysis	Water with nuclear power	4.15–7.00	2
Green	Electrolysis	Water with renewable energy	5.78–23.37	1–2.5
White	-	Hydrogen as a waste product of other chemical processes	0	0

Another possibility is to produce the hydrogen locally at the airport. If hydrogen is produced at the airport, all the following steps must be taken at the airport, resulting in an enormous facility. The cost of a small-scale hydrogen plant facility is between $10-$50 million, which produces less than 1000 kg/h [16]. And because 70-90 % of the production cost is electricity [17], these kinds of investments do not seem to align with the ambitions of airports, especially regional ones, even when their ambition is to become a hydrogen hub. Most airports are also limited in space available, and a facility for electrolysis, liquefaction, and storage plant is estimated in different studies to entail a minimum of 25000 m^2 for a production of 500tons/day to 250000 m^2 for an output of 700tons/day [18].

3.1.2. Compression

Compression is reducing the volume of the produced GH2 by increasing the pressure. This process is necessary for the gas to be stored or transported by truck or pipeline. The gas is stored at a high pressure of 350 or 700 bar. Compressions require electricity input and are estimated to be 0.7-1.0 kWh/kg [19]. This process must occur immediately, unless the gas is liquefied, as described in subsection 3.1.3. The location of the compression is thus dependent on the production location, as described in subsection 3.1.1. Two primary types of compressors are used for hydrogen applications: mechanical and non-mechanical. Examples of mechanical compressors are reciprocating pistons, diaphragms and centrifugal compressors. These are all widely used and considered very reliable, but can have limitations in handling large-scale operations. Examples of non-mechanical compressors are electrochemical and metal-hybrid-based systems.

3.1.3. Liquefaction

The next step in the supply chain of LH2 is liquefaction. Liquefaction is generating a liquid from a solid or a gas. In this case, it is used to convert the GH2 into LH2. When the required substance is GH2, this process does not need to occur unless it turns out that hydrogen transportation is preferred to be done as a liquid, which will be discussed later in subsection 3.1.5. The liquefaction process consists of cooling, compression and expansion. Two kinds of processes are the most used in large-scale industrial applications: the helium Brayton cycles and the Claude process [20]. The Brayton cycle is preferred for small-scale plants with a maximum capacity of 3 tons per day due to its low investment cost. This will result in higher operating costs and lower process efficiency, compared to the Claude cycle, which is thus preferred for larger liquefaction plants [21].

Liquefaction is a process which can be performed off-site and on-site. Off-site, it is again possible to do it in a low-cost region and transport the LH2, or at the port where the GH2 will arrive, before it is transported to the airport. On-site liquefaction means that the GH2 is transported to the airport, which has a liquefaction plant on the premises. The base capital cost of a liquefier is around €36.800.000, and the cost of operating and maintenance is assumed to be 4% of the capital cost, resulting in less than 1.5 million euros.

3.1.4. Storage

When the hydrogen is produced, it must be stored to be transported to the correct location at the right time. GH2 can be stored in underground caverns or above-ground pressure tanks at a maximum pressure of 200 bar. The storage operation is constrained by the maximum loading and unloading mass flows. For example, underground storage is limited to a maximum pressure change of 10 bar/day inside the cavern [22]. Cavern storage is between 15-55 $\$/kg_{GH2}$ depending on the amount of gas stored, while aboveground storage is 300-500 $\$/kg_{GH2}$ which follows from a literature study for which the values are shown in Figure 3.1 and Figure 3.2. But next to the limited maximum pressure change, cavern storage also depends on geographical location and availability of cavern storage in the area, which, especially in the transition phase of the technology, seems unrealistic.

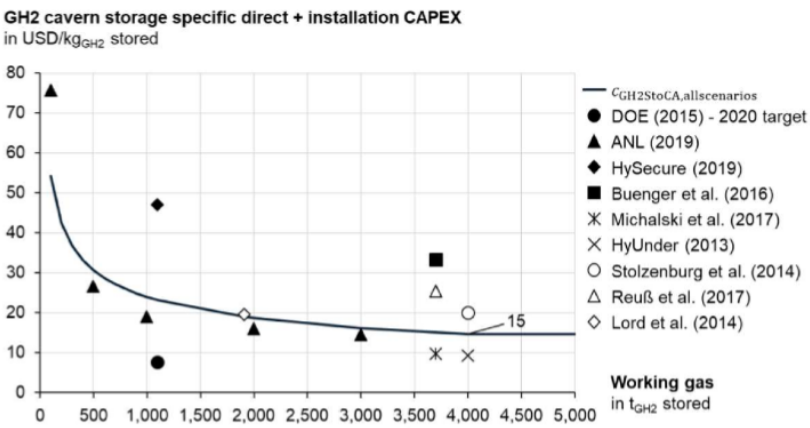


Figure 3.1: CAPEX functions of cavern storage of GH2 gathered from literature [22]

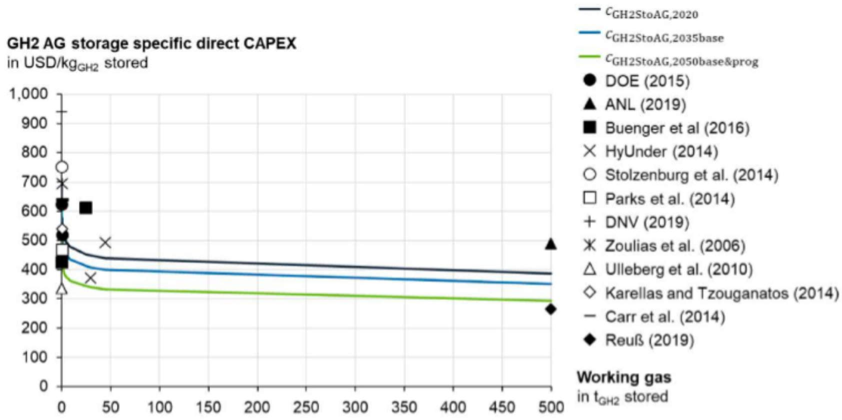


Figure 3.2: CAPEX functions of aboveground storage of GH2 gathered from literature[22]

When the hydrogen has already been liquefied to LH2, it is also possible to store it. LH2 is stored in tanks which come in different shapes. Spherical tanks have a 10% ullage (not usable mass to ensure stable cryo-temperatures), compared to the 5% of cylindrical tanks [22]. Cylindrical tanks are also cheaper to produce, so this shape is standard in most industries. In LH2 storage tanks, boil-off occurs, which is the gradual evaporation of the LH2 because of the heat from its surroundings. Even though the tanks are double-wall vacuum insulated, this effect still occurs in the tank. In a standard LH2 trailer with 4000 kg LH2, the boil-off rate is around 0.3%/day [23]. To store the LH2, it needs to be kept at -253°C, resulting in a heavy, isolated tank which may take a lot of space.

3.1.5. Transportation

The transportation of hydrogen can be done in two different ways, via road or pipeline. Both these options are possible with GH2 and LH2. Road transportation happens with trucks, containing either a tube trailer (with GH2) or an LH2 trailer. For the tube trailer, the GH2 is compressed, as described in subsection 3.1.2. The main truck transportation costs are the operating costs, such as labour costs and truck maintenance. These costs will increase when a longer travel distance is needed. The differences between a tube trailer and an LH2 trailer are given in Table 3.2. Based on these values, the cost of LH2 trailer delivery is about 9% of tube trailer delivery.

Table 3.2: Comparison between Tube trailer and LH_2 trailer [24, 19]

Parameter	Tube Trailer (GH_2)	LH_2 Trailer
Load [kg]	300	4,000
Net delivery [kg]	250	4,000
Load/unload [h/trip]	2	4
Boil-off rate [%/day]	0	0.3
Truck utilization rate [%]	80	80
Tube/tank [€/module]	87,900	395,000
Undercarriage [€]	52,700	52,700
Cab [€]	79,000	79,000
Cost [€/kg]	0.17	1.92

An advantage for an airport could be to leave the hydrogen stored in the truck until it is ready to be used. This would save the cost of a cryogenic tank, as analysed in subsection 3.1.4, but it needs to be investigated if this is realistic for the number of trucks available for the transport and if it is economical for the trucks to stand idle for a certain amount of time. Also, different kinds of truck configurations can be considered. When the delivery trucks are the same as the refuelling trucks, a fuelling arm needs to be available on the truck. There is also the possibility of having a separate truck with a refuelling arm. This has the advantage that standard trucks can be used for hydrogen transportation. From expert knowledge, it becomes clear that all these options are still viable when designing hydrogen trucks.

Next to truck delivery, also pipeline delivery is a viable option. When considering pipeline delivery, LH2 delivery is not supposed to be a viable option. The technology is not advanced enough, and the complexities do not occur in other transportation modes. Especially maintaining the cryogenic temperatures and managing the boil-off losses when transporting the LH2 over longer distances, do not seem viable right now [11]. GH2 delivery by pipeline, however, does seem to be a realistic solution, because GH2 does not need to cool down, and gaseous pipelines are already widely used. Currently used for natural gas, these pipelines can also be used for GH2 transportation because natural gas needs to be downscaled simultaneously. This is already being done; the Port of Rotterdam is part of the European Hydrogen Backbone project, which aims to have forty thousand kilometres of GH2 pipeline to connect Europe's industries. The cost of GH2 transportation is expected to be between 1.72 and 2.41 €/kg [23], which thus has the potential to compete with truck delivery. However, the investment costs and loss of flexibility might be negative consequences of changing to pipeline delivery. These considerations will be analysed when the possibilities for the supply chain are analysed in section 5.2.

3.1.6. Dispensing

When the hydrogen arrives at the airport, it needs to be refuelled in the appropriate vehicle. Safety is the most important factor when considering the methods that can be used for refuelling. Because of safety protocols, other activities on the air side can be disturbed, resulting in a time loss in the airport's processes.

Safety

To consider the safety aspects of hydrogen refuelling, a look is taken at the mitigation strategies used in current GH2 and LH2 refuelling stations. Mechanical integrity is the most essential aspect in preventing hydrogen releases. This consists of selecting compatible materials, using reliable joining methods, and maintaining regular equipment. Important maintenance tasks include leak checks and hose inspections because hydrogen can easily leak. After all, it is a tiny molecule. Next, hydrogen is odourless and has an invisible flame, so it is hard to detect when there is a leak. Systems must be designed to accommodate thermal expansion and contraction, using features like vacuum-jacketed piping, expansion joints and extended-bonnet valves at LH2 systems. For GH2 systems, thermal expansion around the chillers can also cause failures. There are clear codes and standards to ensure that components maintain their mechanical integrity, such as dispenser hoses with breakaway features, which isolate the dispensing system from the vehicle in the case of a vehicle pull-away. Another important factor is a safe installation location, which minimises the impact of a release on people and property. It is therefore essential to use precise setback distances and protective structures to prevent damage from vehicles.

Ventilation, both passive and active, is crucial to prevent hydrogen accumulation, as ambient air helps dilute minor leaks. However, even with ventilation, flammable mixtures can still form in the event of a large leak. Early leak detection is therefore critical, and it can be achieved through preventive maintenance checks, hydrogen gas detectors, and monitoring systems that track pressure or flow rates. Fixed hydrogen detectors, such as dispensers, must be strategically placed above potential leak points, while portable and flame detectors enhance safety around hydrogen equipment. Also, system controls must act as fail-safe mechanisms to isolate hydrogen flow during anomalies, often coupled with remote monitoring and emergency stop buttons around the fuelling system. Ignition risks must be minimised through grounded, intrinsically safe electrical equipment. Vehicles are typically grounded through the tyres to the concrete pad or by a grounding wire.

Venting of hydrogen is the process of safely releasing hydrogen at high elevations, allowing it to disperse quickly. All volumes of hydrogen should be capable of being vented through a designated vent stack, even in the event of a failed closed component or blockage. Unless specifically engineered otherwise, low-pressure gas should be vented separately from high-pressure gas. To ensure safe dispersion, cold GH2 vapour from LH2 tanks must be vented at higher elevations than ambient-temperature GH2. Vent systems for liquid hydrogen are designed to prevent cryo-pumping and facilitate the controlled warming of hydrogen, allowing it to be released as a cold gas rather than in liquid form. Hydrogen release or exposure of cold surfaces to ambient air can lead to fog formation due to the condensation of water vapour. Although fog formation is unavoidable, associated risks are mitigated by venting cold vapours at elevated heights and positioning the system to ensure any fog generated does not harm the surrounding area. Another aspect of refuelling with hydrogen is the need to purge to avoid creating an explosive mixture of air and hydrogen inside any part of the hydrogen system. Three general approaches to purging a system are the following: the flowing gas purge, the pressurising-venting cycle purge and the vacuum purging. The most used method right now is purging the system with helium, due to its compatibility with cryogenic temperatures.

Personnel protection is reinforced with fire-resistant and cryogenic clothing, face shields, and gloves for cold surface interactions. Thorough training for operations personnel, maintenance staff, and emergency responders is essential. They must be comfortable covering safety procedures, emergency response, and hydrogen handling protocols. Finally, emergency response guidelines, developed and coordinated with local emergency services, include the clear marking of emergency stops and routine practice drills to ensure readiness in critical situations.

Viable fuel distribution methods

Refuelling the aircraft is another consideration which impacts the supply of hydrogen. There are two conceptual ideas on how to distribute hydrogen on the airport. The first is to use trucks, which distribute the hydrogen to the refuelling location. A representation of refuelling with an LH2 truck can be seen in Figure 3.4. Refuelling can be executed using the same trucks transporting the hydrogen to the airport. Another option is to bring it to the aircraft by local trucks, which get the hydrogen from the storage at the airport. They can gather the hydrogen from a central storage in their trailer, but it is also possible to have a parking space with trailers so that the trucks can substitute their empty trailers with full ones. This all depends on the chosen storage facility if there is one at all. From this, it can be concluded that all the steps in the supply chain rely on each other, so they should be analysed with the previous steps in mind.

