Preliminary Safety Analysis of Liquid Hydrogen Aircraft Refuelling and Its Operational Consequences for Airports

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Preliminary Safety Analysis of Liquid Hydrogen Aircraft Refuelling and Its Operational Consequences for Airports

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With this thesis, I can put a full stop behind my time as a student at Delft University of Technology. Finishing it brings mixed feelings. I am happy to complete my degree, but I also feel a sense of resignation and the realisation that my student years are now truly over. At the same time, it marks the start of a new phase, which I genuinely look forward to. I look back on my student years with an enormous amount of joy, especially life in Delft, the people I met, and the experiences we shared. I am grateful to close this chapter and step into whatever comes next.

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Bendert de Roy van Zuidewijn
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Contents

List of Figures

List of Tables

List of Abbreviations

Abbreviation	Meaning
ACI	Airports Council International
ACI/ATI	Airports Council International / Aerospace Technology Institute
ALOHA	Areal Locations of Hazardous Atmospheres (hazard modelling tool)
ANOVA	Analysis of Variance
ARFF	Aircraft Rescue and Fire Fighting
ATC	Air Traffic Control
ATEX	ATmosphères EXplosibles (EU explosive-atmospheres equipment framework)
AIRAC	Aeronautical Information Regulation And Control (cycle for aeronautical information updates)
ATI	Aerospace Technology Institute (UK)
BLEVE	Boiling Liquid Expanding Vapour Explosion
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamics
CI	Confidence Interval
CO2	Carbon dioxide
DES	Discrete-Event Simulation
DOE	U.S. Department of Energy
DOE/EERE	U.S. DOE Office of Energy Efficiency and Renewable Energy
DOT/FAA	U.S. Department of Transportation / Federal Aviation Administration (as cited)
EASA	European Union Aviation Safety Agency
EERE	Office of Energy Efficiency and Renewable Energy (U.S. DOE)
EHRD	ICAO airport code for Rotterdam The Hague Airport
EKCC	Emergency Keep Clear Corridor
EIS	Entry Into Service
ER-034	EUROCAE Report 034 (hydrogen fuelling / airport-related guidance in your references)
ESD	Emergency Shut-Down
ETA	Event Tree Analysis
EU	European Union
EUROCAE	European Organisation for Civil Aviation Equipment
FlyZero	FlyZero programme (ATI)
FOD	Foreign Object Debris
FTA	Fault Tree Analysis
FWER	Family-Wise Error Rate
GH2	Gaseous Hydrogen
GOLIAT	Ground Operations of LIquid hydrogen AircrafT (Airbus project name as cited)
GPU	Ground Power Unit
GSE	Ground Support Equipment
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
H2	Hydrogen
HSD	Honestly Significant Difference (Tukey HSD)
HSE	Health and Safety Executive (UK)
HyFlyer	HyFlyer programme/project (as cited)

Abbreviation	Meaning
HyRAM	Hydrogen Risk Assessment Models (tool suite)
HyResponder	HyResponder project (hydrogen emergency response guidance)
HySafe	HySafe network/consortium for hydrogen safety
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICAS	International Council of the Aeronautical Sciences
ICCT	International Council on Clean Transportation
IR	Infrared
ISO	International Organization for Standardization
ISO19880	ISO 19880 series (hydrogen fuelling stations; as cited)
KPI	Key Performance Indicator
LH2	Liquid Hydrogen
LIN	Linde (appears in trailer comparison table)
LVNL	Luchtverkeersleiding Nederland (Air Traffic Control The Netherlands)
NASA	National Aeronautics and Space Administration
NFPA	National Fire Protection Association
NFPA2	NFPA 2: Hydrogen Technologies Code
NLR	Royal Netherlands Aerospace Centre
NM	Nautical Mile(s)
NOx	Nitrogen oxides
OR	Operations Research
OTP15	On-Time Performance within 15 minutes
PGS	Publikatiereeks Gevaarlijke Stoffen (Dutch safety guideline series)
PGS35	PGS 35 (Dutch guideline on hydrogen systems, as cited)
PHAST	Process Hazard Analysis Software Tool (consequence modelling software)
PP	Platform Parking
PPE	Personal Protective Equipment
PR	Penetration Rate
PRESLHY	PRESLHY project (pre-normative research for safe use of liquid hydrogen)
PRV	Pressure Relief Valve
QRA	Quantitative Risk Assessment
ReFuelEU	ReFuelEU Aviation (EU regulation on aviation fuels)
RTHA	Rotterdam The Hague Airport
SAE	SAE International (formerly Society of Automotive Engineers)
SAF	Sustainable Aviation Fuel
SimPy	SimPy (Python discrete-event simulation framework)
ST-18600H	Chart Industries ST-18600H LH2 trailer model
TP	Trailer Parking
TU Delft	Delft University of Technology
UK	United Kingdom
UPS	Uninterruptible Power Supply
USA	United States of America
UV	Ultraviolet
UV/IR	Ultraviolet/Infrared (flame detection)
VCE	Vapour Cloud Explosion
WP	Work Package

I

Scientific Paper

Abstract

Liquid hydrogen (LH_2) is a promising option for deep aviation decarbonisation and could be deployed at airports within the next decade. Compared with Jet-A1, LH_2 refuelling may require larger safety and exclusion zones that reduce stand availability and constrain apron access. Operational studies often assume these zones, while safety studies rarely turn consequence-driven distances into enforceable apron constraints and quantify delay impacts.

This work provides an integrated safety-to-operations assessment for LH_2 refuelling at compact airports. The objective is to identify the main safety distance drivers for open-apron LH_2 releases during refuelling through a qualitative safety assessment and quantify how zone size and enforcement, refuelling logistics, and resource capacity affect departure delays as LH_2 penetration increases.

A qualitative hazard and accident-pathway assessment (HAZID/HAZOP supported by bow-tie logic) was conducted to identify the main LH_2 refuelling hazards and accident pathways, and to determine how these hazards drive conservative safety-distance requirements. The outcomes were then used to select representative scenarios and define zoning modes for the operational analysis. These modes are translated into operational rules (e.g., stand closures and route restrictions) and implemented in a stochastic discrete-event simulation of a regional airport apron with LH_2-specific turnaround processes. Experiments vary penetration rate, stand layouts, refuelling logistics and transfer duration (S1–S5), and LH_2/Jet-A1 truck-fleet sizing. Performance is assessed via statistical comparison of departure-delay metrics.

The safety assessment identifies dispersion-and-ignition outcomes (flash fire and jet fire) as the dominant safety distance drivers for open-apron LH_2 releases and motivates practical distance scales that define the zoning modes. In the operational simulation, zoning has little effect at low LH_2 adoption, but delays increase sharply once conservative zones remove neighbouring stand capacity and push the apron into a capacity-limited regime. For smaller zones, performance is driven mainly by refuelling logistics and refueller availability rather than by routing restrictions. Undersized service fleets primarily worsen the tail of very late departures, with the binding constraint shifting between the LH_2 and Jet-A1 fleets depending on demand. Overall, safe scale-up requires joint design of zoning rules and refuelling resources to prevent structural apron bottlenecks.

1 Introduction

Aviation must reduce its climate impact, which requires scalable low-carbon energy carriers for flight operations. Hydrogen is a leading candidate, and liquid hydrogen (LH_2) is attractive because it can support longer-range missions than gaseous storage. However, LH_2 also introduces new safety-critical ground operations, because refuelling involves cryogenic fluids, potential releases, and ignition hazards on a live apron.

Early LH_2 deployment is expected to start with limited fleets, routes, and airports, with initial use cases at smaller and mid-sized airports and point-to-point networks [31]. Many such airports have compact aprons and limited routing redundancy. In these settings, safety measures that are acceptable in principle can still be difficult to execute in practice because they interact with stand capacity, taxi-lane usage, and service-vehicle access during peak periods.

Compared with Jet-A1, LH_2 refuelling has a different hazard profile. Hydrogen has a wide flammability range and low ignition energy, and cryogenic releases can form cold vapour clouds with dispersion behaviour that differs from ambient-temperature gaseous releases [29]. For open-apron refuelling, separation distances are typically driven by thermal outcomes, notably (i) flash fire after delayed ignition of a dispersed cloud and (ii) jet fire after immediate ignition of a high-momentum release [29, 19, 23]. These outcomes motivate safety zones and operating restrictions around the aircraft and refuelling interface. In the near term, road-delivery concepts (e.g., tanker trucks and mobile refuelling systems) are widely discussed for airport supply and distribution [6, 31], which makes vehicle movements and access rules part of the safety problem.

Existing work addresses key elements, but two gaps remain for airports. First, standards such as NFPA 2 and ISO/TR 15916 provide general separation-distance principles [23, 19], but they are not tailored to airport aprons where refuelling occurs in a dense, time-critical environment with multiple interacting actors (aircraft, refuellers, GSE) and tight spatial coupling between stands and taxi-lanes. Second, airport operations models (including discrete-event simulation) can quantify stand conflicts and delay propagation, but safety zones are often introduced as external geometric assumptions rather than as traceable outputs of a refuelling safety assessment. As a result, different plausible safety assumptions can lead to different zoning rules and different operational conclusions, while the underlying safety rationale and enforceability are not always explicit.

This paper therefore combines a qualitative LH_2 refuelling safety assessment with an apron operations model for a compact airport consistent with early deployment pathways [31]. The primary objective is to establish an airport-relevant and traceable safety basis for practicable zoning and operating restrictions during open-apron LH_2 refuelling. The secondary objective is to quantify the operational consequences of complying with these safety-driven constraints under increasing LH_2 uptake. This objective is captured in the following research question:

> **Which LH_2 refuelling hazards influence safety-zone distances, and what operational impacts result from implementing these zones in airport ground operations?**

The approach has two stages. First, a structured safety assessment identifies refuelling hazards, constructs accident pathways, and selects representative open-apron scenarios using HAZID/HAZOP supported by bow-tie logic and consequence-based reasoning. This yields safety-informed distance scales and associated operating restrictions, which are grouped into a small set of zoning modes with implementable rules using practical thresholds (20 m and 40 m). Second, these zoning modes are implemented as time-varying spatial constraints in a discrete-event simulation of apron operations. The model builds on an existing apron DES (Discrete Event Simulation) framework [20] and extends it with LH_2 refuelling phases, GSE movements, zoning logic, and designed scenario experiments across penetration rates and LH_2 stand layouts, evaluated via replicated stochastic simulation and statistical comparisons.

The main contributions are:

- an airport-relevant qualitative safety assessment for open-apron LH_2 aircraft refuelling that identifies dominant hazard scenarios and consequence drivers for practicable zoning;
- a traceable translation of safety outcomes into enforceable, actor-specific apron constraints suitable for operations modelling;
- an extended apron DES that integrates LH_2 refuelling phases, truck–trailer supply limits, and time-varying blockage-aware routing; and
- a quantitative assessment of operational impacts under safety-driven constraints using replicated experiments and statistical effect measures.

The case study represents a medium-size European airport with an apron layout similar to Rotterdam The Hague Airport, characterised by closely spaced Code C stands and limited routing redundancy. This configuration is sensitive to zone overlap and access restrictions, which makes it suitable for evaluating early LH_2 deployment at compact airports.

The remainder of this paper is organised as follows. Section 2 reviews literature on hydrogen safety, refuelling technologies, hydrogen airport studies, and airport operations modelling. Section 3 introduces the case study, including apron layout and turnaround processes. Section 4 provides an overview of the methodology. Section 5 details the safety assessment workflow and the selection of representative open-apron scenarios and zone definitions. Section 6 describes the model setup, assumptions, and scenario design. Section 7 specifies the discrete-event simulation model, including the event logic, KPI definitions, and verification and validation. Results are presented in Section 8 (safety assessment) and Section 9 (operational modelling), followed by discussion, recommendations, and conclusions in Sections 10, 11, and 12.

2 Related Work

This section reviews the state of the art relevant to the safety and operational integration of liquid hydrogen (LH_2) refuelling at airports. The literature can be grouped into four themes: (i) safety assessment of hydrogen refuelling, (ii) safety zones for hydrogen systems, (iii) hydrogen airport risk studies, and (iv) airport operations modelling.

2.1 Safety Assessment of Hydrogen Refuelling for Aircraft

Although knowledge gaps remain, existing hydrogen safety research provides validated models and experimental evidence for key phenomena (release, dispersion, ignition, and thermal radiation) required to assess LH_2 refuelling hazards. Hydrogen exhibits a wide flammability range (4–75% vol.) and an extremely low minimum ignition energy of approximately 0.02 mJ [8]. LH_2 releases may generate cold buoyant vapour clouds, invisible flames, and rapid dispersion patterns under open-air conditions [10, 28]. Experimental work from the PRESLHY project provides critical evidence on LH_2 release behavior, dispersion, ignition behavior, and jet-fire radiation [30]. Together, these sources enable identification of key hazards which form the main factors that influence the safety distance (safety distance drivers) for hydrogen refuelling and support selection of conservative, representative release scenarios and ignition assumptions.

However, much of the available safety evidence is derived from stationary industrial systems, fueling stations, or controlled experiments rather than airport environments. Aircraft refuelling occurs in a dense and time-critical setting: stand geometry constrains dispersion pathways, mobile equipment moves continuously, and multiple turnaround tasks occur in parallel within limited space. These features influence both the likelihood of ignition and the practical enforceability of restrictions. We therefore use the existing hydrogen safety science primarily to motivate hazard types and conservative distance ranges, while recognizing that airport specific validation of those distances remains limited. In this sense, the safety assessment for apron refuelling is not a direct extraction from the literature, but an informed translation from established physics to an operational context.

2.2 Safety Zones for Hydrogen Systems

International standards provide a necessary baseline for zoning concepts and acceptance criteria, but they do not yet resolve the operational question for aircraft refuelling. NFPA 2 specifies separation distances for gaseous and liquid hydrogen installations based on equipment volume, leak scenarios, and thermal radiation limits [23]. ISO/TR 15916 provides complementary guidance for safe spacing, including ignition prevention measures and dispersion-based hazard distances [19]. We use these documents to frame what constitutes "compliance" and to justify the use of conservative criteria when selecting safety-zone distances for LH_2 systems.

Nevertheless, these standards focus on largely static installations such as storage tanks, pipelines, and fuelling stations, and they do not capture the dense geometries, high traffic densities, and strict temporal coupling that define commercial airport aprons. They also provide limited guidance on how separation distances should be implemented as time-varying operational rules during aircraft turnaround, where some activities may be compatible with refuelling while others are not. Early industry assessments suggest LH_2 refuelling may require safety zones of 20–60 m to mitigate flash-fire and thermal radiation hazards [16], but these values remain preliminary and are not validated through airport-specific modelling or experimental measurements. As a result, standards and early assessments provide a credible starting point, but they leave a practical gap between "distance guidance" and "operationally enforceable zoning" for aircraft refuelling.

2.3 Hydrogen Airport Risk Studies

Airport-focused hydrogen studies help scope the problem, identify implementation barriers, and clarify why airports require actionable guidance. Braun and Classen present a qualitative analysis of LH_2 refuelling risks, emphasising the likelihood of larger safety distances and highlighting operational challenges such as personnel training, procedures, and equipment certification [5]. Gu et al. investigate hydrogen aviation infrastructure requirements and stress the lack of clear guidelines for airport safety zones, refuelling procedures, and ground-operation constraints [14]. Reports from the Aerospace Technology Institute similarly identify the need for updated airport layouts and refuelling processes to accommodate LH_2 aircraft [1]. We draw on these works to motivate the need for a structured airport perspective and to define realistic constraints for early deployment.

However, the outputs of these studies are typically conceptual. Safety distances are often discussed as likely to increase, but they are not consistently derived from a structured scenario set or translated into a small set of enforceable zoning rules. More importantly for airport decision-making, the downstream effects on apron performance, stand utilisation, taxiway accessibility, turnaround coupling, and delay propagation, are usually not quantified. In other words, this literature identifies the key concerns, but it does not provide a method to test whether a proposed zoning concept is operationally feasible for a given layout and demand pattern.

2.4 Airport Operations Modelling

Discrete-event simulation (DES) is widely used to analyse apron operations because it captures how local constraints can create non-linear delay propagation through coupled turnaround processes. Related approaches include agent-based modelling and operations research (OR) methods, which represent heterogeneous actors with individual decision logic and quantify the effects of routing, resource assignment, and capacity constraints.

Janssen [20] developed a DES framework for truck-based LH_2 refuelling on a compact apron and showed that refuelling-related spatial restrictions can affect stand availability and delays. However, the zoning in that model is mainly represented as distance-based stand blocking, which limits its ability to evaluate how zones are implemented in practice and how restrictions interact with detailed ground processes. This study extends the state of the art by modelling safety zones as time-varying, enforceable operational rules and by adding missing operational mechanisms: refuelling scenarios with phase-dependent restrictions, detours and blockage-aware routing, explicit GSE movements, LH_2 trailer exit behaviour, and an Emergency Keep-Clear Corridor. The model combines DES event logic with an agent-based representation of aircraft and service vehicles and OR-style routing and assignment heuristics (graph-based shortest paths and rule-based dispatch). These extensions make it possible to quantify how operational implementation choices, not only zone size, drive apron capacity and delay impacts under increasing LH_2 penetration.

2.5 Research Gap

Hydrogen safety research provides validated knowledge on LH_2 release, dispersion, ignition, and thermal-radiation consequences, which can indicate which refuelling scenarios set separation-distance requirements. Standards such as NFPA 2 and ISO/TR 15916 provide generic principles and baseline criteria for separation distances, but they are not tailored to dense, time-critical apron operations with multiple interacting actors. Airport hydrogen studies discuss implementation and infrastructure implications, while DES-based airport operations models can quantify delay and capacity effects.

The gap is that these strands are rarely connected in a traceable, end-to-end manner for aircraft refuelling on an open apron. Prior work does not combine (i) a structured LH_2 aircraft-refuelling safety assessment that identifies the dominant hazard scenarios and distance thresholds with (ii) an operational apron model that implements the resulting zones as explicit, time-varying rules (e.g., stand closures and access restrictions) and quantifies their effects on apron performance under increasing LH_2 adoption. This thesis addresses that gap by developing a combined safety operations framework that maps safety assessment outputs to a small set of implementable zoning modes and evaluates their operational impacts across adoption and infrastructure scenarios.

3 Case Study: A Representative Medium-Size European Airport

This study applies the combined safety–operations framework to a representative medium-size European regional airport. The case is inspired by Rotterdam The Hague Airport (RTHA) in apron scale and operating context, but it is not a geometric replica. A compact regional-apron setting was selected because such airports are plausible early adopters of hydrogen aircraft and because closely spaced stands and limited routing redundancy make them sensitive to refuelling safety zones.

The system under investigation is the apron and stand environment up to off-block departure: stand allocation, vehicle access to stands, refuelling logistics, and turnaround servicing. Landside passenger flows, pushback, engine start, taxi-out, towing, and de-icing are outside the scope. Operational impacts are evaluated under scenarios that vary LH_2 adoption (penetration rate) and safety-zone implementation modes (Section 6).

3.1 Airport Layout and Operational Environment

The modelled apron consists of twelve Code C stands arranged in four rows of three (A1–A3, B1–B3, C1–C3, D1–D3) directly in front of a terminal-facing taxiway. A simplified taxiway network connects the stands to the main apron flow and includes connectors to a hydrogen trailer parking (TP) and a platform parking (PP). The layout is based on the stand layout of RTHA but is schematic rather than geographically exact: spacing and node locations are idealised for simulation, while the network structure reflects typical routing constraints of compact regional aprons. For movement modelling, the apron is represented as a graph of nodes and edges, where nodes denote stands and key waypoints and edges denote traversable route segments that can be temporarily blocked by safety-zone rules. Figure 1 shows the configuration used in this study.

Due to the compact stand layout, LH_2 refuelling safety zones can overlap with nearby stands and access routes and thereby make them temporarily unavailable. Based on the stand-adjacency logic reported by Janssen [20], an LH_2 aircraft on the leftmost stand can restrict all three opposing stands, the centre stand can restrict two, and the rightmost can restrict one. This restriction arises from a taxi-out lock-in mechanism: when an LH_2 aircraft refuels on an A-stand, the enforced safety zone can overlap with the outbound taxiway behind the A-row, preventing aircraft on the opposing B-stands from taxiing out until refuelling is completed. For the most conservative safety-zone configuration (radius $> 40\,\text{m}$), stands C1 and D1 are additionally restricted due to their proximity to terminal-facing areas and associated access routes; these stands are highlighted in orange in Figure 1 [20]. These assumptions represent a conservative compact-apron case with limited buffer space.

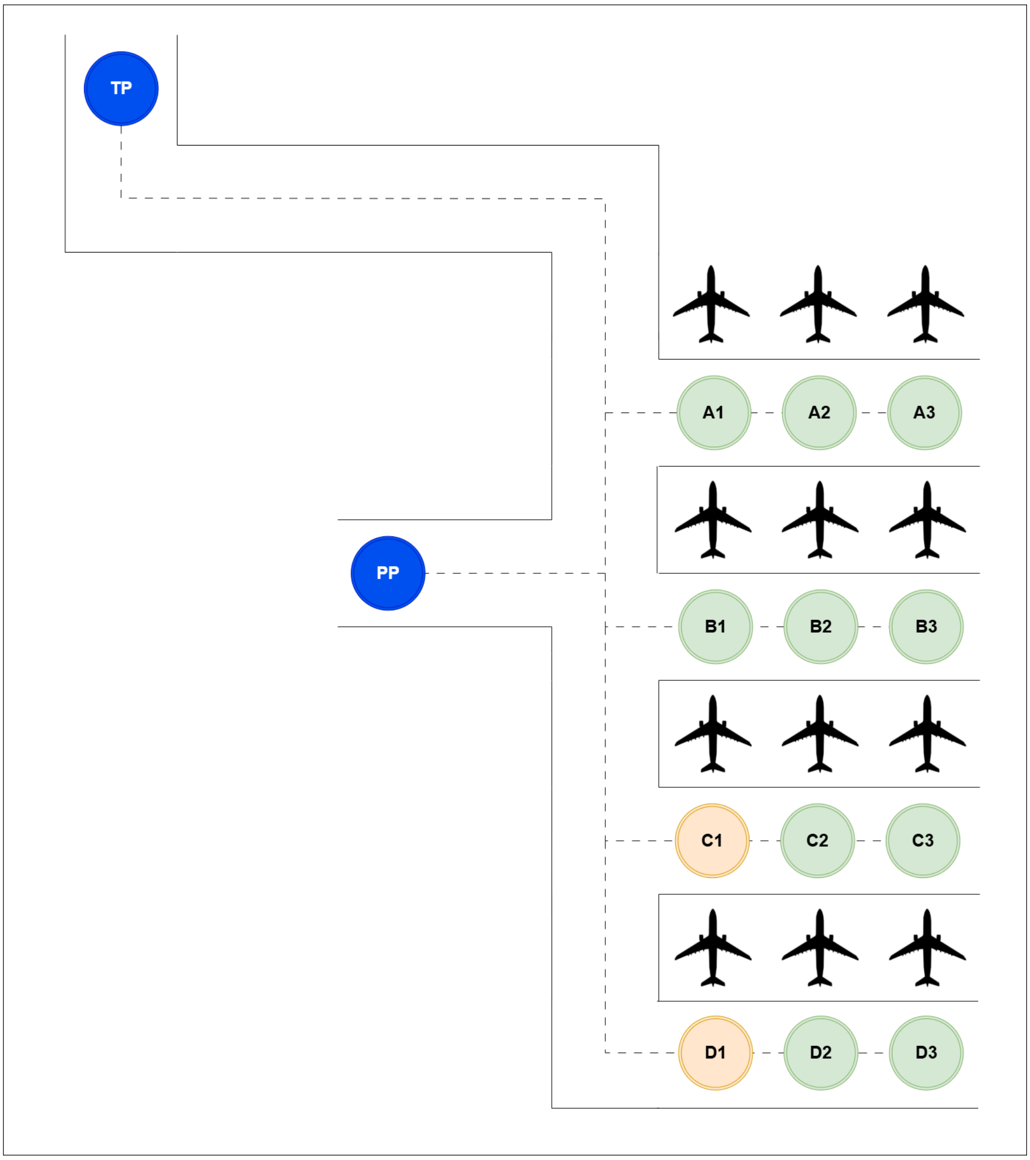


Figure 1: Schematic apron layout used in the case study, including trailer parking (TP) and platform parking (PP)

3.2 Aircraft, Demand, and Baseline Resources

The model represents a single aircraft category: a generic LH_2-compatible regional turboprop. A single aircraft type is used to keep the operational mechanisms identifiable and to avoid introducing a fleet mix that is not supported by detailed input data. Results therefore isolate the effect of refuelling constraints and resource competition and should not be interpreted as predictions for a mixed fleet with different turnaround requirements. For LH_2 flights, a fixed uplift of 900 kg per turnaround is assumed, computed from a 1200 kg onboard tank with a 15% landing reserve and an average refuel-to level of 90%: $(0.90 - 0.15) \times 1200 = 900$ kg (Supporting Work, Section 3.4). LH_2 refuelling performance is varied using five scenarios (S1–S5) that combine trailer capacity and mass-flow rate; scenario definitions and the phased refuelling process model are given in Section 6.3.

Traffic demand is based on a fixed 24-hour day schedule imported from Excel (24 flights with planned arrivals and departures), simulated over a 24-hour horizon starting at 06:00. The schedule is derived from actual RTHA flight data. Using one fixed schedule keeps demand constant across experiments, so performance differences can be attributed to zoning mode, penetration rate, and refuelling logistics. To represent realistic stand occupancy, the schedule is augmented by aircraft already on-stand at the simulation start (morning backlog) and by late-day arrivals that remain parked beyond the simulation horizon (overnighters). Backlog and overnighter aircraft are placed using the same stand-assignment rule as regular arrivals. Fuel type (LH_2 versus Jet-A1) is assigned per flight using a Bernoulli draw based on the scenario penetration rate (PR), which preserves the expected LH_2 share while representing day-to-day variation in which specific flights require LH_2.

Table 2 summarises the baseline case-study inputs used unless varied in experiments. Detailed process logic (turnaround task structure, service-time sampling, queueing rules, stand-assignment logic, and routing under blockages) is described in Section 6.

Table 2: Baseline case-study inputs (unless varied in experiments).

Category	Parameter	Value	Notes
Layout	Code C stands	12	4×3 (A1–D3), Figure 1
Demand	Flights per day	24	24-hour schedule, start 06:00; derived from RTHA flight data
Demand	Morning backlog	3 aircraft	Present on-stand at 06:00; depart between 06:00 and 08:00
Demand	Overnighters	3 arrivals	Arrive between 21:00 and 23:00; remain on-stand beyond horizon
Demand	Fuel-type assignment	Bernoulli(PR)	LH_2 vs Jet-A1 per flight; PR varied in experiments
Aircraft	LH_2 uplift per turnaround	900 kg	Supporting Work (Section 3.4)
Resources	GSE units	12	Single pooled GSE resource
Resources	Jet-A1 trucks / LH_2 trucks	2 / 2	Varied in fleet-sizing experiments
Resources	Jet-A1 trailers / LH_2 trailers	20 / 20	Baseline trailer inventories

3.2.1 Scenario set

To assess future uptake without changing the underlying airport setting, a subset of the results evaluates two planning horizons (2040 and 2050); these uptake results are reported in Section 9.4. The 2040 scenarios represent earlier deployment, whereas the 2050 scenarios represent more mature deployment. Within each horizon, LH_2 adoption is varied using low-, medium-, and high-uptake penetration rates taken from earlier scenario research [17, 9]. To capture both seasonality and peak stress, each penetration setting is simulated on four representative RTHA traffic days (summer/winter; average/peak demand). Outside Section 9.4, the remaining results use the baseline case-study setting and vary penetration rate and zoning mode directly.

3.3 Operational Constraint Elements

LH_2 safety-zone restrictions are activated during the refuelling period and released upon completion of all refuelling phases. The model supports detours via blockage-aware routing: when nodes or edges are blocked, operational vehicles recompute shortest paths around restrictions or queue if no feasible route exists. The model also includes an Emergency Keep-Clear Corridor, implemented as a set of edges that can be blocked for normal operational vehicles during LH_2 refuelling. In the default configuration, the corridor edge list is empty (i.e., inactive) unless explicitly specified in the scenario configuration.

3.4 Performance Measure

Operational impact is quantified in terms of departure delay from a gate perspective. For each flight, departure delay is computed as the positive difference between the actual departure time from the stand (off-block, gate perspective) and the scheduled departure time; early departures are not credited. Total departure delay is the sum of all positive delays, and average delay metrics are computed over all departures and over delayed departures only.

4 Methodological Overview

This study uses a two-stage method to assess liquid hydrogen (LH_2) aircraft refuelling at a representative regional airport. First, a qualitative safety assessment identifies the key refuelling hazards and derives conservative safety-zone distances (Section 5). Second, these zones are implemented as operational constraints in a discrete-event simulation (DES) of apron operations to quantify delay impacts (Figure 2). The scenario design and input assumptions are defined in Section 6, and the DES event logic and KPI computation are specified in Section 7.1.

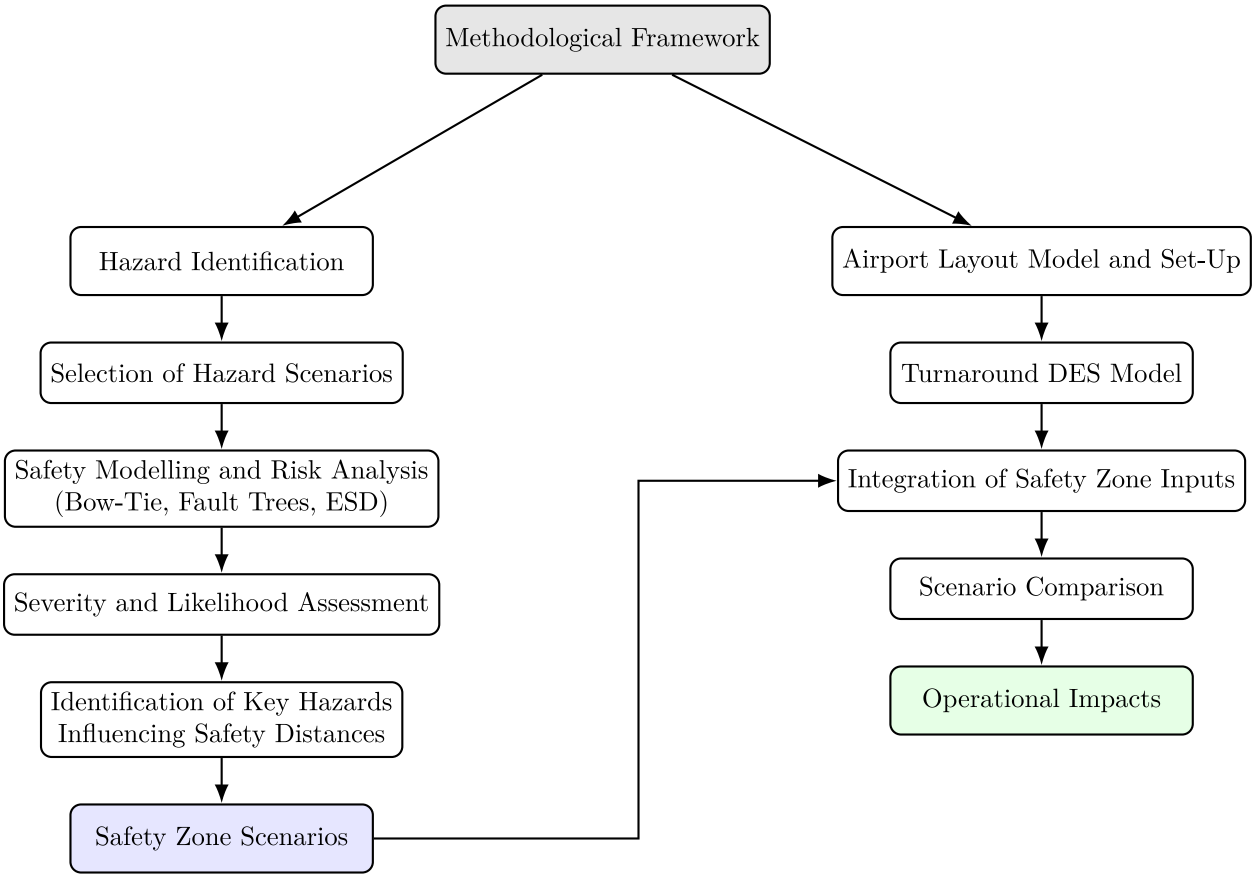


Figure 2: Integrated workflow: safety assessment to airport operations simulation

5 Safety Assessment Methodology

This study applies a layered safety-assessment workflow in which each step refines and structures the outputs of the previous one. The aim is to move from broad hazard discovery to a focused set of critical safety bottlenecks and controls, and finally to the key hazards that drive safety distances/zones that are later translated into operational safety-zone scenarios.

5.1 Overview of the Workflow

The safety assessment follows the sequence below:

1. **HAZID** to identify hazards across the full LH_2 refuelling process, including cause–consequence mapping and safeguards.
2. **Hazard grouping & filtering** to retain only hazards with a direct and credible link to hydrogen release.
3. **HAZOP** to systematically identify deviations from intended operation, using a consistent table structure and numbering logic.
4. **Bow-Tie modelling** to integrate threats, the top event (hydrogen release), consequences, and preventive/mitigative barriers.
5. **ETA/FTA** to structure escalation logic (event sequences) and causal combinations (fault logic) for selected scenarios.
6. **Severity & likelihood assessment** to rank the most relevant scenarios under existing/assumed controls.
7. **Shortlisting** to identify the dominant safety bottlenecks/controls and the hazards that most influence safety distances.

The outcome of this chain is used to define a small set of safety-zone scenarios that can be implemented as spatial constraints in the operational simulation model.

5.2 HAZID: Hazard Discovery, Mapping, and Filtering

A HAZID study was used to compile a comprehensive hazard inventory for LH_2 aircraft refuelling. Hazards were identified across technical, operational, environmental, interface, monitoring/control, and external domains. For each hazard, we recorded (i) initiating causes (e.g., hardware failure, procedural deviation, external trigger), (ii) consequences (from operational disruption to fire, explosion, or personnel harm), and (iii) preventive and mitigative safeguards (technical, procedural, and passive measures). The results were consolidated in a structured hazard register to support traceability and review.

To keep the assessment operationally grounded, hazards were also mapped to refuelling process steps (e.g., arrival, connection, pre-cooling, transfer, venting/purging, disconnection). This mapping clarifies when hazards arise and which actors or systems are involved.

For subsequent scenario modelling, the inventory was filtered and grouped to retain only hazards with a direct, credible link to the top event: hydrogen release during LH_2 refuelling at a parked aircraft. Hazards outside the defined scope (e.g., onboard degradation in non-refuelling states), too indirect to the top event, or not credible for the operational context were excluded. The output of this step is a traceable hazard register and a reduced set of release-relevant hazards that form the input to the HAZOP and Bow-Tie modelling.

5.3 HAZOP: Deviation Analysis and Structured Traceability

After defining the refuelling process and compiling the hazard inventory, a HAZOP study was used to systematically identify deviations from intended operation for each process node. Standard guide words (e.g., No, More, Less, Reverse, As well as, Early, Late) were combined with key parameters (e.g., Flow, Pressure, Temperature, Time, Energy, Direction) to generate deviations and to record their causes, consequences, and safeguards in a consistent table format.

To maintain traceability across methods, each HAZOP entry was assigned a unique identifier of the form `X.YZ`, where `X` denotes the hazard category, `Y` the process step, and `Z` the deviation index within that step/category. This numbering supports cross-referencing and preserves links into later Bow-Tie and tree-based models.

For subsequent modelling and prioritisation, deviations were grouped into hydrogen-refuelling hazard categories (e.g., transfer/connection failures; preparation errors such as purging, cooling, or venting; mechanical impact; ESD failure; external ignition sources). In parallel, hydrogen-release consequences were grouped into consequence classes (e.g., immediate fire outcomes such as flash fire/jet fire; dispersion or accumulation hazards; cryogenic exposure; operational and infrastructure impacts). The output of this step is a structured deviation register with consistent identifiers and categorisations, which provides the direct input for the Bow-Tie and ETA/FTA modelling.

5.4 Bow-Tie Modelling: Threats, Barriers, and Outcomes

A Bow-Tie model was developed to link (left side) grouped threats leading to the top event, hydrogen release during LH_2 refuelling, and (right side) grouped consequences following the release. Preventive barriers were mapped to the threat groups and mitigative barriers to the consequence groups. All barriers and links were referenced to the originating HAZID/HAZOP identifiers to maintain traceability.

To keep the model usable, the Bow-Tie scope was limited to hazards with a direct and credible causal link to the top event in the defined apron context. This focuses the analysis on barriers that meaningfully affect the likelihood of a release or the severity of its outcomes. The output of this step is a consolidated barrier map that supports scenario selection for ETA/FTA and prioritisation of the hazards most relevant for defining safety distances.

5.5 ETA and FTA: Escalation Logic and Causal Combinations

For selected high-relevance scenarios from the Bow-Tie, Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) were used to represent escalation and causal logic. ETA describes post-release escalation paths by branching on barrier success or failure (e.g., detection and emergency shutdown, ventilation or purging effectiveness, and ignition outcomes), which shows which sequences lead to severe consequences. FTA complements this by decomposing selected outcomes into combinations of underlying contributors (procedural, hardware, and environmental) using AND/OR logic, highlighting critical combinations and potential common-cause issues. At this stage, ETA/FTA were applied qualitatively to identify the main likelihood drivers and barrier dependencies. The output is a structured set of escalation sequences and failure combinations that supports scenario ranking and the shortlisting of key hazards.

5.6 Severity and Likelihood Assessment

Selected consequence scenarios were ranked using a qualitative severity–likelihood scheme. Because quantitative frequency data for LH_2 apron refuelling is limited, the ratings are based on three inputs: (i) hydrogen safety literature and guidance (standards, roadmaps, best-practice documents), (ii) evidence from analogous hydrogen and cryogenic handling systems, and (iii) expert judgement from an airport-operations and safety perspective (e.g., NLR/RTHA). The detailed severity and likelihood definitions, including the underlying reasoning and examples used to support the class boundaries, are provided in the Supporting Work (Section 2.2.1 and Section 2.2.2).

Severity was assigned by matching each scenario outcome to the consequence categories (e.g., Catastrophic for outcomes that can plausibly cause multiple fatalities and major asset loss, Critical for severe injury or a single fatality with major equipment damage, and Moderate/Minor for local injuries). Likelihood was assigned as an expected relative frequency under baseline procedural and technical controls, using the defined likelihood classes. For each scenario, the rationale states which enabling conditions are required (e.g., a release plus ignition, or a release plus multiple barrier failures). Where evidence is uncertain, the more conservative class was selected.

This step converts the Bow–Tie and ETA/FTA logic into an explicit and traceable ranking, which is then used to set the scenarios for safety zoning.

5.7 Shortlisting and Outcome: Bottlenecks and Key Hazards

A shortlisting step was used to identify (i) critical safety bottlenecks and controls and (ii) hazards that drive safety distances. The shortlist retained scenarios that combine severe consequences with credibility for the apron context and assumed barriers, and that can be influenced by operational controls (procedures, zoning, detection/ESD performance). Extremely rare "worst imaginable" events were treated primarily through design and emergency planning rather than routine stand-off zoning.

The outcome is summarised in two outputs:

1. Critical safety bottlenecks and controls: integrity of transfer equipment and connections; effective venting/purging and pressure relief; reliable detection and alarming; rapid and redundant emergency shutdown; ignition-source control and zone management; and procedural compliance supported by training.

2. Key hazards influencing safety distances: fire-dominated scenarios that set stand-off requirements, in particular delayed ignition of a dispersed cloud (flash fire/vapour cloud ignition) and immediate ignition of a high-momentum release (jet fire). These hazards form the basis for defining exclusion-zone radii for refuelling operations.

These key hazards are translated into a small set of safety-zone scenarios implemented as spatial constraints in the operational model (introduced in the next chapter), linking safety reasoning to operational impact assessment.

6 Model Setup and Scenarios

This section defines the modelling assumptions and scenario design used in the operational impact assessment. The apron layout, traffic schedule, and baseline parameter values are defined in Section 3. This section specifies (i) baseline turnaround-time inputs and other stochastic input distributions, (ii) fixed modelling assumptions, (iii) the experimental control variables (LH_2 penetration rate, safety mode, and refuelling scenario), and (iv) the design of the safety modes, including the associated stand- and route-restriction sets implemented as operational constraints during LH_2 refuelling. The discrete-event logic that executes turnarounds, dispatch, routing, and time-varying restrictions is specified separately in Section 7.