Figure 3.3: Graphical representation of hydrogen refuelling of Airbus ZEROe turboprop aircraft [25]

Another possibility for hydrogen distribution on the airport is via pipelines and hydrants at the refuelling location. This system is more permanent, resulting in higher investment costs, but could result in more efficient and safe distribution. An example of a place where hydrant distribution is already used is Haneda International Airport in Japan. They have the country's most significant aircraft handling capacity, using such a hydrant distribution system [26]. A hydrant valve must be connected to a refuelling vehicle attached to the aircraft at each gate. Trucks are thus still necessary to drive around the airport, but they are much smaller, safer and do not have to refill their loading, meaning they can be planned and used more efficiently than fuel trucks. Hromádka et al. concluded that only 80% of fuel trucks are necessary, plus two backup fuel trucks [27]. This is an improvement, but for small airports, the difference will be smaller so this solution is expected to be more useful for big airports with a lot of fuel throughput.

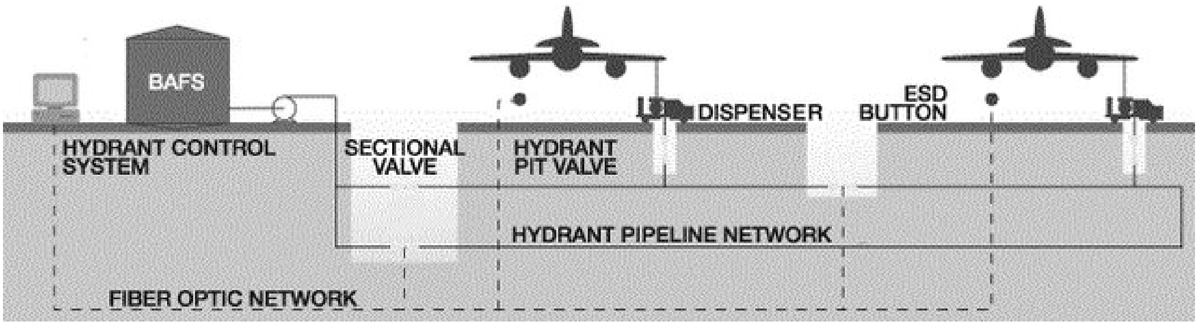


Figure 3.4: Schematic overview of hydrant refuelling at an airport [27]

Another vital aspect is the location of the refuelling. The current situation is that the aircraft is refuelled at the gate, simultaneously with other turnaround processes. Due to different safety protocols around hydrogen, other alternatives should be considered. Such an alternative could be to refuel the aircraft at an alternative location. When getting refuelled with hydrogen, no other turnaround process can occur because of the spark-free zone, an area where no other processes may take place, because they could ignite the fuel if it leaks. The most significant risk of this happening is during the connecting and disconnecting of the fuel hose. This means that no other processes may take place for hydrogen refuelling during this time. The spark-free zone of Jet-A1 fuel is a circular area with a diameter of 3 meters. Different outcomes of research on the spark-free zones of hydrogen fuel can be found, which range in diameter from 8 to 60 meters. The area is expected to get smaller throughout the years because the processes get more optimised and attuned to each other, in Table 3.3, different values of the minimum separation distance have been gathered from various studies on this topic. As can be seen, there is quite a difference between the two studies. In the early stages of the deployment of hydrogen refuelling, it is safer to use a value in the higher ranges. As the technology develops and more practical experience is gathered, this range can be downscaled gradually. In Figure 3.5, an example of the spark-free zone for a regional turboprop of 8 and 20 meters is shown. It can be seen that the zone has a lot of impact on all the processes because at 20 meters, no other GSE is allowed around the aircraft, while in the case of an 8-meter zone, all the equipment is allowed to perform their task.

Table 3.3: Different recommended minimum separation distances in meters from literature [28]

Description	**BCGA**	**BSi**	**EIGA**	**NFPA**	**NASA**
Place of public assembly			20	23	22.9
Public establishments			60		
Compressor, ventilator and air conditioning intakes	15	15	20	23	22.9
Any combustible liquids			10	30.5	30.5
Other LH2 fixed storage				1.5	1.5
Other LH2 tanker			3		
Vehicle parking storage	8			7.6	
Electricity cable and pylons	1.5	10	10		

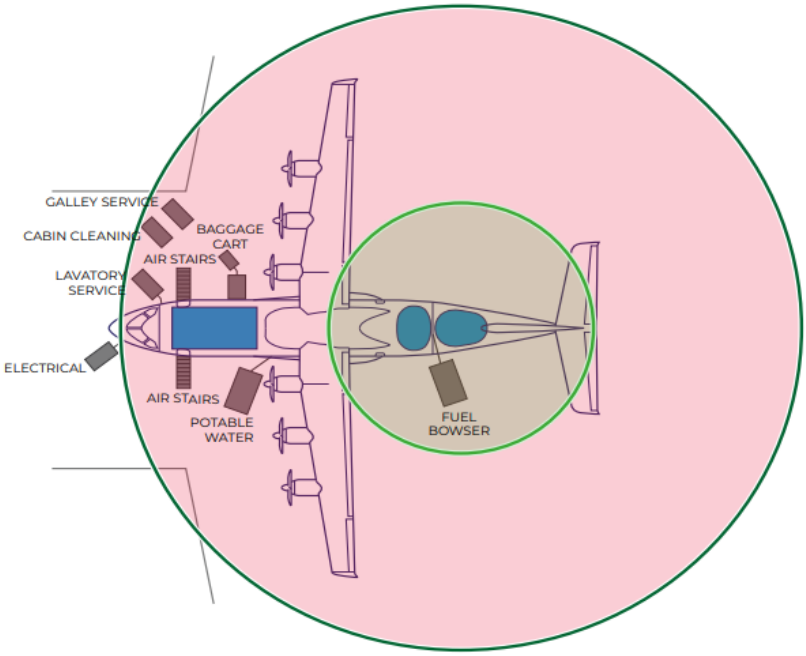


Figure 3.5: Safety zone concept for a spark-free zone of 8m (green) and 20m (red) around a regional turboprop concept [28]

Because of the no-spark zone, no other turnaround processes can be performed while refuelling the aircraft with hydrogen. An exception can be developed for some specific GSE that could be classified to operate. Automated GSE could be allowed near the refuelling equipment because no persons except the refuelling and truck operators are permitted to be in the spark-free zone. Following the planned timeline of FlyZero, trials with autonomous GSE will be started in 2030, with a planned roll-out in 2035 [28]. An example of a viable autonomous GSE is a robotic arm for baggage handling.

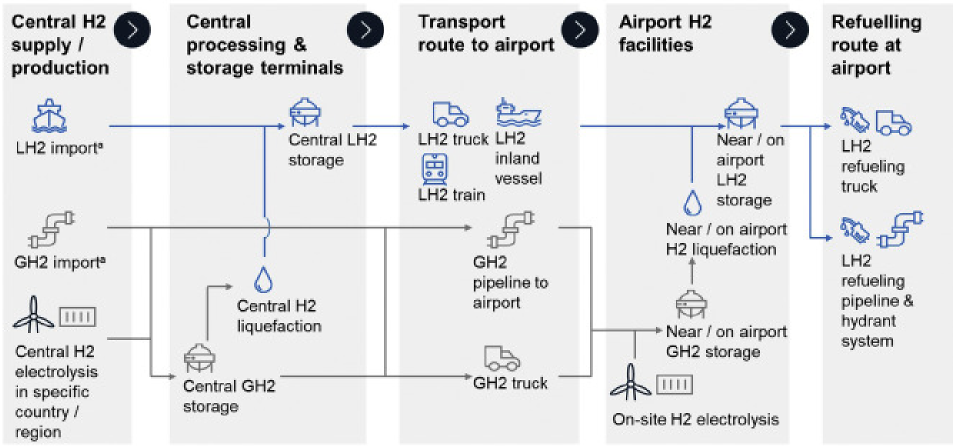
Difference between Jet-A1 and Hydrogen Refuelling

Also, the refuelling will need to be performed in a way other than the current one with Jet-A1 kerosene fuel. The current system has been in place for many years and thus has been perfected and standardised worldwide. The refuelling of hydrogen, therefore, needs to be optimised when the technology is being used. Still, considering the safety aspects mentioned before, it is necessary to analyse all risks involved to minimise the risk of accidents. Currently, concepts are being developed on the refuelling of hydrogen. From expert knowledge, it becomes clear that a viable option might be the need for a different dispensing truck. This truck would have an arm, which can be used to refuel the aircraft, even with big safety zones around the refuelling process. Especially in the early phase, this is considered a necessary option to improve further the safety of persons performing the refuelling. Such a dispenser truck could look similar to one currently used to connect an aircraft refuelling at an airport with a hydrant fuel system. An example of such a truck is shown in Figure 3.6. When a hydrogen dispenser truck is deemed necessary, it will probably have an extended arm to ensure the entire truck is not present in the spark-free zone.

Figure 3.6: Hydrant dispenser

3.2. Hydrogen Supply chain

When all the steps in the supply chain are analysed, a zoomed-out analysis can be done on how to perform those different steps. All these steps influence each other and will decide the next step in the supply chain. These various options have already been analysed in a lot of research. Many supply chain possibilities are analysed and determined based on hydrogen and infrastructure characteristics. All these possibilities are shown in Figure 3.7.



a. H2 import and transport in form of LOHC, NH3 or metal hydrides not shown here

Figure 3.7: Supply chain possibilities for hydrogen transportation [29]

A literature study on all the possibilities for the different steps in the supply chain has been done. Nine articles concerning the hydrogen supply chain to an airport are reviewed, each focusing on the various steps and options. The multiple steps analysed in the papers can be seen in Table 3.4. It also noted whether the research was performed by describing and comparing the different concepts or whether a model was made, which determined the research outcomes.

Table 3.4: Literature review on the supply chain possibilities [18, 30, 31, 14, 28, 32, 22, 23, 15]

	ACI ATI, (2021)	Degirmenci, et al. (2023)	Demir, et al. (2017)	Van Dijk, et al. (2024)	Flyzero, 2022	Gijzen, (2024)	Hoelzen, et al. (2023)	Marsenka, et al. (2022)	Ohmstede, et al. (2023)
Conceptual research	x	x		x	x	x		x	
Modelling research			x			x	x		x
Production									
On-site	x	x			x	x	x	x	
Off-site	x	x	x	x	x	x	x	x	x
Transportation									
Gaseous pipeline	x	x	x	x	x	x	x	x	x
Cryogenic truck	x	x	x	x	x	x	x	x	x
Compressed gas truck			x					x	x
Storage									
Cryogenic tank	x	x	x	x	x	x	x	x	
Compressed gas tank		x		x			x	x	
Liquefaction									
On-site	x	x		x	x	x	x	x	x
Off-site	x		x	x	x	x	x	x	x
Dispensing									
Truck dispensing				x	x	x		x	
Hydrant dispensing					x	x			

3.3. Research gap

As described in section 3.2, many of the steps are already analysed in the supply chain in different varieties. It also becomes clear from the literature that the dispensing part at the airport is analysed the least, while this also influences the rest of the supply chain. The dispensing at the airport is the final step, meaning it should be viable and realistic for an airport to dispense the provided hydrogen efficiently. Only if the airport can provide the aircraft with sufficient hydrogen in a reasonable turnaround time will it become attractive for airlines to start investing in hydrogen aviation. The state of the hydrogen the airport can process is essential, especially for the transportation mode.

It is thus identified that more focus is needed on the hydrogen supply at the airport itself. The conclusions from that research could influence the entire value chain. Operational, infrastructure, and spatial constraints influence the operations of an airport. For this process in the airport, a case study needs to be performed, highlighting the best internal distribution of hydrogen depending on the airport and aircraft pair, as well as available infrastructure. A case study is a more practical approach to achieving conclusions, often combined with a simulation or optimisation model. It can also be concluded in Table 3.4 that most research conceptually analyses the possible supply chain. This further confirms the research gap that a more practical model approach is helpful for this research. This model can then be used to see what a realistic airport could be and see the influence of changing certain input variables. This is helpful in a future problem, where many values are still uncertain and dependent on future developments.

In this research gap, the relevant model will be a truck schedule optimisation model because this can help with analysing the ranges of values in which specific supply chain options are viable for an airport. Such a dynamic model will help with using and obtaining practical values, which then can be analysed if they are feasible for an airport. If not, this will also result in the range of values for which other options will become viable. Supplying hydrogen with a truck is the only step in the chain which can be dynamically modelled.

This research gap will be addressed through a truck schedule optimisation model. This model is relevant because it enables the analysis of value ranges, which are specific when supply chain options become viable for an airport. A dynamic model of this nature provides practical insights into the operational feasibility of truck hydrogen delivery. It allows for evaluating whether these values align with airport requirements. If not, the model can identify the thresholds at which alternative supply chain options, such as pipelines and hydrant supply, become more viable. Truck-based delivery is suited for dynamic modelling among the various steps in the hydrogen supply chain due to its operational flexibility and direct impact on airport logistics.

3.4. Requirements

In this section, the research gap will be further analysed by determining a set of requirements for the research. These requirements will lead to a research objective and questions for the rest of the study, described in chapter 4.

3.4.1. General requirements

First, general requirements are formulated, which will frame the outlines of the research. The requirements are grouped into three categories: General, Infrastructural and Operational. The requirements are listed in **??**. When performing the rest of the research, these requirements will be used as a guideline throughout the study to ensure all parts of the research are considered.

Table 3.5: General requirements

General		**Essential**	**Desirable**
REQ-G1	Reduce operational costs associated with hydrogen supply	x	
REQ-G2	Minimize capital investment in new hydrogen infrastructure	x	
REQ-G3	Analyse scalability of hydrogen supply solution	x	
REQ-G4	Ensure compliance with hydrogen safety standards		x
Infrastructural			
REQ-I1	Determine the number and size of required ground vehicles for the supply	x	
REQ-I2	Identify requirements for different methods of hydrogen supply		x
REQ-I3	Determine method and size of hydrogen storage on the airport		x
REQ-I4	Determine the effect of hydrogen supply on spatial planning on the airport		x
Operational			
REQ-O1	Analyse ground movements to support hydrogen refuelling	x	
REQ-O2	Determine the amount of hydrogen supply necessary	x	
REQ-O3	Minimise the effect on the turnaround process of the aircraft		x
REQ-O4	Analyse the amount of hydrogen boil-off		x

3.4.2. Model requirements

During the case study, a model will be made to help test values and scenarios from which conclusions can be drawn. This model's requirements are devised and listed in Table 3.6. This includes integrating current data, converting daily flight schedules, and determining the number of flights powered by hydrogen aircraft. The model should be able to assign aircraft randomly to available gates, calculate distances between key locations, and allow variations in critical parameters such as aircraft tank capacity, turnaround times, trailer volume, flow rates, and fuel types.

Additionally, the model should simulate the workflow of the relevant refuelling equipment and ensure that all flights are fully refuelled within the specified operational time frame. It must also optimise resource allocation to minimise investment and operational costs while generating detailed outputs, including vehicle schedules, the penetration rate of hydrogen, the required vehicle fleet size and infrastructure, total hydrogen delivered, and losses due to boil-off. This set of requirements ensures the model can provide actionable, data-driven insights to support the choices made in the transition to hydrogen-based aviation. Also, the desired inputs and outputs are specified in Figure 3.8. Different scenarios for the inputs need to be set up to see the consequences for the outputs. From this information, an appropriate model that performs the tasks as described needs to be chosen.

Table 3.6: Model requirements

Model	
REQ-M1	The model should be based on currently available data
REQ-M2	The model should be able to convert a daily flight schedule
REQ-M3	The model should be able to determine which flights in the flight schedule are able to be flown with a hydrogen aircraft, based on the penetration rate input
REQ-M4	The model should be able to select appropriate gates for the aircraft and then randomly assign a gate to the aircraft
REQ-M5	In the model the coordinates of gates and parking spaces should be able to input, from which the distances between all the locations should be calculated
REQ-M6	The model should be able to be varied in the aircraft characteristics, such as the tank volume, TAT and fuel type
REQ-M7	The model should be able to be varied in the trailer characteristics, such as the volume, flow rate, boil-off rate and fuel type
REQ-M8	The model should simulate an entire day where all the flights are fully refuelled within the allowed time frame
REQ-M9	The model should be able to be optimised for the least amount of investment and operational costs for the different vehicles and infrastructure
REQ-M10	The model should output the vehicle schedule of the entire operational day on a 1-minute time-step
REQ-M11	The model should output the total investment and operational costs
REQ-M12	The model should output the optimal number of trucks and trailers necessary
REQ-M13	The model should output the minimum number of trailer parking spaces necessary
REQ-M14	The model should output the total amount of hydrogen delivered
REQ-M15	The model should output the total amount of hydrogen boil-off loss

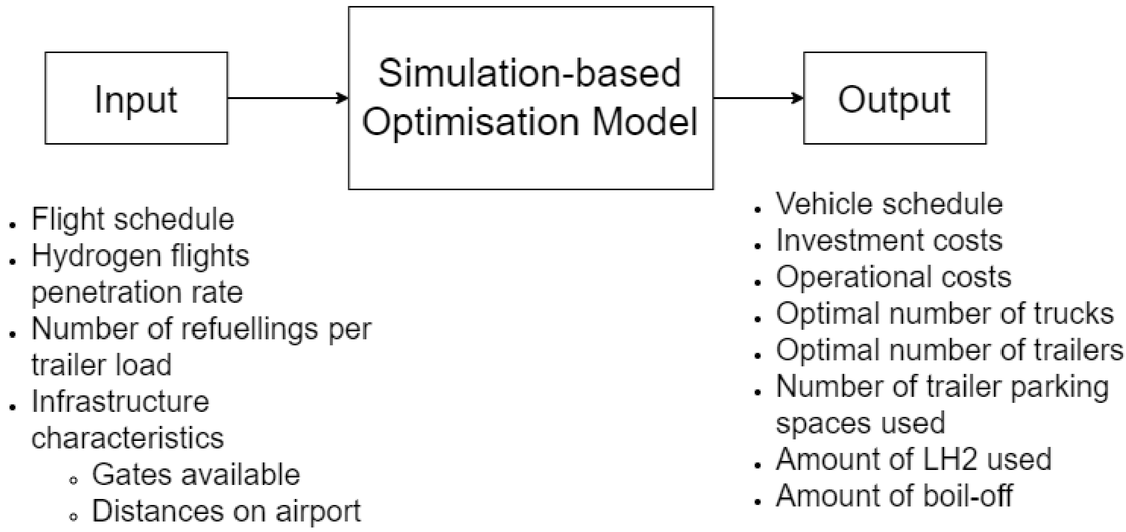


Figure 3.8: Schematic overview of the inputs and outputs of the desired model

4 Research questions

The research questions are formulated in this chapter. These questions follow from the research gap, requirements and case study described in previous chapters. First, the research question is formulated, after which sub-questions are composed that specify the steps in the research. The research question is:

"What are the infrastructure requirements and value chain implications in terms of costs, method and spatial availability, to support hydrogen refuelling operations at a regional airport in 2035, considering a mixed-fuel flight schedule and varying refuelling vehicle characteristics?"

The research question will be answered through the following set of supporting sub-questions:

1. What influences the airport's hydrogen refuelling operations?
   (a) Which stakeholders at the airport will be relevant?
   (b) What are the costs and space requirements for hydrogen refuelling infrastructure?
   (c) How do different vehicle routing strategies impact refuelling times and costs at the airport?
   (d) What are the operational and logistical challenges of integrating LH2 with existing Jet-A1 refuelling operations?
   (e) What hydrogen storage, transport and dispensing advancements are expected to be commercially viable by 2035 and how might they influence airport operations?
2. What ground movements are necessary at the airport to supply the hydrogen to the airport?
   (a) Which relevant vehicles are moving on the platform during the supply process?
   (b) What other ground vehicles and processes will be influenced by the ground operations?
   (c) What vehicles need to be present at the aircraft before it can start refuelling?
   (d) What are the safety implications of operating hydrogen trucks near other ground operations at an airport?
3. What inputs need to be determined for the simulation-based optimisation model?
   (a) What assumptions need to be determined for the model?
   (b) What are the distances between the different relevant locations on the platform?
   (c) What is the speed at which the trucks can drive at the airport?
   (d) What times are considered when performing the refuelling tasks?
   (e) What flight data is available from RTHA?
   (f) What criteria are used to determine whether a flight is eligible to be flown with a hydrogen-powered aircraft?
4. What parameters will be optimised in the model?
   (a) How many vehicles are needed to minimise the investment and operational costs?

   (b) What is the maximum number of parking spaces for which there is space on the airport?

5. What different scenarios will be tested in the model?
   (a) What are the logistical differences between full Jet-A1 refuelling, full hydrogen refuelling and a hybrid process?
   (b) What is the consequence of a different number of refuellings per trailer load?
   (c) What representative days will be chosen to perform the simulation?

6. What are the costs included in the model?
   (a) What are the investment costs of the different ground vehicles?
   (b) What are the operational costs of the different ground vehicles?

7. How will the simulation part of the model be implemented?
   (a) How can the flight data be processed to generate mixed-fuel flight schedules for hydrogen aviation?
   (b) What events need to be simulated in the model?
   (c) What entities and resources need to be generated in the model?

8. How will the optimisation of the model be implemented
   (a) What will the objective function be?
   (b) What will the constraints be?

9. How can the model be evaluated?
   (a) How can the model be verified and validated?
   (b) How sensitive is the model to changes in the input variables?
   (c) What is the statistical significance of the results?

10. What conclusions can be drawn from the analyses done?
   (a) What are the operational impacts on a regional airport considering the costs and the planning?
   (b) What are the upper bounds for other supply modes that trucks to become feasible?
   (c) What is the required supply rate of trailers to the airport?
   (d) What are the infrastructure and spatial planning impacts on a regional airport?

5 Case study Rotterdam The Hague Airport

This research is done in collaboration with Rotterdam The Hague Airport (RTHA). This chapter will present the current situation at RTHA and the predicted future situation concerning hydrogen developments at the airport. First general information about the airport is given in section 5.1. Thereafter, in section 5.2, different realistic scenarios for the supply chain at RTHA are described and analysed.

5.1. Rotterdam The Hague Airport

RTHA is a regional airport in Rotterdam. In 1783, the first manned balloon took off from Rotterdam [33]. First, the airport was located in 'Waalhaven', south of Rotterdam. That airport was destroyed in the Second World War, after which it was reopened as airport 'Zestienhoven' in 1956 at the current location. Since 1990, the airport has been part of the 'Royal Schiphol Group', and the current name was given to the airport in 2010. Some airport characteristics are shown in Table 5.1.

Table 5.1: Characteristics of Rotterdam The Hague Airport [14]

Airport type	Public (level 3 slot coordinated)
ICAO/IATA	EHRD/RTM
Airport capacity	RTHA is not limited by a number of movements but by a yearly noise quota. The number of available slots therefore depends on assumptions for distribution over 24 hours and the types of aircraft used.
Runway details	06 — 2,199 metres 24 — 2,199 metres
Number of passengers (2023)	2,224,276 pax
Total amount of aircraft movements (2023) **— Commercial aviation** **— Business aviation** **— Emergency services** **— other aviation (among it recreational)**	56,480 16,530 6,310 5,780 27,860
Main carriers	Transavia, TUI, British Airways, Pegasus
Aircraft stands for commercial aviation	There are 12 remote stands based on ICAO size C (max. wingspan 36 metres) which feature power-in power-out (PIPO) procedures. ICAO size D or E aircraft require special permission.
Fuelling	JET-A1 is provided by a single fuel supplier that uses a 'pendulum operation' which features the supply of mobile storage trailers from the production site in the Port of Rotterdam to the airport and distribution of the same trailers on airside by a dispensing vehicle.

RTHA has several different missions as an organisation, which are listed below [34]:

- Realising the ultimate passenger experience
- Making business performance more optimised and sustainable
- Connecting with the region
- Developing RTHA as an innovation partner

To make the airport more sustainable, RTHA aims to have their ground-based operations waste- and emission-free by 2030 [33]. The last point is the most relevant for this research because they are investing a lot in becoming an essential player in the innovation of the aviation sector. This also becomes clear from their mission statement: *'Together with partners and the other airports from the Schiphol Group, Rotterdam The Hague Airport sees itself to be the international testing ground for sustainable and high-quality innovation within the aviation sector* [33].

5.1.1. Stakeholders at RTHA

In this section, the different stakeholders are described and analysed, focusing on how they are dependent on RTHA's infrastructure.

Airlines

Airlines are the primary operators of aircraft, responsible for organising ground handling and maintaining direct contact with their passengers. The parking stand's location is important to them, as it directly impacts operational efficiency and passenger satisfaction. This group of stakeholders is diverse due to varying operating profiles and business models. Consequently, their expectations concerning stand allocation differ [35]. At Rotterdam The Hague Airport (RTHA), next to airlines, air carriers such as JetAviation (Private jets) and flight clubs are active and thus relevant. Hydrogen offers airlines a path to reduce emissions and meet environmental targets, though it will require investment in new aircraft technologies, staff training, and adjustments to maintenance protocols. They are, however, dependent on the operational process of RTHA. This must be proven efficient enough for airlines and other air carriers to invest in hydrogen aircraft.

Airport Manager

The Airport Manager oversees apron management, including allocating parking stands to aircraft and ensuring safe ground movements. This role requires managing different time horizons, preparing stand allocation plans, and adjusting them in real time to address disruptions. Unique operational needs at RTHA require tailored airport management strategies, such as guiding aircraft from the runway to stand or vice versa, especially for less familiar pilots and club visitors who may only need guidance for specific movements [35]. The Airport Manager is also responsible for maintaining order and safety on airside, including emergency procedures. Hydrogen refuelling involves developing and managing new infrastructure, adapting operational safety standards, and coordinating with multiple stakeholders to ensure smooth integration with airport systems. In the development period, Jet-A1 and hydrogen will probably be used next to each other on the airport platform, making the process more complicated to manage.

Air Traffic Control

Air Traffic Control (ATC) manages the civil airspace, directing aircraft on taxiways after landing and issuing take-off clearances. At RTHA, ATC responsibilities include indicating taxiways, managing parking stand allocations, and issuing engine-start clearances [35]. RTHA does not have push-back operations, simplifying the ATC's role. ATC may need to adapt routing and scheduling protocols for hydrogen-powered aircraft.

Handling Agents

Handling agents (HA) provide ground-handling services for airlines and other air carriers. Allocating the parking stand is crucial, not only for ensuring efficient service to the designated aircraft but also for managing availability for subsequent operations. At RTHA, AviaPartner handles commercial aviation ground services, while JetAviation and the flight clubs manage their operations. Handling agents would need specialised training and equipment to safely manage hydrogen refuelling processes and new procedures to address the unique characteristics of hydrogen fuel.

Passengers

For passengers (PAX), the parking stand allocation influences their journey from the terminal to the aircraft. At RTHA, no gates directly connect to the aircraft; instead, passengers walk or are transported by buses. Via personal communication with an Airport Manager, it became clear that the preference is to let the passengers walk. Still, because it is forbidden to mix passenger groups, buses are used when more than one aircraft is (de-)boarding. Different types of passengers have varying preferences: while visitors to flight clubs enjoy an unhurried experience, commercial passengers prioritise efficiency. Thus, at RTHA, walking distances and passenger experience are key considerations in stand allocation, influencing overall satisfaction and operational flow [35]. Hydrogen in aviation could mean a quieter, more sustainable flying experience with reduced environmental impact for passengers. However, they may initially encounter slightly different turnaround times as the new technology is integrated in the current system.