6.1 Turnaround Time Representation

Turnaround time is modelled at task level, so total turnaround emerges from sampled task durations and waiting for shared resources (stands, trucks/trailers, GSE, and access routes). Key time components are sampled as discrete-uniform draws in whole minutes (deterministic when min=max), because detailed empirical task-time distributions are not available while the model still requires bounded variability at 1-minute resolution. In the baseline configuration, the pre-service buffer (`before_TAT`) is sampled from 5–12 min and the residual turnaround time from 15–20 min. Jet-A1 refuelling is sampled from 10–20 min. Truck travel speed is set to 15 km/h (10 units/h in the network), and trailer replacement/refill time to 5 min, following Table 8 in Section 4.2 of Janssen [20]. LH_2 refuelling is a phased service (Section 6.3).

Figure 3 summarises the per-flight logic for an LH_2 turnaround. After arrival, the aircraft is assigned a stand (otherwise it waits and retries), then a pre-service buffer `before_TAT` is sampled as 5–12 min. Refuelling starts when a compatible truck and trailer are available; dispatch uses shortest-path routing on the currently feasible network and can be delayed by truck/trailer unavailability, travel time, or active closures. The LH_2 on-stand service is modelled as phased refuelling: docking/connection (2.5 min), purge (3.0 min), chill-down (1.0 min), transfer (scenario-dependent; 5.0–10.7 min for a 900 kg uplift), and disconnect/removal (2.5 min), giving a total LH_2 service time of 14.0–19.7 min. Safety closures (B1) are active for this full on-stand period.

GSE servicing is modelled as explicit queueing and travel. Each aircraft generates three identical GSE tasks. Each task has a service time sampled as 8–15 min, and each task cycle also includes travel from a common base to the stand and back, computed via the routing module (B2). If no GSE unit is available in the pooled fleet, tasks wait in a shared FIFO queue; routing-induced detours or blockage waiting can further extend the task cycle time. In safety modes that prohibit concurrent servicing, GSE cannot overlap with LH_2 refuelling, so GSE is either completed before refuelling starts or postponed until after refuelling ends (Figure 3).

The residual turnaround time is sampled as 15–20 min and starts only after both refuelling and GSE are complete. Departure occurs at the later of turnaround completion and the scheduled departure time, and delay is recorded as realised minus scheduled departure time.

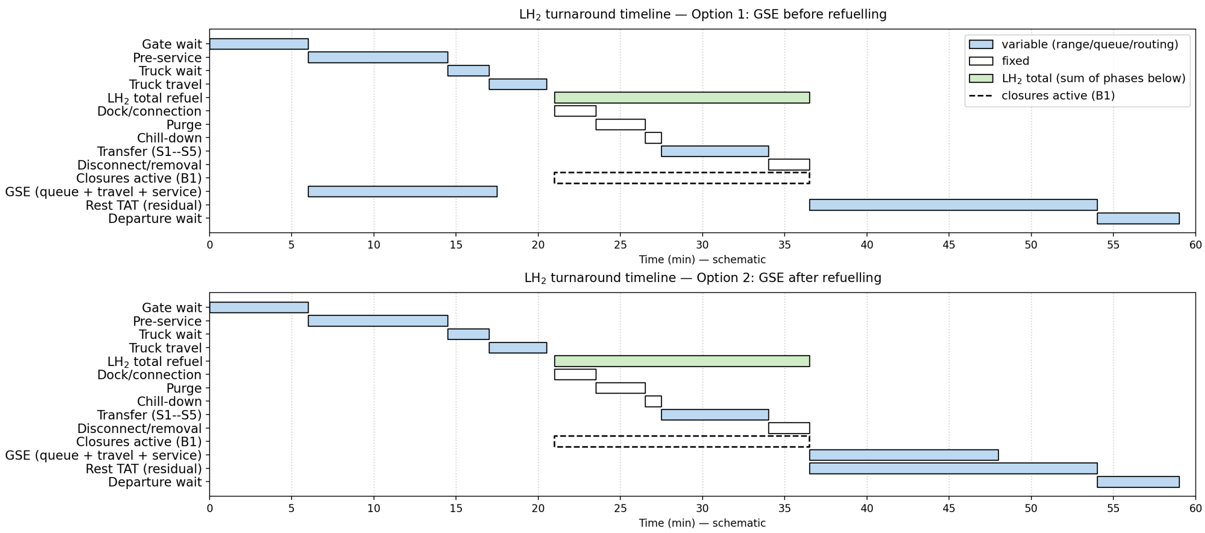


Figure 3: Gantt Diagram Turnaround

6.2 LH_2 Refuelling Safety Zones

The three implementation modes are defined as an operational grouping of the five safety-zone distance scenarios derived in the safety assessment (Table 6). The safety assessment provides five candidate exclusion distances, but several of these distances lead to the same effective constraint regime on the compact apron. To keep the operational experiments interpretable, the five distance cases are therefore aggregated into three modes that represent distinct levels of operational interference. The breakpoints are set at 20 m and 40 m because they match clear changes in how the apron is affected: below 20 m the restriction stays within the refuelling stand, between 20–40 m it mainly blocks access or taxiway segments, and beyond 40 m it starts to block adjacent stands. We did not consider larger radii, because the next clear change would only appear around 60–70 m and such zones would be unrealistic in practice, making normal stand and taxiway use largely impossible.

The detailed stand- and route-level restrictions associated with each mode are specified below.

- Mode 0 (< 20 m): the restricted area remains within the refuelling stand. Adjacent stands remain available and no extra restrictions are imposed on aircraft movements along the taxiway. GSE may service the refuelling stand, but it must approach from the terminal-side lane; access from the apron-side lane is not allowed during refuelling.
- Mode 1 (20–40 m): the restricted area interferes with access routes. The taxiway segment beneath the refuelling stand is blocked for aircraft during refuelling. For service vehicles (GSE and other refuelling trucks), movements from right to left along the same stand row are blocked (e.g., if refuelling takes place at B2, vehicles can move from B1 to B3, but not from B3 to B1), while adjacent stands remain available.
- Mode 2 (> 40 m): the restricted area extends beyond the stand footprint. Adjacent stands become temporarily unavailable for aircraft and servicing. The taxiway remains blocked for aircraft, and links to the left of the refuelling position are also blocked for GSE and refuelling vehicles, further limiting routing options.

Figures 4–6 illustrate the three configurations.

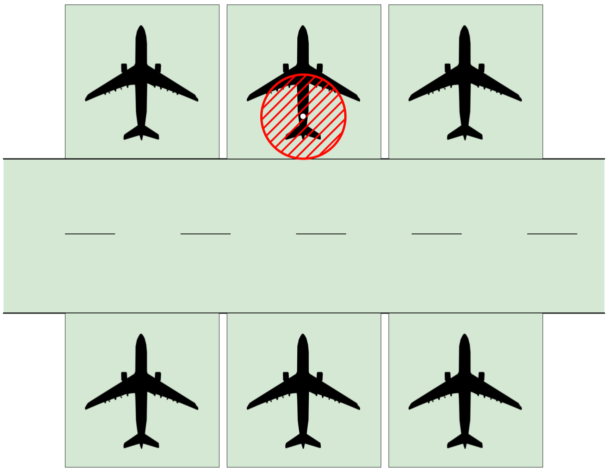


Figure 4: Mode 0 (< 20 m): restricted area contained within the refuelling stand.

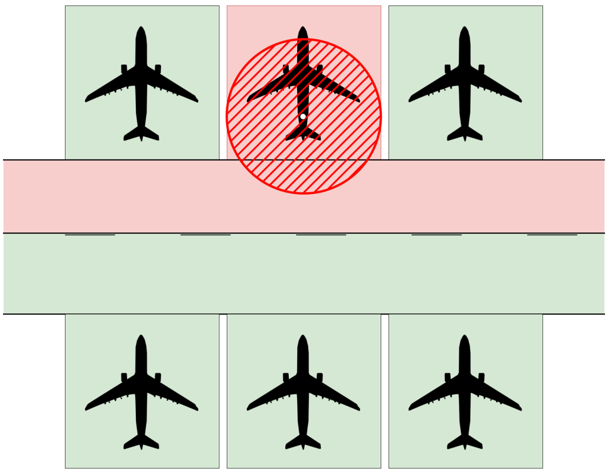


Figure 5: Mode 1 (20–40 m): restricted area covers taxiway but not adjacent stands.

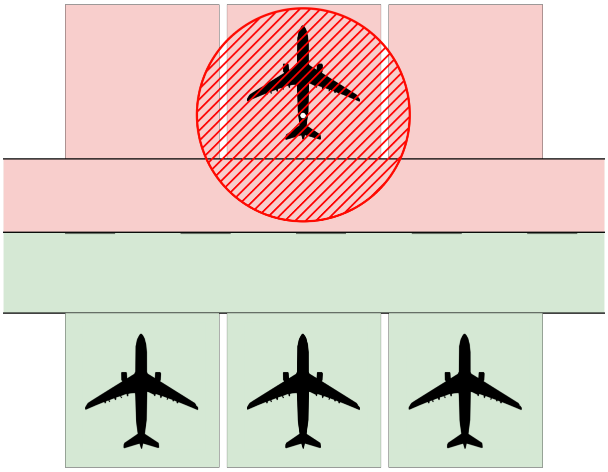


Figure 6: Mode 2 (> 40 m): restricted area covers taxiway and adjacent stands.

6.3 LH_2 Refuelling Scenarios and Process Phases

Five refuelling scenarios (S1–S5) are defined by varying trailer capacity (2 t or 4 t) and achievable mass flow rate (1.40–3.0 kg/s). Trailer capacities of 2 and 4 t are selected as operationally plausible for regional-airport deployment based on available infrastructure studies [9]. The scenario set S1–S5 is constructed as a small sensitivity set that varies only the parameters that directly change refuelling logistics and restriction duration (trailer capacity and transfer performance). This keeps the experiments interpretable and allows the operational impact of plausible early-to-advanced refuelling concepts to be compared under otherwise identical conditions. The scenarios are therefore not forecasts, but structured test cases for robustness of the operational conclusions. The lowest flow level (1.40 kg/s) is used as a credible minimum for early operations (EUROCAE Category C [11]), and is applied to both trailer sizes to isolate the effect of supply scaling at constant refuelling performance. Higher flow levels (1.9 and 3.0 kg/s) follow published industrial concepts and turnaround studies, including Airbus GOLA/GOLIAT-related work and ICCT analyses [2, 27]. Table 3 summarises the scenarios and the implied transfer-phase time for a 900 kg uplift; additional background is provided in the Supporting Work (Section 3.5).

Table 3: Proposed LH_2 refuelling scenarios combining mass flow rate and trailer capacity (900 kg per aircraft turnaround, 10% trailer reserve).

Scenario	**Trailer capacity [t]**	**Usable LH_2 [kg]**	**Aircraft / trailer fill [-]**	**Flow [kg/s]**	**Fill time for 900 kg [min]**
S1 – Standards-based minimum (4 t, low flow)	4	3600	4	1.40	≈10.7
S2 – Standards-based regional (2 t, low flow)	2	1800	2	1.40	≈10.7
S3 – Medium-flow	2	1800	2	1.9	∼7.9
S4 – High-flow regional	2	1800	2	3.0	∼5.0
S5 – High-capacity supply (4 t, high flow)	4	3600	4	3.0	∼5.0

LH_2 refuelling is represented as a sequence of phases: docking/connection, purge, chill-down, transfer, and disconnect/removal. Docking, purge, chill-down, and disconnect durations are taken from Mangold [22] and implemented as fixed times in the baseline (2.5/3.0/1.0/2.5 min). The transfer phase duration is scenario-dependent (Table 3). Table 4 lists the fixed auxiliary phase durations.

Table 4: Auxiliary process durations for LH_2 aircraft refuelling (baseline), based on Mangold [22]. The transfer phase duration is scenario-dependent (Table 3).

Step	Time (min)
Docking/connection	2.5
Purging (pre + post)	3.0
Chill-down	1.0
Disconnect/removal	2.5

6.4 Ground Support and Refuelling Resources

Ground support is modelled as a homogeneous pool of identical GSE vehicles shared across all flights (baseline: 12 units; Table 2). A single pooled GSE resource is used because detailed task-specific fleets (baggage, catering, cleaning, pushback) are not available and are not required to test the zoning and access mechanisms. This abstraction focuses the analysis on access restrictions and shared-capacity effects. The implication is that the model captures overall GSE capacity pressure, but not differences between specialised GSE types. Each aircraft requests three identical GSE tasks; if insufficient vehicles are available, tasks queue in a shared first-in-first-out (FIFO) queue. Assigned GSE vehicles travel from a common base location to the stand, perform the task for a sampled service duration (8–15 min), and return to base via shortest-path routing on a directed GSE network that accounts for temporary safety-related blockages.

Refuelling uses separate truck and trailer resources for Jet-A1 and LH_2. Trucks act as servers that collect an available trailer from the tanking point, drive to the stand, execute the refuelling service, and return the trailer. Trailers represent consumable supply: each trailer supports a limited number of aircraft refuellings before replacement or refill, with a fixed replacement/refill time (5 min). Baseline fleet inventories are 2 Jet-A1 trucks and 2 LH_2 trucks, and 20 Jet-A1 and 20 LH_2 trailers (Table 2).

7 Discrete-Event Simulation Model Specification

This section specifies the discrete-event simulation (DES) used to evaluate how LH_2 refuelling operations and safety-driven spatial restrictions affect apron performance. The baseline process blocks from Janssen [20] are summarised and the extensions introduced in this study (safety zoning, restriction-aware routing, LH_2 refuelling phases, and explicit GSE queuing with travel) are described, including their coupling to the baseline flow. The section concludes with the KPI definitions, replication and effect-size method, and verification and validation approach.

7.1 Simulation Model Overview

The model represents aircraft turnaround processes and the supporting logistics for refuelling and ground-support equipment (GSE). Delays emerge endogenously from queueing for shared resources (stands, vehicles, and access routes) and from temporary spatial restrictions induced by safety zoning. A compact DES specification is provided in table 5 below. The table lists the core model elements using standard DES terminology.

Table 5: DES model specification summary.

Item	**Specification**
Entities	Aircraft, refuelling trucks (Jet-A1 and LH_2), trailers (Jet-A1 and LH_2), GSE vehicles.
Resources	Stands (capacity 1 per stand), refuelling truck fleets, trailer inventories, pooled GSE fleet.
State variables	Stand occupancy; truck availability and position; trailer remaining refuellings; GSE queue length; per-aircraft refuelling status (including refuel ETA and refuelling active window); per-aircraft GSE task status (queued/in service/complete, pre- vs post-refuel); active closures (stands and edges), separated by actor type.
Events	Aircraft arrival; stand assignment; start/end of turnaround buffers; dispatch truck; truck travel; start/end refuelling; LH_2 phase progression; activate/release safety closures; request GSE task; evaluate pre-refuel feasibility (modes 1/2); start/complete GSE task; release deferred GSE after refuel end; truck return and replenish; aircraft departure.
Queues and service discipline	Stand waiting: aircraft retry stand assignment at fixed intervals. Refuelling: trucks act as servers; dispatch selects a truck based on shortest-path distance and availability. GSE: FIFO queue for identical tasks; in modes 1/2, GSE start is allowed pre-refuel only if `now + travel + service_max` ≤ `refuel_ETA`, otherwise the task is deferred until refuelling ends.
Routing representation	Two routing graphs: directed for GSE, undirected for refuelling trucks. Closures remove actor-specific edges and, where relevant, stands from the feasible set. Travel times are computed using shortest-path distance on the modified graph.
Outputs	Departure time and delay; stand-assignment waiting; stand occupancy and utilisation; truck utilisation and waiting; trailer state evolution; GSE waiting and utilisation (and pre- vs post-refuel execution share); closure activity measures (time under restriction).

The operational experiments vary three primary control dimensions. First, the LH_2 penetration rate (PR) sets the expected share of flights assigned to LH_2. Second, three safety modes implement different sets of stand and route restrictions during LH_2 refuelling. Third, five LH_2 refuelling scenarios (S1–S5) vary trailer capacity and transfer performance, which affects trailer logistics and the duration of refuelling-induced restrictions. Additional sensitivity experiments vary resource provisioning (refuelling truck and trailer fleet sizes and, where relevant, GSE fleet size) and test the effect of enabling the GSE routing logic. Unless a parameter is explicitly varied, all other case-study inputs are kept fixed.

Model performance is evaluated with departure-delay and resource-usage indicators. The simulation captures dependencies between shared resources and time-sensitive events, so delays in one process can affect others later in the day; failures, maintenance, and crew constraints are not considered. Key outputs are total and average departure delay, the share of delayed flights, stand-assignment waiting, and waiting times and utilisation for refuelling trucks and GSE. Statistical estimates are obtained from independent replications, as specified in Section 7.4.

7.2 Baseline DES Model

The DES builds on the apron turnaround and refuelling-logistics framework developed by Janssen [20] and is implemented in `salabim`, which provides a lightweight event-scheduling DES structure with explicit resources and queues. The baseline model represents aircraft arrivals, stand assignment, turnaround-task execution, and the dispatch and service of refuelling vehicles. Shared-capacity constraints govern interactions, so delays are not predefined; they occur when aircraft and vehicles have to wait for limited shared resources.

The baseline logic is organised in four main process blocks (A1–A4). In A1, an arriving aircraft is assigned to an available stand; if no stand is available, it waits until one becomes free. In A2, a refuelling request triggers dispatch of a suitable truck (Jet-A1 or LH_2) when one is available. In A3, the truck performs the on-stand refuelling service, occupying both the truck and the stand during service. In A4, the truck leaves the stand, returns, and becomes available for the next assignment, while the associated consumables (trailers) are updated. Baseline GSE servicing is modelled as a pooled capacity that supports turnaround tasks and can create additional waiting when capacity is tight.

A detailed description of blocks A1–A4, including baseline state updates and parameter settings, is provided in Janssen [20], Chapter 3.2. Figure 7 summarises the baseline turnaround and refuelling flow and indicates where the extensions introduced in this study interact with the baseline processes.

7.3 Model Extensions

Relative to the baseline model, this study adds four extensions that implement safety-driven spatial constraints and LH_2 refuelling characteristics as explicit DES components. These extensions are shown as blocks B1–B4 in Figure 7 and are described in detail in the following subsections. The paragraphs below explain how the extension blocks operate and how they couple to the baseline processes.

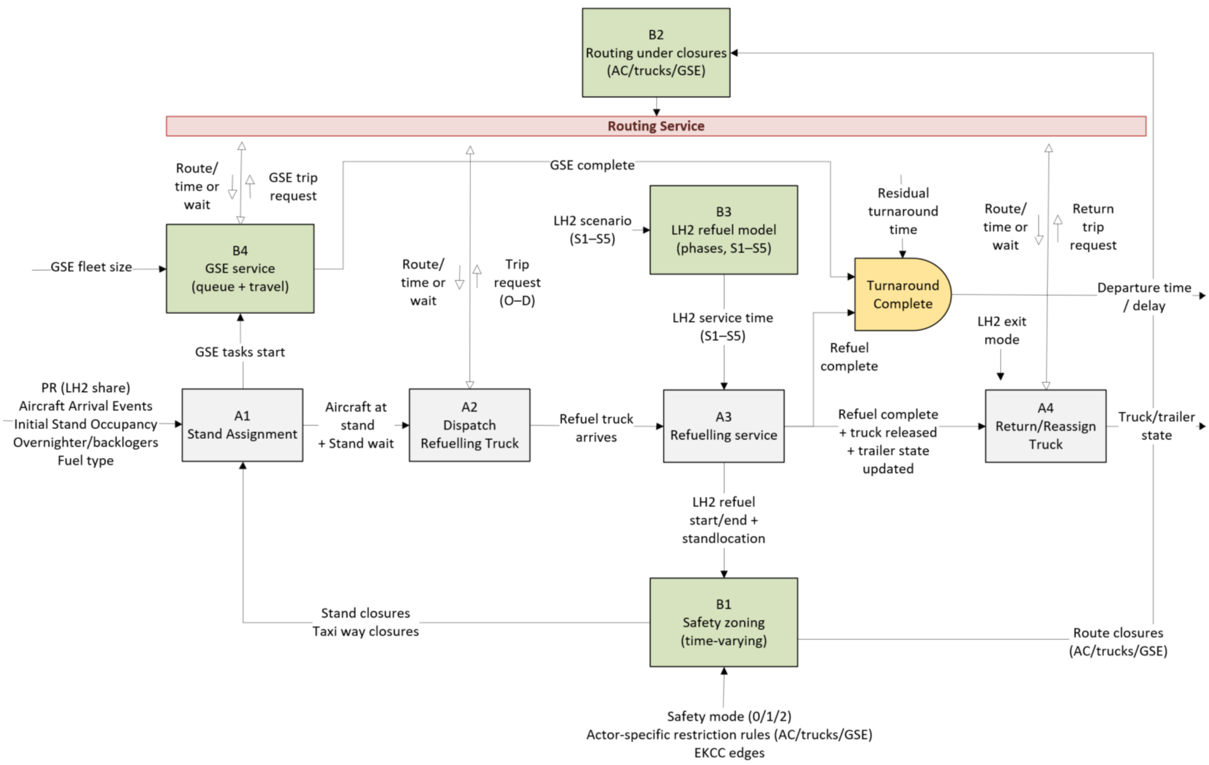


Figure 7: Blockdiagram DES model flow

An overview of the flight turnaround flow and the couplings between A1–A4 and B1–B4, including the purpose, inputs (I), controls (C) and mechanism outputs (M/O) per building block is given in the Supporting Work table 20. A compact summary in the form of pseudocode is given in 4.1.3 to describe how the model programmed.

Baseline Operational Rules that Connect the Blocks

Fuel type (LH_2 versus Jet-A1) is assigned per flight with a Bernoulli draw based on the scenario penetration rate. This is used because the penetration rate is defined as an expected share, while no detailed information is available on fleet-, route-, or time-of-day clustering. The approach preserves the correct expected LH_2 share and allows day-to-day variation in which specific flights are LH_2, which is captured by the replication statistics; schedule inputs and parameter values are defined in Section 3. Stand assignment uses a simple deterministic rule: an arriving aircraft is assigned the available stand with the lowest alphanumeric ID. This keeps the allocation transparent and avoids adding an optimisation or dispatcher model, so the effect of safety restrictions remains identifiable; absolute delay levels may differ from a real airport policy, but relative differences between zoning modes remain comparable. If no stand is available, the aircraft waits and retries every minute until a stand becomes available. During LH_2 refuelling, active safety restrictions can temporarily reduce the set of stands considered available.

B1 – Safety Zoning (Time-Varying Restrictions)

Block B1 adds safety zones as temporary operational restrictions during LH_2 refuelling. It is linked to the LH_2 refuelling service in A3: when LH_2 refuelling starts, the model activates the restrictions for the selected `safety_mode`, and when refuelling ends it removes them. In the simulation, these restrictions change what is available: some stands become temporarily unavailable and some route links become temporarily unusable for certain actors (aircraft, trucks, or GSE). This extension is needed because the safety assessment gives distances, but the simulation needs concrete stand and route restrictions that can cause waiting. Figures 4–6 illustrate the resulting configurations on the case-study apron.

B2 – Routing Under Restrictions (Aircraft/Trucks/GSE)

Block B2 adds routing that reacts to the active restrictions from B1. Vehicle movements are simulated on simplified networks and use shortest-path routing so that dispatch and travel decisions are clear and reproducible. GSE routing uses a directed graph with vertical connections between stand rows to allow detours when lateral movements are restricted, while refuelling trucks use an undirected apron graph because their movements are less constrained by directional rules in the baseline layout. When a movement is initiated, the vehicle computes a shortest path on the modified graph that reflects the current closure set (including directional edge closures). If a feasible path exists, the vehicle travels and incurs the corresponding travel time; if no feasible path exists, the vehicle waits until restrictions are released and then tries again. This extension is needed to represent access rules and to let detours and blockage waiting appear naturally in the results, without adding driver-specific behaviour assumptions.

B3 – LH_2 Refuelling Phases and Scenarios

Block B3 adds a structured LH_2 refuelling model with phases and scenario settings (S1–S5). In the simulation, the active scenario is selected at runtime via the configuration variable `lh2_scenario`. Each scenario defines a parameter set with (i) a reference mass-flow value `lh2_flow_kg_per_s`, (ii) an `aircraft_per_trailer` value that sets how many aircraft refuellings one trailer can support before it must be exchanged/refilled, and (iii) a scenario-specific duration for the transfer (fueling) phase. During an LH_2 service in A3, the refuelling truck follows a fixed phase sequence: the auxiliary phases (docking/connection, purge, chill-down, disconnect/removal) are sampled from configured ranges, while the transfer-phase duration is taken directly from the active scenario. The total on-stand LH_2 service time is computed as the sum of the sampled auxiliary phases and the scenario-defined transfer phase, and this total time determines both how long the LH_2 truck is occupied and how long the safety-zone restrictions from B1 remain active for that turnaround. Scenario differences affect operations through two mechanisms: lower `aircraft_per_trailer` values increase trailer churn and therefore the frequency of trailer exchange/refill trips, while longer transfer durations increase on-stand occupation and the duration of refuelling-induced restrictions, which propagates to stand utilisation and resource waiting. The reference flow values are kept for traceability to the underlying concepts, but in the current implementation they are not used to calculate the transfer duration; the transfer phase is modelled directly as a scenario-defined time.

B4 – GSE Service (Queue + Travel) Linked to Routing and LH_2 Refuelling Windows
Block B4 models ground-support equipment (GSE) as explicit tasks with queueing and travel. For each flight, the aircraft creates a fixed number of identical GSE task requests (three in the baseline). Tasks draw from a single pooled fleet of identical units (`gse_fleet_size`); if no unit is available, the request waits in a shared first-in-first-out (FIFO) queue. Once a unit is assigned, it travels from a common base location to the stand, performs the service for a sampled duration (8–15 min), and returns to base. Both travel legs use the same restriction-aware routing as Block B2 on a directed GSE network, so safety-zone closures from Block B1 can force detours or waiting before accessing the stand.

In safety modes 1–2, on-stand GSE servicing is not allowed to overlap in time with LH_2 refuelling. The model does not cancel GSE tasks; instead, it gates their start time relative to an estimated refuelling start. When an LH_2 truck is dispatched, a truck arrival estimate is set as $t_{\text{truck,ETA}} = t_{\text{now}} + t_{\text{drive}}$. Once the aircraft is ready for refuelling, the earliest refuelling start is estimated as $t_{\text{refuel,ETA}} = \max(t_{\text{ready}}, t_{\text{truck,ETA}})$. Before a GSE unit departs from the base, it computes the travel time to the stand and uses a conservative worst-case service time $t_{\text{serv,max}}$. Pre-refuelling GSE is only allowed if

$$t_{\text{now}} + t_{\text{travel}} + t_{\text{serv,max}} \leq t_{\text{refuel,ETA}}.$$

If this condition is not met, the task waits and is released only after refuelling ends ($t_{\text{refuel,end}}$).

GSE may still run in parallel with `before_TAT` and with the residual turnaround time (rest-TAT), as long as it does not overlap with LH_2 refuelling in modes 1–2. Departure is permitted only after both the turnaround and GSE are complete.

Additional Post-Refuelling Traffic Rules (LH_2 Exit and Emergency Keep-Clear Corridor)
Post-refuelling LH_2 truck departure is controlled by `lh2_exit_mode`. In `direct` mode, the truck returns to the tanking point via the shortest available path. In `right_detour` mode, the truck first moves to the right-adjacent stand within the same row (if available) before rejoining the main network. An Emergency Keep-Clear Corridor can be specified as a list of edges that are blocked for non-emergency traffic during LH_2 refuelling. In the default configuration this list is empty, so the corridor is inactive unless specified.

End-To-End Interaction during an LH_2 Turnaround.
For an LH_2 flight, the baseline process assigns a stand (A1) and dispatches an LH_2 truck (A2). When the truck starts service (A3), B3 sets the LH_2 service duration and B1 activates the safety restrictions that affect stand availability and routing. While restrictions are active, movement requests from trucks and GSE are routed through B2 on the modified graphs, which can generate detours or waiting if no path exists. In parallel, aircraft-generated GSE tasks are processed by B4, and their travel is subject to the same routing constraints. When LH_2 refuelling ends, B1

releases restrictions, A4 updates truck and trailer state and initiates return travel, and blocked movements can resume, which determines the realised departure delays.

7.4 Key Performance Indicators and Statistical Analysis

Operational performance is evaluated with delay, waiting, utilisation, and restriction-activity indicators. For each replication, the primary KPI is departure delay, defined as the realised departure time minus the scheduled departure time. Departure delay is reported as (i) total delay (sum over all flights), (ii) mean delay per flight, and (iii) the share of delayed flights (delay $> 0\,\text{min}$). To diagnose mechanisms behind delay growth, we also report stand-assignment waiting time (arrival to stand-in when no stand is available) and resource waiting times for refuelling trucks and GSE (time spent in the corresponding FIFO queues).

Resource utilisation is computed as the fraction of time a resource is busy (stands occupied, trucks serving or travelling, GSE serving or travelling). To quantify the imposed spatial restrictions, we record the total time that safety-related closures are active (stand-closure time and link-closure time). In addition, blockage-related outcomes are captured via routing-induced waiting and detour effects: we record time spent waiting for a feasible path under active closures and the additional travel time incurred due to detours on the modified routing graph.

Because the model is stochastic, results are estimated from repeated simulation runs with different random-number seeds (independent replications). Unless stated otherwise, each scenario is run with 300 replications. This number was chosen using a confidence-interval precision rule: we increase the number of replications until the 95% confidence interval for the mean departure delay is sufficiently narrow for comparison between scenarios.

To compare scenarios, we report both statistical significance and practical effect size. We use the Vargha–Delaney A statistic as a non-parametric effect-size measure. A can be read as the probability that a randomly selected outcome from one scenario is larger than a randomly selected outcome from another scenario. This is useful because with many replications even small differences can become statistically significant, while A indicates whether the difference is large enough to matter operationally. Where relevant, we also report 95% confidence intervals to show estimation uncertainty.

7.5 Verification and Validation

7.5.1 Verification

Verification targets implementation correctness of the discrete-event logic, resource handling, and routing behaviour. We performed limiting-case tests (PR = 0 with no LH_2 flights, and Mode 0 with safety-zone restrictions disabled), verified state and resource invariants (no double allocation of trucks/GSE and non-negative trailer inventories), and traced LH_2 refuelling phase sequencing and timing (docking, purge, chill-down, transfer, disconnect), including the correct activation and release of safety-zone restrictions. Routing behaviour under blockages was verified by checking that vehicles reroute when feasible and otherwise queue until a path becomes available. The executed verification tests and outcomes are summarised in Appendix 7 (Table 25).

7.5.2 Validation

Given limited empirical data for LH_2 aircraft refuelling operations, validation focuses on structural and face validity. This approach is used because no operational dataset exists for LH_2 aircraft refuelling on aprons that would allow calibration of absolute delay levels. Validation therefore checks whether model structure, task times, and resulting turnaround ranges are consistent with published benchmarks and expected operational behaviour. The implication is that the model is used for comparative scenario analysis rather than exact prediction of absolute delay minutes. Baseline turnaround and service-time outcomes were checked against published turnaround-time ranges for medium (ICAO wake category M) aircraft, for which Eurocontrol-based inputs report scheduled turnaround times in 2022 of 25–80 min (P10–P90; median 45 min) and actual turnaround times of 31–93 min (P10–P90; median 52 min) [12]. Finally, the safety assumptions and hazard types used to motivate distance-based operational constraints were checked for consistency with relevant standards and published evidence on LH_2 releases and hydrogen safety [19, 23, 30].

8 Results - Safety Assessment

This chapter reports the outputs of the safety assessment for open-apron LH_2 refuelling. The results are presented in three steps. First, we summarise the hazard identification and show how the longlist is reduced to the hazards that are relevant for an open-apron release and its consequences. Second, we translate the selected hazards into representative accident scenarios using the Bow–Tie and supporting ETA/FTA logic. Third, we extract the scenarios that can set practical separation distances and use them to define a small set of safety-zone radii for the operational assessment. Figures and tables in Supporting Work provide the full longlists and intermediate ranking details.

8.1 HAZID Outcomes

The HAZID produced a structured hazard inventory for LH_2 apron refuelling, including initiating causes, credible consequences, existing safeguards, and follow-up actions (Supporting Work, Table 9). In total, 15 hazards were identified. The inventory shows that apron risk is driven by loss-of-containment events and by the likelihood that a release is exposed to ignition sources and nearby activities.

The hazards most directly linked to the top event (a hydrogen release during apron refuelling) are dominated by transfer-equipment and interface failures. These include hose/line leakage or rupture due to poor fitting, seal damage, fatigue/vibration, or handling errors, as well as incorrect connection or disconnection. Several hazards were retained because they increase escalation after a release, notably emergency shutdown failures or inaccessibility and deficiencies in detection and alarming. Airport-specific triggers, such as vehicle impact and fire from adjacent activities, were also retained as credible escalation mechanisms in a congested stand environment. Ignition-control hazards (e.g., inadequate bonding/earthing and uncontrolled electrical devices) were included because ignition outcomes dominate the most severe consequences.

Non-fire hazards were recorded where they are safety-critical for personnel and operations, including cryogenic exposure, venting-related failures (ice formation and vent blockage), and loss of power or communications. A filtered subset with a direct and credible link to the top event and to distance-relevant consequences was carried forward into the HAZOP and Bow–Tie stages to keep later modelling focused on hazards that can plausibly drive safety-zone requirements and apron restrictions.

8.2 HAZOP Outcomes

The HAZOP identified deviations from intended operation across the LH_2 refuelling process using guide words and process parameters. The screening table (Supporting Work, Table 10) shows that credible risk pathways occur throughout the sequence, not only during the transfer phase. Deviations most often linked to loss of containment include leak-at-joint and rupture cases driven by connection errors, seal damage, vibration or fatigue, and incomplete preparation steps such as purging and chill-down. A second recurring group concerns control and monitoring failures, such as undetected leaks, delayed alarms, or incorrect status information, because these reduce the chance that a small release is detected and stopped early.

The HAZOP also captures ignition and escalation mechanisms that are relevant on an airport apron, including static discharge from improper earthing, ignition sources within the refuelling area, vehicle impact, and adjacent fire. Deviations that mainly affect controllability were retained when they plausibly increase consequence severity, notably emergency shut-off failure, inaccessibility of emergency controls, and loss of power or communications.

These outcomes narrow the hazard set for the Bow Tie and the tree-based analyses. The selection focuses on loss-of-containment initiators and on consequences that can govern stand-off distances on an open apron. In this study, distance relevance is mainly driven by thermal hazard footprints, in particular delayed ignition of a dispersed vapour cloud (flash fire) and immediate ignition of a release (jet fire). Confined or semi-confined explosions and catastrophic tank failure under fire exposure were retained for completeness and emergency planning, but they were treated separately from routine exclusion-zone sizing.

8.3 Bow Tie Threat and Consequence Classification

The HAZOP produced many detailed deviations. To build a readable Bow Tie around the top event, defined as a hydrogen release during LH_2 refuelling at a parked aircraft, the deviations were consolidated into seven threat clusters (T1–T7) and seven consequence classes (C1–C7). Consolidation reduces redundancy while preserving traceability, because each cluster lists the originating HAZOP IDs. The mapping tables and class definitions are provided in the Supporting Work (Tables 11 and 12).

Threats were grouped by initiating mechanism and the type of barriers required. T1 covers equipment or control malfunctions that can initiate loss of containment. T2 captures hose, joint, and interface failures at the aircraft connection, including incorrect coupling and seal leakage. T3 covers preparation and conditioning failures, including purging, venting, and chill-down, which can increase leak likelihood or create hazardous states before transfer. T4 represents external mechanical damage, mainly vehicle impact on refuelling equipment. T5 covers emergency shutdown and isolation failures that determine whether a release is stopped quickly or escalates. T6 contains external ignition and escalation triggers, such as adjacent fire or lightning, that are conditional on a release but change the consequence pathway. T7 records aircraft-side leaks for completeness and is treated separately because it is not caused by the ground refuelling process and requires different controls.

Items outside the top-event scope, such as sabotage, long-term material compatibility, and general apron FOD, were retained in the hazard inventory but excluded from the Bow Tie. Including them would blur the refuelling-specific causal chain and weaken the link to the safety-zone scenarios analysed later.

Consequences were grouped by dominant physical mechanism and by mitigation approach. C1 contains fire and explosion outcomes, including flash fire, jet fire, and confined or semi-confined explosion, and is central for safety-zone definition because these outcomes can drive stand-off distances. C2 captures dispersion-driven hazards without immediate ignition, such as flammable-cloud formation and delayed ignition potential, which affect detection, access control, and operational decisions. C3 covers cryogenic effects that drive PPE and equipment design. C4 captures operational disruption, such as evacuation, stand closures, and ground-stop effects, to link safety events to apron performance. C5 groups response and escalation factors, such as low flame visibility and sensor or communication failures, because they affect mitigation effectiveness. C6 captures direct personnel harm. C7 covers asset and infrastructure damage relevant for recovery and cost.

Regulatory, financial, and reputational impacts were not used as primary consequence classes in the Bow Tie. They are treated as second-order effects that follow from C1–C7 and are addressed in the discussion of operational and implementation implications.

8.4 Bow–Tie Analysis

The Bow–Tie for the top event, a hydrogen release during LH_2 refuelling at a parked aircraft, is provided in the Supporting Work (Figure 25, Section 1.3). It summarises how representative initiating threats lead to consequence pathways on a congested apron and which preventive and mitigative barriers are assumed in this study. To keep the diagram readable, detailed HAZOP deviations were grouped into threat clusters. Traceability is retained through `X.YZ` identifiers, which link each cluster back to the full mapping table (Supporting Work, Table 11).

On the threat side, the Bow–Tie shows that releases during aircraft tanking are mainly driven by failures at the transfer interface, process control or equipment malfunctions, preparation errors during purge, chill-down, or venting, external mechanical damage, and loss of isolation capability through ESD failure. These threats represent the main ways in which loss of containment can occur during the refuelling sequence. On the consequence side, outcomes are grouped into classes to reflect response logic. For safety-zone definition, the key result is that the distance-relevant cases on an open apron are dominated by fire outcomes after a release. Two pathways govern the footprint that can set practical stand-off distances: delayed ignition of a dispersed vapour cloud, which can lead to a flash fire, and immediate ignition of a high-momentum release, which can lead to a jet fire. Confined or semi-confined explosions and catastrophic tank failure under fire impingement appear as escalation pathways, but they are treated as contingency cases and are not used to size routine exclusion zones.

The Bow–Tie also clarifies which barrier functions control these pathways. Preventive barriers reduce the probability of a release and include procedural checks, interlocks, leak detection, bonding and earthing, and reliable isolation through ESD. Mitigative barriers limit escalation and exposure after a release and include detection and alarming, ignition-source control, evacuation and cordons, and emergency response access. These results are used to justify the scenario selection for consequence-based zone definition and to focus later modelling on the hazard families that can drive safety-zone requirements. Hazards outside the top-event scope or too indirect for the scenario set were retained in the inventory but not carried forward to avoid diluting the causal chain.

8.5 Fault Tree Analysis

Fault-tree logic is represented with AND and OR gates (Figure 26). An OR gate means the output occurs if any input occurs. An AND gate means the output occurs only if all inputs occur.

8.5.1 Fault Tree 1: Hydrogen Leak due to Residual Hydrogen after Failed Purge

The top event is a hydrogen leak caused by residual hydrogen after an incomplete purge. The tree shows that the leak typically requires several conditions to coincide: residual hydrogen remains, a new fuelling operation starts, purge verification does not stop the process, and venting or pressure relief does not work as intended. This result indicates that the event is driven by barrier failure combinations rather than by a single error.

Residual hydrogen can remain if purging is skipped, incomplete, or interrupted, for example by a valve stuck during purge, or if purge completion is not reliably verified by sensing. When fuelling starts, LH_2 introduction can push the remaining gas towards the vent or connection point and cause venting through an unintended path, such as a coupling or vent line. The tree highlights two enabling degradations that increase this likelihood: partial vent-line blockage due to ice or moisture and delayed PRV opening.

This fault tree is included because it represents a credible pathway to delayed-release conditions and supports the use of delayed-ignition scenarios in the safety-zone definition. It also identifies shared control points that reduce several branches at once, notably a purge-verification interlock and measures that keep vent paths and pressure relief available.

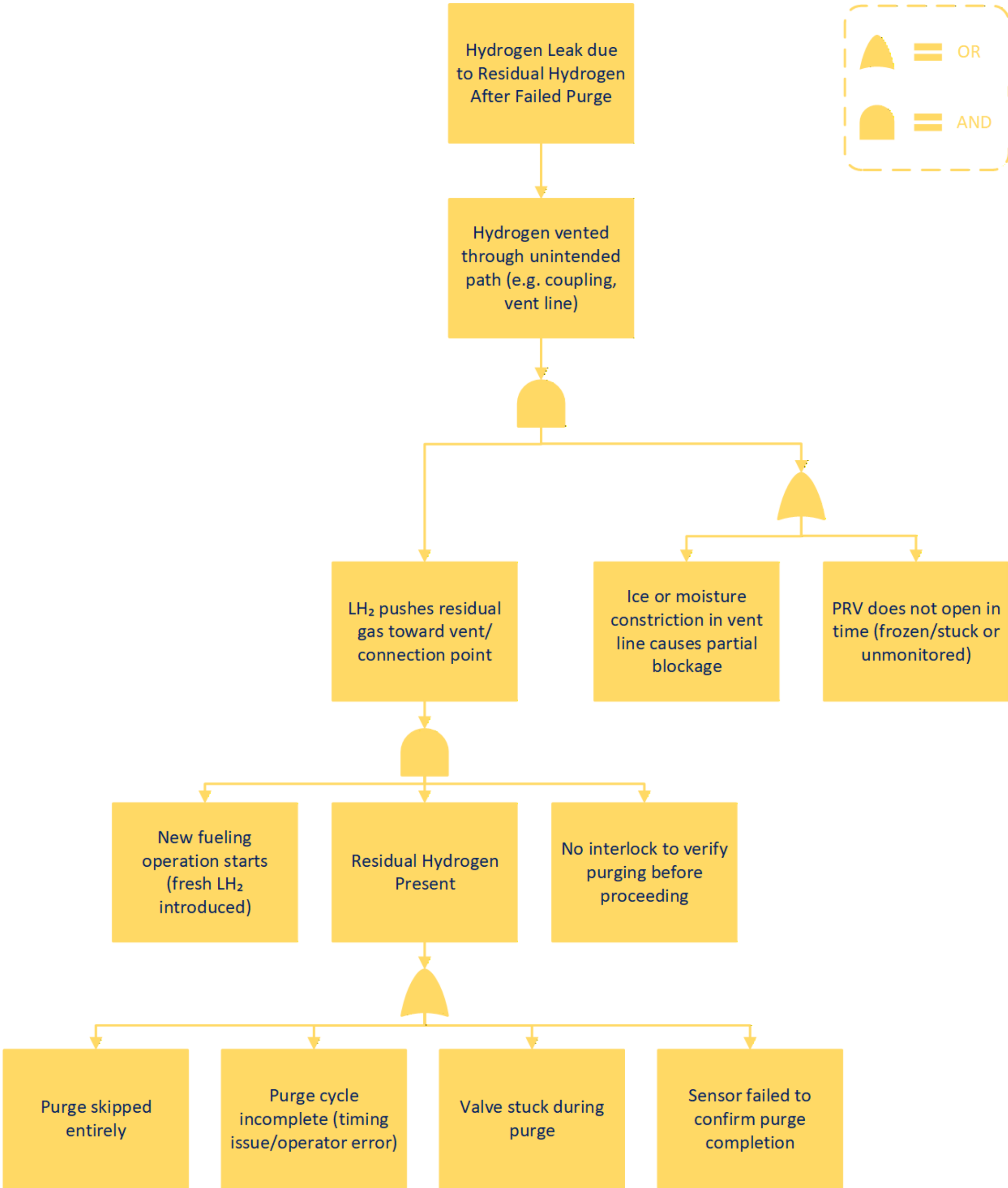


Figure 8: Fault Tree 1: Hydrogen leak due to Residual LH_2 after Failed Purge

8.5.2 Fault Tree 2: Hydrogen leak due to Pipe or Seal Rupture from Thermal Stress

The top event is a hydrogen leak caused by pipe or seal rupture during LH_2 tanking. The tree shows that leakage occurs when component damage coincides with internal pressure build-up during fuelling, making pressure a necessary co-factor.

Damage can be initiated by cryogenic embrittlement, loss of elasticity in seals or gaskets, or fatigue cracking in welds or pipe walls. These mechanisms share a common driver: thermal shock from an abrupt temperature gradient at start-up, when LH_2 is introduced while components are still warm or not yet conditioned and flow is not staged or restricted.

The tree localises the main contributors in pre-cooling and permissive logic. Components may remain too warm if pre-cooling is skipped, the cooling system malfunctions, a temperature sensor gives incorrect readings, or no temperature interlock prevents fuelling. These results motivate the inclusion of high-rate release cases used to represent jet-fire type scenarios and show which controls reduce multiple branches simultaneously. The key controls are enforced temperature interlocks with reliable sensing, robust pre-cooling, staged flow initiation to limit thermal shock, and pressure management during fuelling.

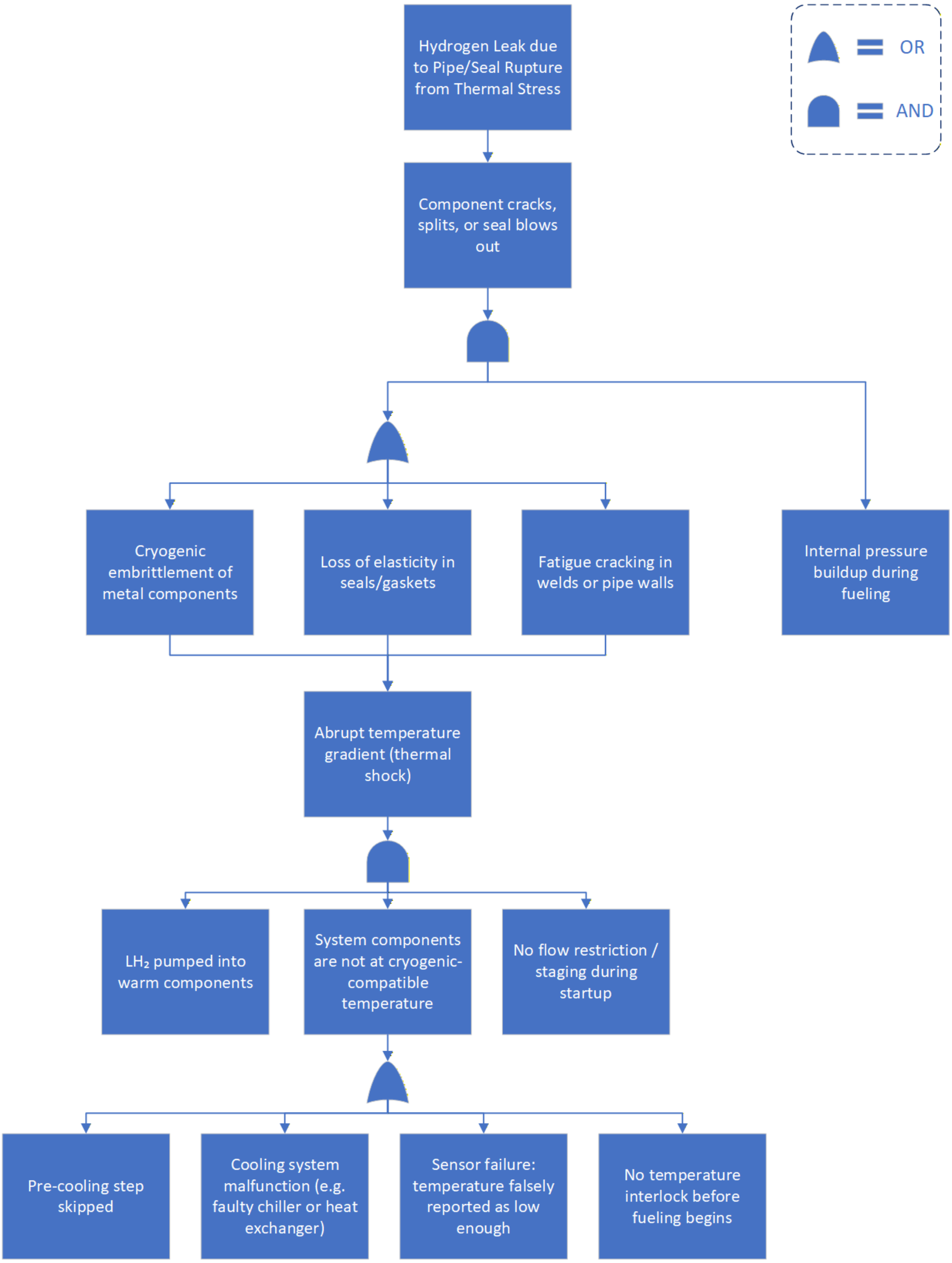


Figure 9: Fault Tree 2: Hydrogen Leak due to Pipe/Seal Rupture from Thermal Stress

8.6 Event Sequence of a Hydrogen Leak

The event sequence diagram is read from left to right. At each safety function, the pathway splits into alternative outcomes. In Figure 10, the horizontal branch denotes YES, meaning the function succeeds, and the downward branch denotes NO, meaning the function fails or is unavailable. Each combination of outcomes leads to a distinct end state.

The main result is that escalation is driven less by the initial leak and more by the performance of a small set of barriers that remove hydrogen and prevent ignition. Early leak detection followed by rapid transfer shutdown has the largest effect because it limits released mass and reduces exposure time.

A second result is that shutdown alone does not remove all risk if residual hydrogen remains in the line. Residual inventory can be released or migrate after the initial response and still create a delayed-ignition pathway that leads to jet fire or flash fire. This makes purge effectiveness and residual-gas management a distinct safety function.

For pathways without immediate ignition, ventilation performance determines whether the event terminates or persists as a latent hazard. Effective ventilation accelerates dispersion and reduces the chance of a flammable cloud, whereas poor ventilation allows accumulation and increases the chance of later ignition.

If ignition occurs, consequence severity is mainly controlled by suppression effectiveness and by whether separation can be maintained. When suppression succeeds and separation is maintained, impacts remain local. When suppression fails and separation cannot be maintained from people, adjacent aircraft, or critical equipment, escalation becomes more likely.

These results justify focusing the scenario set on ignition timing and on barrier performance that affects released inventory and cloud persistence, in particular detection and shutdown, purge and venting effectiveness, and ventilation.

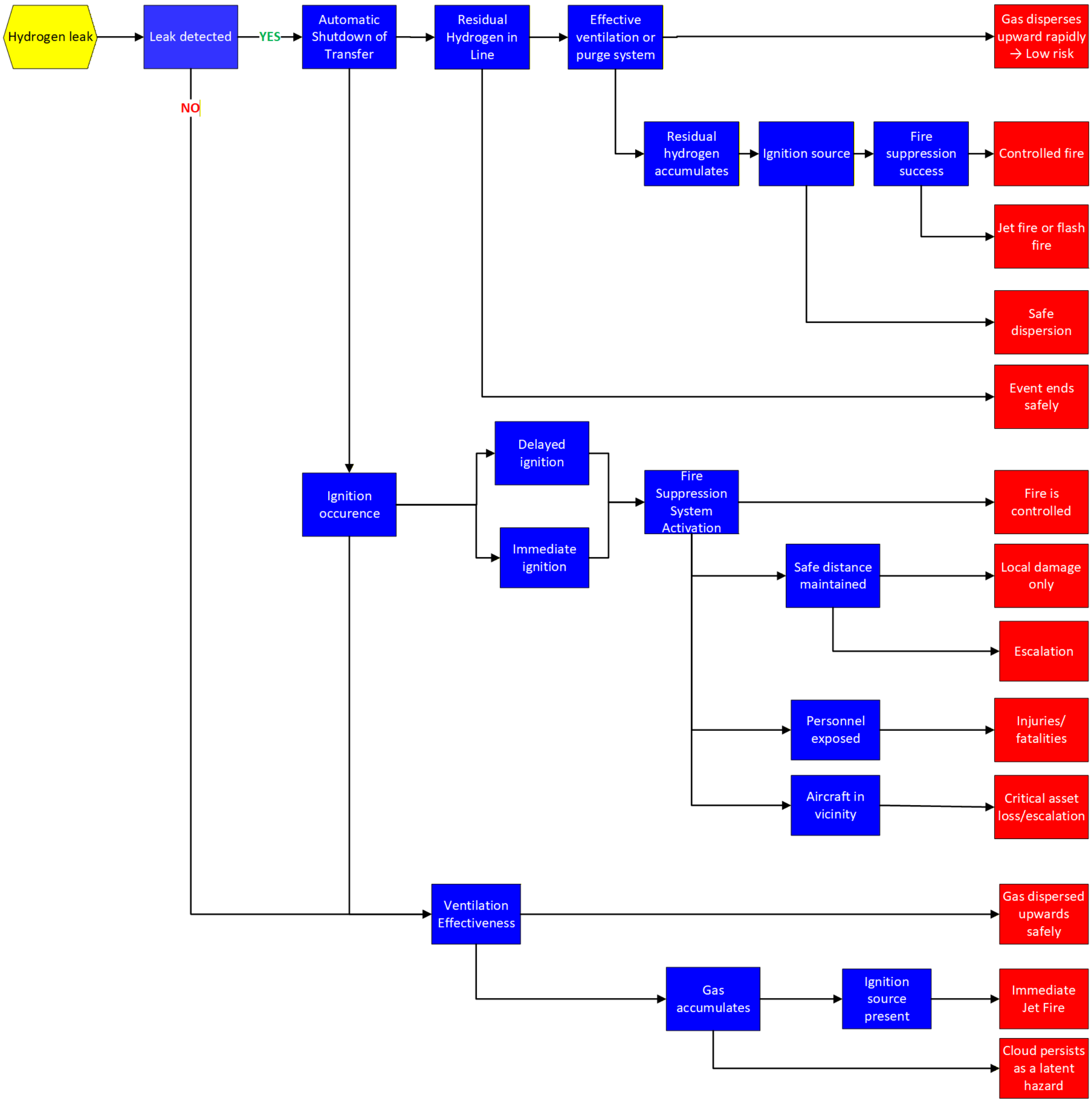


Figure 10: Event sequence diagram of hydrogen leak

8.7 Severity–Likelihood Assessment and Implications

Table 13 summarises the severity–likelihood ranking for the shortlisted hazards from Section 2.1. The key result is that ignition-driven outcomes dominate the operational risk picture. Jet fire and flash fire combine critical severity with medium likelihood, which makes them the most decision-relevant hazards for apron operations.

The highest-consequence cases, vapour cloud explosion and major rupture or burst release, are rated as catastrophic but have low to very low likelihood. They remain relevant for emergency preparedness and design assurance, but they are not a practical basis for routine stand-off zones on an open apron.

Non-fire LH_2 hazards, mainly cryogenic contact and oxygen enrichment, are rated moderate to critical with low to medium likelihood. They translate primarily into design and procedural requirements, such as PPE, insulation integrity, purge and venting practices, and access control, rather than distance-setting criteria.

Several entries act as enablers or consequences rather than independent initiators. Undetected leaks increase exposure time and therefore increase ignition likelihood, while personnel and asset damage are mainly outcomes of the fire cases. This supports focusing controls on preventing ignition-driven escalation through rapid detection, automatic shutdown, verified purge and venting, and maintained separation during active transfer.

Accordingly, jet fire and flash fire are retained as the primary basis for defining safety-zone distances. The remaining hazards are carried forward as mitigation and operational control requirements rather than as determinants of the zone radius.

8.8 Critical Safety Bottlenecks and Controls

The hazards in Table 13 were reviewed to identify critical safety bottlenecks. These are safety functions whose failure increases ignition likelihood or increases the size or duration of a release. Six bottlenecks recur across multiple pathways.

1. **Loss of containment from cryogenic component or interface failure.** Failures of tanks, valves, piping, hoses, and couplings can directly initiate a release. Cryogenic-qualified design, inspection, and containment-preserving features, such as breakaway couplings, reduce this likelihood.

2. **Pressure relief failure and uncontrolled venting.** Inadequate relief capacity, blocked relief paths, or misrouted venting can turn minor upsets into high-rate releases. Controls that preserve relief capacity and keep vent paths clear reduce escalation.

3. **Missed leak or flame detection and delayed alarming.** Hydrogen leaks and flames are difficult to detect without sensors. Delayed detection increases released mass and ignition likelihood. Reliable detection and clear alarms reduce response time and limit escalation.

4. **ESD failure and incomplete isolation.** Actuation faults, loss of power or communications, or poor accessibility can delay shut-off and prolong a release. Rapid shut-off and verified isolation limit released mass and exposure time.

5. **Ignition-source presence and loss of hazardous-area control.** Because ignition-driven events dominate escalation, loss of hazardous-area control increases the chance that a leak transitions into fire. Bonding and earthing integrity and adherence to zoning restrictions therefore directly influence escalation potential.

6. **Procedural deviation and inadequate training.** Skipped purge or chill-down, incorrect sequencing, or poor coordination can initiate releases and reduce barrier effectiveness. Training and SOP compliance are therefore cross-cutting controls.

Together, these bottlenecks link the Bow–Tie and the severity–likelihood results to two outputs. They identify barrier functions that require multiple independent layers and they support focusing the safety-zone definition on ignition-driven scenarios.

8.9 Key Hazards Influencing Safety Distances

For LH_2 refuelling on an airport apron, separation distances are mainly driven by credible loss of containment events that ignite. These events can create severe thermal exposure for people, aircraft, and nearby infrastructure. This section therefore focuses on release and ignition scenarios that are both high consequence and plausible during apron operations. Scenario identifiers (A.1, A.2, A3, B.1, B.4) refer to the hazard register used in this study.

Very severe escalation events are acknowledged, but they are not used to size routine operational zones. Instead, they are addressed through engineering safeguards and emergency response planning.

8.9.1 Flash Fire from Delayed Ignition of a Vapour Cloud (A.1, B.4)

A flash fire can occur when a hydrogen release first disperses and ignites after a delay. The flame then travels through the flammable part of the cloud. LH_2 release experiments indicate that delayed ignition is a credible outcome for releases without immediate ignition [30, 25]. In open air, flash fires typically produce limited overpressure. The main distance driver is the maximum flammable cloud size before ignition.

Controlled LH_2 dispersion experiments and setback methodologies show that flammable footprints can reach tens of metres for realistic releases [30, 16]. The extent depends on release size, isolation time, and wind [16]. As a conservative working basis for preliminary zoning on an open apron, an exclusion radius of about 20 to 30 m is appropriate for delayed ignition flash fire scenarios [16]. Controls such as rapid isolation, venting strategy, and ignition source management reduce likelihood, but they do not remove the need for a conservative stand off distance [3, 25].

8.9.2 Jet Fire from Immediate Ignition (A.2)

A jet fire occurs when a release ignites immediately. It produces a directional flame anchored at the release point and can cause severe thermal exposure close to the source. Hydrogen flames can be hard to see, which increases the need to control activities near the refuelling interface [7, 25, 3]. Best practice guidance therefore prioritises rapid isolation of the flow over extinguishment while the release continues [25].

Operationally, this implies an access control area around the refuelling point that limits personnel exposure, vehicle access, and ignition sources during active transfer. As an illustrative control distance, ACI and ATI report a suggested radius of about 27 m to manage spark ignition vehicles around the aircraft during refuelling [3]. This radius should be treated as an operational control measure and combined with procedures and interlocks that support prompt isolation if a release is detected [3, 25].

8.9.3 Explosion from Accumulation in Confined or Congested Spaces (B.1)

Hydrogen explosions become most hazardous when gas accumulates in confined or congested geometries. HyResponder reports that open, unobstructed combustion can produce overpressures of about 10 kPa, while confinement can increase overpressure substantially. For a near stoichiometric hydrogen air deflagration in a tunnel, reported values are 150 to 175 kPa [18]. This means a single apron wide radial stand off is not an effective routine control for explosion risk.

The practical distance implication is local. The refuelling interface and safety area should be kept clear of openings and partially confined volumes where hydrogen could accumulate, such as pits, ducts, enclosures, and covered interfaces. For emergency response, HyResponder uses an initial exclusion zone of 50 m for hydrogen leak situations, to be refined using measurements and incident specifics [18].

8.9.4 BLEVE and Catastrophic Rupture under Fire Exposure (A.3)

A BLEVE involves catastrophic failure of a vessel containing cryogenic liquid under external heating. PRESLHY notes that severe external heating combined with inadequate venting or failure of the relief path can escalate LH_2 systems towards BLEVE type outcomes [4]. From a distance perspective, such escalation implies stand off distances that are not practical for routine apron refuelling.

For context, the HyResponder European Emergency Response Guide provides distance charts for hydrogen tank rupture in fire. In an illustrative case, a no harm distance is about 160 m [21]. For stationary LH_2 storage siting, EIGA guidance lists recommended minimum separations up to 60 m to certain public exposures [13]. These magnitudes support treating BLEVE type escalation as a contingency managed through prevention and emergency planning, rather than as a basis for routine refuelling zoning [15, 4].

8.9.5 From Key Hazards to Safety-Zone Scenarios

The severity–likelihood assessment was used to narrow the full hazard list to a small set of accident cases that can set the required separation distance on an open apron. The severity and likelihood categories, the assigned ratings, and the supporting rationale are provided in the Supporting Work (Table 13 and Sections 2.2.1 and 2.2.2). Based on this assessment, flash fire after delayed ignition and jet fire after immediate ignition were retained as the main cases used to define the exclusion radius. Confined or semi-confined explosions were kept as a design and procedural concern, but they were not used to size a general apron radius because they depend on confinement conditions that are not representative for open-apron refuelling. BLEVE-type escalation was treated as very unlikely and is addressed via engineering safeguards and emergency planning rather than routine stand-off distances.

To translate these cases into simulation inputs, the scenario set varies only two parameters that directly affect the hazard footprint:

1. the effective opening size D, which controls the release rate, and
2. the ignition timing (immediate, delayed, or no ignition).

For each scenario, a representative safety-zone radius R was assigned using published hydrogen refuelling guidance and aviation-relevant dispersion and fire studies (Section 8.9). The radii were selected as a monotonic set from conservative (largest footprint) to nominal (smallest footprint) and were then implemented in the DES as stand and taxilane restrictions.

8.9.6 Safety-Zone Scenario Set

Table 6: Safety-zone scenarios derived from jet-fire and flash-fire hazard families. D is the effective opening diameter; R is the exclusion radius implemented in the DES.

ID	Accident case (hazard family)	Representative input	Radius R	Why included / link to key hazards
Z1	Full-bore rupture with immediate ignition (jet fire, A.2)	$D = 50$ mm; immediate ignition; high release rate	50 m	Conservative upper-bound case for thermal exposure and operational disruption; used as stress-test for capacity impacts.
Z2	Medium leak with delayed ignition (flash fire, A.1/B.4)	$D = 20$ mm; delayed ignition after cloud formation	30 m	Primary case for defining routine safety-zone distances; flammable-cloud extent is the controlling hazard [30, 16].
Z3	Small leak with delayed ignition (local flash fire)	$D = 8$ mm; delayed ignition; limited cloud growth	15 m	Credible smaller release during connect/disconnect or minor interface faults; tests whether smaller zones preserve capacity while remaining conservative.
Z4	Pinhole leak with rapid isolation, no ignition	$D = 2$ mm; detection and ESD; no ignition	10 m	Mitigation-dominated case; radius represents an operational buffer for response and ignition control rather than a fire footprint.
Z5	Nominal operation (no abnormal release)	No release; standard procedures and controls	5 m	Operational interface buffer during transfer to enforce access and ignition-source control; best-case baseline for comparison.

Z1–Z3 map to the key hazard families in Section 8.9: jet fire (immediate ignition) and flash fire (delayed ignition). Z4–Z5 represent mitigation-dominated and nominal conditions and provide lower-bound operational cases for comparison in the DES. BLEVE and confined-explosion scenarios were not used to dimension R; their implications are addressed through engineering safeguards and procedural constraints (supporting work).

These five scenarios provide the safety-based inputs for the operational assessment. Because the exclusion radius R is derived from a structured safety analysis, the operational model does not rely on arbitrary zone assumptions and the simulated delays can be interpreted as consequences of explicitly justified safety choices. In the operational simulation, each scenarios radius R is implemented as time-varying stand and route restrictions during the LH_2 refuelling window, affecting stand availability, vehicle access, and taxi-out feasibility. The next section groups the five scenarios into a small number of practical zoning modes and quantifies, via discrete-event simulation, how these safety-based restrictions propagate to apron capacity and departure delays as LH_2 penetration increases.

9 Results from Operational Impact Modelling

This section reports the results of the operational impact modelling. Safety-zone distances from the safety assessment (Section 8.9.6) are implemented as operational restrictions in the discrete-event simulation (Section 6) for the case-study apron (Section 3). The aim is to quantify how safety-based zoning affects departure delays as LH_2 penetration increases and to identify the mechanisms driving any delay growth.

Results are presented stepwise. Section 9.1 verifies replication adequacy and tests whether safety modes produce statistically and practically meaningful delay differences across penetration rates. Section 9.2 links delay growth to safety-zone diameter and stand-capacity loss. Section 9.3 analyses a busy peak-summer day and isolates LH_2 refuelling-logistics effects across transfer scenarios (S1–S5), reported in delay minutes. Section 9.4 repeats the analysis for future demand, using 2040 scenarios with lower PR and 2050 scenarios with higher PR to reflect expected adoption. Section 9.5 tests sensitivity to Jet-A1 and LH_2 truck-fleet capacity, and Section 9.6 evaluates whether GSE detours and waits under blockages materially contribute to delays.

9.1 Statistical Analysis and Replication Adequacy

Because the simulation is stochastic, we verified that the number of replications per scenario is sufficient to estimate mean KPIs with acceptable Monte Carlo precision. The test increases n until the estimated mean has a sufficiently narrow 95% confidence interval (half-width h). For each safety mode × penetration rate scenario, we applied a sequential 95% confidence-interval half-width test for the mean, $h = t_{0.975,n-1}\, s/\sqrt{n}$, and increased the number of replications until $h \leq \epsilon$ with $\epsilon = 2.0$ [24]. All scenarios met the target within the available budget; the slowest-converging case required approximately 280 replications. We therefore used 300 replications for all scenarios to ensure uniform precision and comparability. Detailed diagnostics are provided in Supporting Work 5.1.

9.1.1 Statistical Comparison of Safety Modes (ANOVA, Tukey HSD, and Vargha & Delaney's A)

This section tests whether zoning mode choice leads to different delay outcomes. The operational hypothesis is that more restrictive safety-zone implementation can increase departure delays by reducing effective apron capacity through stand and access restrictions. For each KPI and for each penetration rate (PR) and test day, we combine (i) a one-way ANOVA as an overall test across Mode 0/1/2, (ii) Tukey HSD for post-hoc pairwise comparisons (0–1, 0–2, 1–2) while controlling the familywise error rate, and (iii) Vargha & Delaneys A as a distribution-free effect size for each mode pair. Vargha & Delaneys A is defined as $A_{XY} = P(X > Y) + \frac{1}{2}P(X = Y)$, where $A = 0.5$ indicates no difference and the sign of $A - 0.5$ indicates which mode tends to yield larger values. For effect-size magnitude we use the symmetric separation $A^* = \max(A, 1 - A)$ and interpret A^* using Sandora et al. as: 0.56–0.64 small, 0.64–0.71 medium, and > 0.71 large [26]. Full statistical outputs are provided in Supporting Work 5.2.

9.1.2 Results for the Delay KPI across Penetration Rates

The delay KPI shows a consistent threshold pattern across penetration rates. At low penetration (PR 0.00–0.05), there is no evidence of differences between safety modes: ANOVA is non-significant, Tukey HSD rejects no pairwise comparisons, and A remains near 0.5 (negligible practical differences). From PR = 0.10 onward, Mode 2 becomes distinguishable: ANOVA turns significant and Tukey HSD identifies Mode 2 as worse than both Mode 0 and Mode 1, while Mode 0 vs. Mode 1 remains non-significant. From PR ≈ 0.15 and higher, differences between

Mode 2 and the other modes persist with very small adjusted p-values and confidence intervals above zero, indicating higher mean delay under Mode 2. Vargha & Delaneys A corroborates this direction: $A(0,2)$ and $A(1,2)$ drop below 0.5 as PR increases, meaning Mode 2 delays are typically larger than under Modes 0/1, while $A(0,1)$ stays near 0.5. Detailed ANOVA/Tukey outputs, confidence intervals, and effect sizes by PR are reported in Supporting Work 5.2.

9.2 Impact of Safety Zone Diameter on Operational Delays

Figure 11 shows a strongly nonlinear effect of safety-zone diameter (300 replications; two LH_2 trucks). The main increase occurs when moving from Mode 1 (20–40 m) to Mode 2 (>40 m); Mode 0 (<20 m) and Mode 1 remain similar over most penetration levels. This suggests the binding constraint is the stand-capacity loss from blocking adjacent stands.

Mode 2 introduces a congestion regime at moderate-to-high penetration, where small increases in LH_2 penetration cause disproportionately larger delays, consistent with stand-capacity saturation and queue spillback in stand allocation. Operationally, this implies a tipping point beyond which additional LH_2 demand cannot be accommodated without rapidly rising delay.

The two KPIs suggest that stand availability is a major driver of departure delay in Mode 2, but not the only driver. Mode 0 shows increasing departure delay despite negligible stand-assignment waiting, pointing to refuelling resource contention or process-time effects. Therefore, Mode 2 mitigation should prioritise preserving stand capacity (zoning geometry, stand layout, and temporal separation of LH_2 refuelling), while delay reduction in Modes 0–1 is more likely to depend on operational and resource measures than on stand blocking alone.

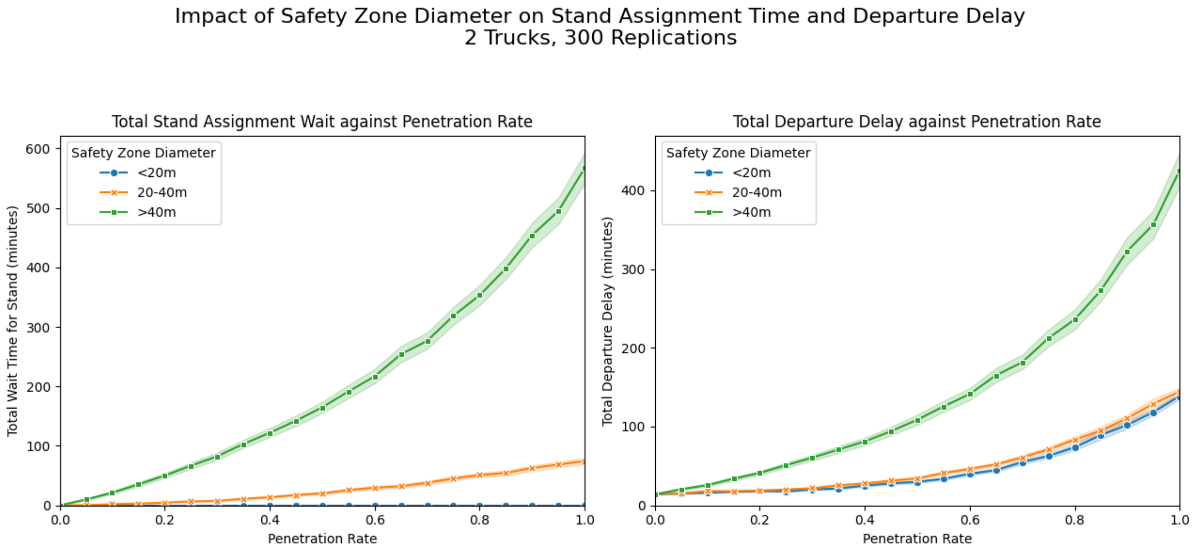


Figure 11: Impact of Safety Zone Diameter on Stand Assignment Time and Departure Delay.

9.3 LH_2 Refuelling Scenarios and Delayed Flights

Figures 12 and 13 compare delayed-flight percentages across penetration rate (PR) and LH_2 refuelling scenario (S1–S5; Table 3) for modes 1 and 2, simulated with two LH_2 trucks.

In mode 1, trailer capacity becomes decision-relevant mainly at higher PR. S1 and S2 are similar at low PR, but the gap widens as PR increases, indicating that the number of aircraft served per trailer before refill/replacement constrains performance under high utilisation. Refuelling time also has a strong effect: S4 yields substantially fewer delayed flights than S2, and this gap becomes relatively larger from about PR ≥ 0.6 than the S1–S2 gap, although it reflects a large fill-time difference. This may occur because refill/replacement downtime can overlap with truck slack, whereas longer on-stand refuelling directly extends occupation at the critical stand resource and propagates delay.

In mode 2, S1–S3 lie closer together and at PR = 1.0 their differences are small; S1 and S2 are nearly identical, indicating that trailer capacity no longer differentiates performance at full penetration. Across all scenarios, the spread at PR = 1.0 is smaller in mode 2 than in mode 1, suggesting a bottleneck shift toward blocked stand capacity that reduces the influence of refuelling time and trailer capacity.

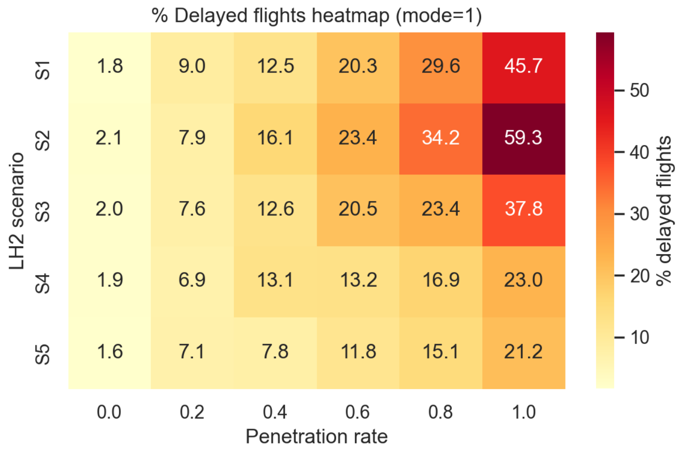


Figure 12: Percentage of delayed flights for different LH_2 refuelling configurations (mode 1).

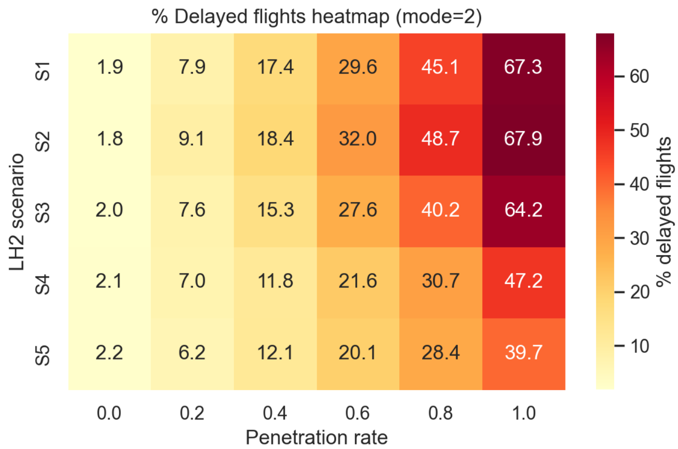


Figure 13: Percentage of delayed flights for different LH_2 refuelling configurations (mode 2).

9.3.1 Total Departure Delay on Peak Summer Day

Figure 14 decomposes total departure delay by LH_2 refuelling scenarios (S1–S5), penetration rate (PR), and safety mode for a peak summer day (26-08). The key result is a strong interaction between PR and safety mode: mode effects are small at low PR for modes 0/1, but become dominant once PR reaches 0.6 and higher.

Mode 2 drives the delay escalation. Already at PR = 0.2 it produces materially higher total delay than modes 0/1, and the gap widens rapidly with PR. At PR = 1.0, mode 2 reaches extreme totals (e.g., about 1400 min for S2), indicating that the system becomes capacity-limited under wide-zone stand blocking. In this regime, incremental increases in LH_2 activity translate into disproportionate delay growth, consistent with persistent stand unavailability and spillover effects in stand assignment and taxi interactions.

Overall, the influence of trailer capacity appears smaller than the influence of refuelling time. This is reflected in the limited differences between S1 (4 t) and S2 (2 t), and likewise between S4 (2 t) and S5 (4 t), whereas the differences between S2, S3, and S4 are substantially larger

Operationally, the figure implies that achieving high LH_2 penetration with acceptable delay requires avoiding mode 2-type adjacent-stand blocking where possible, or compensating with layout and scheduling strategies that preserve effective stand capacity (e.g., distributing LH_2 stands, separating LH_2 turns in time, or increasing buffer/stand availability). Under modes 0–1, these same configurations yield substantially lower totals, indicating that moderate safety-zone footprints can be operationally manageable even at high PR.

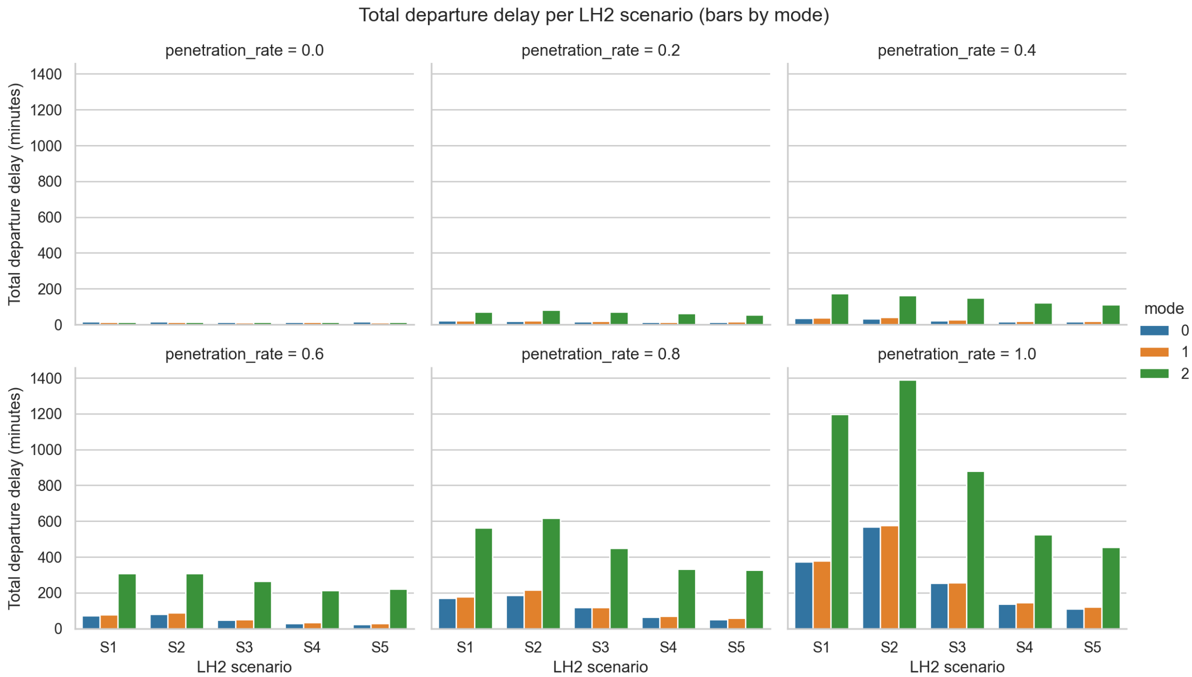


Figure 14: Total departure delay per LH_2 stand scenario, for various penetration rates and safety modes.

9.4 Future Scenarios LH_2 Tanking Effects

To test whether the main delay mechanisms persist under plausible future adoption, we evaluate scenarios for two horizons (2040 and 2050) with increasing LH_2 penetration. For each horizon, low-, medium-, and high-uptake penetration rates are tested, based on earlier scenario work [17, 9], and performance is evaluated on four representative RTHA traffic days (summer/winter; average/peak demand). To illustrate how demand and zoning interact, we highlight a 2050 case with adjacent-stand blocking (Mode 2, Figure 15). The remaining year–mode KPI comparisons are provided in Supporting Work (Figures 28 and 29–32).

To enable comparison with earlier results from Janssen [20], all future scenarios assume a fleet of three LH_2 trucks (and two Jet-A1 trucks). The additional LH_2 truck capacity improves all KPIs, leading to lower delays even under additional operational constraints such as GSE-related restrictions. This improvement is visible even though LH_2 truck utilisation remains relatively low, indicating that an additional truck reduces the probability and duration of peak-time resource contention. One contributing factor may be that detours are modelled explicitly, increasing service and repositioning times and making the system more sensitive to short periods of truck unavailability.