5.1.2. Hydrogen at RTHA

One of the main goals of RTHA is to be a relevant innovation partner in developing new aviation fuels, and hydrogen is considered one of the most promising alternatives for Jet-A1 fuel as described in chapter 2. A lot of research has thus already been done at RTHA. One of the most recent studies is by D. van Dijk, in which a demand scenario is determined for 2040 and 2050 [14]. The prediction is that RTHA will use between 8 and 14 kilotons of LH2 in 2050. Research into hydrogen implementation is an essential project for RTHA, so they are involved with multiple projects, as shown in Table 5.2.

Table 5.2: Current hydrogen projects at RHTA [14]

Project	Technology testing and demonstration	Expected TRL and scale	Timeframe	Involved partners
TULIPS	Demonstration of a LH_2 refuelling and turnaround process executed with a drone. Procedures will be written as if a regular LH_2 will be active on the airport. Realisation of a small-scale storage tank to store and dispense LH_2 at the airport.	TRL 6 | $\sim$280g LH_2	2024	NLR, Air Products, Pipistrel
H_2 leakage detection	Installation of (hydrogen) gas leakage sensors at the LH_2 storage facility. Controlled leakage and incident response by the ARFF will be demonstrated.	TRL 7 | $\sim$9kg LH_2	2025	NLR, Veiligheidsregio Rotterdam and airport fire brigade
ALBATROS	Maintain a high level of safety in aviation given changes brought about by new fuel and energy systems (including hydrogen). Including a fully demonstrated emergency landing with a 'hydrogen aircraft', including incident response.	Up to TRL 6	2023 – 2027	NLR, Pipistrel, Onera, Athens Airport, CIRA, DLR, Airbus, Aegean and others
Hydrogen refuelling station (HRS)	Realisation of a HRS for (heavy-duty) vehicles (350 and 700 bar) on landside including a potential pipeline link to and dispenser on airside.	TRL 9	2024–	Fountain Fuel, Linde Gas
Conscious Aerospace (HAPPS)	Accommodating tier one system integrator Conscious Aerospace which develops a hydrogen fuel cell powertrain at a development centre (hangar) at the airport	TRL 3 – 4	2024–28	Conscious Aerospace, Zepp Solutions, Cryoworld, TU Delft, NLR and others
AeroDelft	GH_2 refuelling and LH_2 refuelling demonstration and ground tests (taxiing) with Sling 4 aircraft that will be retrofitted by TU Delft students.	TRL 6 | $\sim$2.1kg GH_2 and $\sim$8kg LH_2	2024–26	AeroDelft, Air Products, NLR, TU Delft and other partners of AeroDelft
ZeroAvia	GH_2 refuelling and flight demonstration with Cessna Grand Caravan (outfitted with ZA600 powertrain).	TRL 7 | $\sim$80kg GH_2	2025–26	ZeroAvia
GOLIAT (see subsection 5.2.3)	LH_2 refuelling demonstration via a ground refueller and trailer including a research project on future LH_2 operations at airports and infrastructure needs. Refuelling and ground (taxi) demonstrations will be performed with the HY4 aircraft.	TRL 6 | $\sim$3 ton LH_2	2024–28	Airbus, H2FLY, Chart Industries, TU Delft, Leibniz University Hannover, Stuttgart Airport, Lyon Airport, Royal Schiphol Group, VINCI Airports and Budapest Airport

Next to the promising goals and ambitions of RTHA, the airport's location also makes it a unique location. It is located close to the Port of Rotterdam, the busiest port in Europe. The port is also already involved in many projects concerning hydrogen, which is already in use in specific industries. In 2025, the planned capacity of LH2 production in the port will double Europe's total capacity [36]. A local pipeline is currently under construction, and an extension to the future European Hydrogen Backbone is planned for 2028 or 2029. The Port of Rotterdam estimates that imported low-carbon hydrogen could rise to 18 million tons by 2050. All these advancements in the port also influence the possibilities for RTHA.

5.2. Supply chain scenarios at Rotterdam The Hague Airport

This section describes and analyses all the viable supply chain options for RTHA. It then analyses them to determine which scenario is the most realistic in which time frame and further analyses this scenario for the specific case of RTHA.

5.2.1. Scenarios

Two realistic supply chain scenarios are identified and described below, after which they will be further analysed. A third scenario of local production and liquefaction of the hydrogen has already been mentioned in subsection 3.1.1 where it became clear that this is not a viable method for an airport.

Scenario 1

The first option for a supply chain scenario is to perform the production off-site and then transport the hydrogen with road trucks. This can be done in a region where the cost of electricity is low, after which it is transported to the Port of Rotterdam, where it can be transported to the airport by trucks. Another option is to import the GH2, perform the liquefaction at the Port of Rotterdam, and transport the LH2 by truck. These options are feasible, but if this scenario is chosen, a choice will be made between GH2 or LH2 truck transportation. This scenario has a low capital cost and is easy to implement because of the flexibility in using trucks and trailers.

Scenario 2

The second scenario is to import GH2 and supply it to the airport by pipeline. When it arrives at the airport, it needs to be liquefied, after which it can immediately be used or stored. Pipeline transportation is considered the most efficient method, but it requires a lot of investment costs for the pipeline's construction and liquefaction at the airport itself. Because 80-95% of the transportation cost consists of the liquefaction, it could be considered that it is not an economic option to procure such a facility on the airport itself [23]. As described in subsection 5.1.2, pipelines are already in the port of Rotterdam, meaning RTHA could be connected to this network. To connect RTHA to the European Hydrogen Backbone, a pipeline of approximately fourteen kilometres needs to be constructed [14]. This scenario could become realistic when the LH2 demand is high and consistent enough to be worth the investment costs.

5.2.2. Analysis

These two scenarios are considered viable for airports of different sizes until the year 2050. RTHA is assumed to be in the small airport category because, from personal communication with experts on the airport, the maximum predicted number of passengers at RTHA in 2035 is approximately 3.5 million. It becomes clear that scenario 3 will not be realistic for any airport before 2050. The energy requirement to perform electrolysis at the airport is expected to be 50-70 times larger than the regular expected energy [28]. The difference between scenarios 1 and 2, will depend on the amount of road congestion at the local road or off-load points. Once these problems arise, changing to a pipeline connection could be valuable. Still, until that time and especially in the early phases, truck delivery seems to be the most viable option.

Further considering truck transportation, a look is taken at the difference between transporting GH2 or LH2. For this, a trade-off table is made, which is shown in Table 5.3. Four criteria have been set, and they have been given a weight. Cost and safety are the most essential criteria in making this decision. Also, the storage efficiency and operational flexibility are considered with a bit less weight. The conclusions are taken from previous analyses in chapter 3 and from expert knowledge at RTHA. GH2 scores less on cost because more trucks and a liquefaction plant at the airport are necessary, so this solution seems less favourable. GH2 is also prone to leaks, and its odourless and invisible characteristics make it less safe. GH2 has the advantage of being more flexible, but cost and safety are considered more essential characteristics. LH2 truck transportation is thus considered to be the better option for RTHA.

Table 5.3: Trade-off table between GH2 and LH2 delivery by truck for RTHA

	Truck GH2	Truck LH2
Cost (30%)	3 | More trucks needed, because of low energy density. Liquefaction necessary at airport	5 | Less infrastructure cost, less trucks needed
Safety (30%)	2 | Higher leak risk, odorless and invisible	4 | Less leak risk, cryogenic temperatures also pose dangers such as frostbite
Storage efficiency (20%)	3 | Large storage volume required	3 | Lower storage volume, needs to be kept at cryogenic temprature
Operational flexibility (20%)	5 | GH2 can also be used by other transportation modes	3 | Probably only used by aviation
Score	**3.1**	**3.9**

Most of the projects at RTHA, as mentioned in Table 5.2, are also regarding LH2, because there is expected to be a short-term demand for GH2 at the airport. Still, for the medium- and long-term, LH2 will be the primary aircraft fuel [37]. Because this study will focus on the supply and demand in 2035, only LH2 will be considered from this point forward. The most relevant current project at RTHA is the GOLIAT project, which focuses on airports' operational and infrastructure needs for LH2 refuelling, further explained in subsection 5.2.3.

5.2.3. GOLIAT project

The EU-funded GOLIAT (Ground Operations of Liquid Hydrogen Aircraft) project is a four-year project, focusing on the LH2 refuelling via a ground refueller and trailer. This project has a time frame from 2024 until 2028, intending to perform refuelling and ground demonstrations with the HY4 aircraft, which made its first GH2 flight in September 2016 and its first LH2 flight in September 2023 [7]. The aircraft has doubled the range to 1500 kilometres by switching from GH2 to LH2. This is relevant for the GOLIAT project, where the goal is to be tested in RTHA, Stuttgart Airport and Lyon Airport, which would become a close call because the straight-line distance between RTHA and Lyon Airport is almost 700 kilometres [38]. This is thus also one of the reasons why flying with LH2 is preferred over GH2.

The outcomes of the GOLIAT project will have significant implications for the future of hydrogen aviation, by addressing the operational and safety challenges associated with LH2 ground operations. One of the formulated goals of the GOLIAT project is: *'Comprehensive and validated liquid hydrogen demand and supply-matching models at air transport ground infrastructures in Europe and globally, towards a potential entry into service of hydrogen aircraft by 2035'*. The year 2035 is thus an essential goal in advancing hydrogen aviation. Because this research will focus on a medium to long-term solution for hydrogen supply, the year 2035 is chosen as the goal of this project. This is in good agreement with the aim of Airbus of having a commercially available hydrogen-powered aircraft on the market by 2035, the Airbus ZEROe, which will be further analysed in subsection 5.2.4. Thus, it is chosen to focus on the ZEROe aircraft with the predicted necessary demand in 2035.

5.2.4. Airbus ZEROe aircraft

The Airbus ZEROe project aims to develop a hydrogen-powered commercial aircraft by 2035. To reach this goal, the project is exploring multiple options and designs. In 2020, they presented 3 designs: a turboprop, turbofan and blended-wing body [9]. Of these concepts, the turboprop is considered the most promising [39]. This aircraft design has a maximum capacity of 100 passengers and can cover up to 1000 nautical miles. The concept aircraft can reach 40 of the 52 current RTHA destinations, so it will be a valuable part of the fleet at the airport [14]. Also, currently, unserved destinations might open up when they could be reached with zero-emission aircraft, making it interesting to be one of the first airports to be able to provide this option.

6 Research methodology

This chapter will further explain the research methodology, following the research objective and questions and the case study of RTHA.

6.1. Modelling technique

Part of the research will be modelling the vehicle simulation-based optimisation model. Considering the model requirements in subsection 3.4.2, a model will be set up to get more data-driven insights and provide the opportunity to test different scenarios. Some techniques have been identified for the simulation part of the research. The characteristics of the other simulation models have been generated, after which it is decided which simulation technique is the most relevant for the research objective and questions determined in chapter 4.

The considered simulation options are shown in Table 6.1 with some characteristics and relevant examples. Markov Chains (MC) is the least detailed and flexible technique but is preferred when considering more probabilistic events. This is useful for reliability and decision-making models. System Dynamics (SD) is a technique that provides a high-level overview and is helpful for long-term planning. This technique allows for more detailed modelling, which is especially useful when considering continuously changing variables. The other two techniques allow for more detailed modelling, with Discrete Event Simulation (DES) more focused on the processes. These processes are placed in a sequence, with the opportunity to model different queues and resource limits. The model can become very complicated, depending on the complexity and number of events modelled. The last technique, Agent-Based Modelling, is focused on individual agents, which make heterogeneous decisions. This will result in high computational demand and a complex system. This is especially useful when the interactions between the agents are also essential, and decisions on an individual basis need to be taken.

Table 6.1: Different options for the simulation part of the proposed model [40, 41, 42, 43]

Criteria	Markov Chains (MC)	System Dynamics (SD)	Discrete Event Simulation (DES)	Agent-Based Modeling (ABM)
Focus	Probabilistic transitions between discrete states	Continously changing state variables	Process-oriented systems with queued activities	Individual agent interactions in a system
Model Detail	Low: Limited to states and probabilities	Moderate: Models storage/movement relationships	High: Focuses on sequences of discrete events	High: Detailed, individual-based behavior
Scenarios	Systems with known state transitions	Simulates system trends and impacts for extended planning	Processes with queues, tasks, and resource limits	Complex adaptive systems, heterogeneous agents
Computational Demand	Very Low: Minimal computation needed	Low to Moderate: High-level simplifications	Moderate to High: Depends on event complexity	High: Computational cost grows with agents
Flexibility	Low: Restricted to probabilistic systems	Low: High-level models limit details	Moderate: Structured around process flows	High: Highly adaptable to varying agent behaviors
Examples	Unpredictability during boarding process (B. Yildiz et al., 2018)	Levels in fuel tank (M.M. Mota et al., 2017)	Identify bottlenecks in TAT processes (S. Adeleye et al., 2013)	Automated ground handling of aircraft (S. Chen et al., 2023)

When looking at the model requirements in subsection 3.4.2, a detailed model would be preferred for this research. The problem contains no probabilistic events, making MC less applicable to this model. SD is more useful when considering long-term planning, while this research will focus on simulating and optimising the movements in one day. DES and ABM could be useful for this research. Still, because the focus will be on the order and possibility of performing a specific sequence of processes, DES is the preferred method. This can also model queues and resource limits, which will be relevant when considering the necessary trailer parking spaces. The vehicle interactions are irrelevant to the proposed problems, making ABM too complex. DES will thus be more computationally efficient, an advantage because it will need to be run multiple times to optimise the problem.

6.2. Assumptions

This section will make assumptions to bind the research to a specific scope. The assumptions are divided into four categories, each focusing on a particular part of the research.

General

- RTHA is used as a case study
- Only LH2 for the refuelling of the aircraft is considered
- The use and emissions of ground vehicles are not included
- The flight data from 2023 will be used to set up representative days in 2035
- The research uses the currently expected advancements in aircraft or refuelling systems for 2035
- Emissions of the supply chain are not considered
- Hydrogen consumption for each flight is estimated based on average values for the different aircraft types.

Infrastructure

- The refuelling trucks have a predetermined velocity
- A grid map will be drawn to determine the distances on the airport
- Trucks are assumed to follow fixed paths determined by the grid map
- 12 Commercial gates are considered on the airport
- The LH2 trailer parking spaces are considered to be in the same spot as the current Jet-A1 trailer parking
- It is assumed that the existing Jet-A1 infrastructure can be partially repurposed for hydrogen
- Only commercial aviation is considered

Operations

- The study does not consider any changes in operational procedures or layout, except those related to hydrogen implementation
- LH2 is assumed to be produced and liquefied off-site
- The refuelling time includes setup, refuelling and wrap-up phases
- Refuelling truck drivers are assumed to operate with uniform efficiency and do not act individually
- Refuelling equipment is assumed to be fully operational throughout the analysed period, with no downtime considered

Aircraft

- Only full kerosene-powered or full-hydrogen-powered aircraft are considered. No hybrid
- Aircraft are only considered on the stands. The movements of aircraft is not considered
- Aircraft have a set TAT time, based on the average duration of the turnaround processes and the refuelling speed of the relevant trailer
- Aircraft must complete their entire TAT within the set time frame; otherwise, the solution is considered infeasible.

6.3. Research planning

In this section, the research planning is specified, which will be followed throughout the research. This report is the first part of the research, consisting of the Literature study and Research proposal. All the steps and the time frame they need to be performed are drawn up in Table 6.2. These values are all estimations and are prone to change during the research.

Table 6.2: Research planning

	Task	Duration (Weeks)
Literature study	Literature study and Research proposal	6
Input determination	Gathering flight data	0.5
	Determine refuelling infrastructure at RTHA	0.5
	Determining relevant scenarios	1
	Determining aircraft characteristics	0.5
	Determining trailer characteristics	0.5
	Determine road network and distances on airport	0,5
Model building	Generating flight schedule	1
	Set up of different events and entities	1
	Implement simulation model	2
	Set up optimisation model	1
	Prepare mid-term review	1
Analyzing model	Model verification and validation	1
	Analysing different scenarios	2
	Perform sensitivity analysis	0.5
Results	Create visualizations of the results	1
	Determine airport infrastructure conclusions	1
	Determine supply chain conclusions	1
Finalize thesis	Write draft thesis	4
	Prepare green light meeting	2
	Finish research portfolio	2
	Prepare thesis defense	2
	Total	32

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III

Supporting work

1

Supporting work: Model schematics

1.1. IDEF0 Diagrams

Flight Arrival and Stand Assignment

The following paragraphs briefly introduce the purpose and sequence of the key subprocess blocks A1, A2, A22, A23 and A4. Together, these blocks implement the core logic of stand assignment, resource allocation and turnaround completion within the refuelling simulation. Block A1 in Figure 1.1 initiates the workflow by matching each arriving aircraft to a physical stand. Upon aircraft arrival, the routine queries the current stand-availability database and compiles a list of available stands. A subsequent selection algorithm then assigns the arriving flight to one of those stands, yielding the event that drives the downstream refuelling steps. By encapsulating the availability check and the allocation decision under A1, the model ensures that no fuelling action commences until a valid stand has been secured.

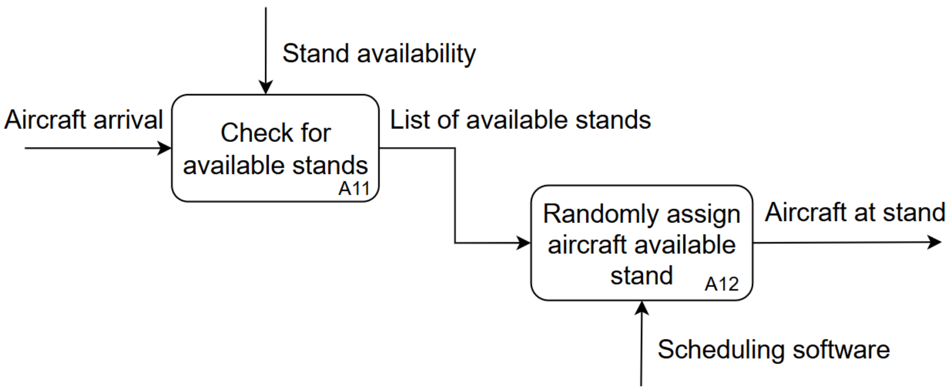

Figure 1.1: Building block A1 of the IDEF0 model

Truck and Trailer Dispatch

In Figure 1.2, block A2 orchestrates the pairing of trucks and trailers to serve the aircraft now occupying a stand. Its first subtask (A21) reserves an idle truck from the pool, while block A22 then determines which trailer carries the correct fuel type and sufficient volume. Once a truck–trailer combination has been identified, block A23 dispatches the trailer from its parking location, coupling it to the assigned truck before departure toward the stand. By splitting resource allocation into these discrete steps, the simulation can capture delays arising from trailer availability, coupling times and parking constraints.

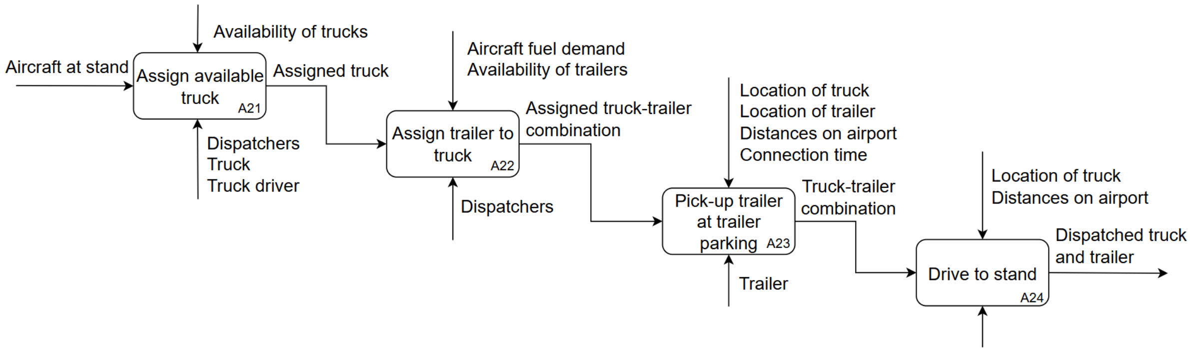

Figure 1.2: Building block A2 of the IDEF0 model

Within A2, block A22 applies the aircraft's fuel-type requirement and current trailer fuel levels to select an appropriate trailer, as shown in Figure 1.3. It draws upon both the dispatchers' schedule and the real-time hydrogen or Jet-A1 trailers inventory, filtering out units without sufficient remaining volume. The chosen trailer is then passed onward to A23 for physical pick-up.

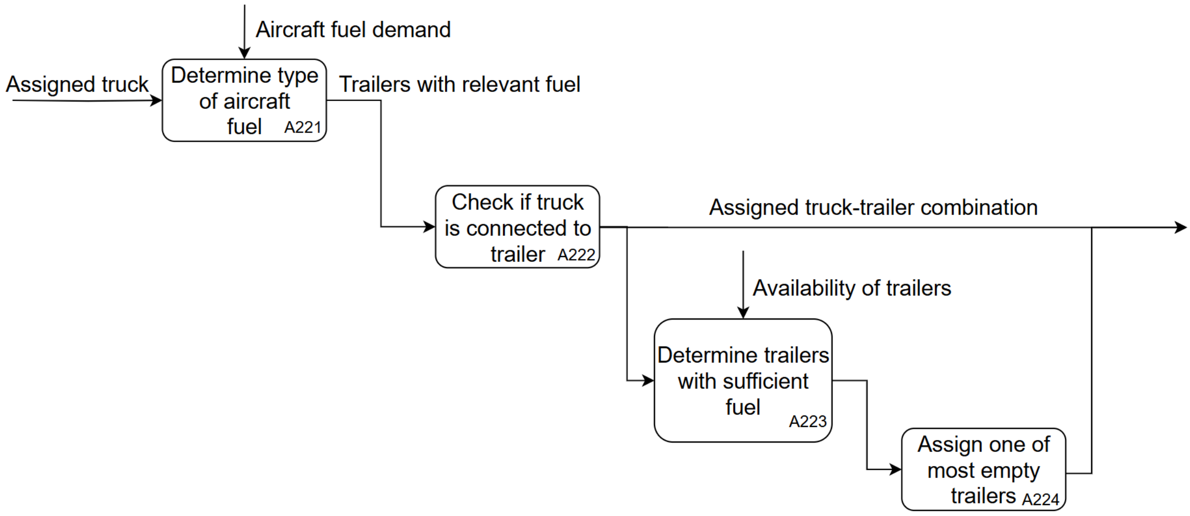

Figure 1.3: Building block A22 of the IDEF0 model

Figure 1.4 is also within A2; block A23 models the spatial and temporal costs of retrieving the trailer. Once a trailer has been earmarked, this subprocess computes the distance along airport taxiways, reserves an open parking bay for reconnection, and applies a fixed coupling-time delay. The output is a fully coupled truck–trailer combination ready to drive to the aircraft stand.

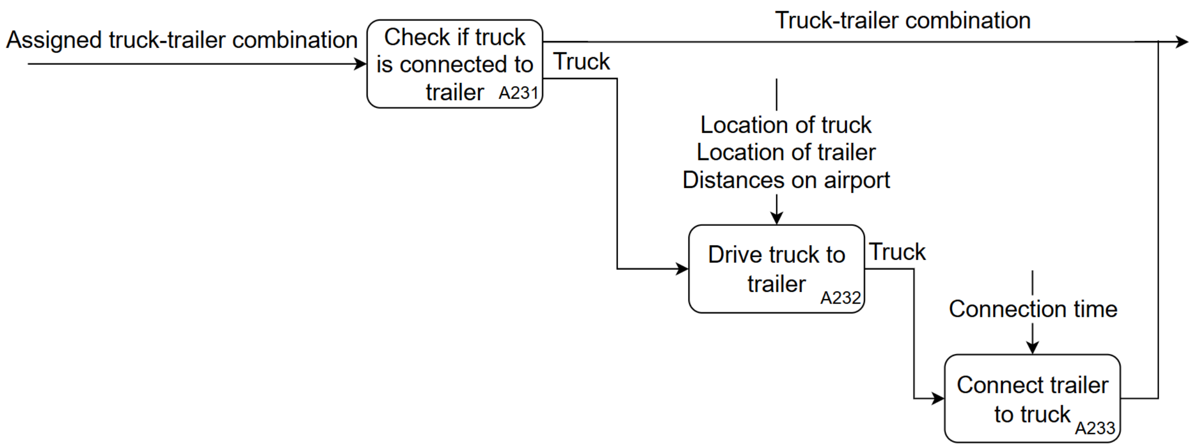

Figure 1.4: Building block A23 of the IDEF0 model

Redeployment and Refilling

Finally, block A4 in Figure 1.5, closes the loop by handling all activities once fuelling is finished. The aircraft's remaining turnaround tasks are executed, the stand is released, and the truck is either dispatched to its next assignment or routed back to a parking area. Simultaneously, the old trailer is replenished (A49), making it unavailable until the Trailer Refill Time has passed. At the end of the simulation, all resource-utilisation statistics are updated. In this way, A4 bridges the gap between a completed refuelling and the system's readiness for the next flight.

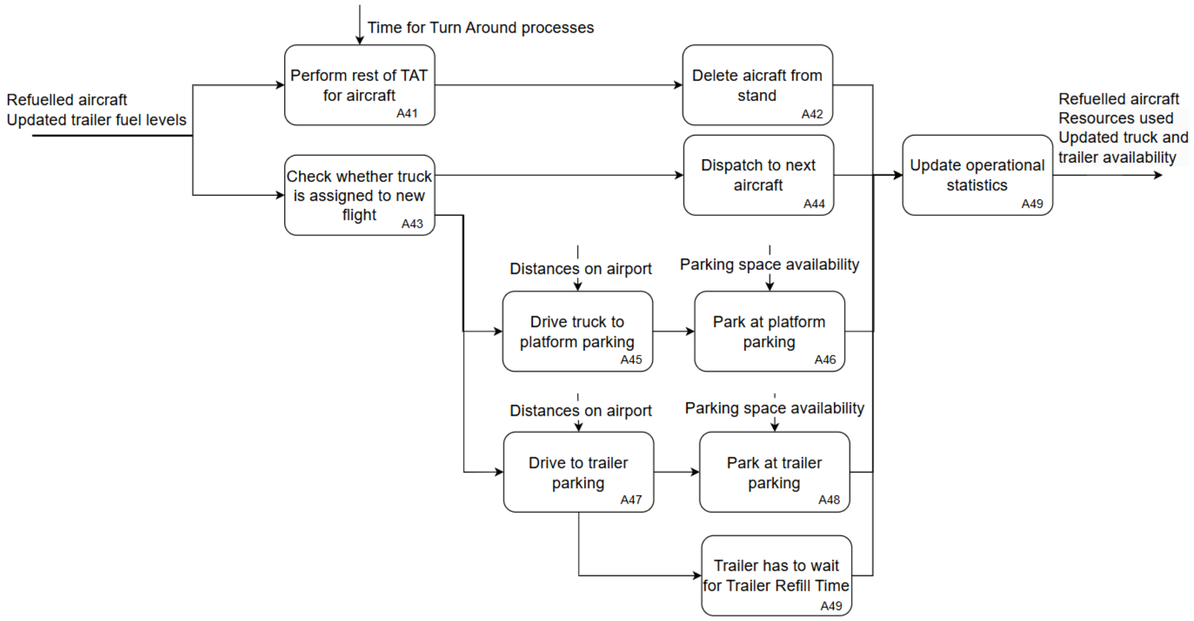

Figure 1.5: Building block A4 of the IDEF0 model

1.2. Swimlane Diagram

In Figure 1.6 and Figure 1.7, the Swimlane diagrams capture the dynamic interaction of the four core components, Aircraft, Aircraft stand, Refuelling Truck and Trailer, within the refuelling workflow. Each lane represents one entity's sequence of activities, from pushback clearance through stand approach, stand allocation and release, fuel delivery and connection, and trailer detachment and refill. Decision points and hand-offs are made explicit, for example, when the Refuelling Truck must await stand availability or when the Trailer departs for replenishment as soon as the truck is reattached. By laying out these parallel processes in a single view, the diagram highlights critical synchronisation points and potential bottlenecks, which give insights that support the model.