Across the future runs, differences between Mode 0 and Mode 1 remain small on all days, indicating that localized access restrictions and resulting detours do not materially increase delay in this apron layout. The dominant contrast is with Mode 2. In 2050, delays rise sharply on peak days once PR exceeds roughly 0.5: on the peak summer day, the share of delayed flights increases from 18.1% to 38.0% and the average delay from 5.6 to 16.2 min as PR increases from 0.52 to 0.90. Similar escalation is observed on the peak winter day (18.4% to 35.4% delayed flights; 5.4 to 15.4 min average delay). This pattern indicates the onset of systemic congestion when neighbouring stand unavailability limits stand-allocation flexibility under high utilisation.

In contrast, the 2040 set remains moderate because PR stays below 0.5. Even at the highest PR (0.42), average delay remains at or below 1.5 min and the delayed-flight share does not exceed 12.9% across the four representative days. Overall, the results indicate that the main future operational risk is not minor access restrictions captured by Mode 1, but loss of effective stand capacity under Mode 2. Under high PR and peak-day demand, adjacent-stand blocking becomes the binding constraint and drives nonlinear delay growth.

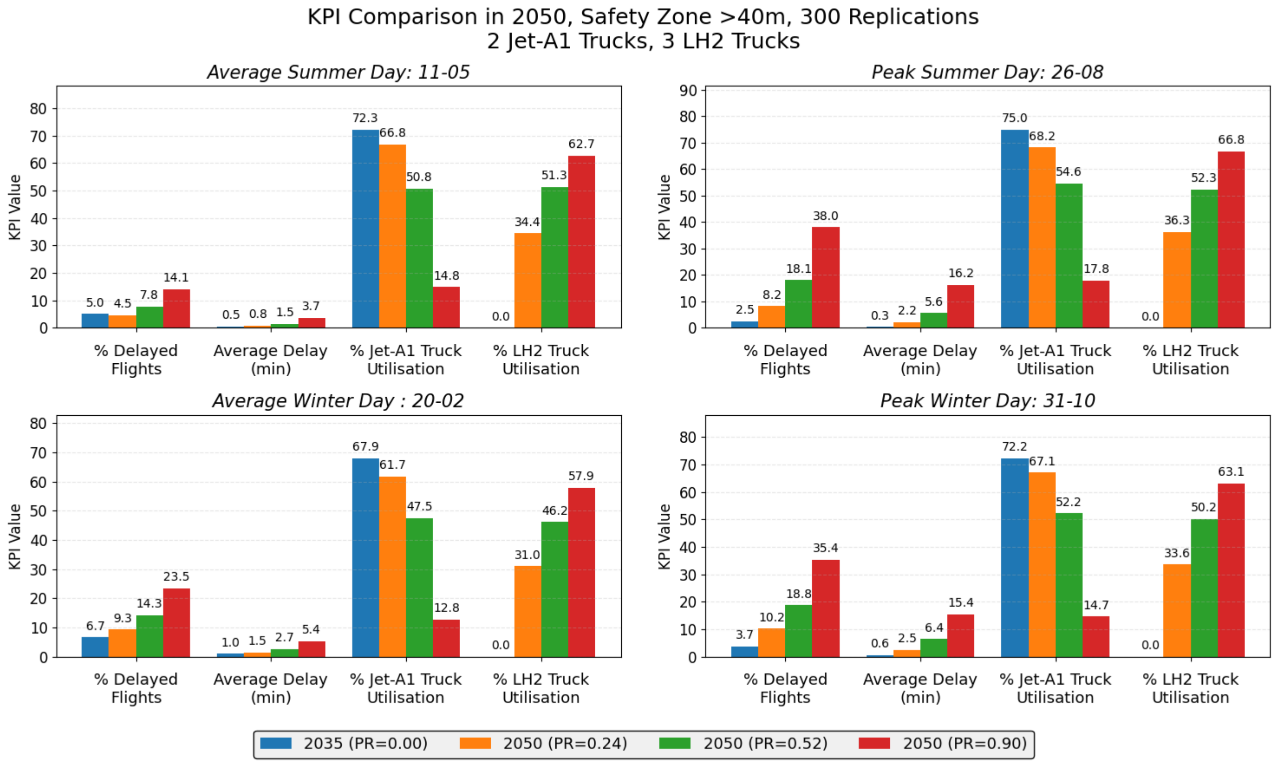


Figure 15: 2050 scenario KPI comparison, Mode 2 (maximum interference configuration)

9.5 Violin Plot: Jet-A1 and LH_2 Truck Fleet Sizing

Figure 16 tests how departure punctuality responds to refuelling-truck capacity on a peak summer day at PR = 0.7 (300 replications). This PR is selected because it lies in the mid-to-high penetration regime, where earlier results indicate congestion effects start to emerge, and because it allows assessing how far a three-truck LH_2 fleet can accommodate demand before additional LH_2 capacity is required. An extended version of this analysis that includes fleet configurations with up to four LH_2 trucks is provided in Supporting Work (Section 6.3, Figure 33).

The main insight is again that delay risk is driven by the late tail of the departure-time distribution rather than by small shifts in the centre. Undersizing a refuelling fleet mainly increases the probability of very late departures, which directly threatens the operational departure window.

At PR = 0.7, LH_2 capacity is the dominant constraint when it is limited to one truck. For all configurations with one LH_2 truck (1/2/3 Jet-A1 + 1 LH_2), the late tail extends well beyond the planned cutoff and can approach or exceed the latest allowable time. Adding Jet-A1 trucks does not remove this extreme tail, indicating that LH_2 service capacity is binding in this regime.

Increasing LH_2 capacity from one to two trucks yields the largest reduction in tail risk. With two LH_2 trucks, the extreme late tail contracts sharply and most departures remain close to the planned cutoff across Jet-A1 fleet sizes. In contrast, increasing from two to three LH_2 trucks provides a smaller additional tightening of the distribution, consistent with diminishing returns once the most severe LH_2 queueing is removed.

Jet-A1 fleet size appears second-order at this PR once LH_2 capacity is at least two trucks. The distributions for 1/2/3 Jet-A1 + 2 LH_2 and 1/2/3 Jet-A1 + 3 LH_2 are similar in the late tail compared to the large changes induced by moving from one to two LH_2 trucks, suggesting that residual late departures are increasingly driven by non-fuel mechanisms (e.g., stand assignment interactions and operational coupling on the apron) rather than by fuel-truck capacity alone.

For this day and PR, the results indicate that one LH_2 truck is insufficient, two LH_2 trucks remove most extreme lateness, and a third LH_2 truck provides additional robustness with diminishing returns. A balanced fleet therefore remains preferable to adding capacity on only one fuel type, but the primary sensitivity at PR = 0.7 is to LH_2 truck availability.

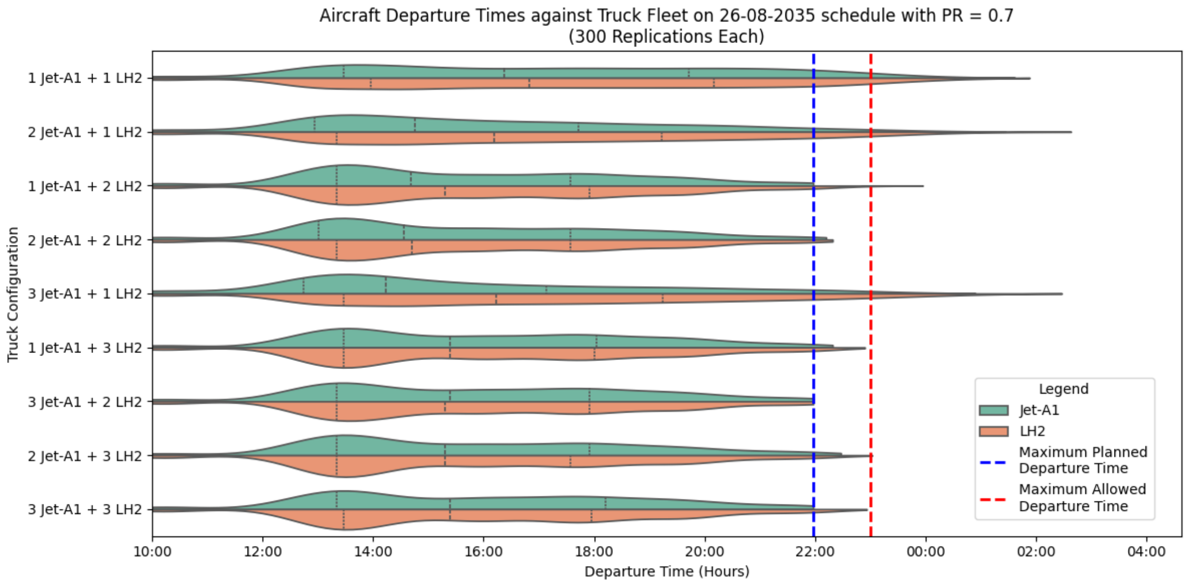


Figure 16: Aircraft departure time distributions for PR=0.7 against Truck Fleet on busy summer day.

9.6 GSE Impact

Figure 38 shows that switching GSE rerouting on/off hardly changes the percentage of delayed flights across penetration rate (PR) and safety modes. This implies that delays are dominated by aircraft-side capacity limits (stand availability under safety zoning and refuelling capacity), not by GSE routing.

At the same time, the updated stand-access logic leads to higher mean GSE waiting in modes 1–2 and the wait increases with PR (Figure 17). This wait comes from restricted stand access during LH_2 refuelling. Mode 2 does not increase GSE waiting relative to mode 1, which suggests that the extra mode 2 constraints mainly reduce aircraft stand capacity rather than creating additional GSE queuing.

In the model, GSE tasks cannot be executed on a stand while LH_2 refuelling is ongoing. Therefore, GSE can in principle be done either before refuelling starts or after it ends. In practice, almost all GSE is scheduled after refuelling. This is caused by a conservative rule: a GSE unit may only depart once the refuelling ETA is known (typically after a truck is assigned and already on its way). Then, feasibility is checked using a worst-case completion test (`service_max` plus travel time). As a result, the "pre-refuel" option is rarely feasible, even though it exists in theory.

A higher GSE wait does not automatically mean more departure delays. The earliest possible departure is

$$t_{\text{earliest}} = \max(t_{\text{refuel\_end}} + t_{\text{restTAT}},\ t_{\text{GSE\_complete}})\,. \tag{1}$$

So GSE can extend the turnaround beyond `refuel_end + restTAT`. However, a delay is only recorded if t_{earliest} exceeds the scheduled departure time. In the schedule, there is often slack between arrival and planned departure, so part of the extra GSE time is absorbed without creating a departure delay. This is consistent with the delay attribution: GSE-driven delay is very limited to only 0.52% of the flights with a mean average of 1.1 minutes per affected flight.

Overall, GSE effects are secondary in this model. They increase stand-access waiting in modes 1–2, but they rarely become the main reason why an aircraft departs late. The delay growth with PR is instead driven by reduced effective aircraft capacity and refuelling resource limits.

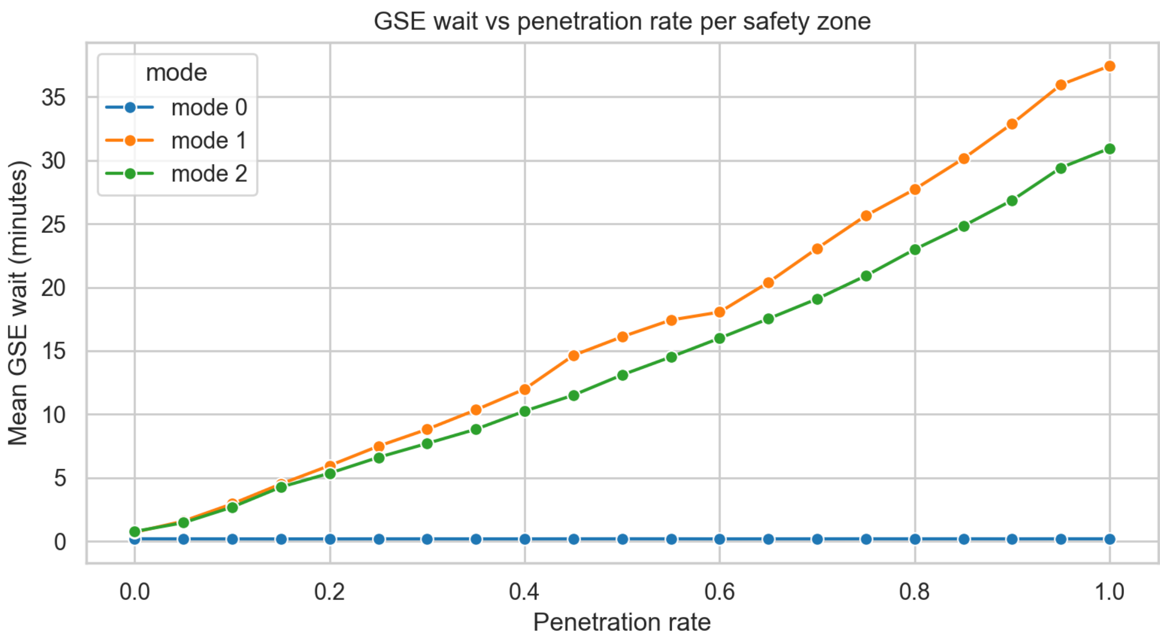


Figure 17: Mean GSE stand-access wait time vs. penetration rate by safety mode.

10 Discussion

This study uses findings from the LH_2 refuelling safety analysis to define safety-zone operating constraints and assess their impact on apron performance in a stochastic discrete-event simulation model. Safety is an operational objective and constraint, alongside efficiency and capacity, and it shapes apron performance through the same scarce assets: stands, access routes, and refuelling resources. The results support two main interpretations.

First, for open apron operations the distance-setting hazard set can be reduced to flash fire (delayed ignition) and jet fire (immediate ignition), while extreme escalation events primarily affect design and emergency planning. This is appropriate for routine zoning, but it also means that the chosen radii are hypothesized rather than definitive because they are not derived from a full QRA or detailed dispersion modelling.

Second, operational penalties are driven by a capacity mechanism with a regime change. When zones remain within a single-stand footprint, disruption is limited because aircraft flow is rarely blocked. When zones restrict neighbouring stands and access, delay growth becomes non-linear because stand unavailability creates queues and propagates across arrivals and departures. This implies that the enforceability and timing of the exclusion concept matter at least as much as the nominal radius.

The fleet-sizing sensitivity results support this mechanism. Increasing the number of LH_2 refuelling trucks reduces delay only until the binding constraint shifts from refueller availability to safety-driven stand unavailability. Beyond that point, additional trucks cannot restore throughput because aircraft cannot access stands or taxi out. This indicates that fleet sizing and zoning must be co-designed; truck capacity alone cannot compensate for multi-stand closures on compact aprons.

Several modelling choices limit generalisability. The airport representation is stylised, with simplified geometry, routing, and fleet behaviour. Gate assignment follows a deterministic rule rather than an optimisation or explicit queue-based policy, which can change congestion patterns in real operations. Ground handling is represented as aggregated GSE rather than vehicle-specific processes, so the model may understate interactions between individual services and constrained access. Safety zones are implemented as static circular areas, while real hazard footprints depend on wind, release orientation, local obstacles, and vent locations. The model is also two-dimensional and does not capture height effects, which may matter for exposure at wing level or for elevated jets and plumes. Finally, the study focuses on routine operations and does not model degraded or emergency conditions, which can impose stricter access rules and longer recovery times than assumed here.

Despite these limitations, the model is useful for identifying which levers dominate early operational feasibility. It suggests that hydrogen share is a first-order stressor, that multi-stand zoning can create structural capacity limits on compact aprons, and that operating concepts allowing safe partial overlap of activities can reduce delay for a given radius. These insights are actionable for early-adopter airports, but they should be re-tested with airport-specific layouts and more detailed hazard footprint modelling before being used for siting or compliance decisions.

11 Recommendations for Future Work

This thesis provides a first quantitative link between LH_2 refuelling safety zones and apron performance. Future work should first make the results easier to use for operational decisions, then represent zoning and mitigations in a more realistic way, and finally strengthen the safety basis and the validation of the model.

Service Levels and Refuelling Logistics

The most useful next step is to report results against clear service levels, not mainly mean delays. Mean values can hide a small set of flights with very large delays, while these late tails often drive operational problems. Therefore, future studies should include tail-focused KPIs such as percentile delays (e.g. the 95th percentile) and the share of departures outside an operational window. Once these targets are defined, LH_2 logistics can be treated as a sizing and dispatch problem. Future work should vary and optimise fleet size, dispatch rules, trailer sizing, and standby policies to meet the selected service levels. The same approach should also be applied to Jet-A1 fleets when both fuels operate in parallel, because scarcity in either fleet can dominate late-departure risk.

Operational Zoning and Enforcement

After service levels are defined, the next step is to model zoning in a way that better matches real operations. Static circular zones are a first approximation, but in practice restrictions depend on wind direction and on the refuelling phase. Future work should therefore use phase-dependent and directional footprints, such as downwind dispersion areas and jet-fire-axis constraints. Within these footprints, zones should be split into subzones with different access rules for personnel, GSE, vehicles, and ignition sources, instead of using one binary closure. This can reduce unnecessary blocking while still keeping strict control close to the refuelling interface.

Mitigation and Footprint Reduction

Mitigation should be modelled explicitly and linked to operational footprint. Key drivers are detection time, emergency shutdown response time, isolation effectiveness, and venting or deflection strategies. These inputs should be represented as distributions rather than fixed values, so that sensitivity analysis shows which parameters drive both operational impact and uncertainty. Future work should also test combined concepts that mix technical and procedural measures, such as improved detection, faster shutdown, alternative refuelling concepts, dedicated hydrogen stands, and sequencing rules. The aim is to quantify how much footprint can be reduced, and what this delivers in terms of service levels.

Safety Basis for Zoning Distances

The physical basis for exclusion distances should be strengthened using consequence modelling for representative LH_2 release cases at stands. Future studies should include dispersion and thermal-radiation modelling with validated correlations and CFD where justified. Weather variability, obstacle effects, and release orientation should be included because they can change the cloud and flame extent. Where feasible, these consequence results should be complemented with quantitative risk assessment (QRA), so that scenario frequencies and the reliability of protection layers (e.g. detection and emergency shutdown) are included when deriving or comparing zoning distances. The translation from consequence outputs to explicit acceptance criteria used in hydrogen and aviation contexts should be stated clearly to improve traceability.

Broader Operational Realism and Large-Zone Cases

Operational modelling should be extended beyond the current stand cluster. Future work should represent more realistic apron topology, including multiple taxilanes, alternative routings, and explicit pushback and taxi conflicts, as well as interaction with terminal-facing areas. Larger zones (> 40 m) should be tested with impacts beyond the stands, including terminal boundaries, buildings, equipment areas, evacuation paths, and emergency-access routes, because these constraints may become dominant once zones grow. The framework should also be applied to different airport layouts and traffic patterns, and coupling to stand-planning tools would help assess wider network effects.

Validation and Emergency Scenarios

Finally, stronger validation is needed. As demonstrators and early deployments produce data, model parameters should be calibrated against measured refuelling times, vehicle movements, blockage durations, enforcement practices, and incident-response durations. Emergency and degraded-mode operations should be included explicitly, such as stand evacuation, unplanned closures, and recovery times. This is needed to quantify how disruptions propagate through daily schedules and to test contingency procedures.

12 Conclusions

This work quantified how LH_2 refuelling safety zoning can constrain apron operations when hydrogen flights become part of the daily schedule. It combines (i) a qualitative safety analysis to identify key hazards for determining safety zones and key safety functions and (ii) an operational impact assessment that implements representative zones as spatial restrictions in a stochastic discrete-event model of a medium-size airport apron. Treating safety and operations at the same level clarifies both what drives practical stand-off distances and how those distances translate into delay and capacity effects at system level.

From the safety analysis, routine separation distances for open and well-ventilated apron stands are mainly driven by loss-of-containment outcomes with ignition: delayed-ignition flash fire and immediate-ignition jet fire. Other hazards remain important for design and procedures, including cryogenic exposure, oxygen enrichment, and failures in purge, venting, and verification, but they do not set the operational radius under the assumptions used. The fault trees and event sequence analysis identify a small set of cross-cutting safety functions that dominate escalation control: mechanical integrity of the cryogenic transfer chain, controlled venting and pressure protection, reliable leak/flame detection, rapid isolation (ESD), and strong ignition-source control supported by clear procedures.

From the operational assessment, delay is driven primarily by how much stand capacity and access is removed while refuelling is in progress, not by the presence of LH_2 service activities per se. When the safety concept stays close to a single-stand footprint, mode-to-mode differences remain small over a wide range of penetration rates. Once zoning leads to multi-stand blocking and stronger access restrictions, delays rise sharply and the system can enter a congested regime in which queues and stand unavailability dominate performance. This effect is nonlinear: at low penetration rates the system absorbs LH_2 operations with limited delay impact, while at higher penetration rates small additional blocking produces large increases in delayed-flight share and total delay.

Sensitivity across LH_2 stand and tanking configurations shows that effective refuelling time is the key operational lever because it sets how long stands and access routes are constrained. Differences in logistics choices (e.g. trailer involvement or tank capacity) matter mainly under high system stress and can become secondary once the apron is capacity-limited by stand availability. Within this modelling framework, GSE delays are a measurable side effect of the safety concept, but they do not explain the system-level delay growth; the dominant mechanism is aircraft-level capacity loss and refuelling resource contention during peak periods.

Overall, the combined findings imply that early LH_2 adoption at selected stands can be operationally feasible under conservative zoning if (i) zoning avoids multi-stand capacity loss where possible, (ii) refuelling duration and planning keep the constrained time short, and (iii) refuelling resources are sized for peak-day demand. In contrast, high penetration without dedicated stand concepts or revised apron procedures is likely to create strong delay and capacity penalties if multi-stand exclusion concepts are applied unchanged. The main practical value of the study is therefore the identification of safety functions and operational constraints that should be co-designed, rather than treated separately, when planning LH_2 airport refuelling.

References (Paper)

[1] Aerospace Technology Institute. *Hydrogen in Aviation: Progress and Outlook*. Tech. rep. Accessed 2025. Aerospace Technology Institute (ATI), 2024. URL: https://www.ati.org.uk/insight/hydrogen-in-aviation/.

[2] Airbus / GOLIAT Consortium. *GOLA: Ground Operations of Liquid Hydrogen Aircraft*. Project brochure, EU Horizon GOLIAT. Specifies LH_2 refuelling transfer capability of 5–6 t/h. 2024. URL: https://mediaassets.airbus.com/pm_38_747_747228-ni0nsggi79.pdf.

[3] Airports Council International (ACI) and Aerospace Technology Institute (ATI). *Integration of Hydrogen Aircraft into the Air Transport System*. White paper discussing operational and safety considerations, suggesting a 27 m exclusion zone during refueling. 2021. URL: https://www.ati.org.uk.

[4] L. Bernard et al. *D6.2: Novel guidelines for safe design and operation of LH2 systems and infrastructure*. Tech. rep. Project Deliverable, Version 3.0; Submission date: 30 April 2021. PRESLHY (Grant Agreement No. 779613), 2021. URL: https://hysafe.info/wp-content/uploads/sites/3/2021/05/PRESLHY_D6.2_3.0_finalversion.pdf.

[5] L. Braun and J. Classen. "Qualitative risk assessment of LH_2 refuelling for future hydrogen-powered aircraft". In: *International Journal of Hydrogen Energy* 47.19 (2022), pp. 11671–11685. URL: https://www.sciencedirect.com/science/article/pii/S2352146523012541.

[6] Clean Sky 2 Joint Undertaking and Fuel Cells and Hydrogen 2 Joint Undertaking. *Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050*. Tech. rep. Prepared by McKinsey & Company for the Joint Undertakings. Luxembourg: Clean Sky 2 Joint Undertaking, Fuel Cells, and Hydrogen 2 Joint Undertaking, May 2020. DOI: 10.2843/471510. URL: https://www.clean-hydrogen.europa.eu/system/files/2020-06/20200507_Hydrogen%2520Powered%2520Aviation%2520report_FINAL%2520web%2520%2528ID%25208706035%2529.pdf (visited on 12/18/2025).

[7] HySafe Consortium. *Ignition Probability and Jet Flame Behavior*. HySafe Knowledge Base. 2022. URL: https://www.hysafe.info.

[8] Jörgen Depken et al. "Safety Considerations of Hydrogen Application in Shipping in Comparison to LNG". In: *Energies* 15.9 (2022). Provides hydrogen combustion properties including flammability range (4–75 vol.%) and minimum ignition energy (0.02 mJ); Accessed 2025, p. 3250. DOI: 10.3390/en15093250. URL: https://www.mdpi.com/1996-1073/15/9/3250.

[9] Daan van Dijk et al. "Integrating liquid hydrogen infrastructure at airports: Conclusions from an ecosystem approach at Rotterdam The Hague Airport". In: *Journal of Airport Management* 18.4 (2024). Preprint available via ResearchGate; published by Henry Stewart Publications, pp. 367–396. DOI: 10.69554/UUEU4515. URL: https://www.researchgate.net/publication/384337905_Integrating_liquid_hydrogen_infrastructure_at_airports_Conclusions_from_an_ecosystem_approach_at_Rotterdam_The_Hague_Airport.

[10] *Dispersion of Gaseous Hydrogen Clouds*. H_2Tools Best Practices Note. Describes cold vapour cloud formation and rapid dispersion of cryogenic hydrogen vapours; Accessed 2025. n.d. URL: https://h2tools.org/sites/default/files/dispersion.pdf.

[11] EUROCAE. *ER-034: Hydrogen Fueling Stations for Airports in both gaseous and liquid form*. Tech. rep. Developed jointly with SAE (AE-5CH). EUROCAE, 2024. URL: https://www.eurocae.net/product/er-034-hydrogen-fueling-stations-for-airports-in-both-gaseous-and-liquid-form/.

[12] EUROCONTROL. *Standard Inputs for Economic Analyses: Turnaround time*. Accessed 2025-12-17. 2025. URL: https://ansperformance.eu/economics/cba/standard-inputs/latest/chapters/turnaround_time.html.

[13] European Industrial Gases Association (EIGA). *Safety in Storage, Handling and Distribution of Liquid Hydrogen*. Tech. rep. Doc 06/02/E. Replaces IGC Doc 06/93. EIGA, 2002. URL: https://h2tools.org/sites/default/files/Doc6_02SafetyLiquidHydrogen.pdf.

[14] Y. Gu et al. "Hydrogen-Powered Aircraft at Airports: A review of the infrastructure requirements and planning challenges". In: *Sustainability* 15.21 (2023), p. 15539. DOI: 10.3390/su152115539.

[15] Ethan S. Hecht, Brian D. Ehrhart, and Benjamin B. Schroeder. "Methodology for consequence-based setback distance calculations for bulk liquid hydrogen storage systems". In: *International Conference on Hydrogen Safety (ICHS) 2023*. Conference paper; publication date: 21 September 2023. 2023. URL: https://hysafe.info/uploads/papers/2023/140.pdf.

[16] Ethan S. Hecht et al. "Methodology for consequence-based hydrogen setback distances". In: *International Journal of Hydrogen Energy* 48.10 (2023). Provides flash-fire and jet-fire consequence distances typically ranging from 20–60 m for hydrogen releases, pp. 4201–4219. DOI: 10.1016/j.ijhydene.2022.11.178. URL: https://doi.org/10.1016/j.ijhydene.2022.11.178.

[17] Julian Hoelzen et al. "H2-Powered Aviation at Airports – Design and Economics of LH2 Refueling Systems". In: *Energy Conversion and Management: X* 14 (2022), p. 100206. DOI: 10.1016/j.ecmx.2022.100206.

[18] HyResponder Consortium. *Hydrogen Emergency Response Training for First Responders BLEVE Risk and Mitigation*. EU HyResponder Project Report. 2023. URL: https://www.hyresponder.eu.

[19] *ISO/TR 15916:2015 Basic considerations for the safety of hydrogen systems*. Technical Report. International Organization for Standardization. Geneva, Switzerland, 2015. URL: https://cdn.standards.iteh.ai/samples/56546/ea6f718a98c340279b350c7d48c03d80/ISO-TR-15916-2015.pdf.

[20] Gijs Janssen. "Modelling Hydrogen Refuelling Operations at Airports". Accessed 2025. MSc Thesis. Delft, The Netherlands: Delft University of Technology, 2023. URL: https://repository.tudelft.nl/.

[21] Laurent Lecomte et al. *European Emergency Response Guide (EERG) for First Responders*. HyResponder – European Train the Trainer Programme for Responders (FCH JU Grant Agreement No. 875089). Version: December 2022 (EERG V15). 2022. URL: https://hyresponder.eu/wp-content/uploads/2023/05/Final-English-EERG-December-2022_VFinal.pdf.

[22] D. Mangold et al. "Refueling of LH2 Aircraft—Assessment of Turnaround Procedures and Aircraft Design Implication". In: *Energies* 15.7 (2022), p. 2475. DOI: 10.3390/en15072475.

[23] National Fire Protection Association. *NFPA 2: Hydrogen Technologies Code*. 2019 Edition. NFPA. Quincy, MA, 2023.

[24] NIST/SEMATECH. *Confidence Limits for the Mean*. Accessed 2025-12-17. 2012. URL: https://www.itl.nist.gov/div898/handbook/eda/section3/eda352.htm.

[25] Pacific Northwest National Laboratory. *Hydrogen Properties, Hazards, and Best Practices*. H_2Tools Best Practices. Provides guidance on hydrogen ignition behaviour, flame visibility, and safety practices. n.d. URL: https://h2tools.org/bestpractices.

[26] Jan Sandora et al. "The Abbreviated Overall Anxiety Severity and Impairment Scale (OASIS) and the Abbreviated Overall Depression Severity and Impairment Scale (ODSIS): Psychometric Properties and Evaluation of the Czech Versions". In: *International Journal of Environmental Research and Public Health* 18.19 (2021), p. 10337. DOI: 10.3390/ijerph181910337.

[27] A. Tan et al. *Quick pit stops: A challenge for zero-emission planes?* International Council on Clean Transportation, accessed 2025. 2023. URL: https://theicct.org/quick-pit-stops-a-challenge-for-zero-emission-planes/.

[28] Unknown. *Safety Considerations for Hydrogen Use*. Tech. rep. States hydrogen flames are not visible in daylight; Accessed 2025. NASA Technical Report, 1997. URL: https://ntrs.nasa.gov/api/citations/19970033338/downloads/19970033338.pdf.

[29] K. Verfondern et al. *Handbook of Hydrogen Safety — Chapter on Liquid Hydrogen*. PRESLHY Deliverable D3.9, European Hydrogen Safety Panel. 2021. URL: https://hysafe.info/wp-content/uploads/sites/3/2021/04/D39_2021-01-PRESLHY_ChapterLH2-v3.pdf.

[30] K. Verfondern et al. *PRESLHY Handbook of Hydrogen Safety: Liquid Hydrogen Chapter*. Tech. rep. Deliverable D3.9. Contains LH_2 release, dispersion, ignition and jet fire experimental results. PRESLHY / European Hydrogen Safety Panel (EHSP), 2021. URL: https://www.hysafe.info/wp-content/uploads/sites/3/2021/04/D39_2021-01-PRESLHY_ChapterLH2-v3.pdf.

[31] World Economic Forum. *Target True Zero: Delivering the Infrastructure for Battery and Hydrogen-Powered Flight*. Tech. rep. White paper (Target True Zero initiative). PDF is linked from the publication page. World Economic Forum, Apr. 2023. URL: https://www.weforum.org/publications/target-true-zero-delivering-the-infrastructure-for-battery-and-hydrogen-powered-flight/ (visited on 12/18/2025).

II

Literature Study

Abstract

Liquid hydrogen (LH_2) is widely considered a promising pathway for decarbonising short- to medium-range aviation, but it introduces major integration challenges at airports. In particular, LH_2 refuelling requires cryogenic storage and transfer systems, robust vapour handling and emergency shut-down functions, and crucially well–defined safety and exclusion zones that may be substantially larger than those used for conventional Jet A-1 operations. These zones can constrain stand layouts, restrict concurrent turnaround activities, and reduce apron capacity if not designed and managed carefully.

This literature study synthesises current knowledge on (i) hydrogen aviation roadmaps and early-adopter airport concepts, (ii) LH_2 supply chains, on-site storage and distribution architectures (mobile bowsers versus hydrant systems), and (iii) the safety fundamentals that underpin separation distances, including dispersion behaviour, ignition phenomena, and dominant fire/explosion scenarios. It reviews the state of codes, standards and emerging aviation guidance (ISO, NFPA, PGS, SAE/EUROCAE and airport-focused studies), highlighting that existing separation-distance methodologies are largely derived from stationary industrial facilities and road-vehicle fuelling rather than dynamic apron environments. The review identifies flash fire (delayed ignition of a flammable cloud) and jet fire (immediate ignition of a high-pressure leak) as the main hazards used to define safety-zone distances for open-apron refuelling, while confined explosions and BLEVE-type escalation are treated mainly through design safeguards and emergency planning.

Finally, the study frames a key research gap: current airport hydrogen literature discusses safety zones and operational impacts largely in isolation, with limited quantitative coupling between consequence-driven safety zoning and apron performance metrics (stand availability, turnaround delay, and safety-zone penetrations). This gap motivates the thesis approach of embedding consequence-based safety zones into a discrete-event simulation of apron operations to assess safety–operations trade-offs for LH_2 refuelling.

13 Introduction

Decarbonizing aviation is critical for meeting global net-zero emissions targets by 2050. Hydrogen fuel particularly in the form of liquid hydrogen (LH_2)is increasingly considered a promising pathway toward low-carbon aviation because it eliminates CO_2 emissions at the point of use and offers high specific energy. In terms of timing, a first commercial hydrogen-powered flight is often discussed on a near-term horizon (mid-2020s), while the next generation of short-range hydrogen aircraft is expected to enter service around 2030–2035 [30]. Airbus has publicly positioned 2035 as a target for a hydrogen-powered commercial aircraft concept [45]. Jacobs further notes that hydrogen-powered aircraft could reduce the climate impact of flights by roughly 50–75% (estimate), depending on the operational context [45].

Realizing this transition will require profound systemic transformations at airports. Gu et al. emphasize that the technical requirements for hydrogen refuelling differ fundamentally from todays airport fuelling systems and that existing equipment cannot be directly adopted without major changes, implying significant investment in refuelling systems and associated ground infrastructure [30]. Beyond refuelling hardware, the transition affects airport planning across land use, utilities, safety and training, and therefore requires early integration into airport master planning to accommodate long lead times [30, 45].

A central operational challenge within this transition is ensuring safety during aircraft refuelling. Conventional aviation refuelling practices typically apply a harmonized fuel safety zone of about a 3 m radius in which ignition sources are not allowed [42, 39]. For LH_2 operations, larger refuelling exclusion zones are commonly anticipated in early concepts; Braun and Classen report indicative estimates in the range of about 8–20 m for safety exclusion zones during LH_2 refuelling [7]. Such enlarged zones may have major operational consequences: if tens of meters around an aircraft must remain clear, simultaneous activities such as boarding, catering, or the use of nearby stands may be constrained. This creates a need for scientifically grounded methods to define safety zones that satisfy safety requirements while remaining operationally workable.

Given the long lead times to plan, permit, and build new facilities, airports must begin integrating hydrogen provisions into master plans well before hydrogen aircraft are widespread, so that initial refuelling capabilities can be deployed and then scaled through the 2030s toward 2040 [30, 45]. Accordingly, this report reviews the systemic changes needed to enable LH_2 refuelling at airports by 2040, covering (i) infrastructure requirements and supply chain pathways, (ii) operational and safety considerations and evolving guidance, (iii) adoption and scalability across airport sizes, and (iv) regulatory and economic enablers and barriers.

14 Hydrogen aviation context & problem framing

Hydrogen is increasingly positioned as a key option in long-term aviation decarbonisation strategies, particularly for short- to medium-range flights where battery-electric concepts face gravimetric and volumetric limits.[2, 30, 40, 28] In this context, liquid hydrogen (LH_2) is one of the few energy carriers with sufficient specific energy for aviation applications, but it fundamentally reshapes aircraft design, airport infrastructure, and day-to-day ground operations.[1, 49, 32] This thesis focuses on one of the critical integration challenges: reconciling LH_2 refuelling safety zones with the operational realities of busy airport aprons.

14.1 From early concepts to demonstrators and roadmaps

Hydrogen-fuelled aircraft have been investigated since at least the 1970s, when NASA and industry partners explored experimental LH_2 aircraft configurations and associated airport requirements.[8] Although these early studies demonstrated technical feasibility, the combination of low fuel prices, infrastructure cost, and immature environmental policy meant that hydrogen did not progress beyond conceptual and experimental work.

The current wave of interest is driven by climate policy, corporate net-zero commitments, and advances in hydrogen technologies across sectors.[2, 40] Recent strategic roadmaps by the Aerospace Technology Institute (ATI), IATA and other organisations explicitly include hydrogen aircraft as a contributor to meeting 2050 climate targets, especially for short-haul routes.[2, 40, 38] In parallel, demonstration projects have moved from paper concepts to flight trials and airport pilots:

- OEM-led initiatives (e.g. Airbus ZEROe and "hydrogen hubs" concepts) investigate how commercial hydrogen aircraft could be integrated into future airport ecosystems.[5, 1]
- Operator-led demonstrators (e.g. ZeroAvias 19-seat hydrogen-electric aircraft and Universal Hydrogens capsule-based refuelling concept) explore regional-scale operations and modular refuelling approaches.[78, 72]
- Infrastructure-focused projects (e.g. GOLIAT and Zero Emission Flight Infrastructure reports) analyse options for hydrogen supply, storage and distribution at airports.[10, 75]

15 Why liquid hydrogen for aviation?

Hydrogen can be stored either as compressed gas (GH_2) or as cryogenic liquid (LH_2). For aviation, LH_2 is widely regarded as the more promising option for anything beyond very short ranges because of its significantly higher volumetric energy density compared to compressed hydrogen at practical pressures.[2, 30] While LH_2 still requires substantially more tank volume than conventional Jet A-1, its combination of high specific energy and reduced tank mass makes it attractive for new airframe designs.[49, 32]

However, this choice introduces several system-level challenges:

- **Cryogenic handling and boil-off:** LH_2 must be stored and transferred at around 20 K, with corresponding risks of cold burns, material embrittlement and boil-off management.[70, 74]
- **Tank and system integration:** LH_2 tanks tend to be larger and more spherical or cylindrical, pushing towards aft-fuselage or overhead integration rather than wing tanks, with direct implications for refuelling interfaces and ground handling.[2, 30]
- **Infrastructure intensity:** Producing, liquefying, transporting and storing hydrogen at airports adds significant electricity demand, CAPEX and safety constraints compared to drop-in sustainable aviation fuels.[10, 18]

Figure 18 shows a representative hydrogen supply and refuelling layout at a regional airport, with separate GH_2 and LH_2 storage, compression/liquefaction steps and mobile refuelling trucks.[24] In practice, such hydrogen systems would coexist with, or partially replace, conventional Jet A-1 farms; relative to a kerosene-only layout they illustrate the need for dedicated compounds, transfer lines and larger separation distances suggested in current guidance.[1, 10]

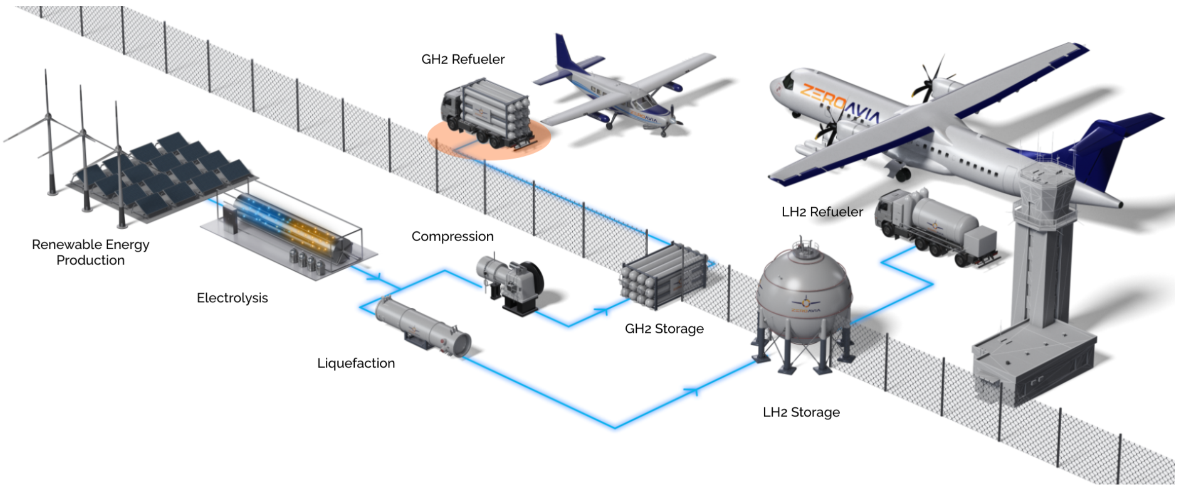


Figure 18: Conceptual layout of a hydrogen supply and refuelling system at a regional airport, including renewable power, electrolysis, GH_2 and LH_2 storage and mobile refuelling trucks. [24]

Because of these factors, many strategic studies conclude that LH_2 is technically plausible but heavily constrained by infrastructure and ground operations, especially at early-adopter airports with limited space and high traffic density.[1, 2, 30]

16 Early-adopter airports and apron refuelling

Policy frameworks such as the EU "Fit for 55" package, the ReFuelEU Aviation regulation and national hydrogen strategies encourage early deployment of hydrogen infrastructure in transport hubs, including airports.[21, 25, 12] In practice, only a subset of airports is likely to become early adopters in the 20302040 timeframe, typically those with:

- sufficient and relatively predictable short-haul traffic,
- available land or redevelopment opportunities for new energy infrastructure,
- strong decarbonisation commitments from airlines, airport operators and local authorities.[1, 2, 10]

Most hydrogen integration studies assume that initial operations will use existing aprons, stands and taxiways with as few disruptive layout changes as possible.[1, 30, 10] This implies that LH_2 refuelling will take place at or very close to conventional contact stands, often in parallel with other turnaround activities such as baggage handling, catering, cleaning and conventional refuelling for non-hydrogen flights.

Several infrastructure options are considered in the literature:

- **Mobile trailers and LH_2 trucks**, providing flexible but GSE-intensive refuelling to specific stands.[49, 49]
- **Semi-fixed LH_2 storage and distribution**, with cryogenic pipelines to hydrogen-capable gates.[32, 1]
- **Modular or capsule-based concepts**, where pre-filled modules are swapped rather than refuelling tanks in situ.[72, 24]

All of these concepts have in common that they bring cryogenic hydrogen, transfer equipment and additional GSE into an already crowded apron environment. This amplifies the importance of understanding how safety-driven stand-off distances and exclusion zones interact with turnaround processes and stand capacity.

17 Safety zones as an operational bottleneck

Hydrogen safety fundamentals are well documented in codes, standards and technical reports.[44, 70, 54, 74] Key properties such as wide flammability limits, low minimum ignition energy, high diffusivity and buoyant dispersion govern the design of separation distances, ventilation strategies and detection systems. For LH_2, additional cryogenic and phase-change phenomena (e.g. rain-out, cold clouds, liquid pooling) must be considered.[76, 34] Generic hydrogen standards (e.g. ISO/TR 15916, ISO 19880-1, NFPA 2, PGS 35) translate these phenomena into separation distance concepts for storage vessels, dispensers and process equipment, but they are largely based on stationary installations and road-vehicle fuelling stations.[44, 43, 53, 61]

Recent aviation-focused guidance, such as ATI/ACI integration reports and airport hydrogen infrastructure studies, begin to transpose these ideas to apron and gate layouts.[1, 2, 10] They qualitatively distinguish between zones in which hydrogen equipment may be located, areas where ignition sources are prohibited, and regions that must remain clear for emergency access. However, these documents do not yet provide fully validated, apron-specific LH_2 refuelling safety zones that account for realistic operations, stand adjacency and dynamic GSE movements.

Figure 19 provides an illustrative example of how refuelling-related zones can constrain apron activities. In the AZEA/ACI EUROPE factsheet, a large refuelling safety zone extends well beyond the stand, while only a smaller inner area is available for the fuel bowser and essential personnel.[77] This depiction reinforces the concern that conservative hydrogen safety distances may conflict with typical patterns of GSE movements and concurrent servicing around the aircraft.

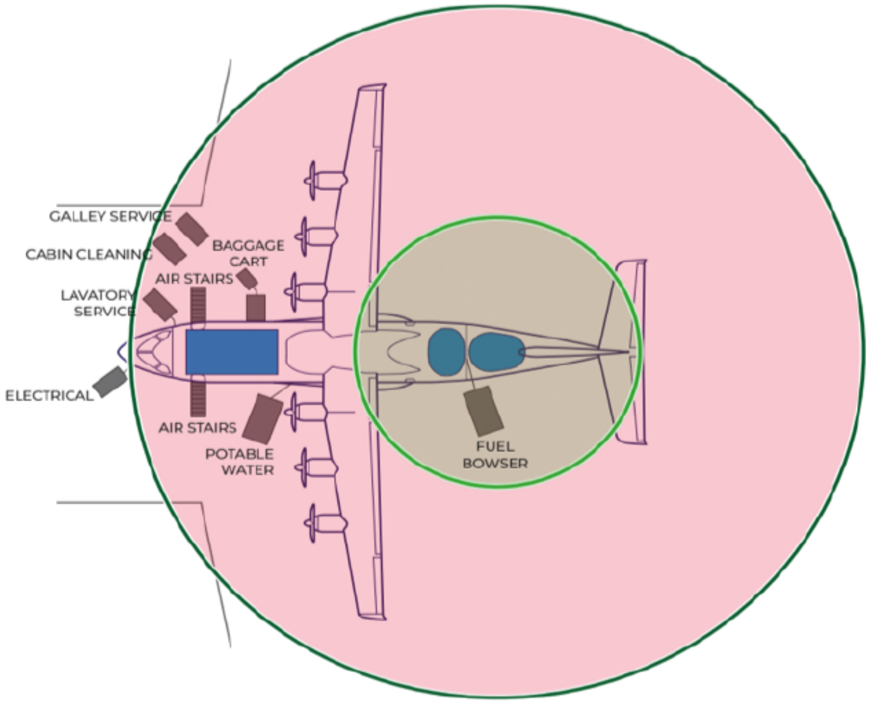


Figure 19: Illustrative refuelling safety zone around an aircraft stand, showing how a hydrogen refuelling area (inner zone) interacts with other ground-handling activities (outer zone). Adapted from the AZEA "Airports Infrastructure Factsheets Tool" for zero-emission aviation.[77]

The central problem that emerges from this literature is that safety zones are typically derived assuming conservative bounding scenarios and idealised layouts, whereas apron operations are highly dynamic, stochastic and constrained by stand geometry and airline schedules.[1, 2, 30] Existing airport hydrogen studies acknowledge potential conflicts, such as reduced stand availability, GSE rerouting, and extended turnaround times, but they do not explicitly model how different safety zone sizes, shapes and enforcement strategies affect operational performance metrics.

This thesis addresses that gap by coupling consequence-driven safety zones (based primarily on jet fire and flash fire endpoints) to a discrete-event simulation of apron operations. In subsequent chapters, the safety zones defined by hydrogen safety theory are translated into dynamic spatial constraints on stands and GSE routing, and their impact on stand occupancy, delay propagation and safety-zone penetration rates is quantified under realistic traffic scenarios.

17.1 Fueling safety zones and procedures

One immediate difference between conventional and hydrogen operations is the safety perimeter required during refuelling. With Jet A-1 kerosene, industry standards (e.g. IATA guidelines) typically establish a fuel safety zone of about a 3 m radius around the fuel vent and truck, within which ignition sources are prohibited during refuelling. In contrast, for liquid hydrogen, preliminary assessments indicate a much larger zone may be needed. Early studies suggest an initial safety zone on the order of 30–60 m radius for LH_2 refuelling operations, reflecting the greater potential hazard of hydrogen (e.g. fire or explosion risk if a leak occurs and ignites).[30] This zone could potentially be reduced with improved technology and refined procedures: for example, some concepts envision shrinking the zone to about 20 m during hose connection/disconnection and to 8–10 m during steady fuel flow.[30] Even so, these distances are considerably larger than for jet fuel and could significantly affect ramp operations, potentially preventing passenger boarding or servicing of the aircraft during refuelling unless stand layouts and turnaround sequences are adapted.

In this thesis, three terms are used consistently to frame the safety-operations interaction:

- **Safety zone** (or hazardous distance): a radius or footprint around the refuelling equipment and aircraft within which certain ignition sources, personnel or equipment are restricted during LH_2 refuelling. It is typically derived from consequence modelling (e.g. flash fire or jet fire endpoints).
- **Exclusion zone**: the area in which access is prohibited during refuelling, except for essential personnel and equipment directly involved in the operation. This may be equal to or larger than the safety zone, depending on operational policy.
- **Keep-clear corridor**: a directional extension of the exclusion zone (for example along the expected jet fire axis or hose routing), where mobile GSE and non-essential staff are not allowed to dwell or pass during sensitive phases.

In practical terms, these zones translate into a set of operational controls during LH_2 refuelling:

- Only trained hydrogen fuelling personnel are allowed near the aircraft during refuelling. Other staff and passengers must keep clear of the exclusion zone. This may require modifications to boarding bridges, stand layouts or sequencing (e.g. boarding after fuelling is complete).
- No ignition sources (sparks, open flames, certain electrical equipment) can be present in the safety zone. Ground power units and other vehicles near the aircraft may need to be hydrogen–fuelled or electrically powered units with appropriate certification.
- The refuelling team will typically wear protective gear (insulated gloves, face shields, etc.) to guard against cryogenic burns and will follow strict checklists for line purging, connections and disconnections.
- Coordination with the flight deck is crucial. The pilots must be informed of hydrogen fuelling status, as certain aircraft systems (such as ignition sources, radio transmitters or air conditioning packs) might need to be off during refuelling to avoid hazards.
- Emergency stop procedures must be in place: for instance, how to immediately halt fuel flow and safely vent pressure if a problem occurs. For LH_2, spill management is primarily about safe vapour dispersion rather than liquid containment, so preventing hydrogen accumulation in pits or enclosed areas is essential.

The aviation industry, through bodies such as SAE International and EUROCAE, is actively developing standards and guidelines for hydrogen refuelling processes (e.g. SAE AIR8547 and Airbus/ATI integration studies) to ensure that these zones and procedures are defined in a consistent, certifiable way.[65, 1, 2] Over time, airports are expected to integrate such guidance into their operating manuals and training programmes for fuel handlers and apron staff.

17.2 Firefighting and Emergency Response

Hydrogen necessitates new approaches to airport firefighting and emergency planning. Airport Rescue and Firefighting (ARFF) crews will need additional training and equipment to address hydrogen incidents [30]. Key considerations include:

- **Detection and monitoring:** Hydrogen fires burn with a nearly invisible flame and little radiant heat, so firefighters will use thermal imaging cameras or ultraviolet detectors to detect LH_2 fires. Hydrogen leak detectors around storage areas and aprons will aid in early warning.

- **Fire suppression agents:** While hydrogen fires cannot be smothered by conventional foam (since hydrogen carries its own oxidizer when burning in air), firefighters may use water sprays to cool adjacent structures and let a hydrogen fire burn itself out if it is venting upward safely. Dry chemical agents could be used on a small hydrogen flame, but the primary strategy is to isolate the hydrogen source. Specialized training scenarios will be developed for hydrogen leaks (unignited) vs. hydrogen fires.

- **Personal protective equipment (PPE):** ARFF teams will require PPE that can handle extreme cold (if contacting cryogenic liquid) as well as fire. Cryogenic protective suits or gloves might be added to standard turnout gear for certain response units.

- **Pre–incident planning:** Airports will establish clear protocols for hydrogen emergencies. For example, in the event of a significant hydrogen leak, sections of the airport may need evacuation due to the risk of gas accumulation. Fire crews must know how to safely shut off hydrogen flow remotely (emergency shutoff valves on tanks and hydrants) and how to approach an aircraft with hydrogen onboard that is in distress.

The location of hydrogen facilities will be chosen to mitigate risks. LH_2 storage tanks are likely to be placed in open, fenced areas away from terminals and busy aprons, reducing the impact of any incident. Blast walls or berms might be constructed around storage as a precaution. Similarly, hydrogen production or liquefaction plants (for those airports pursuing on–site generation) will have dedicated safety systems and buffer zones.

Coordination with local municipal fire departments and hazmat units will also be important, since off–airport agencies might assist in a large–scale hydrogen incident. Regular drills and simulations will ensure that all responders are familiar with hydrogens properties and the necessary response actions. Early studies suggest that while hydrogen poses different dangers than jet fuel (e.g., risk of detonation in confined spaces, extreme low temperature burns), the overall airport risk can be managed with proper preparation and does not make hydrogen–fueled aviation untenable from a safety perspective [30]. In fact, some properties of hydrogen are advantageous: it is non-toxic, disperses quickly upwards (being much lighter than air), and if it does burn, it produces no smoke, which could improve visibility for evacuation compared to a kerosene fire.

Figure 20: Emergency response exercise at Rotterdam The Hague Airport (RTHA) simulating a hydrogen leak scenario. [73].

17.3 Training and Regulatory Frameworks

The successful adoption of hydrogen at airports will hinge on extensive training and the evolution of regulations. All personnel who will work with or around hydrogen need to be educated on its characteristics and the new procedures. This ranges from fuel technicians and firefighters to ramp supervisors and air traffic controllers (who might need to know procedures for routing hydrogen tanker trucks or parking hydrogen-fueled aircraft in designated areas).

Training programs must cover hydrogen safety, equipment operation, emergency procedures, and routine maintenance of hydrogen systems. For instance, ground crews must learn to recognize the sound or frost patterns that might indicate a hydrogen leak. They should be able to implement evacuation of an area swiftly if alarms indicate a hydrogen release. Staff will also need to be familiar with personal protection measures when dealing with cryogens.

On the regulatory side, many rules will need to be developed or updated:

- **Aircraft certification and fueling standards:** Aviation regulators (like FAA, EASA) are in the process of establishing certification criteria for hydrogen-powered aircraft and associated systems. These will include standards for fuel tanks on aircraft, fueling ports, and ground handling procedures. Airports will coordinate with regulators to ensure compliance.

- **Airport design regulations:** Bodies such as the International Civil Aviation Organization (ICAO) and national authorities will issue guidance on airport facilities for hydrogen, including recommended practices for storage siting, fueling area ventilation, electrical equipment rating in hydrogen areas, and fire protection. Already, working groups (e.g. the Alliance for Zero-Emission Aviation in Europe) are bringing stakeholders together to formulate these standards [40].

- **Operational regulations:** Current rules (airport safety manuals, fueling operation regulations, etc.) will be amended to incorporate hydrogen. For example, codes may specify how many hydrogen-fueled aircraft can be refueled simultaneously, or what weather conditions (lightning, etc.) may suspend hydrogen fueling. There may also be new regulations on training certifications for hydrogen handlers.

- **Environmental regulations:** Handling hydrogen will involve some boil-off gas venting or flaring. Environmental authorities might set standards for hydrogen venting (though hydrogen itself is not a pollutant or greenhouse gas, any associated NOx from flame combustion could be of concern).

Airports that are early adopters of hydrogen (expected in the late 2020s) will play a role in validating and refining these regulations. Its likely that initial operations will occur under strict experimental or demonstration allowances, and as confidence grows, regulations will solidify by the mid-2030s. The period from 2025 to 2035 is identified as crucial for developing the regulatory framework and best practices in parallel with the technology development of hydrogen aircraft and ground systems [30]. Close collaboration is required across the aviation industry (aircraft manufacturers, airlines, fuel companies, airports, and regulators) to ensure that by 2040 a robust set of rules and procedures is in place for routine hydrogen flight operations [30].

Crucially, hydrogen safety and operational procedures must achieve a reliability level on par with or better than current jet fuel operations to gain public and industry confidence. History has shown that new aviation fuels (from early kerosene to todays evolving sustainable fuels) undergo intense scrutiny. Hydrogen will be no different, and comprehensive risk assessments and technology trials will underpin the eventual routine use of hydrogen at airports. Given the necessary lead time, those milestones need to be reached in the 2020s and early 2030s so that any outstanding issues can be resolved well before 2040.

18 LH_2 aircraft refuelling concepts and ground infrastructure

The refuelling system for liquid hydrogen (LH_2) aircraft spans the entire chain from hydrogen supply to the airport, via on-site storage and distribution, down to the transfer equipment at the aircraft stand. This section provides the technical basis for the scenarios modelled later in this thesis, focusing on architectures, transfer steps, mass-flow regimes and key components.

18.1 Airport hydrogen supply and on-site storage

Industry roadmaps typically distinguish three main ways for airports to procure hydrogen fuel:[45, 2, 30, 40]

1. **Trucked LH_2 from off-site production.** Hydrogen is produced and liquefied at industrial plants and delivered as LH_2 in road tankers. At the airport, the liquid is transferred into one or more vacuum-insulated storage tanks. This option has low upfront CAPEX and leverages existing industrial gas logistics, making it attractive for early, low-volume deployment.[45, 30] Its scalability is limited by the number of tanker movements, boil-off losses and the dependence on external supply chains.

2. **Pipeline GH_2 with on-site liquefaction.** Gaseous hydrogen (GH_2) is supplied via pipeline from a regional production hub or hydrogen backbone. An on-site liquefier converts GH_2 to LH_2 for storage and refuelling.[2, 40] This concept supports high, continuous throughput and reduces road traffic but requires major capital investment, long lead times and substantial electrical power for liquefaction.

3. **On-site hydrogen production by electrolysis.** The airport hosts electrolysers, powered by grid and/or local renewables, and may also include on-site liquefaction.[45, 2] This turns the airport into an energy hub that can supply hydrogen to aircraft, ground support

equipment (GSE) and potentially surrounding users. The concept is attractive for very large future demands but implies very high CAPEX, a large spatial footprint and strong dependence on low-carbon electricity availability.[30]

In all three cases, a common element is an on-site LH_2 storage facility sized to the expected daily or multi-day fuel demand. Studies and industrial guidance suggest above-ground spherical or horizontal cylindrical tanks with capacities from tens to several hundreds of tonnes of LH_2, equipped with vacuum insulation, boil-off gas handling (compression, reliquefaction or venting) and spill containment.[10, 23, 47] Separation distances from occupied buildings and public areas are typically derived from generic industrial standards and hydrogen safety guidelines rather than apron-specific analysis.[23, 44, 76]

These airport-side supply options sit within a broader hydrogen value chain that runs from primary energy and hydrogen production to on-site storage and, ultimately, into-plane refuelling. Figure 21 summarises this chain schematically: the three procurement pathways above correspond to different upstream segments, while the focus of this thesis lies in the downstream elementsairport storage, distribution and refuelling at the apron.[4]

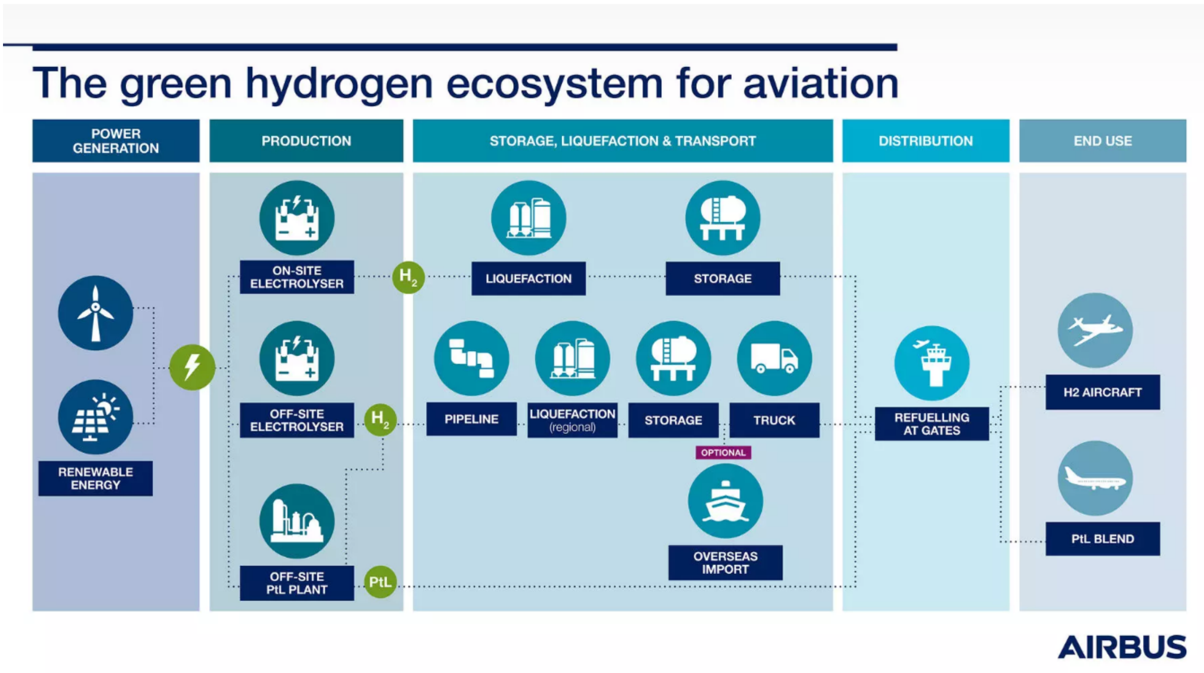


Figure 21: Illustrative hydrogen value chain from production to end use in aviation, reproduced from Airbus.[4]

Viewed from this value-chain perspective, hydrogen aviation is not a distant vision but a near- to mid-term integration problem for specific airports and use cases: decisions on supply route, storage concept and apron distribution architecture jointly determine both infrastructure needs and the safety constraints considered later in this thesis.

18.2 Distribution to the apron: mobile refuellers versus hydrant systems

From the central storage, LH_2 must be brought to individual aircraft stands. Two main distribution architectures are anticipated for aviation:[49, 1, 10]

Mobile LH_2 refuellers (bowsers). In this concept, cryogenic tanker trucks or large carts are filled at the storage area and drive to the stand, analogous to todays into-plane refuelling trucks for Jet A-1.[1, 79] Each refueller contains an insulated tank, a cryogenic pump (or pressurisation system), transfer hoses and instrumentation. Mobile refuellers offer high flexibility, relatively low fixed infrastructure cost and are therefore the favoured option for early deployments and at smaller airports.[10, 30] The trade-off is increased GSE traffic on the apron, more complex routing interactions and the need to manage safety zones around moving vehicles.

Fixed LH_2 hydrant systems. For large hubs with high hydrogen traffic, a fixed hydrant system is often proposed: LH_2 is pumped from storage through a network of vacuum-jacketed underground lines to hydrant pits near each stand, where a short hose or refuelling cart connects to the aircraft.[32, 49] This reduces tanker movements, can shorten refuelling times and centralises safety functions (e.g. emergency shut-down, vent routing). However, designing cryogenic hydrant systems is significantly more complex than for Jet A-1, requiring careful management of heat leak, pressure drop, maintenance and leak detection.[2, 10] Given CAPEX and construction complexity, several studies conclude that fixed LH_2 hydrants are mainly justified at very busy hubs in later phases of adoption, while most airports will rely on mobile refuellers well beyond 2040.[2, 30]

Modular or capsule-based refuelling concepts (e.g. containerised hydrogen modules loaded into aircraft) offer an alternative architecture, but these are not the primary focus of this thesis.[72]

18.3 Aircraft LH_2 transfer chain

Regardless of distribution architecture, the actual transfer of LH_2 into the aircraft follows a set of phases that are broadly consistent across concepts and emerging guidance such as SAE AIR8547 and related airport studies.[65, 49, 1]

1. **Positioning and preparation.** The refueller (truck or hydrant cart) is positioned at the stand within the designated safety zone. Wheel chocks are applied, the vehicle is bonded/grounded to the aircraft or a grounding point, and pre-refuel checks are completed.

2. **Connection and leak-tightness check.** The cryogenic hose is coupled to the aircraft receptacle using a dedicated LH_2 nozzle. Interlocks ensure correct alignment and locking. A brief low-pressure GH_2 or inert-gas pre-flow may be used to perform leak checks at the interface.[16, 59]

3. **Line pre-cooling and chill-down.** To avoid excessive flashing and thermal shock, the transfer line and parts of the aircraft feed system are cooled down by circulating a small flow of cold hydrogen until temperature and two-phase conditions are within specified limits.[49]

4. **Bulk LH_2 transfer.** Once chilled, bulk transfer proceeds at the target mass flow. Depending on the system design, flow is driven by a pump on the refueller or by tank pressurisation. Tank level, temperature and pressure are monitored in real time.[49, 32]

5. **Topping and pressure equalisation.** As the required fill level is approached, flow is reduced to avoid overfilling, and the aircraft tank pressure is equalised with the refuelling system. Automatic shut-off valves or high-level switches prevent overfill.[65]

6. **Blow-down and purging.** After main transfer, LH_2 in the hoses is typically blown back or allowed to vaporise, and the lines are purged with GH_2 or inert gas to remove residual liquid and air/oxygen, reducing the risk of flammable mixtures on the next connection.[76, 57]

7. **Vent management and disconnection.** Displaced vapour and boil-off during and after refuelling are routed to vent stacks or reliquefaction systems located outside critical

zones.[60, 23] Once conditions are confirmed safe, the nozzle is disconnected using a "clean break" sequence, and the refueller is prepared to leave the stand.

In this thesis, the most safety-critical phases for hazard identification and safety-zone definition are line pre-cooling, bulk transfer, topping and purging, when LH_2 flow and GH_2 release potential are highest.

18.4 Mass-flow regimes and turnaround compatibility

Hydrogen refuelling concepts must be compatible with airline turnaround requirements. Aircraft- and station-level studies suggest that LH_2 systems should target mass-flow rates broadly comparable to conventional jet fuel to avoid excessive ground time.[49, 32, 2]

Airport system studies such as GOLIAT estimate that a single refuelling position may need to handle approximately 5–6 t/h of LH_2 throughput to support typical short-haul operations, depending on fleet and schedule.[29] At aircraft level, Mangold et al.[49] and ten Damme et al.[11] report benchmark flows of roughly 15–25 kg/s per connection for single-aisle aircraft, resulting in bulk transfer times of 8–15 min for 8–15 t of fuel, assuming optimised thermal conditions. SAE AIR8547 adopts similar orders of magnitude when discussing performance targets for LH_2 aircraft refuelling systems.[65]

However, total refuelling time is more than just bulk flow. Thermal conditioning, purging, safety checks and connection/disconnection can add several minutes, particularly in conservative early-phase procedures.[49] Moreover, current hydrogen safety guidance and preliminary airport studies point to significantly larger exclusion zones during LH_2 refuelling compared to Jet A-1, which may restrict parallel ground operations such as boarding, catering or baggage handling.[1, 2, 30] Even if bulk LH_2 transfer can match jet fuel flow rates, enlarged safety zones and stricter operational modes may therefore become the true bottleneck for turnaround performance, an effect that this thesis investigates via discrete-event simulation.

18.5 Refuelling equipment, interfaces and safety functions

The above concepts rely on a set of specialised components and safety functions that differ in important ways from conventional fuel systems.

Cryogenic transfer lines and hoses. LH_2 is conveyed through vacuum-jacketed rigid lines and flexible hoses with low heat leak and controlled bend radius.[16, 59] Insulation integrity is critical to limit boil-off and avoid cold spots that could damage pavement or equipment.

Nozzles, couplings and breakaway devices. The nozzlereceptacle interface must provide rapid, leak-tight connection with minimal spillage and accommodate thermal contraction.[16] Breakaway couplers are typically installed to disconnect and seal both sides in the event of an unintended vehicle movement or excessive hose tension, reducing the risk of large releases.[35]

Emergency shut-down (ESD) and interlocks. ESD systems link pressure, temperature and leak detection sensors to automatic valves and pump controls.[65, 27] Typical designs provide local ESD buttons on the refueller, at the stand and at the storage facility. Activation of the emergency shutdown (ESD) isolates the hydrogen supply by closing the dispensers automatic shut-off valve; the ESD can be initiated manually or automatically (e.g. after an unsuccessful pressure integrity check, disconnection of the hose breakaway device, hydrogen detection, or ventilation/detection system failure).[17]

Vapour handling and vent routing. Boil-off from storage, pipeline heat leak and displaced vapour during refuelling are handled through dedicated GH_2 systems. Best-practice guidance recommends elevated vent stacks, unobstructed discharge locations and routing away from buildings, air intakes and traffic areas.[60, 23] Some designs include reliquefaction to minimise losses.[47]

Instrumentation and leak / flame detection. Hydrogen gas detectors are typically installed in areas where leaks may occur or where hydrogen could accumulate (e.g. equipment enclosures), and flame detectors are used to monitor areas where hydrogen is dispensed or handled.[37] Continuous monitoring supports early leak detection and informs both automatic ESD and operator response.

These equipment and safety functions form the barrier set used later in the hazard analysis and bow-tie models. Together with the refuelling architectures and mass-flow regimes described above, they define the technical boundary conditions for the safety-zone and operations assessment developed in subsequent chapters.

19 Hydrogen safety fundamentals

Hydrogen safety has been studied for decades in industrial, energy and transport applications, and a substantial body of work now exists on both gaseous and liquid hydrogen (LH_2).[44] For this thesis, the key role of this literature is to justify the selection of dominant hazards (in particular flash fire and jet fire) and to understand how release and dispersion behaviour translates into operationally relevant safety distances.

19.1 Key properties of gaseous and liquid hydrogen

Hydrogen safety guidance documents and reviews consistently highlight a set of properties that distinguish hydrogen from conventional hydrocarbon fuels.[3] In gaseous form, hydrogen has:

- a **wide flammability range** in air, much wider than that of typical hydrocarbons, which increases the probability that a leak will form a combustible cloud;[3]
- a **very low minimum ignition energy** compared to many other fuels, making ignition possible from weak sources such as static discharge or hot surfaces;[3]
- **high diffusivity and low density**, meaning that hydrogen released in open air tends to disperse rapidly upwards, which can be beneficial for risk reduction in well-ventilated environments but also leads to tall, buoyant plumes that can intersect elevated structures;[70]
- a **high laminar flame speed**, which can increase overpressure potential in partially confined geometries (though this is less critical for the open apron environment considered here).[44]

To highlight how unusual these properties are, Table 22 compares typical values for hydrogen with methane and gasoline vapour.

Fuel / vapour	Flammability range [% vol in air]	Min. ignition energy [mJ]	Diffusivity in air (qualitative)	Density vs air (relative)
Hydrogen (H_2)	$\approx$ 4–75	$\approx$ 0.02	Very high	$\approx$ 0.07
Methane (CH_4)	$\approx$ 5–15	$\approx$ 0.28	Moderate	$\approx$ 0.55
Gasoline vapour	$\approx$ 1–7	$\approx$ 0.20	Low–moderate	3–4

Figure 22: Illustrative comparison of key safety-relevant properties for hydrogen, methane and gasoline vapour, based on typical values compiled in hydrogen safety comparisons.[54]

Although liquid hydrogen (LH_2) is stored at near-ambient pressure, the refuelling system still involves significant pressure differences between tanks, lines and vent systems. Transfer lines and aircraft tanks must tolerate transients due to start-up, chill-down and emergency shut-down, and relief devices must safely discharge hydrogen in case of overpressure.[70] If a line or component fails, these pressure differences can drive high-momentum two-phase jets, so the same considerations that apply to high-pressure GH_2 (jet momentum, rapid gas expansion and associated cooling) also influence LH_2 release behaviour, even though nominal storage pressures are modest.

Liquid hydrogen adds pronounced cryogenic and phase-change hazards on top of these gaseous properties. LH_2 must be stored at approximately 20 K, and hydrogen safety handbooks emphasise risks of cold burns, material embrittlement, and thermal shock in structural components exposed to spills or cold vapour.[76] When LH_2 is released, a portion flashes to gas while the remainder may form a spreading cryogenic pool that gradually boils off; both phases contribute to the vapour cloud.[34] Very low temperatures affect material selection for tanks, piping and couplings (for example, favouring austenitic stainless steels and aluminium alloys over carbon steels) and can induce cracking or loss of ductility in unsuitable materials.[76] Cold hydrogen and associated chill-down of surrounding air can also produce oxygen-enriched "liquid air" and dense fog, which enhance combustion risk and reduce visibility around the leak.[58] From an infrastructure perspective, pavements and drainage need to be designed so that spilled LH_2 cannot accumulate under vehicles or aircraft and is directed towards safe, well-ventilated areas, limiting exposure of structures and personnel to extreme cold.[76]

Hydrogen flames can be difficult to see in daylight (often appearing pale blue and nearly invisible) and they emit low radiant heat.[36] As a result, visual detection cannot be relied upon; hydrogen-specific gas and flame detectors are treated as essential layers of protection in modern best-practice guidance.[55] These combined properties motivate conservative assumptions on ignition probability, leak detection and response times in the hazard selection for LH_2 refuelling.

19.2 Release types and LH_2 behaviour

Hydrogen systems at airports can experience a spectrum of release types, from very small leakage through seals or instrumentation ports to large full-bore ruptures of lines or hoses. Hydrogen safety standards and risk assessments typically distinguish between:[61]

- Pinhole or weeping leaks, which generate relatively low-momentum jets or diffuse seepage and may only pose a hazard in confined or poorly ventilated spaces;
- Intermediate leaks (e.g. small-bore piping failures), which produce visible high-velocity jets capable of forming flammable clouds or sustained jet fires;
- Full-bore breaks or catastrophic releases, where a major line or connection fails and large quantities of hydrogen are released in a short time.

For gaseous hydrogen, releases from high-pressure systems typically generate high-momentum jets with a narrow core and a surrounding turbulent mixing zone.[15] The flame length and thermal radiation footprint of a jet fire scale with release rate, nozzle size, and orientation, and are often used as endpoints when defining safety distances for hydrogen refuelling equipment.[50]

For LH_2 releases, the sequence from an initial highmomentum jet to a spreading pool and cold vapour cloud can be summarised in a few characteristic stages, as illustrated in Fig. 23.

Large-scale spill tests and associated modelling work show that an LH_2 release initially behaves as a dense, cold vapour cloud in the near field.[64] Immediately after release, rapid flashing and mixing with ambient air produce a cold hydrogenair mixture that may remain heavier than the surrounding air because of entrained cold nitrogen, oxygen and water droplets. This can lead to:

- a spreading pool of liquid hydrogen on the ground, whose evaporation drives vapour generation over tens of seconds to minutes;[34]
- a cold vapour cloud that can travel downwind close to the ground before gradually warming, becoming lighter than air and ultimately rising;[33]
- the formation of visible fog from condensed ambient moisture and, under some conditions, local oxygen enrichment near very cold surfaces.[56]

Ignited LH_2 releases have been studied in dedicated experiments. HSE reports on ignited LH_2 spills show transition from pool fires to large jet-like flames as the release conditions change, with hazard distances dominated by thermal radiation and flame impingement rather than explosion overpressure in open configurations.[31] This experimental evidence underpins the use of jet fire and flash fire endpoints, rather than vapour cloud explosion (VCE) or BLEVE, as the primary safety distance drivers for open-air LH_2 systems.[76]

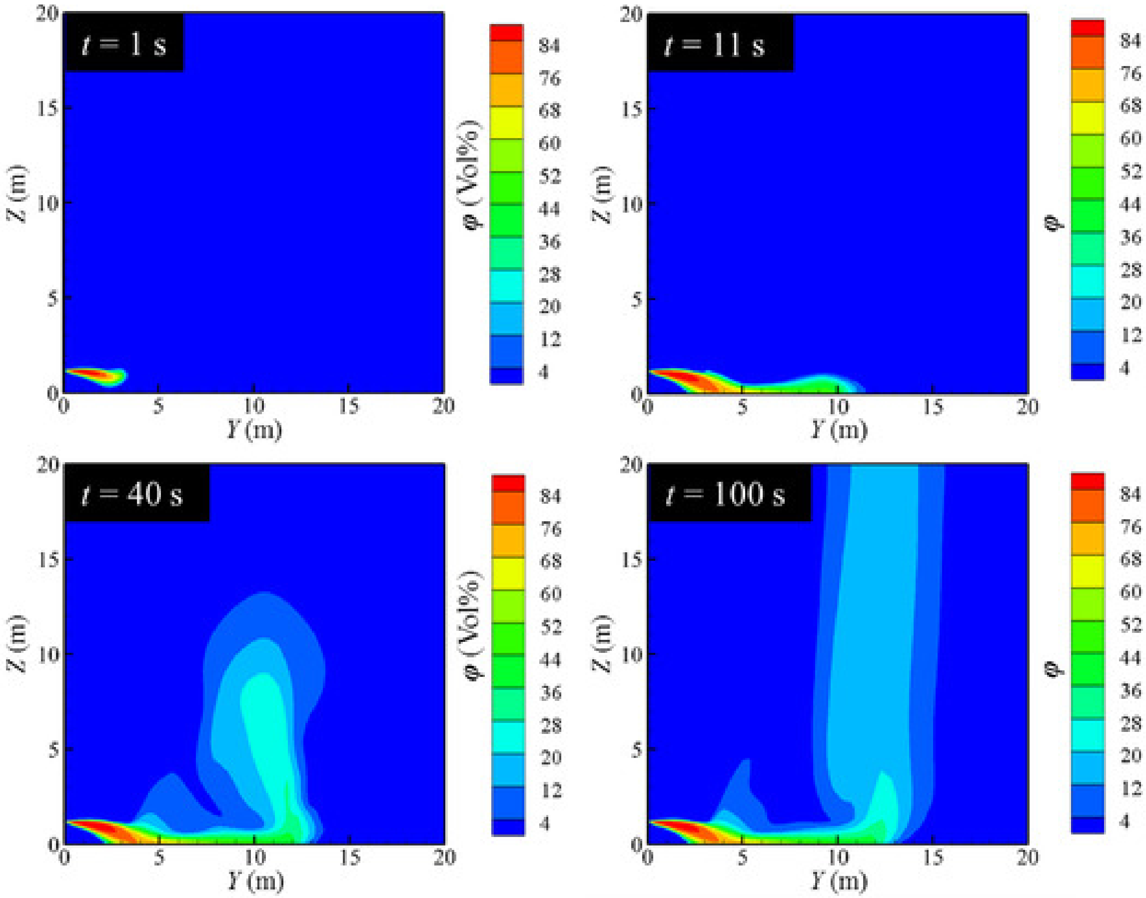


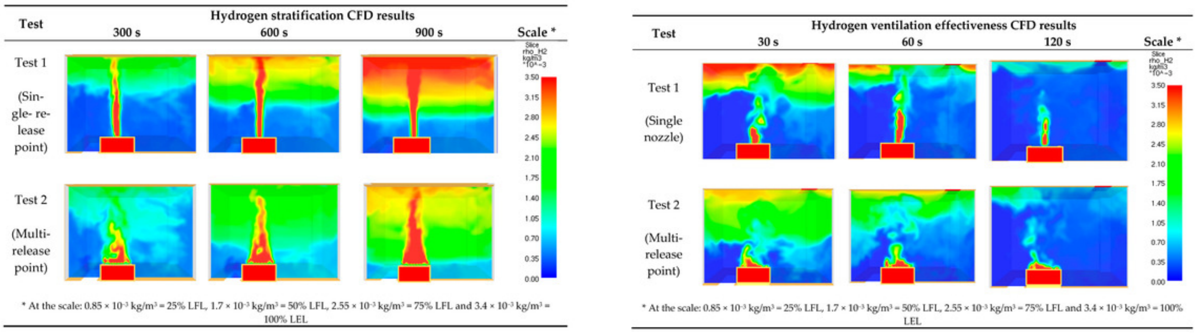
Figure 23: Illustrative evolution of an LH_2 release from an initial jet and liquid pool to a cold vapour cloud and subsequent buoyant plume rise, based on large-scale spill tests and modelling studies.[64]

19.3 Dispersion drivers and the apron environment

The dispersion of hydrogen from a release is controlled by a combination of source characteristics (release rate, temperature, orientation, phase), meteorology and local geometry.[6] Key drivers include:

- **Wind speed and direction**: higher wind speeds generally promote dilution and reduce near-field concentrations but can elongate flammable clouds downwind; low winds and stable atmospheric conditions favour larger horizontal extents.[64]
- **Obstacles and semi-confined regions**: buildings, equipment, and under-wing volumes can trap or redirect hydrogen plumes, leading to local pockets of high concentration or recirculation zones.[9]
- **Release orientation and elevation**: upward releases allow rapid vertical dispersion, while horizontal or downward releases (for example from low-mounted piping or spills) tend to interact more strongly with the ground and obstacles, increasing cloud footprint at human height.[15]

Studies of hydrogen behaviour in enclosures and partially confined spaces show that even small leaks can accumulate to flammable concentrations in roof spaces or under ceilings, particularly when ventilation is poor or intermittent.[9] Brzezińska[9] performed full-scale experiments and CFD simulations of continuous hydrogen releases in a closed room, demonstrating strong stratification of hydrogen-rich layers under the ceiling when no mechanical ventilation is present, and their rapid removal once ventilation is activated (Fig. 24). These results underpin strict ventilation and leak-detection requirements for indoor or enclosed hydrogen systems.