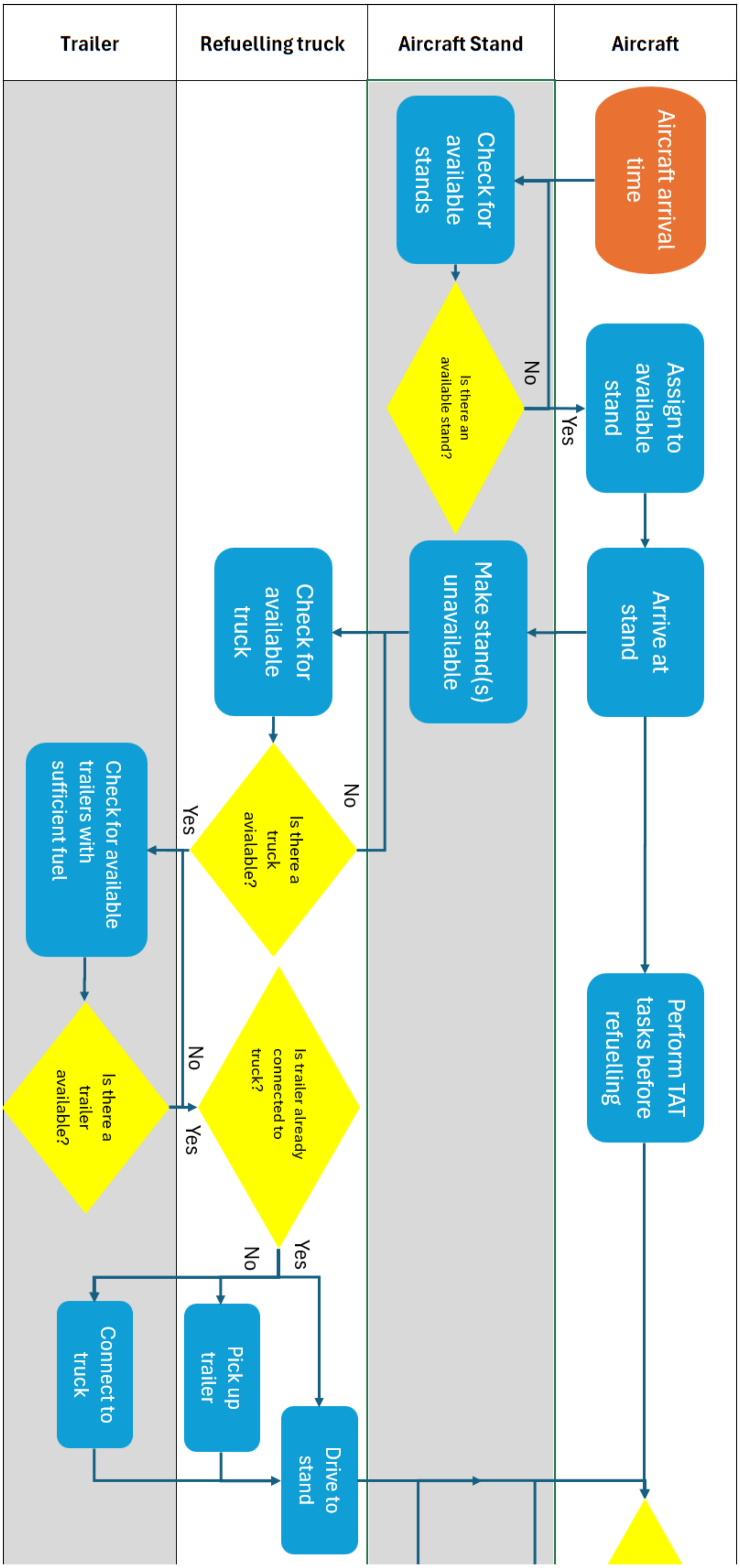

Figure 1.6: Swimlane diagram first part

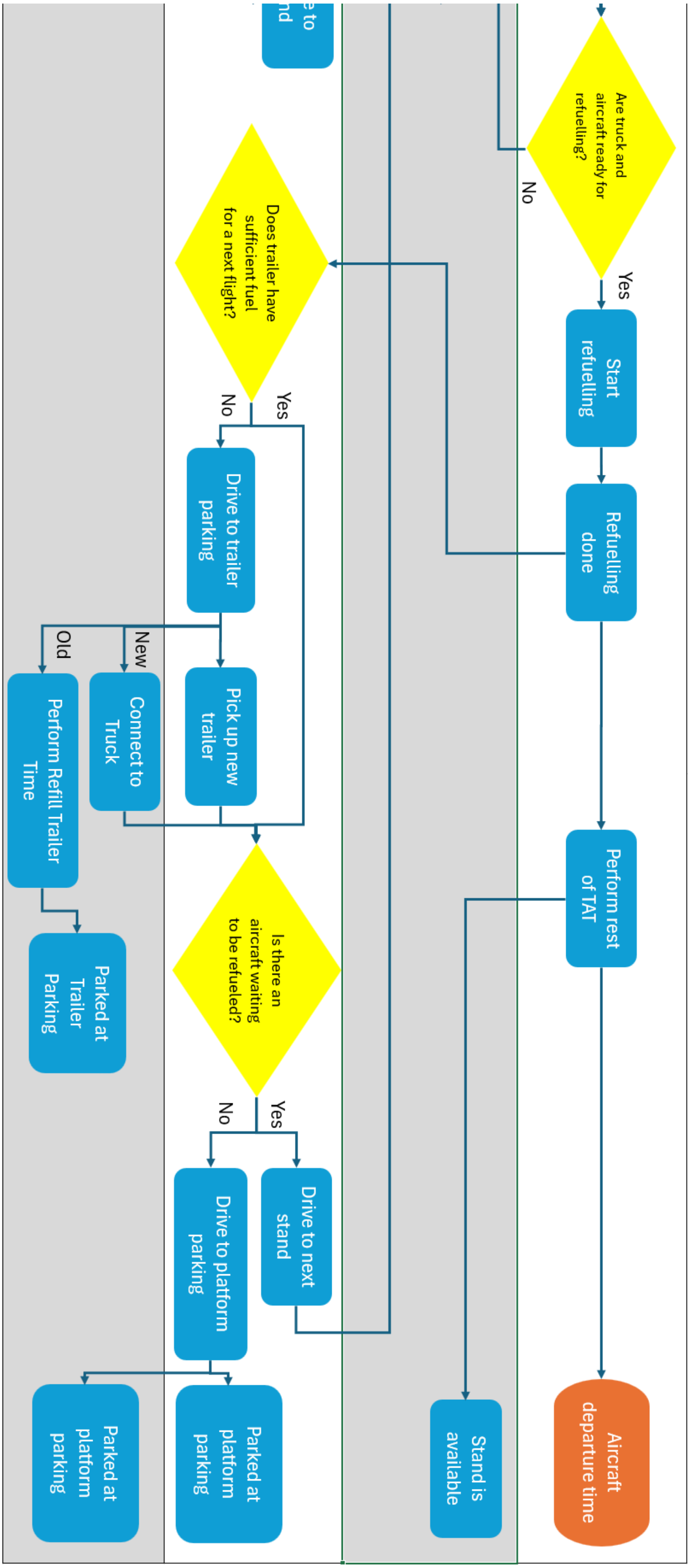

Figure 1.7: Swimlane diagram second part

2

Supporting Work: Model Verification

A verification process was conducted to ensure the simulation model was correctly implemented. A small, straightforward airport layout was designed for this, with only two aircraft stands. This layout could then be used to verify all the processes within the model, including unit testing of individual components and scenario-based verification to confirm expected system behaviour under controlled inputs. Unit tests were designed to check the accuracy of fundamental model functions, such as vehicle movement, queue logic, and refuelling operations. For example, tests were devised to confirm that a single truck always dispatches correctly when arrivals are widely spaced, or that a trailer is replaced immediately when it becomes empty. Scenario-based tests then exercised the entire model under specific conditions, ranging from zero-load cases to artificially high demand, to ensure that overall behaviour aligned with conceptual expectations. This two-pronged approach increased confidence that each building block was implemented correctly and that all pieces worked together as intended. An overview of the key verification tests and their expected outcomes is provided in Table 2.1. This table outlines the scenarios, test objectives, and whether the results confirmed the expected model behaviour.

Table 2.1: Model verification

Verification Criteria	**Input Parameters**	**Expected Outcome**	**Simulation Outcome**	**Status**
Truck Dispatch Accuracy	1 truck, fixed arrivals every 30 min	Trucks dispatched on arrival, no queueing	Trucks dispatched correctly, no delays	✓
Trailer Replacement Logic	1 refuelling per aircraft	Trailer replaced after each refuelling	Replacement occurs after each aircraft	✓
Fuel-specific Equipment Handling	50% LH2 penetration, separate truck fleets	Correct truck type assigned to fuel type	Correct trucks consistently assigned	✓
Timing Accuracy and Delay Calculation	3 aircraft arrivals close in time, 2 trucks	1 aircraft delayed due to truck shortage	Correct delay identified and recorded	✓
Spatial Movements and Grid Logic	Fixed grid layout, truck speed 1 unit/min	Correct travel times calculated manually	Simulated travel times match calculation	✓
Random Seed Reproducibility	Two runs with identical random seed	All KPI outputs match exactly	Identical KPI results observed across runs	✓
Safety-Zone Diameter Verification	Six arrivals, three stands zones	No block: no queue Block front: three park, others queue Block front and adjacent: one at a time	No block: zero hold Block front: first three at stand, next three waited until stand freed Block front and adjacent: only one parked at a time	✓
Trailer Refill Time Verification	Single LH2 trailer with capacity = 3, refill time = 45 min, four rapid arrivals	Trailer serves three, then refills. Fourth waits, then served	Trailer completed three services, refilled for 45 min, fourth queued then served	✓

3

Supporting Work: Flight Schedule Analysis

A flight schedule is necessary to run the simulation-based optimisation model. This schedule must be representative of a day. The flights at Rotterdam The Hague Airport (RTHA) will be analysed to determine representative days for a flight schedule and how to adjust them to predict future flight schedules. The first step is to investigate all the commercial flights at the airport. In this analysis, only flights which arrive and depart on the same day will be considered. This means that flights which stay overnight are not included. This could be flights that depart early in the morning or arrive during the day and do not leave anymore. When these are filtered from the total flight schedule, Figure 3.1 shows the total number of flights every day during 2024. From this graph, it becomes clear that the summer period is busier than the winter and that there is still quite a lot of variation in the total flights in every period.

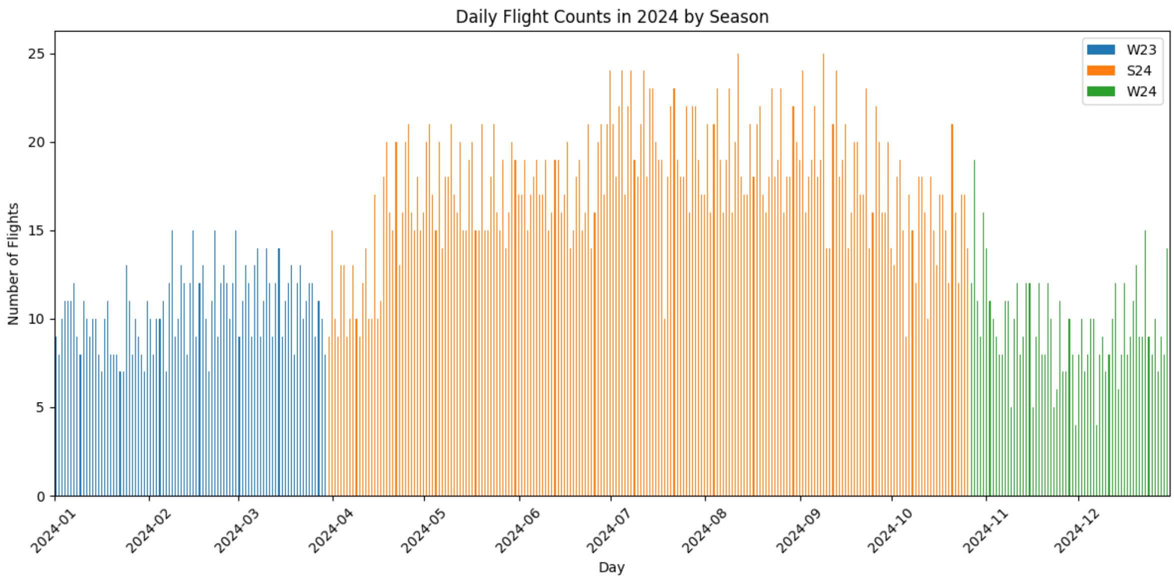

Figure 3.1: The number of flights, which have both arrived and departed, per day at Rotterdam The Hague Airport in 2024

Another critical aspect to consider for the research is to look at the number of overlapping flights at a particular moment. When many flights are on the platform simultaneously, this means a busier schedule for the refuelling trucks at the same time, compared to a more spread-out day. This is checked by looking at every time an aircraft arrives and counting the number of aircraft on the platform. This could also mean aircraft which have been standing on the platform for a long time and have already been serviced. The airport RTHA has twelve gates available, accommodating twelve aircraft simultaneously. The queuing and cluttering that could happen during the plane's taxiing are not part of the scope of this research. In Figure 3.2, the maximum overlapping flights in a day are presented. It becomes clear that this also varies a lot throughout the year, but in 2024, there were two days when eight flights were overlapping. These days, it is also interesting to analyse and see which method of choice is most limiting for this research.