(a) No mechanical ventilation

(b) With mechanical ventilation

Figure 24: Hydrogen dispersion in a sealed enclosure without (a) and with (b) mechanical ventilation. [9]

The open airport apron differs in several important respects from the stationary industrial environments for which many hydrogen standards were originally developed.[1] First, aprons are typically highly ventilated open spaces, so long-term accumulation of hydrogen is less likely; instead, the dominant concern is the transient footprint of flammable clouds or jet flames during and immediately after a release. Second, the geometry is complex but not fully congested: aircraft fuselages, wings, boarding bridges and GSE create local semi-confined regions (e.g. under-wing volumes, between aircraft and terminal), but there is generally more open sky than in dense process plants. Third, the area is operationally dense, with frequent movement of vehicles and personnel, so the chance that a flammable cloud intersects ignition sources (vehicles, ground power units, electrostatic discharge) is high unless operations are tightly controlled.[2]

Consequently, for apron LH_2 refuelling, the literature supports focusing on flash fire (delayed ignition of a transient flammable cloud) and jet fire (immediate ignition of a high-momentum release) as the primary hazards that influence safety distances, while treating confined explosions and BLEVE primarily as design and emergency response considerations for storage and process equipment.[33]

20 Codes, standards and aviation guidance

Hydrogen use is already covered by a substantial body of generic safety codes and standards, most of which were developed for stationary industrial facilities and road-vehicle refuelling rather than airport apron operations. For LH_2 aircraft refuelling, these documents provide important boundary conditions (e.g. design principles, separation distance methodologies), but they do not yet offer validated, apron-specific safety zones for routine operations.

20.1 Generic hydrogen codes and standards

At international level, ISO/TR 15916 provides an overarching introduction to hydrogen properties, main hazards and basic safety measures (e.g. ventilation, leak detection, segregation of ignition sources) for a wide range of applications.[44] NFPA 2, the *Hydrogen Technologies Code*, consolidates requirements for the production, storage, piping and use of gaseous and liquid hydrogen, including hydrogen vehicle refuelling systems.[53] It defines design requirements, area classification and minimum separation distances for storage vessels, dispensers and process equipment, based largely on historic industrial experience and risk-informed correlation methods.

For gaseous hydrogen fuelling stations, ISO 19880-1 sets out general requirements for design, operation and safety, including a structured approach to determining safety distances using risk assessments and validated models.[43] In the Dutch context, PGS 35 translates such concepts into prescriptive and risk-based rules for hydrogen installations that deliver fuel to vehicles and equipment, with safety distances linked to quantitative risk criteria for the public and workers.[61] Recent guidance from the European Hydrogen Safety Panel (EHSP) complements these documents by promoting a systematic, risk-informed hydrogen safety engineering approach (scenario selection, modelling, validation and uncertainty treatment) across infrastructure projects.[22]

Other regulatory instruments, such as the ATEX Directive 2014/34/EU, govern the selection and certification of equipment used in potentially explosive atmospheres.[13] These frameworks ensure that components (e.g. electrical equipment, instruments, valves) in hydrogen systems meet minimum ignition protection requirements, but they do not prescribe geometry- or operation-specific safety zones at the level of an aircraft stand.

20.2 Aviation and airport-specific guidance

Airports and airlines operate within broader aviation safety frameworks (e.g. ICAO standards, EASA/FAA regulations and IATA operational guidance), which define high-level requirements for safety management, ground operations and fueling but remain largely fuel-agnostic.[40] Recent strategic reports on hydrogen aviation—such as the ATI/ACI study on integration of hydrogen aircraft into the air transport system—begin to transpose generic hydrogen safety concepts to airport layouts.[1] These documents discuss the need for increased separation distances around hydrogen equipment and, in some cases, suggest indicative “spark-free” zones and stand-off distances, but they stop short of providing validated numerical safety-zone envelopes for LH_2 refuelling on the apron.

The FAA’s *Hydrogen-Fueled Aircraft Safety and Certification Roadmap* identifies the key hazards of hydrogen (wide flammability, low ignition energy, cryogenic effects) and highlights the need for new ground-infrastructure standards and guidance covering fueling, storage and emergency response.[71] However, it explicitly frames this as a research and standardisation agenda rather than issuing prescriptive apron layouts or exclusion distances.

More targeted hydrogen-aviation documents are now emerging. SAE AIR 8547 provides performance and safety guidance for liquid hydrogen aircraft fueling, addressing topics such as fueling system architecture, emergency shutdown and safety interlocks.[65] In parallel, a joint SAE/EUROCAE effort has produced guidance for hydrogen fueling stations at airports (AIR8466 / ER034), which adapts vehicular-fuelling concepts (e.g. ISO 19880-1 methodologies) to airport contexts and sets high-level safety and performance requirements for hydrogen supply and dispensing systems.[19] These documents recognise the importance of safety zones around fueling operations and refer back to generic codes such as NFPA 2, but they do not yet provide a fully harmonised, quantitatively validated set of apron safety distances for LH_2 aircraft refuelling with mobile equipment.

20.3 Regulatory gap for LH_2 apron refuelling

Recent airport-focused risk studies and reviews consistently note a gap between generic hydrogen standards and the practical needs of apron operations.[7, 30] Existing codes (NFPA, ISO, PGS) and hydrogen safety engineering guidance (EHSP) provide the tools to *derive* safety distances, but they are based on stationary installations or road-vehicle stations and assume relatively controlled layouts.[53, 43, 61] Aviation roadmaps and SAE/EUROCAE documents acknowledge hydrogen-specific hazards and sketch qualitative stand layouts but do not yet deliver apron-wide,

LH_2-specific refuelling safety zones that have been validated against realistic airport geometries and operations.[1, 65, 19]

In particular, there is currently no publicly available guidance that simultaneously:

1. specifies quantitative safety and exclusion-zone distances for LH_2 aircraft refuelling on open aprons (including mobile tanker and hydrant concepts) under a range of credible leak and ignition scenarios;

2. links these distances to standard airport stand layouts, adjacent stands and typical ground support equipment routes; and

3. evaluates the operational compatibility of such zones in terms of stand availability, turnaround time and conflict with other apron activities.

This regulatory gap motivates the approach in this thesis: to use consequence-based hydrogen safety insights (e.g. flash fire and jet fire endpoints) as inputs to a discrete-event simulation of apron operations, and to assess how different safety-zone assumptions affect operational performance. In that sense, the work aims to complement and inform evolving standards, rather than to replace or compete with existing hydrogen and aviation codes.

21 Airport hydrogen risk studies and safety assessments

A growing body of work examines how hydrogen, and in particular liquid hydrogen (LH_2), can be integrated into airport operations from a safety and risk perspective. These studies provide important context and qualitative insights for this thesis, but they generally stop short of quantitatively assessing operational performance impacts of safety zones.

Early airport-level analyses focus on conceptual layouts and hazard identification rather than detailed risk quantification. Braun and Classen [7] develop a qualitative risk assessment framework for "hydrogen-enabled airports", comparing different fuelling and storage concepts using a structured risk matrix. Their work highlights large indicative separation distances, the importance of emergency response preparedness, and the need for early integration of hydrogen safety into master planning, but does not quantify turnaround or stand-availability impacts. Gu et al. [30] review infrastructure requirements and planning challenges for hydrogen-powered aircraft at airports and emphasise siting constraints, regulatory uncertainty and training needs for airport staff as key implementation barriers.

Several applied projects translate hydrogen safety knowledge into airport-specific guidance. The ATI/ACI white paper on integrating hydrogen aircraft into the air transport system [1] and the ATI FlyZero infrastructure report [2] outline representative airport layouts with on-site LH_2 storage, distribution systems and stand concepts. They discuss safety zones qualitatively, pointing to potentially large exclusion areas around storage and refuelling operations and the resulting pressure on apron real estate. Connected Places Catapult similarly surveys hydrogen infrastructure options for airports, identifying land-take, zoning constraints and certification of new equipment as primary challenges rather than providing detailed risk contours [10]. EU demonstration projects such as GOLIAT and TULIPS extend this work by defining indicative operational requirements for airport implementation (e.g. target LH_2 refuelling flow rates for competitive turnaround) and by outlining safety, emergency response and training considerations for early deployment at airports.[29, 69] .

More focused technical studies address specific parts of the hydrogen airport system. Mangold et al. [49] analyse LH_2 aircraft refuelling turnaround procedures and identify critical steps (docking, purging, chill-down, venting) from both safety and timing perspectives, but treat safety distances as given inputs rather than variables. Recent safety assessments of hydrogen systems for aviation infrastructure adopt a mixture of HAZID/HAZOP-style approaches and preliminary consequence analysis. For example, Simonetto et al. [68] present a preliminary safety assessment of an LH_2 storage system for commercial aviation, identifying key hazards, safeguards and escalation paths, while Jaffary and Wiedemann [46] combine structured hazard analysis with incident data and expert input to explore safe hydrogen refuelling at airports. These studies converge on similar themes: jet fires and flash fires as dominant scenarios in open-air settings, the importance of leak detection and emergency shutdown, and the need for robust training and procedures.

Across this literature, scenario selection and modelling assumptions are typically anchored in existing hydrogen safety knowledge and codes. Representative leak sizes, release orientations and weather conditions are chosen, and consequence models or published results are used to infer indicative safety distances for LH_2 storage and refuelling equipment.[7, 1, 49, 68] However, the resulting zones are generally treated as static design constraints. Airport reports and academic papers acknowledge that large safety or exclusion zones could reduce stand availability, restrict concurrent ground operations and increase turnaround times, but they do not explicitly couple these zones to an airport operations model that can quantify delay, stand blocking or conflict rates.[30, 2, 10, 29, 46]

This thesis positions itself in that gap. It builds on the hazards, safety distances and qualitative insights from the above airport hydrogen risk studies, but moves a step further by embedding consequence-driven safety zones in a discrete-event simulation of apron operations. In doing so, it aims to assess how different LH_2 refuelling safety-zone assumptions translate into operational metrics such as stand occupancy, delay propagation and safety-zone penetration rates, complementing existing safety assessments rather than replacing established hydrogen and aviation standards.

22 Airport apron operations modelling and delay propagation

Airport operations form a complex network of interdependent processes and stakeholders (airlines, ground handlers, ANSPs, airport operator), in which delays can propagate from one node to another.[63] Conceptual frameworks of the airport operations network show how disturbances in the rotation phase between inbound and outbound flights—including gate occupancy, turnaround tasks and pushback—can amplify reactionary delays and affect overall punctuality.[63] For this thesis, the apron and turnaround processes are the main interface between safety constraints (e.g. refuelling zones) and operational performance.

22.1 Discrete-event simulation for apron and turnaround processes

Discrete-event simulation (DES) is a natural choice for modelling apron operations because it represents systems as a sequence of events (arrivals, start/end of tasks, resource releases) that change the system state in time.[62] Aircraft, ground support equipment (GSE) and service teams can be modelled as entities competing for limited resources (stands, fuel trucks, loading teams), while queues and waiting times emerge when demand temporarily exceeds capacity.

In a typical apron DES model, each aircraft turnaround is decomposed into a set of activities (e.g. deboarding, catering, cleaning, refuelling, baggage handling, boarding) with precedence constraints and stochastic durations. Stands and GSE units are modelled as shared resources; when a flight arrives or is ready for a service, it seizes the required resources if available or waits in a queue if not. Taxi-in, pushback and taxi-out phases can be included at a high level to capture stand occupancy and potential conflicts at apron taxiway. This structure allows the model to capture:

- **Stand occupancy and blocking**, when arriving aircraft cannot park because stands are still occupied by delayed departures;

- **Resource contention**, when limited numbers of fuel trucks, loaders or tow tractors must be shared across neighbouring stands;
- **Routing interactions**, for example when GSE movements between stands create additional travel time or interfere with pushback and taxi flows.

DES is particularly suited to studying "what-if" changes in procedures or constraints—such as introducing LH_2 refuelling safety zones—because the underlying event logic (who can move where and when) can be modified without changing the overall modelling paradigm.[62]

22.2 Delay metrics and reactionary propagation

From an operations perspective, the primary performance outputs of apron DES models are delay-related metrics. Building on the broader airport delay literature,[63] typical indicators include:

- **Departure delay** relative to scheduled time, both as an average and as the fraction of flights exceeding a threshold (e.g. D+15);
- **Turnaround extension**, defined as the difference between planned and realised turnaround time for each flight;
- **Stand unavailability**, measured as the time during which arriving flights cannot access their planned stand because it is occupied or blocked;
- **Queue and waiting times** for critical resources (fuel trucks, de-icing trucks, loading teams), which indicate where congestion builds up;
- **Reactionary delay**, where late arrivals cause subsequent outbound legs to depart late because turnaround buffers are insufficient.

Rodríguez Sanz et al. show, at whole-airport level, how delays arising from capacity shortfalls or inefficient resource use in the rotation and turnaround phases can propagate through the airport operations network and contribute significantly to network-wide delay.[63] In a DES model focused on the apron, this propagation is represented explicitly: a delay in one service (e.g. refuelling or loading) can postpone pushback, extend stand occupancy, and ripple to other flights that depend on the same stand or GSE.

22.3 Validation and verification considerations

As with any simulation study, the credibility of apron DES results depends on careful verification and validation. Standard DES practice includes debugging the event logic (verification) and comparing model outputs against historical data or operational expert judgement (validation).[62] For apron operations, this typically involves:

- checking that simulated stand occupancy, taxi times and service durations fall within realistic ranges;
- reproducing baseline statistics such as average departure delay, distribution of turnaround times and typical GSE utilisation levels;
- consulting ground handling and apron control experts to ensure that routing rules, priority policies and operational constraints are represented faithfully.

In this thesis, DES is therefore used as a structured way to translate safety-zone assumptions for LH_2 refuelling into quantitative changes in stand occupancy, resource contention and delay propagation, rather than as an optimisation tool in its own right. The emphasis is on comparing relative scenarios (e.g. different safety radii or concurrent-operations policies) under a consistent, validated operational model.

23 Adoption Scenarios and Timeline for Implementation

Airports will not all transition to hydrogen at once; different adoption scenarios exist regarding how hydrogen refuelling infrastructure and operations might scale up over time. In this section, we outline plausible scenarios for the introduction and growth of hydrogen fueling at airports, considering the period up to 2040. These scenarios take into account both the technological readiness and the demand for hydrogen-fueled flight services.

One scenario **(Scenario A: Niche Early Adoption)** assumes that by the 2030s, hydrogen refuelling is introduced at only a small number of airports, primarily small to medium facilities in selected regions, to support short-range demonstrator routes. In this conservative scenario, hydrogen aircraft remain a niche (serving perhaps regional commuter flights or cargo feeders) through 2040. Only dozens of airports worldwide might be equipped for hydrogen by 2040, primarily using delivered liquid hydrogen. Larger hubs might delay investment until hydrogen aircraft performance improves for medium-haul routes. This cautious approach could result from slower technology progress or preference for drop-in Sustainable Aviation Fuels (SAF) in the interim. Airports in this scenario focus on minimal infrastructure, just enough to handle a small number of hydrogen flights per week.

A second scenario (**Scenario B: Gradual Expansion**) sees a steady but moderate uptake. Here, initial hydrogen flights start around 2028-2030 on regional routes. By mid-2030s, a number of national and regional airports in pioneering countries (e.g., in Europe, North America, East Asia) have installed basic hydrogen facilities. Perhaps 100-200 airports globally are hydrogen-capable by 2040, including some major hubs that service short-haul traffic. In this scenario, airports implement hydrogen in phases: first using trucked LH_2, then expanding storage, and possibly planning for pipeline supply by the late 2040s. Hydrogen aircraft might capture a few percent of short-haul flights by 2040, with corresponding infrastructure sized for that level. This scenario aligns with industry roadmaps that assume hydrogen starts with regional aircraft and gradually moves to single-aisle short/medium flights by the 2040s [40]. Airports and airlines would be learning and scaling together, with each year seeing incremental improvements in procedures and cost reductions.

A third scenario (**Scenario C: Rapid Transformation**) posits more aggressive adoption. In this future, technological breakthroughs and strong climate policies drive airlines to invest heavily in hydrogen. Several major aircraft manufacturers field hydrogen-powered models by the mid-2030s, including a single-aisle airliner capable of 10001500 km missions. By 2040, hydrogen aircraft could account for a significant share of short-haul flights (perhaps 1520% of the fleet on those routes). To support this, many large airports, potentially the majority of hubs in Europe and Asia, have hydrogen infrastructure in place or under construction by 2040. This would likely necessitate pipeline supply or on-site production at the biggest airports to meet the volume (tens of thousands of kilograms of H_2 per day per airport). In this scenario, hydrogen fueling becomes a routine part of operations at hundreds of airports, and global standards and supply chains for hydrogen aviation are mature. Airports might interconnect with hydrogen pipelines and share resources as part of a broad energy network.

Each scenario has different implications for the systemic changes required:

- In the slow adoption case (A), only modest investment is needed initially, but this could leave the sector behind on climate goals. Airports might struggle later to catch up if hydrogen suddenly becomes necessary.

- The gradual case (B) is perhaps the most realistic, with manageable investments spread over time and the chance to refine systems with pilot programs. Airports in this scenario would ensure some level of hydrogen readiness in the 2030s (e.g., allocating space for hydrogen facilities, training a core team, starting with a small storage tank and a truck refueler) then expand as aircraft availability grows [45].
- The rapid case (C) would require coordinated, proactive planning starting now. Many airports would need to begin design and construction of hydrogen infrastructure before 2030 to be ready for a large wave of hydrogen aircraft by 2040 [30]. This would also demand strong policy support and capital expenditure on the promise that hydrogen aircraft will arrive.

Notably, even in the faster scenarios, conventional jet fuel and SAF will still be used at airports in parallel with hydrogen through 2040 and beyond. The transition will be gradual on the global scale; thus airports must plan for a hybrid fuel ecosystem. This includes managing two separate fueling systems (and ensuring safety in such a mixed environment). It may also require decisions about which gates or zones are designated for hydrogen-fueled aircraft versus conventional ones, and how to flexibly allocate infrastructure if the balance shifts.

An alternative approach to hydrogen fueling that could influence adoption scenarios is the concept of modular hydrogen fuel cartridges. Companies like Universal Hydrogen have proposed delivering hydrogen to aircraft in pre-filled modules (cylinders or capsules) that are loaded into the aircraft, rather than pumping hydrogen on the tarmac [40]. This would eliminate on-airport liquefaction and possibly even on-airport storage (if the modules are filled off-site and delivered as needed). Such a system could reduce the initial infrastructure burden on airports, making early adoption easier. For instance, an airport could use a forklift to swap hydrogen modules on a regional airplane, avoiding the need for cryogenic transfers on the apron. However, widespread use of modular capsules would require aircraft designs compatible with that approach and a logistics system for moving heavy hydrogen containers. It remains one of the innovative ideas to potentially streamline hydrogen introduction.

In summary, the period to 2040 will likely see a transition from small-scale hydrogen refuelling trials to integrated, higher-volume operations at major airports. A plausible sequence includes early commercial hydrogen flights in the mid-2020s, initial refuelling facilities at a limited number of airports around 2030, entry into service of hydrogen airliners in the mid-2030s, followed by broader airport rollout in the late 2030s. By 2040, hydrogen operations could become routine on selected international networks. The pace of adoption will depend on technical maturity and coordinated commitment across industry and regulators. Even under a moderate uptake scenario, airports need to start preparatory work now. The next section discusses how rollout strategies differ between small and large airports

24 Scalability Across Different Airport Types

Airports vary widely in size, throughput, and resources. A one-size-fits-all approach to hydrogen integration will not be feasible. Instead, the strategies and pace of adoption will differ for small regional airports versus large international hubs. This section examines how hydrogen refuelling infrastructure can be scaled and tailored to different airport categories, and the unique challenges and opportunities each faces.

24.1 Small and Regional Airports

Smaller airports (e.g., general aviation airports, regional airports with a few commercial flights a day) could both benefit from and be challenged by hydrogen. On one hand, these airports often serve short-haul routes that are the early targets for hydrogen aircraft. A regional airport could be the terminus for a 30-seat hydrogen commuter plane or a 70-seat short-hop flight, making it a candidate for early hydrogen fueling facilities. On the other hand, small airports have limited finances and space, and they will not invest in complex infrastructure unless absolutely needed.

For many regional airports, the initial hydrogen solution will likely be the simplest: periodic delivery of a small amount of liquid hydrogen via tanker trailer, stored in a compact dewar tank, and dispensed by a mobile refueler. In some cases, if the aircraft using the airport are very small (e.g., 10-20 seaters or retrofitted aircraft with hydrogen fuel cells), gaseous hydrogen refuelling might even suffice, using high-pressure gas trailers, since those aircraft might carry gaseous hydrogen instead of liquid to save cost. Indeed, analysis suggests that gaseous hydrogen could be practical at the very small end of aviation and that only larger airports will need liquid hydrogen [10]. The Connected Places Catapult study in the UK, for example, indicated that the two smallest archetype airports would primarily use gaseous hydrogen or have low enough demand to be met with truck deliveries, whereas larger airports move to liquid [10].

Small airports will likely not build on-site hydrogen production in the 2040 timeframe, as their volumes wont justify it. They will rely on the broader supply chain (regional production and trucking). Given the low flight frequency, even a single storage tank and one refuelling truck might be adequate through 2040. The adoption may also be reactive: a small airport might only install hydrogen facilities once an airline commits to hydrogen service at that location. Until then, they might take a wait and see approach.

An important consideration is that small airports often have more flexibility in land use (open space for a hydrogen tank might be easier to find compared to dense hubs) but fewer resources for specialist staff. They might depend on third-party companies to handle hydrogen delivery and fueling operations. For instance, an airline or a hydrogen fuel provider might set up a self-contained hydrogen refuelling unit at the regional airport to support its routes, with the airport authority only providing the site and oversight.

24.2 Large Hub Airports

Major airports (large hubs with tens of millions of passengers per year) face a different scenario. These airports are central to airline networks and will eventually need to accommodate hydrogen to meet airlines fleet changes and environmental goals. A crucial aspect is volume: a busy hub in a hydrogen future could require an enormous quantity of hydrogen. IATAs analysis forecasts that a single large airport could demand on the order of thousands of tonnes of liquid hydrogen per day by mid-century if a substantial portion of flights convert to hydrogen [40]. Even by 2040, if hydrogen remains limited to short-haul flights, the busiest hubs might still need on the order of 100–300 tonnes of LH_2 per day to fuel a fraction of their departures.

Such volumes are beyond the practical limit of tanker truck deliveries alone. For context, a typical LH_2 tanker might carry 34 tonnes per load. To supply 200 tonnes in a day would require 50+ truck deliveries daily, which is logistically impractical and would congest airport access roads. Therefore, large hubs will likely have to transition to pipeline delivery or large-scale on-site generation as hydrogen demand grows [10]. In the interim (2030s), they may start with truck delivery for small pilot operations, but by 2040, planning for pipelines could be underway. In fact, studies suggest that for the biggest airports, hydrogen pipeline infrastructure becomes the only feasible solution to supply the required fuel by the 2040s [10]. Some proposals include connecting airports to national hydrogen pipeline networks (such as the European Hydrogen Backbone concept) or building dedicated spurs. This is a massive undertaking that requires coordination at national/international levels, underlining why early planning is needed.

Space is another premium at hubs. Installing large LH_2 storage (potentially multiple tanks each the size of a building) and liquefaction or pumping stations will be challenging at land-constrained airports. Planners might consider using peripheral land or even off-site facilities linked via pipeline to the terminals. Safety distances from passenger terminals and runways will factor into site selection for hydrogen systems. The integration of hydrogen must also consider not disrupting existing fuel farms and operations.

An advantage larger airports have is access to capital and the ability to form partnerships. Many hubs are operated by well-funded entities that can invest in innovative projects. We may see joint ventures between airports, energy companies, and governments to build hydrogen infrastructure at hubs. For example, an airport could partner with an industrial gas company to install and run a hydrogen liquefaction plant on airport property, supplying both the airport and perhaps other local consumers. Some major airports are already exploring becoming multi-fuel energy hubs (providing not just kerosene but also electric charging, hydrogen, etc. in the future).

Large hubs also will push the boundaries of technology usage. They might be the first to implement hydrant refuelling for hydrogen if gate utilization is high. They will also likely serve as key nodes in any early hydrogen flight network, so their ability to handle hydrogen reliably is crucial to the overall success of hydrogen aviation.

24.3 Medium-Sized Airports

Medium airports (say 515 million passengers/year or primarily domestic hubs) sit somewhere between the two extremes. Their approach may depend on their role:

- If a medium airport is a base for short-haul operations (e.g., a hub for a low-cost carrier), it could adopt hydrogen relatively early for those routes. Its volume might outgrow pure truck delivery by 2040 but could be met with a combination of multiple daily truck deliveries and perhaps a small on-site electrolyzer for supplementary supply if the business case allows.

- Conversely, if the airports traffic is mostly long-haul or its in a region slow to move to hydrogen, it might not invest until later, focusing instead on SAF for widebody flights.

Medium airports have an opportunity to learn from both ends: they can observe trials at small airports and the large infrastructure builds at big hubs, then choose a right-sized solution. Many medium airports might ultimately implement a Scenario 1 (truck delivery) approach through the 2030s and only consider more advanced options post-2040 if hydrogen scales up. This avoids stranding investments if hydrogen adoption is slower than anticipated.

Table 7 provides a qualitative overview of how hydrogen refuelling might scale for different airport types by 2040, highlighting their likely strategies and infrastructure choices.

It is worth noting that not every large hub will be an early mover. Some major airports might delay hydrogen adoption if their home carriers focus on drop-in SAFs for decarbonization. Conversely, some smaller airports could aggressively pursue hydrogen if it aligns with regional economic opportunities (for instance, an airport in an area with abundant renewable energy might see hydrogen as a chance to become a fuel producer). Thus, while size is a good general predictor of strategy, local factors will also play a role.

Nonetheless, scale does matter for hydrogen. Economic analyses show significant economies of scale in hydrogen production and logistics [32]. Larger airports can leverage this by implementing bigger facilities that drive down per-unit costs (for example, a large liquefier is more efficient than many small ones). Small airports, purchasing lower volumes, will face higher unit costs for hydrogen fuel delivered. This could potentially create a gap where flying hydrogen into smaller markets is more expensive, unless subsidized or balanced by policy (just as fuel costs vary by airport today).

Policymakers might need to ensure smaller airports are not left behind; for instance, government grants could help fund hydrogen infrastructure at remote airports that would otherwise not afford it but are essential for regional connectivity. Collaboration between large and small airports (sharing lessons, joint procurement of hydrogen fuel in bulk, etc.) may also help the overall network adoption.

In summary, by 2040 we expect for small airports: limited, truck-based hydrogen operations for niche routes; otherwise mostly unchanged. Medium airports: incremental hydrogen facilities sized for short-haul flights, primarily using delivered liquid and modular growth. Large airports: substantial hydrogen infrastructure with advanced supply solutions (pipeline or on-site production) in progress to handle significant demand, integrated into their overall fuel systems.

25 Integrating safety zones and apron operations

The hydrogen airport literature has so far developed along two largely parallel tracks: safety-focused studies that derive or discuss hazard scenarios and safety distances, and operations-focused studies that analyse airport capacity, turnaround performance and delay propagation. Very few works attempt to couple these perspectives in a quantitative way for LH_2 apron refuelling.

On the safety side, several airport-oriented studies qualitatively assess the risks of hydrogen aircraft ground operations and highlight the need for substantial safety and exclusion zones. Ehrhart et al. develop a qualitative risk ranking framework for hydrogen fueling at airports, emphasising ignition control, training and layout constraints, but without explicitly computing operational impacts[14]. Braun and Classen analyse future hydrogen-enabled airports and identify large safety distances, emergency planning and staff competence as key design drivers[7]. More recent work by Jaffary and Wiedemann, as well as Simonetto, extends this line of analysis to LH_2 storage and refuelling concepts, combining HAZOP-style hazard identification with preliminary safety architectures for airport hydrogen systems[46, 68]. Strategic infrastructure studies (e.g. ATI/ACI, Connected Places Catapult, GOLIAT and TULIPS) discuss hydrogen-specific hazards and propose indicative stand layouts and safety distances, typically derived from existing standards and preliminary risk assessments rather than being coupled to a detailed airport operations model[1, 10, 29, 69, 39].

In parallel, a mature body of airport operations research uses discrete-event simulation (DES), queuing models and scheduling theory to study stand occupancy, turnaround processes and delay propagation [62]. These models typically resolve aircraft turn processes (fueling, catering, cleaning, boarding), resource contention (stands, gates, ground support equipment) and gate/stand allocation policies, and they evaluate performance metrics such as average delay, on-time performance (e.g. D+15), and resource utilisation [67, 66, 48, 20]. However, this literature almost always assumes conventional Jet A-1 fueling and does not introduce hydrogen-specific spatial or temporal constraints such as enlarged refuelling safety zones, exclusion areas or keep-clear corridors.

A small number of recent hydrogen aviation studies acknowledge that safety zones could constrain apron capacity or delay operations, but only at a conceptual level. For example, Mangold et al. show that LH_2 refuelling durations can be made broadly compatible with current turnaround times for single-aisle aircraft, but they do not propagate safety-zone radii into a full apron operations model[49]. Reviews by Gu et al. and ATI highlight that stand layout and separation requirements could become a bottleneck, especially at space-constrained hubs, yet they stop short of formalising these zones as dynamic constraints in DES or gate-allocation models [30, 2].

To the author's knowledge, there is currently no published work that simultaneously:

1. derives or selects LH_2 refuelling safety and exclusion-zone distances from hydrogen safety theory and consequence modelling;
2. embeds these zones as spatial constraints and "no-go" areas within a stochastic apron DES model (for both tanker-truck and hydrant concepts); and

3. quantifies how zone size, enforcement stringency and penetration behaviour affect key operational performance indicators such as turnaround delay, stand availability, and the penetration rate of vehicles or personnel into restricted areas.

This gap motivates the approach in this thesis. Consequence-based safety zones (dominated by jet fire and flash fire endpoints) are used as inputs to a discrete-event model of apron operations, in which refuelling safety zones are represented as dynamic spatial constraints on aircraft stands and ground support equipment routing. By comparing scenarios with different zone radii, enforcement modes and penetration behaviour, the model aims to estimate both operational impacts (delay, stand conflicts, resource queues) and operational safety metrics (zone penetration rates) in a consistent framework.

Table 7: Hydrogen Refuelling Implementation by Airport Type (circa 2040) [30, 45, 10]

Airport Type	Hydrogen Refuelling Approach by 2040
Small regional airport (light commercial or general aviation)	Few hydrogen flights (if any) served. Likely uses truck-delivered LH_2 on an as-needed basis. A small cryogenic tank (or even just the supply tanker itself) suffices for storage. May employ portable or skid-mounted hydrogen fueling equipment operated by a third-party. Unlikely to invest in dedicated infrastructure until traffic justifies. In some cases, might support gaseous hydrogen refuelling for fuel-cell aircraft instead of liquid. Overall adoption is minimal and reactive, depending on specific airline plans.
Medium airport (regional hub or mid-size city airport)	Moderate hydrogen operations if short-haul routes are hydrogen-powered. Likely started with Scenario 1 (truck delivery of LH_2) in the 2030s; by 2040 has expanded storage (e.g., multiple tanks) and improved fueling logistics to handle daily flights. Still primarily uses tanker refuelers for delivery to aircraft. Possibly evaluating on-site hydrogen production or pipeline connection for post-2040 if demand is expected to keep rising. Infrastructure is modular, scaling up in steps (e.g., adding extra storage or a larger off-loading facility for more frequent tanker deliveries). Coordination with airlines on future requirements is ongoing.
Large international hub (major world airport)	By 2040, has dedicated hydrogen infrastructure in place or under construction. Large-scale LH_2 storage (multiple very large tanks) located in a safe, accessible area. Likely moving beyond truck delivery: either a high-capacity hydrogen pipeline feeds the airports storage, or a substantial on-site hydrogen plant is operational to produce and liquefy hydrogen [10]. Hydrogen refuelling is integrated into operations at many gates, potentially via fixed hydrant systems at new hydrogen-equipped gates or still using a fleet of advanced cryogenic fuel trucks. Extensive safety systems and monitoring are deployed. The airport has trained in-house teams for hydrogen management and works closely with fuel suppliers. Long-term agreements ensure hydrogen supply availability. Planning considers that hydrogen demand could grow exponentially towards 2050, including possibly servicing long-haul hydrogen aircraft if they emerge. As a result, designs are future-proofed (e.g., space allocated for additional tanks or pipeline expansions). The airport likely participates in industry groups to standardize hydrogen operations and may host demonstration projects (such as trials of new refuelling technologies) given its prominence.

26 Operational and Safety Considerations

Hydrogen introduces new operational protocols and safety requirements in the airport environment. Both the properties of the fuel (extremely low temperature, light molecular weight, high diffusivity, wide flammability range) and the novel refuelling methods mean that airports must adopt revised procedures to maintain safety and efficiency.

26.1 Current practice and challenges

In conventional aircraft fueling with kerosene, a safety distance of approximately 3 meters around the fueling point is common practice, within which no ignition sources or unauthorized persons are permitted. This is, for example, maintained as a harmonized zone in IATA guidelines[41]. For hydrogen, safety experts expect significantly larger distances, depending on the phase and form of refuelling. International fire safety codes such as NFPA 2 provide indicative distances for hydrogen fueling systems based on hazardous area classification. For vehicle hydrogen fueling points, the no-ignition-source zone is typically about 7.6 m for liquid hydrogen and about 4.6 m for gaseous hydrogen[52].

As of 2025, specific aviation standards for hydrogen aircraft refuelling are still lacking, although EASA has outlined at a high level what airport infrastructure will be needed for alternative fuels such as hydrogen[26]. Recent studies indicate that airports in their current form are not yet prepared for large hydrogen safety zones[30]. These studies emphasize the need for substantial adaptations across the entire airport environment (from landside to airside and emergency services) to integrate hydrogen safely. For instance, a white paper by Munich Airport International (2022) identifies significant investments in fueling infrastructure, storage, and logistics required for large-scale hydrogen implementation[51].

A direct consequence of larger safety zones is that gates may need to be spaced further apart or that certain stands can only be used alternately (to ensure sufficient separation between two hydrogen aircraft). It may also be necessary to designate specific hydrogen gates, for example at the end of a pier or on isolated aprons, so that a 30–60 m exclusion zone does not overlap other aircraft positions or terminal areas. Airbus and partners are already considering layouts in which hydrogen aircraft are not positioned directly adjacent to conventional aircraft during refuelling, or in which refuelling occurs via a remote hydrant system away from the gate. Another solution is to strategically position the refuelling connections on the aircraft itself: one concept is to place fueling points toward the tail or at the outer wing tips, so that the 8–20 m hazard zone is oriented as much as possible "away from the terminal".

Beyond operational adjustments, technical innovations are also being explored to reduce risks. A notable concept is that of modular hydrogen capsules. The company Universal Hydrogen proposed not to transfer hydrogen into the aircraft via a tanker truck or hydrant, but instead to load ready-to-use, prefilled hydrogen modules (tanks) into the aircraft. After landing, empty capsules would be removed and replaced with full ones, which are filled externally (outside the airport). This means that no open liquid or gas transfer with the aircraft needs to occur on the apron, substantially reducing the likelihood of leaks during normal operations. Universal Hydrogen demonstrated the swapping of such modules in an ATR-72 test aircraft in 2023[72], and reported that the process is comparable to swapping batteries or cargo. According to the company, their approach requires "no additional airport infrastructure"[72], because the hydrogen is delivered in closed pressure vessels via standard freight logistics. Naturally, these capsules themselves must meet stringent safety requirements (including automatic pressure relief and leak detection). If modular refuelling succeeds at scale, airports may require far fewer modifications to gate and apron design. The safety zone around an aircraft using modular hydrogen would then likely be limited to a small buffer (comparable to kerosene) during loading and unloading of the modules. This concept is therefore being followed with considerable interest as a potentially risk-reducing innovation.

In summary, the literature shows that hydrogen safety at airports is a multidisciplinary challenge. On the one hand, physical risks of fire, explosion, and cold injury must be well understood and modeled. On the other hand, the resulting safety measures must remain workable within the operational context of a busy airport. Knowledge gaps remain regarding the precise distances required and how future airports can accommodate them. This leads to the central research question of this proposal: *How can we determine safe safety distances around hydrogen refuelling operations that comply with applicable safety standards while simultaneously minimizing the impact on airport operations?* The next section outlines the research plan designed to answer this question.

References (Paper)

[1] Aerospace Technology Institute and Airports Council International. *Integration of Hydrogen Aircraft into the Air Transport System*. Tech. rep. ATI / ACI, 2021. URL: https://www.ati.org.uk/wp-content/uploads/2021/08/aci-ati-hydrogen-report-1.pdf.

[2] Aerospace Technology Institute (ATI). *Hydrogen Infrastructure and Operations: Airports, Airlines and Airspace (FlyZero Report FZO-CST-POS-0035)*. Tech. rep. Aerospace Technology Institute, 2022. URL: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf.

[3] Air Products and Chemicals, Inc. *Safetygram #9: Liquid Hydrogen*. PDF; hosted on U.S. Department of Energy (EERE) website; accessed 15 Dec 2025. 2007. URL: https://www.energy.gov/eere/fuelcells/articles/safetygram-9-liquid-hydrogen.

[4] Airbus. *Exploring hydrogen: The green hydrogen ecosystem for aviation*. Online article. Figure "The green hydrogen ecosystem for aviation" used as illustrative hydrogen value chain. 2021. URL: https://www.aircraft.airbus.com/en/newsroom/news/2021-09-exploring-hydrogen.

[5] Airbus. *Hydrogen Hubs at Airports Developing a global hydrogen ecosystem*. 2023. URL: https://www.airbus.com/hydrogen-hubs-at-airports.

[6] C. D. Barley and K. Gawlik. *Buoyancy-Driven Ventilation of Hydrogen from Buildings: Laboratory Test and Model Validation*. Tech. rep. NREL/TP-550-45804. Golden, CO: National Renewable Energy Laboratory, 2009. DOI: 10.2172/956886. URL: https://docs.nrel.gov/docs/fy09osti/45804.pdf.

[7] M. Braun and A. B. Classen. "Qualitative risk assessment for future hydrogen-enabled airports". In: *Transportation Research Procedia* 75 (2023), pp. 86–95. DOI: 10.1016/j.trpro.2023.12.011.

[8] Brewer, G. D. (Ed.) *LH2 Airport Requirements Study*. NASA Contractor Report (NASA CR-2700), October 1976, PDF. 1976. URL: https://ntrs.nasa.gov/api/citations/19770003090/downloads/19770003090.pdf.

[9] Dorota Brzeziska. "Hydrogen Dispersion and Ventilation Effects in Enclosures under Different Release Conditions". In: *Energies* 14.13 (2021), p. 4029. DOI: 10.3390/en14134029. URL: https://www.mdpi.com/1996-1073/14/13/4029.

[10] Connected Places Catapult. *Zero Emission Flight Infrastructure Hydrogen Infrastructure Options for Airports*. Tech. rep. 2023. URL: https://cp-catapult.s3.amazonaws.com/uploads/2023/03/Zero-Emission-Flight-Infrastructure-%E2%80%93-Hydrogen-Infrastructure-Options-for-Airports.pdf.

[11] L. ten Damme et al. "Simulation of the Refuelling Process for an LH_2-Powered Aircraft". In: *International Journal of Hydrogen Energy* (2025). Online first. URL: https://www.sciencedirect.com/science/article/pii/S0360319925051717.

[12] Department for Energy Security and Net Zero. *Hydrogen strategy update to the market: December 2024*. Policy paper. PDF available at: https://assets.publishing.service.gov.uk/media/6761915126a strategy-update-to-the-market-december-2024.pdf. Dec. 2024. URL: https://www.gov.uk/government/publications/hydrogen-strategy-update-to-the-market-december-2024.

[13] *Directive 2014/34/EU on equipment and protective systems intended for use in potentially explosive atmospheres (ATEX)*. Official Journal of the European Union. 2014. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0034.

[14] Brian Ehrhart. *Hydrogen Safety Codes and Standards*. Presentation (H2@Airports Workshop), Sandia National Laboratories. SAND2020-11250PE. Nov. 2020. URL: https://www.energy.gov/sites/prod/files/2020/12/f81/hfto-h2-airports-workshop-2020-ehrhart.pdf.

[15] I. W. Ekoto et al. "Updated Jet Flame Radiation Modeling with Buoyancy Corrections". In: *5th International Conference on Hydrogen Safety (ICHS 2013)*. Brussels, Belgium, 2013. URL: https://hysafe.info/ichs2013/images/papers/110.pdf.

[16] Elaflex. *H2 Hydrogen & Carbon Capture News 2023 – Information 9.22*. Product information sheet (PDF). Reports an LH_2/sLH_2 nozzle flow rate of 150 L/min (640 kg/h). Rev. 8/2023. 2023. URL: https://elaflex.de/dokumente/download/ElaflexInformation/ELAFLEX_Information_9.22.pdf.

[17] Electrical and Mechanical Services Department (EMSD). *Code of Practice for Hydrogen Filling Stations*. Issue 0, February 2024, PDF. 2024. URL: https://cnsd.gov.hk/wp-content/uploads/2024/03/CoP-for-HFS-issue-0_r1.pdf.

[18] Transport & Environment. "The Cost of Hydrogen Aviation Briefing". In: *T&E* (2022). URL: https://te-cdn.ams3.cdn.digitaloceanspaces.com/files/The-cost-of-hydrogen-aviation-Final-Briefing-2.pdf.

[19] EUROCAE. *ER-034: Hydrogen Fueling Stations for Airports in both gaseous and liquid form*. Tech. rep. Developed jointly with SAE (AE-5CH). EUROCAE, 2024. URL: https://www.eurocae.net/product/er-034-hydrogen-fueling-stations-for-airports-in-both-gaseous-and-liquid-form/.

[20] EUROCONTROL. *Punctuality (OTP15)*. Definition page. URL: https://ansperformance.eu/definition/punctuality/.

[21] European Commission. *'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality*. 2021. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0550.

[22] European Hydrogen Safety Panel. *Guidance on Hydrogen Safety Engineering*. Tech. rep. Brussels, Belgium: Clean Hydrogen Joint Undertaking, 2023. URL: https://www.clean-hydrogen.europa.eu/system/files/2023-05/EHSP%20Guidance%20on%20Hydrogen%20Safety%20Engineering%20-%20v1-Final.pdf.

[23] European Industrial Gases Association. *Safety in Storage, Handling and Distribution of Liquid Hydrogen*. Tech. rep. Doc 06/19. Brussels, Belgium, 2019. URL: https://www.eiga.eu/uploads/documents/DOC006.pdf.

[24] European Marine Energy Centre (EMEC). *HyFlyer II first flight test of hydrogen-electric engine*. Online article. Describes ZeroAvias maiden flight of the 19-seat Dornier 228 hydrogen-electric testbed and associated (mobile) hydrogen refuelling set-up. Jan. 2023. URL: https://www.emec.org.uk/hyflyer-ii-first-flight-test-of-hydrogen-electric-engine/.

[25] European Parliament and Council of the European Union. *Regulation (EU) 2023/2405 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation)*. 2023. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023R2405.

[26] European Union Aviation Safety Agency (EASA). *EASA H2 Activities – General Overview (June 2023)*. Accessed 2025. 2023. URL: https://www.easa.europa.eu/en/downloads/138051/en.

[27] Federal Aviation Administration. *Hydrogen-Fueled Aircraft Safety and Certification Roadmap*. FAA Report. Describes emergency shut-off design requirements, fail-safe valves, and operational redundancy. 2024. URL: https://www.faa.gov/aircraft/air_cert/step/disciplines/propulsion_systems/hydrogen-fueled_aircraft_roadmap.

[28] Stephen Gifford. *Powering the Skies: The Rise of Electric and Low-Carbon Aircraft*. Tech. rep. Faraday Insights – Issue 19. Faraday Institution, Apr. 2024. URL: https://www.faraday.ac.uk/wp-content/uploads/2024/04/Faraday_Insights_19_FINAL.pdf.

[29] GOLIAT Consortium. *GOLIAT – Ground Operations of LIquid hydrogen Aircraft*. Tech. rep. Report stating 5 - 6 t/h LH2 refuel flow requirement. European Union Horizon Project, 2024. URL: https://mediaassets.airbus.com/pm_38_747_747228-ni0nsggi79.pdf.

[30] Yue Gu et al. "Hydrogen-Powered Aircraft at Airports: A Review of the Infrastructure Requirements and Planning Challenges". In: *Sustainability* 15.21 (2023), p. 15539. DOI: 10.3390/su152115539.

[31] J. E. Hall, P. Hooker, and D. Willoughby. *Ignited releases of liquid hydrogen (LH_2)*. Tech. rep. HSE Research Report RR987. UK Health and Safety Executive, 2014. URL: https://hysafe.info/ichs2013/images/papers/147.pdf.

[32] Julian Hoelzen et al. "H2-Powered Aviation at Airports – Design and Economics of LH2 Refueling Systems". In: *Energy Conversion and Management: X* 14 (2022), p. 100206. DOI: 10.1016/j.ecmx.2022.100206.

[33] P. G. Holborn, C. M. Benson, and J. M. Ingram. "Modelling hazardous distances for large-scale liquid hydrogen pool releases". In: *International Journal of Hydrogen Energy* 45.43 (Sept. 2020). Accepted manuscript (PDF), accessed 15 Dec 2025, pp. 23851–23871. DOI: 10.1016/j.ijhydene.2020.06.131. URL: https://openresearch.lsbu.ac.uk/download/660d73b6099b0ff849253f983b62ef3b3888a30a54b9b85649cceafb4e4b43d1/1649658/Holborn%20IJHE%202020%20Model%20LH2%20Spill%20Flammable%20Cloud%20Distance%20Accepted.pdf.

[34] P. Hooker et al. "Experimental Releases of Liquid Hydrogen". In: *Hazards XXIII Symposium*. Southport, UK, 2012, pp. 496–504. URL: https://www.icheme.org/media/9062/xxiii-paper-65.pdf.

[35] Hydrogen Tools (H2tools). *Design Considerations Indoor Refueling of Hydrogen-Powered Industrial Trucks*. Webpage (states dispensers should use self-sealing break-away joints), accessed 15 Dec 2025. URL: https://h2tools.org/bestpractices/indoor-refueling-of-hydrogen-powered-industrial-trucks/design-considerations.

[36] Hydrogen Tools (H2tools). *Flame Detection*. Best Practices webpage, accessed 15 Dec 2025. URL: https://h2tools.org/bestpractices/hydrogen-properties-and-leak-detection-considerations/flame-detection.

[37] Hydrogen Tools (H2tools). *Hydrogen Properties & Leak Detection Considerations*. Best Practices webpage, accessed 15 Dec 2025. URL: https://h2tools.org/bestpractices/hydrogen-properties-and-leak-detection-considerations.

[38] ICAO. *ICAO Destination 2050 Vision for Sustainable Aviation*. 2022. URL: https://www.icao.int/sites/default/files/about-icao/StrategicPlan/ICAO-Strategic-Plan-2026-2050-WEB-F5.pdf.

[39] International Air Transport Association (IATA). *Concept of Operations of Battery and Hydrogen-Powered Aircraft at Aerodromes*. PDF. 2025. URL: https://www.iata.org/globalassets/iata/publications/sustainability/concept-of-operations-of-battery-and-hydrogen-powered-aircraft-at-aerodromes.pdf.

[40] International Air Transport Association (IATA). *Energy and New Fuels Infrastructure – Net Zero Roadmap*. Tech. rep. Technical Report, available online at IATA.org. 2022. URL: https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/energy-and-new-fuels-infrastructure-net-zero-roadmap.pdf.

[41] International Air Transport Association (IATA). *Hydrogen for aviation: A future decarbonization solution for air travel?* PDF factsheet (V2.0). Feb. 2025. URL: https://www.iata.org/globalassets/iata/publications/sustainability/h2-for-aviation-facts.pdf.

[42] International Air Transport Association (IATA). *IFTP Standard Fueling Procedures: Service Levels and Safety*. Version v1.00, 17-FEB-2020. 2020. URL: https://www.iata.org/contentassets/828efe1a6a2a487aacaa8fe7642f0c72/iftp-standard-fueling-procedures_service-levels-and-safety-v1.00.pdf.

[43] *ISO 19880-1:2020 — Gaseous hydrogen — Fuelling stations — Part 1: General requirements*. Geneva, Switzerland: International Organization for Standardization, 2020.

[44] *ISO/TR 15916:2015 — Basic considerations for the safety of hydrogen systems*. Geneva, Switzerland: International Organization for Standardization, 2015.

[45] Jacobs. *How Can Airports Get Hydrogen Ready Now to Land Net Zero Targets?* Jacobs Thought Leadership article, June 15, 2022. URL: https://www.jacobs.com/newsroom/thought-leadership/how-can-airports-get-hydrogen-ready-now-land-net-zero-targets (visited on 05/15/2025).

[46] Z. Jaffary and M. Wiedemann. "Towards net-zero aviation: Exploring safe hydrogen refuelling at airports". In: *Journal of Air Transport Research Society* 4 (2025), p. 100048. URL: https://www.sciencedirect.com/science/article/pii/S2941198X24000599.

[47] Linde Engineering. *Hydrogen Technologies – Transport and Storage*. Corporate hydrogen brochure. Accessed 2025. 2024. URL: https://assets.linde.com/-/media/celum-connect/2025/07/14/13/25/le_staticequipment_trailer_emea_broschure_a4_rz_144dpi_lbs180_194174.pdf.

[48] Wouter van Lingen and Paul Roling. "Modelling the effects of gate planning on apron congestion". In: *AIAA Aviation 2019 Forum*. 2019. DOI: 10.2514/6.2019-3047. URL: https://doi.org/10.2514/6.2019-3047.

[49] Jonas Mangold et al. "Refueling of LH2 Aircraft – Assessment of Turnaround Procedures and Aircraft Design Implication". In: *Energies* 15.7 (2022), p. 2475. DOI: 10.3390/en15072475.

[50] Toshio Mogi and Sadashige Horiguchi. "Experimental study on the hazards of high-pressure hydrogen jet diffusion flames". In: *Journal of Loss Prevention in the Process Industries* 22.1 (2009), pp. 45–51. DOI: 10.1016/j.jlp.2008.08.006. URL: https://www.sciencedirect.com/science/article/pii/S0950423008000879.

[51] Munich Airport International / Munich Airport. *Hydrogen at Airports: Climate-friendly Propulsion*. Public web resource (use this only if you cannot provide the claimed 2022 white paper PDF). 2024. URL: https://www.munich-airport.de/international/climate-friendly-propulsion.

[52] National Fire Protection Association. *NFPA 2: Hydrogen Technologies Code*. 2019 Edition (requirements include separation distances/hazardous area extents in feet/meters; verify exact table used). 2019. URL: https://www.nfpa.org/product/nfpa-2-hydrogen-technologies-code/p0002code.

[53] *NFPA 2: Hydrogen Technologies Code*. Quincy, MA: National Fire Protection Association, 2023. URL: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=2.

[54] Pacific Northwest National Laboratory. *Hydrogen Compared to Other Fuels*. Online resource; accessed 2025. n.d. URL: https://h2tools.org/bestpractices/gaseous-gh2-and-liquid-h2-fueling-stations/hydrogen-compared-to-other-fuels.

[55] Pacific Northwest National Laboratory. *Hydrogen Leak and Flame Detection Best Practices*. HTools Best Practices. Describes placement, calibration, power backup, and necessity of H gas and flame detectors. n.d. URL: https://h2tools.org/bestpractices/laboratory-safety/laboratory-design/leak-and-flame-detection.

[56] Pacific Northwest National Laboratory. *Liquid Hydrogen Properties and Behaviors*. H_2Tools Best Practices. Details on cryogenic burns and LH_2 hazards. n.d. URL: https://h2tools.org/bestpractices/best-practices-overview/hydrogen-basics/liquid-hydrogen-properties-and-behaviors.

[57] Pacific Northwest National Laboratory. *Operational Procedures and Safety Culture for Hydrogen Fueling Systems*. HTools Best Practices. Addresses procedural adherence, training, purging and safety culture aspects. n.d. URL: https://h2tools.org/bestpractices/operating-procedures.

[58] Pacific Northwest National Laboratory. *Oxygen Hazards in Hydrogen Systems*. H_2Tools Best Practices. Explains danger of oxygen enrichment from liquid air contamination. n.d. URL: https://h2tools.org/bestpractices/electrolyzer-safety/oxygen-hazards.

[59] Pacific Northwest National Laboratory. *Vacuum-Jacketed Piping in Hydrogen Systems*. Hydrogen Tools Best Practices. n.d. URL: https://h2tools.org/bestpractices/hydrogen-system-components/liquid-piping-systems/vacuum-jacketed-piping.

[60] Pacific Northwest National Laboratory. *Venting Guidelines for Hydrogen Storage and Handling*. Hydrogen Tools Best Practices. Recommendations for routing, elevation, and obstruction avoidance of vent lines. n.d. URL: https://h2tools.org/bestpractices/hydrogen-properties-and-leak-detection-considerations/venting.

[61] *PGS 35: Waterstofinstallaties voor het afleveren van waterstof aan voertuigen en werktuigen*. Versie 1.0 (augustus 2021). Publicatiereeks Gevaarlijke Stoffen (PGS). The Netherlands, 2021. URL: https://publicatiereeksgevaarlijkestoffen.nl/publicaties/online/pgs-35/2021/1-0-augustus-2021/.

[62] Michael L. Pinedo. *Scheduling: Theory, Algorithms, and Systems*. 5th. Springer, 2016. DOI: https://doi.org/10.1007/978-3-319-26580-3.

[63] Álvaro Rodríguez Sanz, Fernando Gómez Comendador, and Rosa Arnaldo Valdés. "Reduction of Uncertainty Propagation in the Airport Operations Network". In: *Proceedings of the XII Congreso de Ingeniería del Transporte (CIT 2016)*. València, Spain, 2016. DOI: 10.4995/CIT2016.2016.3484.

[64] M. Royle and D. Willoughby. *Releases of unignited liquid hydrogen (LH_2)*. Tech. rep. HSE Research Report RR986. UK Health and Safety Executive, 2014. URL: https://webarchive.nationalarchives.gov.uk/ukgwa/20241208025909/https://www.hse.gov.uk/research/rrhtm/rr986.htm.

[65] SAE International. *AIR8547: Liquid Hydrogen Aircraft Fueling Performance & Safety Guideline*. Aerospace Information Report. 2024. URL: https://www.sae.org/standards/air8547-liquid-hydrogen-aircraft-fueling-performance-safety-guideline.

[66] Siddhanta Saggar et al. "Enhanced Operational Management of Airport Ground Support Equipment for Better Aircraft Turnaround Performance". In: *Proceedings of the 2021 Winter Simulation Conference (WSC)*. PDF. 2021. URL: https://www.informs-sim.org/wsc21papers/025.pdf.

[67] Michael Schultz. "Fast Aircraft Turnaround Enabled by Reliable Passenger Boarding". In: *Aerospace* 5.1 (2018), p. 8. DOI: 10.3390/aerospace5010008. URL: https://www.mdpi.com/2226-4310/5/1/8.

[68] M. Simonetto, J.A. Pascoe, and A. Sharpanskykh. "Preliminary Safety Assessment of a Liquid Hydrogen Storage System for Commercial Aviation". In: *Safety* 11.1 (2025), p. 27. DOI: 10.3390/safety11010027.

[69] TULIPS Consortium. *Hydrogen Airport Ground Operations Deliverable Report*. Tech. rep. European Union Horizon Project, 2024. URL: https://tulips-greenairports.eu/wp-content/uploads/2024/12/TULIPS_Deliverable_D2.4_final.pdf.

[70] U.S. Department of Energy. *Overview of Hydrogen Safety, Codes and Standards*. Tech. rep. Washington, DC: DOE/EERE, 2014. URL: https://www.energy.gov/sites/prod/files/2014/03/f12/overview_final.pdf.

[71] U.S. Federal Aviation Administration. *Hydrogen-Fueled Aircraft Safety and Certification Roadmap*. FAA Report. 2024. URL: https://www.faa.gov/aircraft/air_cert/step/disciplines/propulsion_systems/hydrogen-fueled_aircraft_roadmap.

[72] Universal Hydrogen. *Universal Hydrogen Successfully Completes First Flight of Hydrogen Regional Airliner*. Press release (Business Wire). Describes modular hydrogen capsules/modules and the associated logistics concept. Accessed 15 December 2025. Mar. 2023. URL: https://www.businesswire.com/news/home/20230302005768/en/Universal-Hydrogen-Successfully-Completes-First-Flight-of-Hydrogen-Regional-Airliner.

[73] van Dijk, Daan. *PAN PAN PAN - preparing airports for hydrogen emergencies!* LinkedIn post (image), accessed 15 Dec 2025. 2025. URL: https://www.linkedin.com/posts/daanvandijk1992_research-incidentresponse-hydrogen-activity-7399717088250200064-sCLX.

[74] K. Verfondern et al. *Handbook of Hydrogen Safety — Chapter on Liquid Hydrogen*. PRESLHY Deliverable D3.9, European Hydrogen Safety Panel. 2021. URL: https://hysafe.info/wp-content/uploads/sites/3/2021/04/D39_2021-01-PRESLHY_ChapterLH2-v3.pdf.

[75] VINCI Airports. *Innovative aviation liquid hydrogen project launched*. Online newsroom article. Describes the GOLIAT project scope including high-flow LH_2 handling/refuelling for airport operations and assessment of hydrogen value chains for airports. Accessed 15 December 2025. May 2024. URL: https://en.newsroom.vinci-airports.com/news/innovative-aviation-liquid-hydrogen-project-launched-70a8-46ae7.html.

[76] K. van Wingerden et al. *Safety of Liquid Hydrogen: PRESLHY White Paper*. Tech. rep. HySafe / PRESLHY Project, 2021. URL: https://hysafe.info/wp-content/uploads/sites/3/2021/06/PRESLHY_D6_4_WhitePaper_202101505_V2p1.pdf.

[77] Zero Emission Aviation Alliance (AZEA) and ACI EUROPE. *Helping Airports Understand the Challenge of Zero-Emission Aviation: AZEA Airports Infrastructure Factsheets Tool*. Tech. rep. Includes operational factsheets on hydrogen aircraft, refuelling safety zones and stand configuration. Zero Emission Aviation Alliance (AZEA) / ACI EUROPE, Mar. 2025. URL: https://www.aci-europe.org/downloads/resources/AZEA%20Airports%20Infrastructure%20Factsheets%20Tool.pdf.

[78] ZeroAvia. *Flight Testing Hydrogen-Electric Powerplant*. Online page. Describes flight testing on the 19-seat Dornier 228 hydrogen-electric testbed aircraft. Accessed 15 December 2025. 2023. URL: https://zeroavia.com/flight-testing/.

[79] ZeroAvia. *Lay out hydrogen airport*. 2023. URL: https://zeroavia.com/hare/.

III

Research Methodology

Preliminary Safety Analysis of Liquid Hydrogen Aircraft Refuelling and Its Operational Consequences for Airports

Thesis Project Plan

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Introduction and Relevance of the Project

Hydrogen is increasingly positioned as a key zero-carbon aircraft fuel option for short- to medium-range aviation. In particular, liquid hydrogen (LH_2) is one of the few energy carriers with sufficient specific energy to support meaningful payload–range performance, but its use at airports introduces fundamentally different safety considerations during refuelling and ground handling. Unlike conventional Jet A-1, hydrogen has a much wider flammability range and a far lower minimum ignition energy, so even relatively small leaks can form flammable clouds that ignite from weak ignition sources and burn with an almost invisible flame.[14, 13, 12] Large-scale experiments and compilations of best practice show that LH_2 spills can rapidly flash and evaporate into cold vapour clouds before eventually dispersing upwards, combining cryogenic hazards (cold burns, material embrittlement, oxygen condensation) with fire and explosion risks.[14, 12] At the same time, hydrogens high buoyancy and diffusivity promote rapid vertical dispersion in well-ventilated, open-air environments, which can help to limit long-lived accumulations.[12] Balancing these competing effects is central to defining safe but practicable operations on the airport apron.

At present, there is no dedicated, apron-specific regulatory framework for LH_2 aircraft refuelling safety zones. Generic hydrogen codes such as NFPA 2 provide prescriptive separation distances for gaseous and liquid hydrogen production, storage and vehicle fuelling systems,[11] but these were developed primarily for stationary industrial installations and road-vehicle stations. They do not directly address large commercial aircraft, crowded contact stands or the high density of ground support equipment and personnel typical of busy aprons. Early airport-focused studies and industry roadmaps suggest that conservative LH_2 refuelling exclusion zones could extend to tens of metres (on the order of 30–60 m), substantially larger than current kerosene fuelling zones and with the potential to interfere with neighbouring stands, boarding operations and ground service activities.[3, 4] This raises an operational challenge: airports must integrate hydrogen safely without undermining stand capacity and turnaround performance.

Recent research underlines that this is both a hydrogen safety problem and an airport operations problem. Projects such as PRESLHY have improved understanding of LH_2 release, dispersion and ignition behaviour and provide a basis for consequence-based hazard distances in open-air conditions.[14] Qualitative airport studies by Braun and Classen highlight the likelihood of larger safety zones, the importance of training and emergency preparedness, and the need to consider hydrogen safety early in airport master planning.[3] Gu *et al.* emphasise infrastructure constraints, regulatory uncertainty and the absence of clear, apron-specific safety-zone guidance as key barriers for hydrogen-powered flight.[4] However, existing work rarely quantifies how candidate LH_2 safety zones would interact with day-to-day apron operations in terms of stand availability, delay propagation and conflicts with other ground activities.

In summary, there is a clear need for methods that link hydrogen safety fundamentals and consequence-based safety distances to operationally meaningful metrics at the apron level. This project addresses that need by focusing on LH_2 aircraft refuelling safety zones as both a safety requirement and a potential operational bottleneck in future hydrogen-enabled airports.

Research objective. The objective of this project is to develop and apply a methodology that derives consequence-based safety zones for LH_2 aircraft refuelling and evaluates their impact on apron operations, in order to identify safety-zone configurations that satisfy accepted hydrogen safety criteria while remaining compatible with stand capacity, turnaround performance and routine ground-handling processes.

Research Question(s)

Building on the context above, the central research question of this project is:

Which LH2 refuelling hazards influence safety-zone distances, and what operational impacts result from implementing these zones in airport ground operations

To answer this main question, the following sub-questions are formulated. Together, they mirror the structure of the literature review and the methodological steps of the thesis:

- **Hydrogen hazard characteristics and dominant scenarios.** How do the key properties of hydrogen and LH_2 (flammability range, ignition energy, buoyancy, cryogenic behaviour) translate into credible release and accident scenarios for apron refuelling, and why do flash fire and jet fire emerge as the key hazards for determining safety zones compared to, for example, vapour cloud explosion or BLEVE?
- **Refuelling concepts, equipment and mitigations.** How do different LH_2 refuelling architectures (e.g. mobile tanker trucks versus fixed hydrant systems, with GH_2 only as a comparison where relevant), associated equipment (hoses, couplings, ESD, venting) and procedural safeguards influence the likelihood and consequences of refuelling incidents and thus the size and shape of required safety and exclusion zones?
- **From consequences and codes to safety-zone distances.** How can existing hydrogen safety codes and standards (e.g. NFPA 2, ISO/TR 15916, ISO 19880-1, PGS 35) and published consequence-modelling results for LH_2 releases be combined into a transparent, hydrogen-safety-informed approach for deriving candidate refuelling safety-zone distances for representative apron scenarios?
- **Operational impact of LH_2 safety zones on the apron.** When these candidate safety and exclusion-zone distances are imposed as spatial and temporal constraints in apron operations (e.g. via discrete-event simulation of stands, ground support equipment and turnarounds), what is their impact on key performance indicators such as stand availability, turnaround delay, GSE routing conflicts and safety-zone penetration rates?
- **Trade-offs and optimal configurations.** How can the safety and operational insights from the previous sub-questions be synthesised to identify refuelling safety-zone configurations (e.g. radii, keep-clear corridors and concurrent-operations policies) that offer an acceptable trade-off between hydrogen safety requirements and apron operability for early-adopter airports?

These sub-questions together cover the physical and regulatory basis for LH_2 refuelling hazards, the translation of those hazards into practicable safety zones, and the quantitative assessment of how such zones interact with apron operations. Answering them will provide a coherent and well-founded response to the central research question.

Methods, Tools, and Expected Results

To address the research questions, the project uses a two-stage workflow that couples hydrogen safety analysis to airport operations modelling. The first stage develops a qualitative but structured safety assessment of LH_2 aircraft refuelling and derives a small set of key hazards and associated safety zones. The second stage embeds these safety zones as spatial constraints in a discrete-event simulation (DES) of apron operations to quantify their operational impact. Together, these stages provide a risk-informed yet operationally meaningful assessment of LH_2 refuelling safety zones.

Stage 1: Safety assessment and key hazards for determining safety zones

Hazard identification and scenario structuring (HAZID, HAZOP, Bow–Tie). The starting point is a broad hazard identification (HAZID) of LH_2 aircraft refuelling, covering the full transfer chain from truck positioning and connection through chill-down, bulk transfer, topping and purging/venting. Hazards are identified across technical, operational, interface, monitoring and external domains, with causes, consequences and safeguards recorded in a structured hazard table.[5, 7] From this inventory, hazards with a direct and credible link to hydrogen release are filtered and grouped.

For the refuelling operation itself, a focused HAZOP-style analysis is then applied to key steps (connection, pre-cooling, bulk transfer, purging), using deviations (e.g. "more/less flow", "no purge", "leak at coupling") to systematically uncover failure modes and human-factor issues.[10, 6] The most relevant failure modes (such as hose or coupling leaks, stuck-open valves, failed purging or malfunctioning ESD) are carried into Bow–Tie models with the top event defined as "hydrogen release during refuelling". On the left-hand side, initiating threats are linked to preventive barriers (design integrity, inspection, procedures); on the right-hand side, consequence branches (jet fire, flash fire, confined accumulation, cryogenic exposure) are linked to mitigative barriers (detection, shutdown, vent routing, emergency response). This creates a traceable link between refuelling steps, failure modes, barriers and outcomes.

Expected result: a prioritised set of refuelling accident scenarios (grouped by hazard family) and a clear mapping of preventive/mitigative controls, providing the qualitative backbone for later safety-zone choices.

Escalation logic and qualitative risk ranking (ETA/FTA, severity–likelihood). For a subset of high-relevance pathways identified in the Bow–Tie, Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) are used to structure escalation and causal logic without requiring full quantitative data. ETAs capture key post-release branches (detection success/failure, shutdown success/failure, ignition timing, venting effectiveness), while FTAs decompose selected critical paths into combinations of underlying hardware, procedural and external failures.[13, 12]

These models are then summarised in a qualitative severity–likelihood assessment. Severity categories (e.g. Minor, Moderate, Critical, Catastrophic) are assigned based on potential harm to people, aircraft and infrastructure, while likelihood categories (e.g. Improbable, Remote, Occasional) are assigned under an assumed baseline barrier set. This ranking step is used to shortlist (i) critical safety bottlenecks and (ii) the hazards that actually drive stand-off distances.

Expected result: a small number of key hazard families (dominated by flash fire and jet fire in open-air apron conditions) and an associated set of critical controls (integrity of cryogenic equipment, detection and alarming, ESD, ignition-source control, procedural adherence) that must be protected with defence-in-depth.

From hazards to candidate safety-zone scenarios. Building on the shortlisted hazard families, the project derives candidate refuelling safety zones using a hydrogen-safety-informed, consequence-based approach rather than new CFD or detailed QRA. Published LH_2 release and ignition experiments (e.g. PRESLHY) and aviation-relevant consequence studies are combined with indicative distances from generic hydrogen codes and airport hydrogen studies (e.g. NFPA 2, ISO/TR 15916, PGS 35, ATI/ACI reports) to obtain conservative but realistic ranges for flash-fire footprints and jet-fire thermal exposure in apron-like conditions.[11, 14, 2, 1]

From this evidence base, a small scenario set S1–S5 is defined by varying the two parameters that most strongly affect hazard extent: (i) effective opening size (small leak versus medium leak versus full-bore rupture) and (ii) ignition timing (immediate ignition / jet fire versus delayed ignition / flash fire versus no ignition with successful isolation). Each scenario is assigned a representative exclusion radius R (e.g. $\sim$10–15 m for small-leak flash fire, 20–30 m for medium-leak flash fire, 30–50 m for full-bore jet fire) consistent with the literature ranges, forming a monotonic set from conservative to more constrained zones.

For use in operations modelling, these radii are then grouped into a small number of *safety modes* (e.g. Mode 0: minimal zone / close to current practice; Mode 1: intermediate hydrogen-informed zone; Mode 2: conservative hydrogen-informed zone with additional keep-clear corridors). Each mode corresponds to a distinct policy on which activities and ground support equipment (GSE) are allowed within the zone while refuelling is active.

Expected result: a transparent set of candidate LH_2 refuelling safety zones (radii and enforcement modes) explicitly linked to key hazards that influence the safety zoning the most and hydrogen safety evidence, ready to be implemented as spatial constraints in the DES model.

Stage 2: Apron operations modelling and safety-zone integration

Discrete-event simulation of apron operations. The second stage quantifies how the candidate LH_2 safety zones interact with airport operations. A discrete-event simulation (DES) model is developed in Python (using SimPy) for a representative medium-size European airport inspired by Rotterdam The Hague Airport: a compact apron with closely spaced Code C stands, a terminal-facing taxiway and limited routing redundancy.[9]

In the DES, each aircraft turnaround is modelled as a sequence of stochastic activities (taxi-in, deboarding, cleaning, catering, refuelling, baggage handling, boarding, pushback), with precedence constraints and shared resources (stands, refuelling trucks, loading teams, taxiway segments). Ground support equipment and refuelling trucks are modelled as mobile resources that follow routing rules on a simplified apron network. Baseline process times and variability are taken from literature, existing DES studies and, where necessary, reasonable engineering assumptions, with sensitivity checks on key parameters.

Tools: Python with Salabim for the core DES engine; standard scientific libraries (NumPy, pandas, SciPy) for data handling and statistics; and simple visualisation for sanity checks of stand utilisation and GSE movements.

Implementation of safety zones and experimental design. LH_2 refuelling operations and their safety zones are represented as dynamic spatio-temporal constraints in the DES:

- When an LH_2 refuelling event is active at a stand, a circular exclusion area with radius R is instantiated (according to the selected safety mode). Within this area, certain GSE types and activities (e.g. neighbouring stand operations, crossing traffic on adjacent taxiway segments) are either delayed, rerouted or forbidden, depending on the enforcement policy.

- Keep-clear corridors can be modelled as directional extensions of the zone (e.g. along the expected jet-fire axis or refuelling-hose routing), where only essential refuelling resources are allowed to enter.

- Different hydrogen penetration rates (fraction of flights using LH_2) are tested to represent early-adopter and more mature adoption scenarios.

A set of simulation experiments is then designed in which safety mode (0/1/2), hydrogen penetration rate and refuelling concept assumptions are varied. For each scenario, multiple replications are run to obtain stable statistics. Key performance indicators (KPIs) include average and percentile departure delay, stand waiting time, GSE queueing, stand utilisation, and a simple measure of how often other operations would like to enter the safety zone but are blocked (a proxy for "zone pressure").

Expected result: a quantitative comparison of operational performance across safety modes and penetration rates, revealing how sensitive apron capacity and delays are to the assumed hydrogen refuelling safety zones.

Analysis and synthesis of safety–operations trade-offs. Finally, the simulation outputs are analysed using a combination of descriptive statistics and standard statistical tests (e.g. ANOVA, Tukey HSD for pairwise mode comparisons, and non-parametric effect sizes such as Vargha & Delaneys A) to distinguish statistically and practically relevant differences between safety modes.[8] Results are interpreted in terms of both safety and operations:

- From the safety side, the focus is on whether the candidate zones remain anchored in key hazards (flash fire / jet fire) and whether stricter modes offer clear additional protection in terms of reduced zone utilisation or conflict potential.
- From the operations side, the focus is on the additional delay and stand-capacity penalty associated with moving from a minimal to a conservative safety mode, and on identifying threshold penetration rates at which LH_2 refuelling begins to materially degrade performance.

Expected result: a set of safety-zone recommendations (radii and enforcement policies) that are (i) clearly justified by hydrogen safety reasoning and literature, and (ii) shown to be compatible, or at least manageable, with apron operations for early-adopter airports. These recommendations will be synthesised into practical guidance on where conservative hydrogen safety zones are most critical, where more constrained zones may be acceptable with strong controls, and how airports can plan stand layouts and procedures to accommodate LH_2 refuelling without unacceptable loss of capacity.

Table 8: Expected data types, formats, sources, and usage in the project.

Type of data	File format(s)	Data collection (source)	Purpose of processing	Storage location	Access (who)
Hydrogen properties and experimental safety data (LH_2 and GH_2)	Reports, PDFs, datasets	Re-use of published data from projects (e.g. PRESLHY deliverables, NASA technical reports) and safety manuals	Validate and calibrate consequence models (ensure simulations reflect real behavior of hydrogen leaks, fires, etc.)	Project repository (university server or SURF-drive)	Project team (student, supervisors); external co-researchers as needed
Refuelling failure frequencies and risk parameters	Tables, .csv files	Literature and databases (e.g. UK HSE reports, industry reliability data; no restrictions on public reports)	Input for QRA to calculate likelihood of scenarios and risk levels for safety zone evaluation	Project repository (secured folder)	Project team; anonymized aggregates may be shared in thesis
Simulation output data (consequence modeling results)	Numeric data files, graphs	Generated by software tools (PHAST, ALOHA, HyRAM runs for various scenarios)	Determine hazard distances (flammable limits, overpressure radii, etc.) for each scenario; data will be post-processed for analysis	Local machine (backed up to TU Delft OneDrive)	Project team (raw outputs), processed results in thesis
Airport operations scenario data	Scripts, .csv	Combination of synthetic data and public domain info (e.g. generic flight schedule from open data, airport layout from literature)	Input for SimPy simulation to model gate usage and scheduling under safety zone constraints	Project repository (SimPy model files)	Project team; simulation code and scenario assumptions to be shared in appendix

Planning

The project is structured into ten work packages (WP) with an estimated total duration of approximately 8 months. Figure A.1 in Appendix A presents a Gantt chart of these WPs, their timelines, and interdependencies. Below is an overview of each work package, including key tasks, expected duration, and contingencies:

1. **WP1 Literature Review and Problem Definition (Month 1):** Survey academic literature, industry reports, and safety codes on hydrogen fueling (covering hydrogen properties, prior risk studies, regulations like DOE and NFPA standards). Refine the problem statement and objectives based on knowledge gaps identified. *Dependency:* None (starts at project kickoff). *Deliverable:* Annotated bibliography and refined research scope. *Contingency:* If specific data (e.g. for LH_2 behavior) are scarce, plan to consult experts or use conservative estimates from analogous sources.

2. **WP2 Hazard Analysis (Month 1 - 2):** Perform HAZOP and bow-tie analyses to identify potential accident scenarios and safety measures (building on WP1 insights). Select representative worst-case scenarios for detailed study. *Dependency:* WP1 (uses information gathered on failure modes). *Milestone:* **Green-light Review** at end of WP2 present initial findings (hazard scenarios and approach) to get approval to proceed. *Contingency:* If expert availability for HAZOP is limited, use documented failure modes from literature and validate later with an expert panel.

3. **WP3 Consequence Modeling (Month 2 - 4):** For each selected scenario, simulate physical effects using PHAST, ALOHA, and HyRAM. Compute preliminary safety distances (e.g. for thermal radiation, overpressure, and flammable cloud). *Dependency:* WP2 (uses scenarios defined). *Overlap:* WP3 can run partly in parallel with WP4 once some scenarios are modeled. *Contingency:* If a software tool is not available or a model proves unreliable for hydrogen, switch to an alternative (e.g. open-source CFD tools or empirical correlations) to estimate distances.

4. **WP4 Risk Assessment (Month 3 - 5):** Conduct the QRA using scenario frequencies and consequences. Determine required safety zone sizes to meet risk acceptance criteria. Iterate as needed: adjust distances or consider added safeguards if risk is too high. *Dependency:* WP3 (needs consequence data; can begin with initial results while remaining scenarios are modeled). *Overlap:* Overlaps with late WP3 and WP5. *Contingency:* If quantitative risk targets cannot be met even with very large zones, re-examine scenario assumptions or incorporate additional mitigation (e.g. improved fuel system design) and document a plan B for risk reduction.

5. **WP5 Operational Impact Analysis (Month 3 - 5):** Develop and run the SimPy discrete-event simulation of airport operations to assess how the tentative safety zones from WP3/WP4 affect gate management and turnaround times. *Dependency:* Starts after WP2 (once initial zone estimates are known, even if preliminary). *Overlap:* Runs in parallel with WP3WP4. *Contingency:* If simulation complexity is overwhelming or if real airport data cannot be obtained, use a simplified model or scenario (e.g. fewer gates or generic schedule) to still gauge the order-of-magnitude impacts.

6. **WP6 Synthesis of Results (Month 6):** Integrate findings from WP3, WP4, and WP5. Determine the optimal safety zone recommendation that balances safety and operational efficiency (for example, X meters radius, with specified conditions or mitigations). Formulate guidelines for implementation (e.g. required equipment, fueling procedures, training) based on the analysis. *Dependency:* WP4 & WP5 (completed analysis). *Contingency:* If results conflict (e.g. operational needs push for smaller zone but risk analysis requires larger), explore compromise solutions such as phased fueling (fuel at remote stand then tow to gate) or enhanced mitigations to reduce required distance.

7. **WP7 Validation and Stakeholder Feedback (Month 6):** Validate the proposed safety zone and methodology with external feedback. This involves sanity checks against any real-world emerging data or expert opinions (e.g. consult hydrogen safety experts or airport fuel handlers). If possible, compare the recommendations with any preliminary

guidelines from authorities (CAA, EASA, FAA). *Dependency:* WP6 (initial recommendation ready). *Contingency:* If no external experts are available, perform an internal validation (e.g. sensitivity analysis or peer review with university colleagues) to test the robustness of results.

8. **WP8 Documentation and Report Writing (Month 7):** Compile the project report (thesis) detailing the methods, results, and recommendations. Prepare visual materials (plots of hazard zones, risk contour maps, simulation graphs, etc.) and ensure all analysis is well-documented. *Dependency:* WP3WP6 (all results in hand). *Overlap:* Writing can begin earlier (e.g. drafting methodology section during analysis phases) to save time. *Contingency:* Allocate extra time for revisions; if some results are delayed, document interim findings and update later.

9. **WP9 Presentation and Defense Preparation (Month 8):** Prepare the final presentation for the thesis defense and any required summary (e.g. executive summary or poster if needed). *Dependency:* WP8 (completed or near-final report). *Contingency:* If unexpected results emerge late, include them in presentation with discussion, even if the written report is finalized be transparent about any last-minute insights.

10. **WP10 Project Management and Buffer (Ongoing):** Continuously monitor progress, update the schedule as needed, and manage risks (e.g. tool issues, illness, etc.). This WP spans the entire project, ensuring coordination of tasks and communication with supervisors. It also includes a buffer period for unforeseen delays (approximately 2 weeks slack built into the schedule). *Dependency:* All WPs (supports all phases). *Contingency:* Utilize the built-in buffer or re-prioritize tasks if delays occur (e.g. focus on critical path tasks first, defer nice-to-have analyses if necessary to meet deadlines).

Key milestones and deliverables are embedded in the above timeline. Notably, the **Kick-off meeting** (Month 0) and submission of this project plan mark the project start. The **Green-light review** (around Month 2-3, after WP2) will evaluate whether the project is feasible to continue. A **mid-term review** with supervisors is planned around Month 5 to present preliminary findings (consequence modeling and initial QRA results) and get feedback. Finally, the **thesis submission and defense** (end of Month 8) conclude the project, with deliverables including the written thesis and a presentation to the assessment committee. Holidays and non-working periods have been accounted for in the schedule, and multiple work packages run in parallel to optimize the use of time (for example, modeling and operations analysis overlap). The plan is designed to be realistic yet flexible: if any primary approach fails, fallback options are in place (as noted in each WP), ensuring the project can still achieve its core objectives within the allotted time.