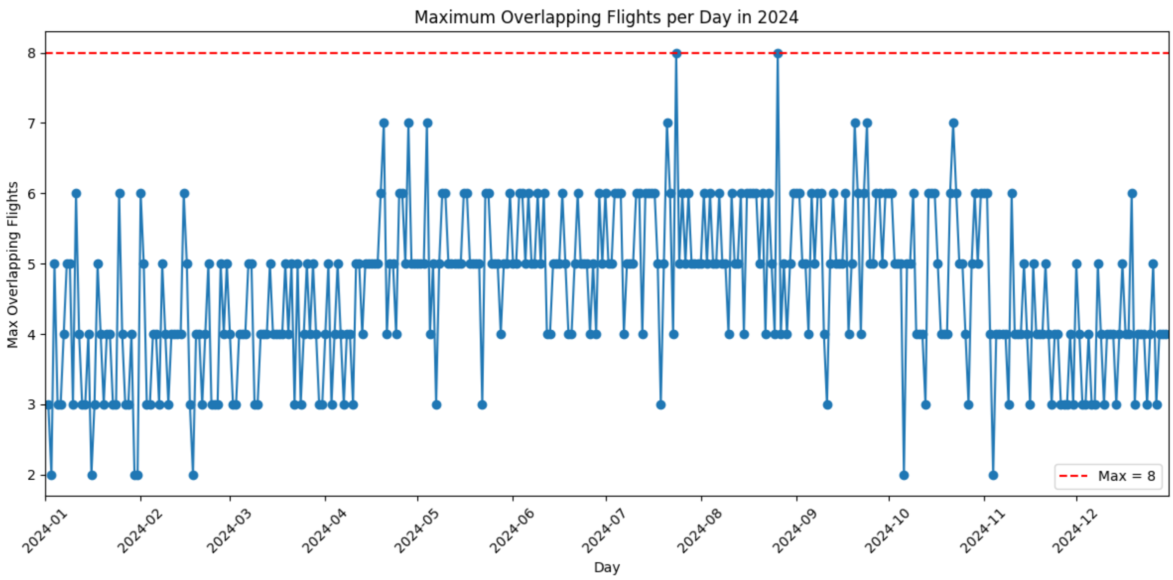

Figure 3.2: The maximum number of overlapping turnaround times per day at Rotterdam The Hague Airport in 2024

Table 3.1 shows the selected average and peak days for both the summer and winter seasons, along with the maximum number of overlapping flights and total flights simulated. These metrics illustrate typical and worst-case operational loads under baseline conditions, providing context for how seasonal demand fluctuations impact airport congestion and service performance.

Table 3.1: Chosen peak and average days for Summer and Winter season with the maximum overlapping flight and the total number of flights

Season	Day type	Date	Max. Overlapping Flights	Total Flights
Summer	Average	11-05-2024	5	17
	Peak	26-08-2024	8	23
Winter	Average	20-02-2024	4	10
	Peak	31-10-2024	6	16

With four representative days for the flight schedules, a decision should be made on how this will look when considering future scenarios. For this, the expected number of PAX is analysed. These numbers are gathered from internal communications at the airport. Until 2035, there are estimations for these numbers; a linear extrapolation has been performed for the later years. These figures are unrealistic because many more factors, such as the airport's maximum capacity and spatial constraints, are relevant to these numbers. These figures can, however, be used to determine a growth factor throughout these years, which can also be used for relevant parameters of this research.

Table 3.2: Expected passenger numbers at Rotterdam The Hague Airport based on internal communication

Year	Passengers (million)	Growth factor
2024	2.24	-
2030	2.80	1.25
2035	3.25	1.16

4

Supporting Work: Specification of Results

4.1. Future scenarios

The impact of adding a third LH2 truck in the 2050 high-penetration scenario is illustrated in Figure 4.1. In both the low- and mid-penetration cases, KPIs remain nearly unchanged, with a maximum reduction of one minute in average departure delay on the average winter day. In contrast, the high-penetration scenario shows a dramatic decrease in delays: average departure delay on the summer peak day falls by nearly 18 minutes when a third truck is deployed. This represents a meaningful operational benefit, as longer delays on the busiest day propagate through the schedule and degrade reliability. Truck utilisation shifts into a more tolerable range: where LH2 trucks previously operated near saturation, the additional vehicle restores slack in the system, enabling more robust handling of unexpected events or variability. These results confirm that, under the most extreme hydrogen-demand conditions projected for 2050, a third LH2 truck is essential to maintain acceptable on-time performance and avoid crippling congestion on peak days.

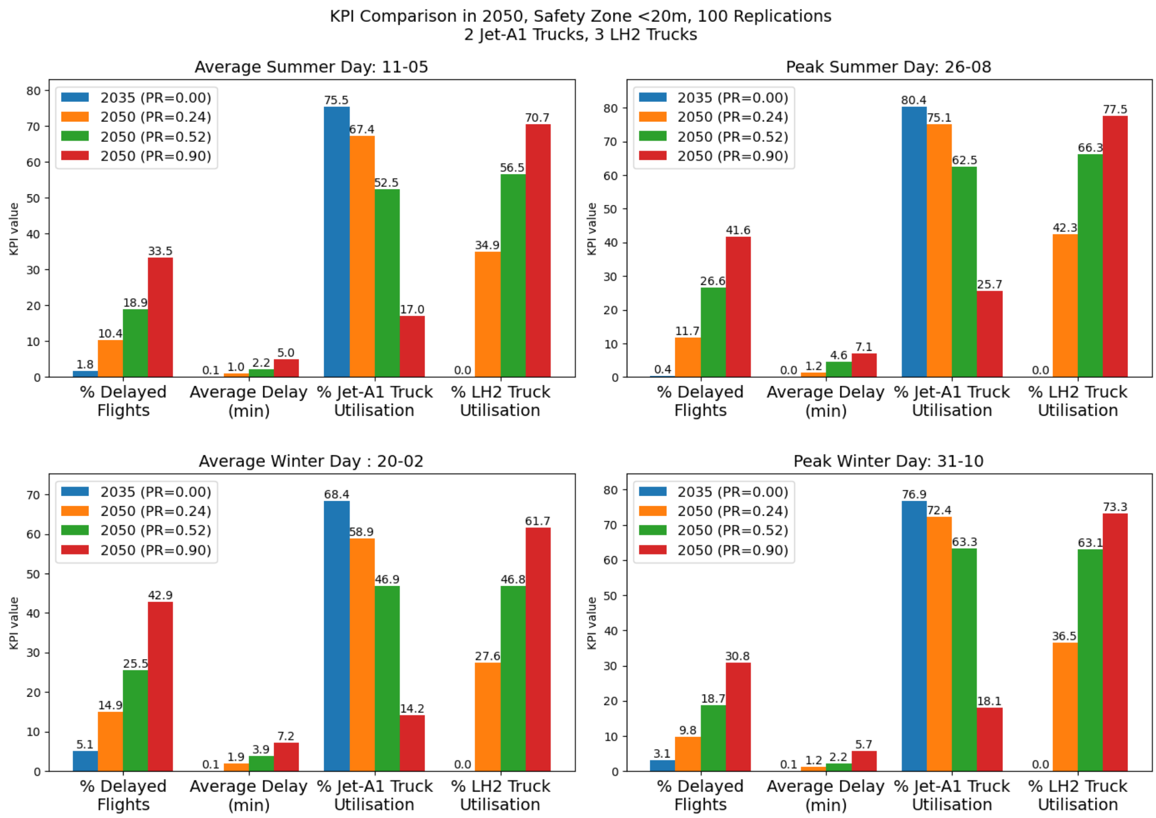

Figure 4.1: The KPIs for the four future scenarios in 2050 with 2 Jet-A1 and 3 LH2 trucks, a safety zone of <20m and 100 replications per scenario

4.2. Global Sensitivity Analysis

This appendix provides detailed results from the various sensitivity analyses conducted in this study to assess how different parameters influence the performance of the hydrogen refuelling system at Rotterdam The Hague Airport (RTHA). These analyses identify which input variables most significantly affect key performance indicators (KPIs), such as flight delays, truck utilisation, and equipment requirements. Each table or figure includes exact values and 95% confidence intervals where relevant. These detailed insights support the main text's conclusions and help pinpoint critical infrastructure thresholds and optimisation opportunities.

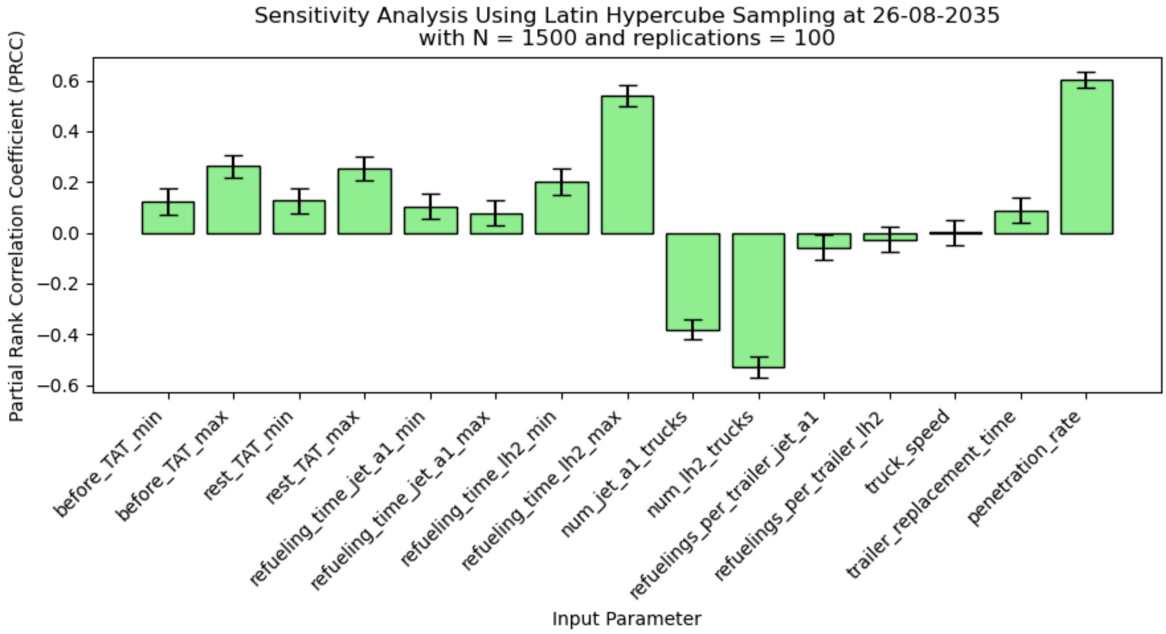

Figure 4.2: Global Sensitivity Analysis for the average delay, with low Safety zone Diameter <20m for 100 replications and 1500 samples

Table 4.1: Global Sensitivity Analysis for the average delay, with low Safety Zone Diameter <20 m for 100 replications and 1500 samples. The bold parameters have statistically significant effects.

Group	Parameter	PRCC	95% CI	p-value
Time Parameters	Before Refuel TAT Min	0.123	[0.073, 0.173]	0.0000
	Before Refuel TAT Max	**0.263**	**[0.218, 0.308]**	**0.0000**
	After Refuel Time Min	0.126	[0.076, 0.176]	0.0000
	After Refuel Time Max	**0.254**	**[0.209, 0.299]**	**0.0000**
	Refuel Time Jet-A1 Min	0.103	[0.053, 0.153]	0.0001
	Refuel Time Jet-A1 Max	0.078	[0.028, 0.128]	0.0028
	Refuel Time LH2 Min	**0.202**	**[0.152, 0.252]**	**0.0000**
	Refuel Time LH2 Max	**0.540**	**[0.500, 0.580]**	**0.0000**
Resources	**Number of Jet-A1 Trucks**	**-0.382**	**[-0.422, -0.342]**	**0.0000**
	Number of LH2 Trucks	**-0.530**	**[-0.570, -0.490]**	**0.0000**
Operational Parameters	Refuelings per Trailer Jet-A1	-0.059	[-0.109, -0.009]	0.0228
	Refuelings per Trailer LH2	-0.027	[-0.077, 0.023]	0.2983
	Truck Speed	0.003	[-0.047, 0.053]	0.9228
	Trailer Replacement Time	0.089	[0.039, 0.139]	0.0006
Fleet Mix	**Penetration Rate**	**0.603**	**[0.573, 0.633]**	**0.0000**

This is also done for the maximum safety zone of >40m, limiting adjacent and in front stands. The graph is shown in Figure 4.3 and the values further specified in Table 4.4. From this analysis, it becomes clear that the penetration rate is the most influential in this scenario. This can be explained by the fact that LH2 aircraft block other aircraft from reaching their stand. Increasing the number of LH2 flights will thus significantly affect the delay of different aircraft. Next to the penetration rate, the number of trucks and the maximum LH2 refuelling time are statistically significant. The number of Jet-A1 trucks seems to have a greater impact on the output, which can be explained by the fact that the delays from LH2 flights are due to the stand assignment, so for Jet-A1, the number of trucks has a greater relative influence.

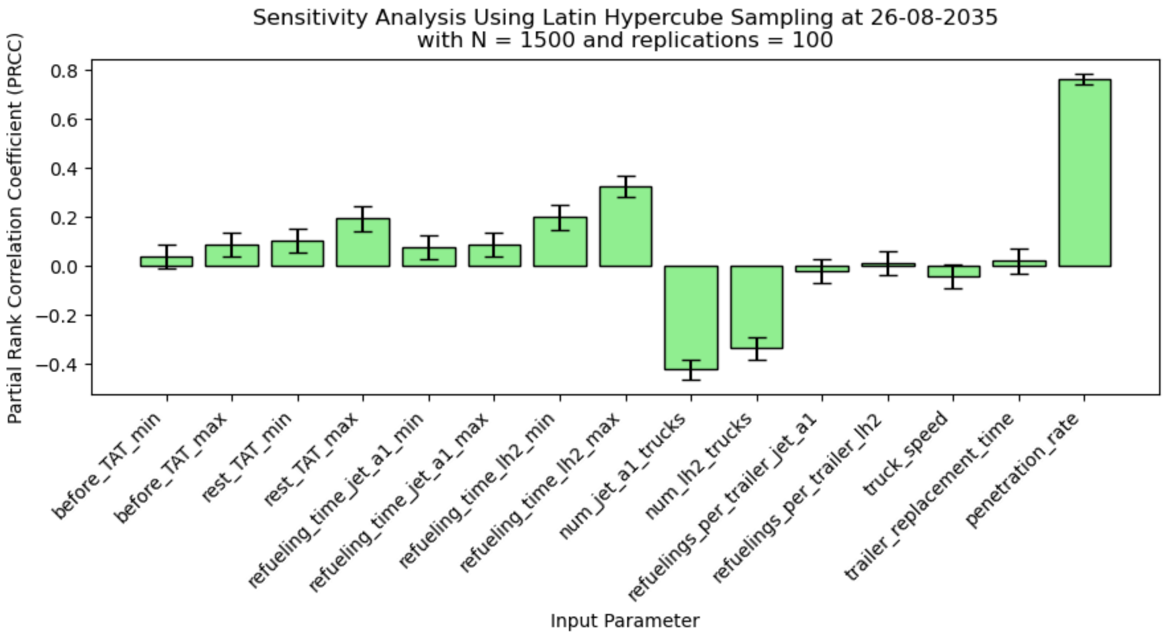

Figure 4.3: Global Sensitivity Analysis for the average delay with high Safety Zone Diameter >40m for 100 replications and 1500 samples

Table 4.2: Global Sensitivity Analysis for the average delay, with high Safety Zone Diameter >40m for 100 replications and 1500 samples. The bold parameters have statistically significant effects.

Group	Parameter	PRCC	95% CI	p-value
Time Parameters	Before Refuel TAT Min	0.040	[-0.010, 0.090]	0.1202
	Before Refuel TAT Max	0.090	[0.040, 0.140]	0.0005
	After Refuel Time Min	0.106	[0.056, 0.156]	0.0000
	After Refuel Time Max	0.194	[0.144, 0.244]	0.0000
	Refuel Time Jet-A1 Min	0.077	[0.027, 0.127]	0.0030
	Refuel Time Jet-A1 Max	0.088	[0.038, 0.138]	0.0007
	Refuel Time LH2 Min	**0.200**	**[0.150, 0.250]**	**0.0000**
	Refuel Time LH2 Max	**0.327**	**[0.282, 0.372]**	**0.0000**
Resources	**Number of Jet-A1 Trucks**	**-0.421**	**[-0.461, -0.381]**	**0.0000**
	Number of LH2 Trucks	**-0.335**	**[-0.380, -0.290]**	**0.0000**
Operational Parameters	Refuelings per Trailer Jet-A1	-0.020	[-0.070, 0.030]	0.4374
	Refuelings per Trailer LH2	0.012	[-0.038, 0.062]	0.6388
	Truck Speed	-0.040	[-0.090, 0.010]	0.1242
	Trailer Replacement Time	0.021	[-0.029, 0.071]	0.4155
Fleet Mix	**Penetration Rate**	**0.764**	**[0.744, 0.784]**	**0.0000**

A separate global sensitivity analysis was conducted with Jet-A1 and LH2 truck utilisation rates as output variables. The resulting parameter influences are visualised in Figure 4.4 and Figure 4.5. For Jet-A1 truck utilisation, the most statistically significant parameters are the number of Jet-A1 trucks and the penetration rate. A higher number of trucks reduces the utilisation rate, as the workload is spread over a larger fleet. The penetration rate also shows a negative influence, as increasing hydrogen flights lessen the demand for Jet-A1 refuelling operations, lowering utilisation. Refuelling duration parameters (Jet-A1 Min and Max) have only a limited impact, likely due to their relatively small variation and the efficient scheduling enabled by the compact airport layout.

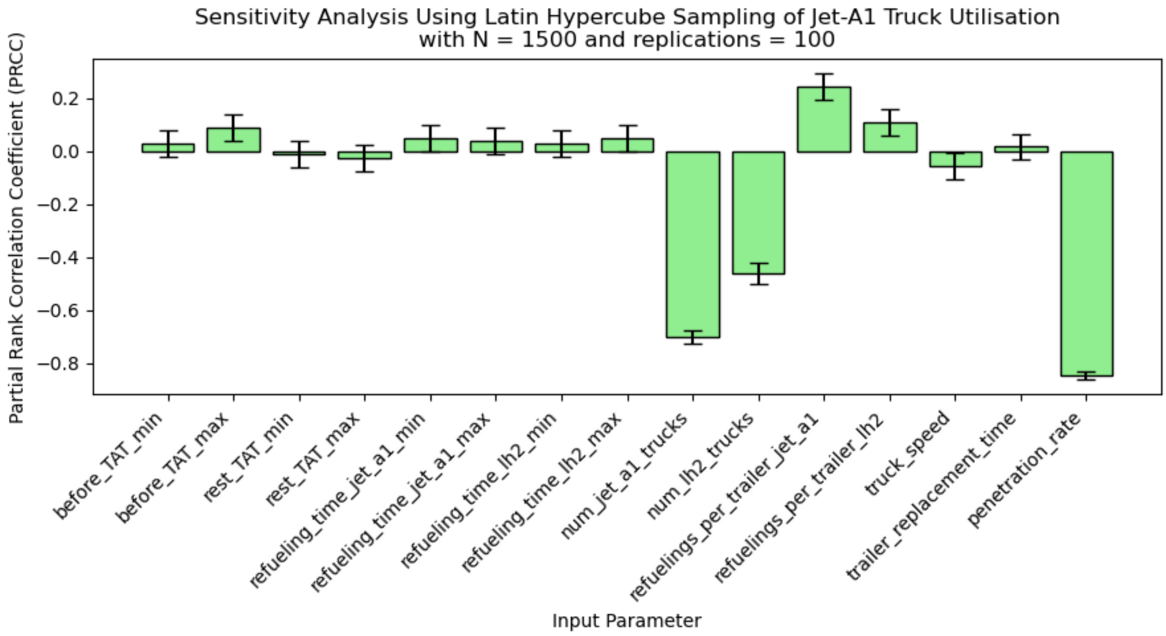

Figure 4.4: Global Sensitivity Analysis for the Jet-A1 Truck Utilisation with low Safety Zone Diameter <20m for 100 replications and 1500 samples

Table 4.3: Global Sensitivity Analysis for Jet-A1 Truck Utilisation, with low Safety Zone Diameter <20m for 100 replications and 1500 samples. The bold parameters have statistically significant effects.

Group	Parameter	PRCC	95% CI	p-value
Time Parameters	Before Refuel TAT Min	0.032	[-0.018, 0.082]	0.2249
	Before Refuel TAT Max	0.090	[0.040, 0.140]	0.0005
	After Refuel Time Min	-0.009	[-0.059, 0.041]	0.7170
	After Refuel Time Max	-0.027	[-0.077, 0.023]	0.3037
	Refuel Time Jet-A1 Min	0.050	[-0.000, 0.100]	0.0545
	Refuel Time Jet-A1 Max	0.042	[-0.008, 0.092]	0.1094
	Refuel Time LH2 Min	0.030	[-0.020, 0.080]	0.2434
	Refuel Time LH2 Max	0.049	[-0.001, 0.099]	0.0590
Resources	**Number of Jet-A1 Trucks**	**-0.702**	**[-0.727, -0.677]**	**0.0000**
	Number of LH2 Trucks	**-0.463**	**[-0.503, -0.423]**	**0.0000**
Operational Parameters	Refuelings per Trailer Jet-A1	-0.063	[-0.113, -0.013]	0.0151
	Refuelings per Trailer LH2	0.109	[0.059, 0.159]	0.0000
	Truck Speed	-0.058	[-0.108, -0.008]	0.0258
	Trailer Replacement Time	0.017	[-0.033, 0.067]	0.5121
Fleet Mix	**Penetration Rate**	**-0.845**	**[-0.860, -0.830]**	**0.0000**

For LH2 truck utilisation, the analysis identifies the number of LH2 trucks, the penetration rate, and the maximum LH2 refuelling time as the dominant factors. Notably, LH2 truck utilisation increases significantly with longer refuelling durations and higher hydrogen penetration rates, increasing demand and tightening turnaround windows. Conversely, adding more LH2 trucks reduces individual utilisation. This behaviour underscores the trade-off between maintaining high utilisation and preventing delays. The results confirm that LH2 refuelling time and fleet sizing are critical levers in balancing efficiency and performance under hydrogen integration scenarios.

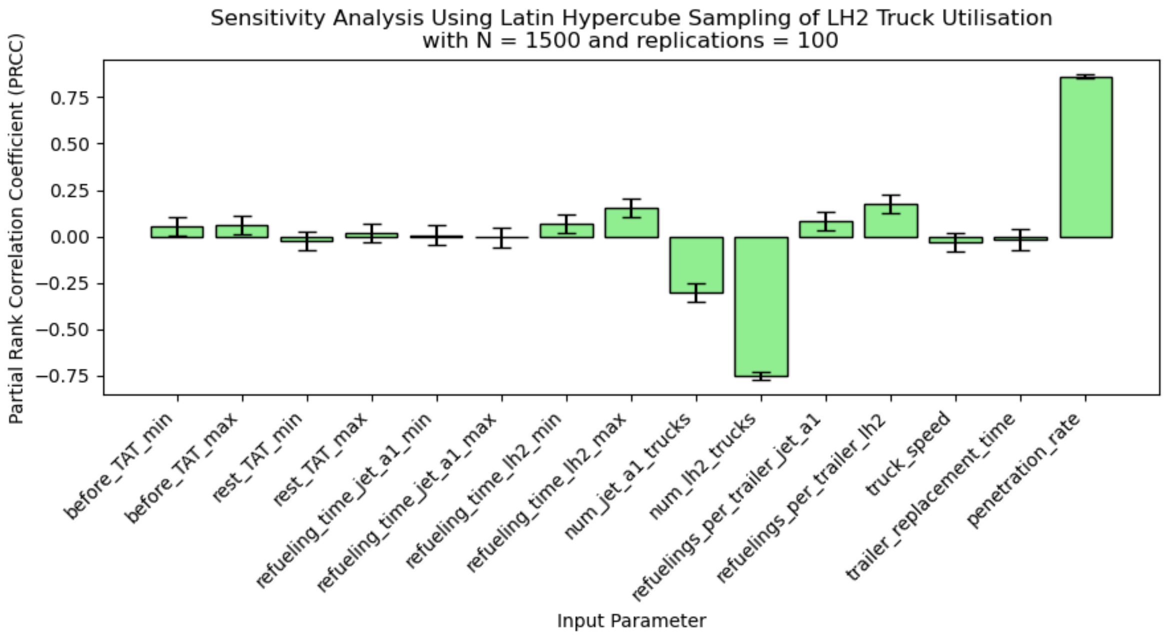

Figure 4.5: Global Sensitivity Analysis for the LH2 Truck Utilisation with low Safety Zone Diameter <20m for 100 replications and 1500 samples

Table 4.4: Global Sensitivity Analysis for the LH2 Truck utilisation, with low Safety Zone Diameter <20m for 100 replications and 1500 samples. The bold parameters have statistically significant effects.

Group	Parameter	PRCC	95% CI	p-value
Time Parameters	Before Refuel TAT Min	0.054	[0.004, 0.104]	0.0362
	Before Refuel TAT Max	0.059	[0.009, 0.109]	0.0240
	After Refuel Time Min	-0.022	[-0.072, 0.028]	0.3970
	After Refuel Time Max	0.021	[-0.029, 0.071]	0.4281
	Refuel Time Jet-A1 Min	0.008	[-0.042, 0.058]	0.7630
	Refuel Time Jet-A1 Max	-0.006	[-0.061, 0.049]	0.8313
	Refuel Time LH2 Min	0.067	[0.017, 0.117]	0.0093
	Refuel Time LH2 Max	0.152	[0.102, 0.202]	0.0000
Resources	**Number of Jet-A1 Trucks**	**-0.301**	**[-0.351, -0.251]**	**0.0000**
	Number of LH2 Trucks	**-0.750**	**[-0.770, -0.730]**	**0.0000**
Operational Parameters	Refuelings per Trailer Jet-A1	0.081	[0.031, 0.131]	0.0019
	Refuelings per Trailer LH2	0.173	[0.123, 0.223]	0.0000
	Truck Speed	-0.032	[-0.082, 0.018]	0.2133
	Trailer Replacement Time	-0.016	[-0.071, 0.039]	0.5479
Fleet Mix	**Penetration Rate**	**0.861**	**[0.851, 0.871]**	**0.0000**