Conclusions

This project will develop an integrated methodology to determine safety zones for hydrogen aircraft fueling, blending state-of-the-art safety science with operational analysis. The expected outcome is threefold. First, the project will advance **methodology** by combining HAZOP, advanced consequence modeling, QRA, and discrete-event simulation in a novel way to tackle an emerging aviation safety problem. Second, it will contribute to **scientific understanding** by quantifying the differences between gaseous and liquid hydrogen refuelling hazards and identifying how various factors (fueling methods, mitigations) influence required safety distances. Third, it will provide **practical guidance** for airport planners and regulators by recommending safety zone dimensions and mitigation measures that enable hydrogen refuelling to be performed safely with minimal disruption to airport operations. Ultimately, this work supports the aviation industrys transition to sustainable hydrogen fuel by ensuring that safety infrastructure and operational procedures are grounded in rigorous analysis and tailored to real-world airport conditions.

Appendix A: Gantt Chart

Figure A.1: Gantt chart illustrating the timeline of work packages (WP1WP10) across the project duration, including key milestones. (The Gantt chart is provided as a separate figure.)

References (Research Methodologies)

[1] Aerospace Technology Institute (ATI) and FlyZero. *Hydrogen Infrastructure and Operations: Airports, Airlines and Airspace*. Tech. rep. Report ID: FZO-CST-POS-0035. ATI / FlyZero, 2022. URL: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf (visited on 12/16/2025).

[2] Airports Council International (ACI) and Aerospace Technology Institute (ATI). *Integration of Hydrogen Aircraft into the Air Transport System*. Tech. rep. ACI / ATI, 2021. URL: https://www.ati.org.uk/wp-content/uploads/2021/08/aci-ati-hydrogen-report-1.pdf (visited on 12/16/2025).

[3] M. Braun and A. B. Classen. "Qualitative Risk Assessment for Future Hydrogen-Enabled Airports". In: *Transportation Research Procedia* 75 (2023), pp. 86–95.

[4] Y. Gu et al. "Hydrogen-Powered Aircraft at Airports: A Review of the Infrastructure Requirements and Planning Challenges". In: *Sustainability* 15.21 (2023), p. 15539.

[5] International Organization for Standardization. *ISO/TR 15916:2015 Basic considerations for the safety of hydrogen systems*. Technical Report. 2015. URL: https://www.iso.org/standard/56546.html (visited on 12/16/2025).

[6] Zahra Jaffary and Mirjam Wiedemann. "Towards net zero aviation: Exploring safe hydrogen refuelling at airports". In: *Journal of Air Transport Research Society* 4 (2025). Open-access record page (TRID). The DOI resolves to the publisher version., p. 100048. DOI: 10.1016/j.jatrs.2024.100048. URL: https://trid.trb.org/View/2548179 (visited on 12/16/2025).

[7] T. Jordan and J. L. Saw. *PRESLHY Deliverable D6.4 (D42): White Paper*. Tech. rep. Version 2.1 (May 2021). PRESLHY Consortium, 2021. URL: https://hysafe.info/wp-content/uploads/sites/3/2021/06/PRESLHY_D6_4_WhitePaper_202101505_V2p1.pdf (visited on 12/16/2025).

[8] Averill M. Law. *Simulation Modeling and Analysis*. 5th ed. McGraw-Hill Higher Education, 2015. ISBN: 9780073401324. URL: https://www.vitalsource.com/products/simulation-modeling-and-analysis-averill-law-v0077595963 (visited on 12/16/2025).

[9] Luchtverkeersleiding Nederland (LVNL). *eAIP Netherlands: EHRD (Rotterdam The Hague Airport) Aerodrome Information*. eAIP AIRAC AMDT 12-2025 (reference for layout/operational environment source material). 2025. URL: https://eaip.lvnl.nl/web/eaip/AIRAC%20AMDT%2012-2025_2025_11_27/eAIP/EH-AD%202%20EHRD%201-en-GB.html (visited on 12/16/2025).

[10] J. Mangold et al. "Refueling of LH_2 Aircraft—Assessment of Turnaround Procedures and Aircraft Design Implication". In: *Energies* 15 (2022), p. 2475. DOI: 10.3390/en15072475. URL: https://elib.dlr.de/193092/1/energies-15-02475-v3.pdf (visited on 12/16/2025).

[11] National Fire Protection Association. *NFPA 2: Hydrogen Technologies Code*. Standard. 2019 Edition, Quincy, MA, USA. 2023.

[12] Pacific Northwest National Laboratory. *Hydrogen Compared to Other Fuels*. Hydrogen Tools – Best Practices. Online resource, accessed 2025. 2025. URL: https://h2tools.org/bestpractices/gaseous-gh2-and-liquid-h2-fueling-stations/hydrogen-compared-to-other-fuels.

[13] U.S. Department of Energy. *Overview of Hydrogen Safety, Codes and Standards*. Tech. rep. Washington, DC, USA. DOE/EERE, 2014. URL: https://www.energy.gov/sites/prod/files/2014/03/f12/overview_final.pdf.

[14] K. Verfondern et al. *Handbook of Hydrogen Safety – Chapter on Liquid Hydrogen*. Tech. rep. PRESLHY Deliverable D3.9. European Hydrogen Safety Panel, 2021. URL: https://hysafe.info/wp-content/uploads/sites/3/2021/04/D39_2021-01-PRESLHY_ChapterLH2-v3.pdf.

IV

Supporting Work

1 Safety Assessment Supporting Material

1.1 Method Selection and Sequence of Safety Assessment

To ensure a comprehensive and structured risk analysis for hydrogen tanking operations, multiple complementary methodologies were applied in a sequential manner. The specific order, starting with HAZID, followed by HAZOP, and subsequently Bow-Tie modeling, supported by Event Tree and Fault Tree Analysis, was deliberately chosen to reflect both the maturity of system knowledge and the analytical depth required at each phase of the assessment.

HAZID: Broad Early Hazard Recognition
The process began with a Hazard Identification (HAZID) study. This was chosen as the first step because it is particularly suited for early-phase risk exploration when system knowledge is still being developed. HAZID provides a high-level, qualitative overview of potential hazards, including those related to external events, operational errors, or system-level interactions. The purpose was to establish a comprehensive inventory of hazards across all process steps and system boundaries, without yet requiring detailed system drawings or operating parameters. This broad view was essential to avoid prematurely narrowing the scope of the analysis.

HAZOP: Systematic Deviation Analysis
Once the system concept and operating procedures were sufficiently understood, a more detailed Hazard and Operability (HAZOP) study was conducted. HAZOP was selected as the second method because of its structured and rigorous approach to identifying deviations from design intent. It builds upon the hazard inventory established during HAZID and enables systematic exploration of credible causes of process deviations, such as "No Flow", "More Pressure", or "Reverse Operation", within defined nodes of the system. HAZOP is especially valuable for uncovering hidden failure scenarios, internal process interactions, or control issues that may not emerge during higher-level HAZID sessions. It also serves as a foundation for later semi-quantitative methods such as Layer of Protection Analysis (LOPA).

Bow-Tie Analysis: Integrating Causes, Consequences, and Barriers
With both the list of hazards and deviation scenarios available, the next step was to develop a Bow-Tie model to visualize the relationships between threats, top events (e.g. hydrogen leak), consequences, and safeguards. Bow-Tie analysis was chosen as the third method due to its communicative clarity and ability to integrate both preventive and mitigative barriers in a single diagram. It allows risk ownership to be made visible and supports cross-disciplinary discussions. In this project, Bow-Tie modeling helped structure the safety strategy around a limited number of top events, avoiding complexity overload while maintaining traceability to earlier hazard analyses.

ETA and FTA: Scenario Logic and Quantification
To further deepen the analysis, the final stage involves applying Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) to selected high-risk scenarios identified in the Bow-Tie. ETA is used to model the sequence of outcomes stemming from an initiating event (such as a hydrogen leak), including the success or failure of safety functions. This helps understand the likelihood and severity of various consequence pathways. FTA, on the other hand, provides a top-down logical breakdown of how different failures (technical, human, or external) can combine to cause a particular top event. These methods are particularly useful for quantifying scenario frequencies, evaluating barrier effectiveness, and identifying critical components or failure combinations. They also support alignment with Quantitative Risk Assessment (QRA) methods, which may be required for regulatory compliance.

Method Integration
By applying HAZID, HAZOP, Bow-Tie, ETA, and FTA in this sequence, the analysis moves from qualitative broad screening to structured scenario exploration, and ultimately toward quantifiable risk modeling. Each method builds on the outputs of the previous one, creating a coherent chain of reasoning and risk traceability. This integrated approach ensures both thoroughness and clarity in managing the unique safety challenges of liquid hydrogen fueling operations at airports.

1.2 HAZID and HAZOP analysis

Rationale for Sequence

A sequential approach was adopted in this safety assessment, starting with a broad Hazard Identification (HAZID) and followed by a structured Hazard and Operability Study (HAZOP). This sequence was chosen to match the system maturity and risk modeling objectives:

- **HAZID** was used first to develop a comprehensive inventory of potential hazards across the entire refuelling operation. It is well-suited for early-stage risk exploration when full system details are not yet finalized.
- **HAZOP** was applied next to systematically analyze deviations from design intent within specific parts of the system, based on established process steps. This ensured that critical process-related hazards were evaluated in detail.

This layered approach ensures both breadth and depth in hazard discovery, avoiding early narrowing of scope and enabling traceability from high-level hazards to specific failure scenarios.

HAZID Execution

The HAZID was conducted using expert judgment, incident reports, and reference documents (e.g., PRESLHY, NFPA codes). For each process step, a brainstorming-based checklist method was used to identify hazards, their potential causes, consequences, and any existing or suggested safeguards. The outputs formed the initial hazard inventory and provided the basis for HAZOP.

HAZOP Execution

The HAZOP was applied per process node, using the following guide words and parameters:

- **Guide words**: No, More, Less, Reverse, As well as, Early, Late
- **Parameters**: Flow, Pressure, Temperature, Time, Energy, Direction

Each combination of process step, guide word, and parameter was evaluated using the standard HAZOP logic:

1. What could go wrong (deviation)?
2. What might cause this?
3. What would be the consequence?
4. Are there existing safeguards?
5. What additional measures are recommended?

All outcomes were documented in a structured HAZOP table. Each entry was traceable to a specific process step, guide word, deviation, and linked back to the initial HAZID list.

Logic and Traceability

The final hazard list is the result of a structured, multi-step process:

- Top-down decomposition of the LH_2 refuelling operation into process steps
- Broad hazard brainstorming (HAZID) across all steps
- Classification of hazards by origin (technical, human, environmental, etc.)
- Detailed deviation analysis (HAZOP) using guide words for selected nodes
- Mapping hazards to Bow-Tie diagrams and further to Event and Fault Trees

This logical flow ensures that all identified hazards are grounded in the defined system concept and are traceable across analysis layers. It also enables future refinement as system designs evolve or new failure data becomes available.

1.2.1 HAZID table

Table 9: HAZID overview for LH_2 aircraft refuelling: key hazards, causes, consequences, existing safeguards, and follow-up actions.

Hazard	**Potential causes**	**Potential consequences**	**Existing safeguards**	**Recommen-dations / follow-up**
LH_2 leak from transfer line	Joint fatigue, poor fitting, vibration, human error	Flammable vapor cloud, fire/explosion, cryogenic exposure	Leak detection sensors, inspection routines, trained staff	Include in HAZOP, install breakaway couplings
Ignition due to static discharge	Lack of proper grounding, dry climate	Immediate ignition of hydrogen cloud	Ground verification checklist, automatic ground interlocks	Add audible/visual alert if grounding not verified
Overfilling of aircraft tank	Valve failure, flow mismanagement, sensor error	Overpressure, tank rupture, venting	Automatic shut-off valves, tank level sensors	Review control logic, add redundant fill limits
Cryogenic burns to operator	Contact with vented LH_2, spills, hose malfunction	Severe injury (frostbite, tissue damage)	PPE, training, shielded connectors	Reinforce training, use quick-disconnect nozzles
Oxygen freezing on surfaces	Ambient air contact with supercooled hardware	Ignition source if mixed with hydrocarbons	Surface insulation, venting control	Review vent design and insulation quality
Ice plug in vent line	Moisture ingress, inadequate purging	Pressure build-up, blocked flow	Heated or insulated lines, purge cycles	Analyze humidity control, review purge frequency

Table 9: HAZID overview for LH_2 aircraft refuelling (continued).

Hazard	**Potential causes**	**Potential consequences**	**Existing safeguards**	**Recommen-dations / follow-up**
Failure of ESD system	Sensor fault, actuator jam, software error	Hydrogen release during emergency	Redundant shutdown paths, manual overrides	Add passive mechanical backup (spring-loaded valves)
Fire from adjacent activity	Fueling of nearby aircraft, GSE vehicle fire	Thermal radiation, escalation to LH_2 tank fire	Spatial zoning, fire detection and suppression	Review airport layout and separation distances
Incorrect hose connection	Human error, incompatible fitting	Leakage at joint, sudden hydrogen release	Double-check procedures, standardized fittings	Introduce interlocks and visual confirmation systems
Power or comms loss	Grid failure, cable damage, software bug	Loss of control, failed shutdown	UPS systems, manual backups, alarm memory	Assess cyber-physical failure cases
Hydrogen accumulation in low areas	Poor ventilation, leak during calm weather	Asphyxiation, explosion risk	Passive venting, H_2 gas detectors	Increase detector density, simulate dispersion models
Use of incompatible materials	Steel degradation, hydrogen embrittlement	Fracture or fatigue over time	Use of cryo-rated stainless steel/alloys	Perform long-term material compatibility testing
Weather impact	Lightning, high wind, heavy rain, extreme cold	Damage to refuelling unit or loss of control	Lightning arrestors, windbreaks, climate-rated equipment	Incorporate weather shutoff protocols
Vehicle collision	Ground service vehicles, fuel trucks	Pipe rupture, hydrogen leak, impact fire	Protective bollards, route marking, driver training	Reevaluate vehicle access control near refuel zones
Unauthorized access / sabotage	Poor fencing, badge failure, insider threat	Vandalism, deliberate leak or explosion	Access control, surveillance, alarms	Conduct vulnerability assessment, simulate intrusion scenarios

1.2.2 HAZOP ANALYSIS

Structure and Numbering Logic of the HAZOP Table

The HAZOP analysis presented in this report is structured around a systematic breakdown of the liquid hydrogen (LH_2) refuelling process into distinct process steps, covering both technical operations and supporting procedures. To ensure clarity and traceability across the large number of identified deviations, each HAZOP entry is uniquely numbered using a structured three-part code.

Each HAZOP entry is assigned a unique identifier in the format **X.YZ**, where:

- **X** is the hazard category number (1 to 11, as described above)
- **Y** is the process step number (matching the P1P10 steps listed above)
- **Z** is the sequence number of the deviation within that process step and category

Example: Entry `1.32` refers to:

- Category `1`: Process Interface Hazards
- Process Step `3`: Access Control to Fueling Zone
- Second deviation listed for that step and category

Note that numbering is not strictly sequential across process steps. That is, process step numbering (Y) and deviation numbering (Z) are used independently of the entry sequence in the table. This allows hazards to be added flexibly without disturbing the structure.

Hazard Category Scheme

To systematically identify and classify the wide range of potential hazards, the following categories were defined and applied throughout the analysis. This structured categorization helped ensure a comprehensive and complete hazard inventory, reducing the likelihood of overlooking relevant scenarios. This approach facilitated the development of hydrogen-specific refuelling categories (described in the subsection below) while minimizing the risk of overlooking any relevant hazard types.

- **Technical**: leaks, rupture, valve failures, material degradation
- **Operational**: procedural errors, human mistakes, skipped steps
- **Environmental**: wind, rain, lightning, temperature extremes
- **Interface-related**: connection errors, incompatible fittings
- **Monitoring and control**: sensor failures, delayed alarms
- **External threats**: sabotage, adjacent fire, vehicle impact

Hazard Categories for Hydrogen Refuelling

Following the initial evaluation of general hazard categories, more specific categories were developed based on the key aspects of hydrogen aircraft refuelling. Within each category, hazards were systematically brainstormed and identified. These hazards were then organized according to smaller, distinct process steps, each of which falls under one of the defined categories.

hazard categories:

- **1 Process Interface Hazards** (e.g., fueling equipment, hose, valves)
- **2 Mobile Infrastructure Hazards** (e.g., refuelling truck, piping)

- **3 Hydrogen Properties Hazards** (e.g., flammability, flame invisibility)
- **4 Onboard Fuel Cell System Hazards**
- **5 Aircraft Fuel Tank/System Hazards**
- **6 Ground Handling and Human Factors**
- **7 Monitoring, Emergency, Awareness, Communication**
- **8 Transfer Operations (Flow, Pressure, Cooling)**
- **9 Venting and Purging Hazards**
- **10 External Environmental Hazards**
- **11 Emergency Shut-Off (ESD) Hazards**

These categories help group similar hazards and enable efficient cross-referencing between HAZOP tables, Bow-Tie analysis, and fault trees.

Purpose of This Structure

This numbering system serves multiple purposes:

- Maintains a clear link between hazards, system components, and procedural steps
- Facilitates traceability in risk modeling (e.g., Bow-Tie, Event Tree)
- Enables cross-referencing in recommendations and mitigation strategies
- Supports future updates as new scenarios or failure modes are identified

This structured approach was especially necessary due to the large number of deviations identified across various refuelling configurations and operational contexts.

Node: LH_2 Refuelling Process (From storage to aircraft via tanker or pipeline)

1.2.3 HAZOP table

Table 10: HAZOP table for LH_2 aircraft refuelling (with input from NLR experts).[25]

Process Step	Deviation	Possible Causes	Consequences	Safeguards Existing Controls	Recommen -dations	ID
Fueling area	Fan ignition source	Use of unshielded fan or combustion engine	Ignition of leaked hydrogen	Equipment type restrictions, hazardous area classification	Use intrinsically safe or explosion-proof equipment	1.10
Venting operation	Blocked vent during operation	Personnel/ equipment blocking vent area	Pressure build-up, improper venting	Marking of vent zones, operational procedures	Add sensors or alarms to detect vent obstruction	1.20
Fueling zone access	Use of electronic devices in fueling zone	Operator using unauthorized device	Spark ignition of hydrogen	Safety training, warning signs	Enforce no-device policy, install signal jammers	1.31
Fueling zone access	Open flame within fueling zone	Smoking, vehicle exhaust, maintenance work	Immediate ignition of hydrogen cloud	Open flame prohibition, supervision	Physical patrols and automated flame detection	1.32
Fueling equipment	GPU operation during fueling	Ground power unit switched on/off	Arc formation, ignition risk	Fueling co-ordination procedures	Introduce interlock between GPU and fueling process	1.40
Fueling setup	Obstructed vehicle escape path	Poor parking layout, blocked zone	Delayed removal during emergency	Marked evacuation lanes	Enforce clearance area checks pre-fueling	1.51
Fueling setup	Improper fueling vehicle position	Aircraft settles under fuel weight	Hose strain, mechanical failure	Training, visual guides for position	Use height compensation systems or flexible hoses	1.52
Fueling operation	Fueling during nearby thunderstorm	Operational pressure, lack of monitoring	Lightning strike during fueling	Weather monitoring procedures	Install weather lockout system on fueling equipment	1.60
Fueling control	Procedural error valve mismanagement	Human error, poor training	Premature vapor release	SOPs, operator certification	Introduce dual-check system for valve control	1.70

Table 10: HAZOP table for LH_2 aircraft refuelling (continued).

Process Step	Deviation	Possible Causes	Consequences	Safeguards Existing Controls	Recommen -dations	ID
Fueling hoses	Improper purging of hoses	Bypassed step, malfunctioning purge valve	Explosive hydrogen-air mixture forms	Purge protocol, manual checklists	Install automated purge validation sensors	1.81
Fueling hoses	Improper precooling of hoses	Step skipped, misjudged temperature	LH_2 flashing, material stress	Pre-cooling checklist, temp sensors	Add pre-fill temperature interlock	1.82
Refuelling truck tank	Rupture of LH_2 tank on refueling truck	Over-pressure, impact damage, thermal stress	Major hydrogen release, fire/explosion	Tank pressure monitoring, thermal insulation, safety valves	Include thermal shielding, implement tank impact testing protocols	2.11
Refuelling truck tank	Puncture of mobile hydrogen container	Vehicle collision, sabotage, dropped objects	Sudden release of pressurized hydrogen	Physical barriers, reinforced tank casings	Enhance traffic management, conduct sabotage drills	2.12
Refuelling truck tank	Truck tank PRV stuck open	Mechanical failure, ice formation, sensor error	Continuous hydrogen release	Regular PRV inspection, pressure monitoring	Use dual-pressure relief system with thermal monitoring	2.13
Refuelling truck tank	Crack in truck insulation	Thermal cycling, mechanical damage	Boil-off increase, pressure rise	Insulation inspection routines	Add insulation health diagnostics, pre-fill temperature check	2.14
Refuelling truck tank	Explosion from truck tank rupture (high temp)	Tank exposed to fire, failed venting	Fireball, blast wave, thermal flux	ESD system, separation zones	Add passive thermal blowout panel or shield	2.15
Refuelling truck piping	Rupture of truck system piping/valves	Vibration, loose fittings, fatigue	Flame jet or flammable cloud formation	Pre-transfer leak check, vibration damping	Include piping diagnostics, real-time sensor alarms	2.20

Table 10: HAZOP table for LH_2 aircraft refuelling (continued).

Process Step	Deviation	Possible Causes	Consequences	Safeguards Existing Controls	Recommen -dations	ID
All indoor operations	Hydrogen accumulation near ceiling	Hydrogen is lighter than air, poor ceiling ventilation	Explosion at ceiling level, structural damage	Floor-level gas detectors, passive ventilation	Install H_2 detectors near ceiling in enclosed areas, simulate ceiling stratification	3.10
Fire detection / monitoring	Flame not visually detected	Hydrogen burns with near-invisible flame	Delayed response to active flame, personnel unaware of fire	Operator awareness, routine safety patrols	Install UV/IR flame detectors, include flame status indicators	3.21
Fire detection / monitoring	Flame emits little heat radiation	Hydrogen flame gives weak IR signature	Flame not sensed until too close, late evacuation	Basic IR cameras, PPE	Use multispectral detection, train on hydrogen flame hazards	3.22
Fire proximity	Flame approached too closely	Flame has low radiant intensity perpendicular to its axis	Operator unknowingly walks into flame	PPE, operator training	Add flame proximity indicators or warning lights	3.30
Ignition control	Ignition from very low energy source	Hydrogen's low ignition energy, minor static or spark	Ignition of leak, explosion risk	Grounding, spark-free tools, ESD system	Expand spark/ignition risk zoning, reinforce static control measures	3.40
Aircraft fuel cell system	Heat generation during standby	Fuel cell idle mode still producing residual heat	Thermal stress on nearby systems, material degradation	Passive cooling, separation distance	Add thermal shielding near refuelling areas	4.11
Aircraft fuel cell system	Unintention hydrogen or water release	Internal leakage, purge valve fault	Hydrogen accumulation, slippery surfaces, fire risk	Regular system diagnostics, isolation during refuelling	Ensure fuel cells are powered down and isolated during fueling	4.12

Table 10: HAZOP table for LH_2 aircraft refuelling (continued).

Process Step	**Deviation**	**Possible Causes**	**Consequences**	**Safeguards Existing Controls**	**Recommen -dations**	**ID**
Aircraft fuel cell system	Hydrogen leakage from storage/piping	Material fatigue, poor sealing, post-flight expansion	Flammable cloud, suffocation in confined ground areas	Hydrogen sensors, system pressure checks	Integrate with ground leak detection, require cooldown before refuelling	4.13
Aircraft fuel cell system	Fuel cell fire	Short circuit, cooling system failure	Fire on board during ground ops, propagation to fuel area	Fire suppression system, crew training	Prohibit fueling if cell overheat or fire status active	4.14
Aircraft fuel cell system	Fuel cell explosion	Ignition in internal chamber or from hydrogen pocket	Blast, debris hazard, ignition of adjacent systems	Containment design, automatic shut-off	Include in safety interlock logic to disable fueling when fault detected	4.15
Aircraft fuel system	Unintended H_2 release in cabin	Valve malfunction, piping leak, sensor failure	Accumulation of flammable gas in confined area, fire or asphyxiation	Tank isolation valves, leak sensors, purge systems	Add cabin-integrated H_2 sensors, verify cabin venting during fueling	5.11
Aircraft fuel system	H_2 leak from onboard piping	Embrittleme vibration fatigue, connector failure	Onboard fire, suffocation risk for maintenance crew	Material selection, fire detectors, fuel cell isolation	Include H_2 leak risk in maintenance SOPs, run pre/post-fueling leak test	5.12
Aircraft tank system	High-pressure leak from onboard tank	Fitting failure, rupture, valve malfunction	Jet release of H_2, fire/explosion risk	Tank pressure monitoring, structural inspection	Reinforce tank integrity checks, add high-pressure relief diagnostics	5.21
Aircraft tank system	Low-pressure leak from onboard tank	Seal degradation, material embrittlement, fatigue	Formation of flammable vapor cloud	Pressure decay monitoring, visual inspections	Increase low-pressure sensor density, implement real-time alarm thresholds	5.22
Pre-fueling setup	Procedure not followed	Operator oversight, poor training	Incorrect equipment setup, increased accident risk	SOPs, operator certification	Enhance training, implement dual-operator signoff	6.11

Table 10: HAZOP table for LH_2 aircraft refuelling (continued).

Process Step	**Deviation**	**Possible Causes**	**Consequences**	**Safeguards Existing Controls**	**Recommen -dations**	**ID**
Pre-fueling setup	Lack of PPE	Insufficient supply, poor enforcement	Cryogenic burns, chemical exposure	PPE inventory management, supervision	Introduce PPE checks before operation	6.12
Pre-fueling setup	Degraded PPE	Wear and tear, improper storage	Reduced protection, operator injury	Inspection routines	Add pre-shift PPE integrity checklist	6.13
Pre-fueling setup	PPE not worn	Discomfort, time pressure	Exposure to cryogenic liquid or fire	Supervision, comfort-focused PPE design	Improve PPE ergonomics, enforce usage	6.14
Pre-fueling setup	Time pressure	Operational delays, scheduling conflict	Procedural shortcuts, safety lapses	Shift planning, buffer time	Include realistic turnaround times in planning	6.15
Pre-fueling setup	High workload	Staff shortage, multiple tasks	Operator fatigue, missed steps	Task delegation, rest breaks	Automate low-risk steps, increase staffing	6.16
Pre-fueling setup	Lack of co-ordination	Multi-org operation, unclear roles	Procedure conflicts, missed hazards	Joint fueling protocols	Organize pre-fueling coordination briefings	6.17
Fueling area layout	Ambiguous layout	Unclear markings, poor lighting	Vehicle/pedestri routing errors	Marked zones, reflective paint	Redesign stand layout, standardize markings	6.18
Human operations	Adverse weather	Rain, wind, snow	Slips, poor visibility, equipment strain	Weather monitoring, proper gear	Weather-based work halt rules	6.20
GSE traffic	Unsafe separation	No dedicated routes, narrow stands	GSE collision or injury	Route planning, reflective barriers	Redesign traffic flows, restrict simultaneous ops	6.31
GSE traffic	GSE collision due to space limits	Tight parking, blind spots	Fuel line rupture, personnel injury	Route marking, mirrors, training	Install collision sensors or cameras	6.32

Table 10: HAZOP table for LH_2 aircraft refuelling (continued).

Process Step	Deviation	Possible Causes	Consequences	Safeguards Existing Controls	Recommen -dations	ID
Fueling zone space	Confined space	Small stand size, multiple GSE	Tripping, limited escape routes	Staggered operations, layout plans	Use smaller GSE or modular fueling kits	6.40
Apron surface	Foreign Object Debris (FOD)	Loose materials, ineffective cleaning	Damage to fueling gear, trip hazard	FOD walks, magnetic sweepers	Automated FOD detection or cleanup bots	6.51
Apron surface	Slippery/ degraded stand surface	Oil, rain, surface cracks	Operator slips, hose mishandling	Anti-slip coating, drainage	Introduce surface condition inspection routine	6.52
Human error	Intentional deviation from procedures	Overconfide	Bypassing critical safety steps	Supervision, SOP clarity	Incorporate behavioral safety program	6.60
Aircraft stand	Aircraft damage due to GSE	Improper maneuver-ing, distraction	Aircraft system damage, leak	Driver training, barriers	Install soft buffers and speed limits	6.70
Moni-toring	Undetected ground leak	Sensor malfunc-tion or failure	Accumulation of hydrogen, explosion risk	Redundant ground sensors	Add self-test and maintenance schedule for sensors	7.11
Moni-toring	Undetected ground fire	Faulty flame detector, poor visibility	Uncontrolled fire escalation	Flame detection system, camera monitoring	Include IR/UV detection for H_2 flames	7.12
Moni-toring	Undetected onboard leak	Sensor failure, location not monitored	Onboard explosion/ asphyxiation	Built-in leak detectors	Add cross-checking logic, increased sensor coverage	7.13
Moni-toring	Undetected onboard fire	Flame not visible, detector error	Delayed response, fire spread	Flame detectors, cabin monitors	Add redundant detection and alarm path	7.14
Moni-toring / control	Power or communi-cation loss	Grid failure, cable damage, software bug	Loss of control, failed emergency response	UPS systems, alarm memory, manual overrides	Assess cyber-physical failure scenarios	7.15

Table 10: HAZOP table for LH_2 aircraft refuelling (continued).

Process Step	**Deviation**	**Possible Causes**	**Consequences**	**Safeguards Existing Controls**	**Recommen -dations**	**ID**
Ground crew awareness	Leak/fire not recognized by handler	Monitoring distraction, insufficient training	Failure to evacuate/alert others	Alarm panel, sensor dashboard	Add alert repeaters and procedural training	7.21
Ground crew awareness	No notification of fire/leak	System failure, missed alert	Personnel unaware of danger	Broadcast and mobile alert system	Add redundancy in alert routing and drill scenario	7.22
Communication	Loss of comms with fire staff	Radio failure, network issue	Delayed or no emergency response	Secondary comm systems, emergency phones	Add automatic alert beacons to fire teams	7.31
Communication	Contact with ATC lost	Equipment failure, power outage	Delayed coordination, increased risk	Backup radio systems	Add mobile ATC liaison or fallback channel	7.32
Communication	Contact with airport authority lost	Network failure, coordination lapse	No ground support, delayed decisions	Dispatch coordination protocols	Implement robust fallback contact mechanism	7.33
Emergency response	Firefighting staff unavailable	Understaffing, miscommunication	Delay in suppression, escalation	Firefighting shift schedules, alert protocols	Introduce backup crew rotation plan	7.40
Fueling	Unable to stop fueling	Valve jam, system error	Hydrogen continues to flow, major hazard	Manual shut-off, ESD button	Add mechanical isolation valve and verify accessibility	7.41
PPE	PPE not used/ provided correctly	Lack of availability or comfort	Injury during leak/fire	PPE policy, inspection routines	Increase comfort design, enforce checklists	7.50
Bonding /Earthing	Incorrect bonding/ earthing	Human error, unclear procedure	Ignition due to static discharge	Earthing checklist, visual interlocks	Use auto-sensing interlocks for earthing	7.60
Access	Fuel cell cannot be reached	Obstruction fire proximity	Fire cannot be extinguished, prolonged leak	Fuel cell access plans, remote diagnostics	Redesign access panels, add firefighting drone path	7.71

Table 10: HAZOP table for LH_2 aircraft refuelling (continued).

Process Step	**Deviation**	**Possible Causes**	**Consequences**	**Safeguards Existing Controls**	**Recommen -dations**	**ID**
Access	Hydrant or ESD inaccessible	Blocked by vehicle or cargo	Cannot isolate hydrogen flow in time	Clearance zones, markings	Mark critical path, relocate hydrants where needed	7.72
Access	Ramp access obstructed	Poor layout, parked GSE	Delay in emergency reach/ evacuation	Marked access lanes	Reassess layout and mark evacuation zones clearly	7.73
Access	Ramp egress obstructed	Clutter, people congestion	Trapped personnel in emergency	Egress signage, ramp rules	Add lighted egress path and enforce clearance	7.74
Spillage	Late notification to supervisor	Procedural lapse, confusion	Improper response, escalation risk	Reporting protocol	Automate notification, provide emergency cue cards	7.80
Transfer to tanker or pipeline	No flow	Valve closed, pump failure, sensor failure, ice plug	Delay in refuelling, potential for pressure buildup	Redundant sensors, manual checks, alarm systems	Install pump interlocks and flow verification or real-time ice detection sensor	8.11
Transfer to tanker or pipeline	Less flow	Ice blockage, pump cavitation	Incomplete fill, possible overcooling in line	Flow monitoring, backup lines	Regular purge cycle for cryogenic lines	8.12
Transfer to tanker or pipeline	More flow	Valve stuck open, control failure	Overfilling, rapid pressure rise, spillage	Pressure relief valves, flow limiters	Introduce automatic shutoff based on fill level	8.13
Transfer to tanker or pipeline	Reverse flow	Back-pressure, valve malfunction	Hydrogen flows back to storage or tanker, contamination risk	Non-return valves, pressure monitoring	Install additional check valves	8.14
Cooling/ pre-chill phase	No cooling	Skip step, operator error, pre-cool bypassed	Thermal shock to system, risk of damage and leakage	Operating procedure, operator training	Interlock to require pre-cool before fill	8.21

Table 10: HAZOP table for LH_2 aircraft refuelling (continued).

Process Step	**Deviation**	**Possible Causes**	**Consequences**	**Safeguards Existing Controls**	**Recommen -dations**	**ID**
Cooling/ pre-chill phase	Inadequate cooling	Insufficient LH_2 flow, thermal insulation degraded	Material embrittlement, failure during filling	Temperature sensors, insulation inspections	Add temperature interlocks	8.22
Connection to aircraft	Leak at joint	Improper fitting, damaged seal, ice in connector	Hydrogen release, fire/explosion risk	Leak test, double-check by second operator	Implement quick-release breakaway couplings	8.23
Connection to aircraft	No grounding	Ground wire not connected	Static electricity discharge, ignition risk	Visual checklist, ground interlock systems	Audible alarm if grounding is incomplete	8.24
Connection to aircraft	Ignition due to static discharge	Dry climate, lack of grounding, static buildup	Immediate ignition of leaked hydrogen	Visual checklist, grounding interlock systems	Add audible/visual alert if grounding not verified	8.25
Connection to aircraft	Incorrect hose connection	Human error, incompatible fittings	Leak at joint, sudden hydrogen release	Standardized connectors, checklists	Introduce interlocks and visual confirmation systems	8.26
Disconnection	Early disconnection	Premature operator action	Hydrogen leak, potential jet release	Procedure lockout, operator training	Delay-timer interlock to prevent early detach	8.41
Disconnection	Late disconnection	Human error, distracted operator	Hose/tank damage, overfilling	Pressure limit sensor, tank level monitor	Audible/visual fill completion alarms	8.42
Discon -nection	Cryogenic burns to operator	Contact with vented LH_2, hose malfunction	Severe injury (frostbite, tissue damage)	PPE, operator training, shielded connectors	Reinforce training, use quick-disconnect nozzles	8.43
Venting /purge	No purge	Skipped step, valve malfunction	Residual hydrogen in lines, risk on next connection	SOP checklist, ESD requirement	Purge verification via hydrogen sensor	9.11

Table 10: HAZOP table for LH_2 aircraft refuelling (continued).

Process Step	**Deviation**	**Possible Causes**	**Consequences**	**Safeguards Existing Controls**	**Recommen -dations**	**ID**
Venting /purge	Excess purge	Faulty timer, operator misjudg-ment	Waste of hydrogen, increased leak/flare load	Manual control with timer	Automate purge timing and vent monitoring	9.12
Venting /purge	Oxygen freezing on surfaces	Super-cooled surfaces in contact with ambient air	Flammable oxygen-rich layer, ignition risk	Surface insulation, controlled venting	Review vent design and insulation quality	9.13
Venting /purge	Ice plug in vent line	Moisture ingress, insufficient purging	Pressure build-up, blocked vent path	Heated lines, purge cycles	Analyze humidity control, review purge frequency	9.14
All steps (exter-nal)	Fire from adjacent activity	Nearby fueling, GSE vehicle fire	Radiant heat exposure, escalation to LH_2 tank	Spatial zoning, fire detection/ suppression systems	Review airport layout and increase minimum distances	10.10
All hardware-related steps	Use of in-compatible materials	Hydrogen embrittle-ment, unsuitable metals	Gradual material degradation, fracture risk	Cryo-rated materials (SS316L, etc.)	Perform long-term material compatibility testing	10.20
All oper-ations	Adverse weather conditions	Lightning, wind, rain, extreme cold	Equipment failure, loss of operator control	Weather-resistant components, grounding, enclosures	Integrate weather-based shutoff protocols	10.32
All oper-ations	Vehicle collision	GSE or fuel truck impact	Pipe rupture, hydrogen leak, secondary ignition	Protective barriers, route marking, training	Reevaluate vehicle access near refuelling zone	10.32
All oper-ations	Un-authorized access / sabotage	Weak access control, insider threat	Deliberate hydrogen release or ignition	Fencing, surveillance, ID systems	Conduct vulnerability assessment and response drills	10.33
Emer-gency shut-off (ESD)	Unexpected activation	False sensor trip, electrical fault	Sudden system shutdown, stress on components	Signal verification, ESD delay timers	Add sensor filtering logic	11.11

Table 10: HAZOP table for LH_2 aircraft refuelling (continued).

Process Step	**Deviation**	**Possible Causes**	**Consequences**	**Safeguards Existing Controls**	**Recommen -dations**	**ID**
Emer-gency shut-off	ESD system failure	Sensor fault, actuator jam, software failure	Uncontrolled hydrogen release during emergency	Redundant shutdown paths, manual override	Add passive mechanical backup (e.g., spring-loaded valves)	11.12
Emer-gency shut-off (ESD)	No response	Actuator failure, system disabled	Uncontrolled hydrogen release during incident	Regular ESD tests, redundancy	Add passive ESD (failsafe mechanical cut-off)	11.13

1.2.4 Categorization of Hydrogen Leak Hazards

The table below provides a clear and structured categorization of all relevant hazards directly contributing to a hydrogen leak during LH_2 tanking operations at the airport. Each hazard is assigned to a logical cluster based on similarity of origin, failure mode, or consequence. This structure enables intuitive construction of the left side (threats and preventive barriers) of a bow-tie diagram. Hazard IDs refer to original HAZOP references. To emphasize, this categorization is specifically done for the main event of a hydrogen leak hazard which will later be used for the Bow-Tie analysis.

Table 11: Clustering of selected HAZOP hazards for the LH_2 refuelling bow-tie analysis.

Cluster	**Hazards Included (HAZOP IDs)**	**Explanation**
1. Equipment or Control System Malfunction	1.7, 2.13: Pump or valve malfunction 7.41, 8.118.13: Transfer to tank errors or pipeline faults 8.21: Inadequate cooling	Failures in pumps, valves, control units or cooling subsystems that lead to loss of containment or improper hydrogen flow management. These are common failure points in fueling systems.
2. Improper or Faulty Hose/Joint Connection	6.52, 8.26, 8.41 - 8.42: Incorrect hose connection 8.23: Leak at joint or connector	Misconnection or damage to joints, couplings or hoses which directly results in hydrogen leakage. This includes human error and wear-related issues.
3. Pre-fueling Line Preparation Errors (Purging, Cooling, Venting)	1.81: Improper purging 1.82, 8.21: Improper pre-cooling 9.119.14: Vent/purge errors	Failures during pre-fueling setup including incomplete purging, poor cooling, or ineffective venting, leading to hydrogen-air mixtures and overpressures.
4. Mechanical Damage from Vehicle or Object Impact	6.32, 6.7, 10.32: Vehicle collision	External mechanical loads (e.g. collisions with trucks or GSE) that cause physical rupture of hoses, valves, tanks or pipes.

Table 11: Clustering of selected HAZOP hazards for the LH_2 refuelling bow-tie analysis (continued).

Cluster	Hazards Included (HAZOP IDs)	Explanation
5. Failure of Emergency Shutdown System (ESD)	7.72, 11.12, 11.13	The emergency shutoff system may fail due to actuator/sensor/software fault, leaving hydrogen flowing during an incident. Critical for escalation prevention.
6. External Ignition Source (Fire, Explosion)	2.15, 3.10: Fire/explosion from adjacent activity 1.6: Adverse weather conditions (e.g. lightning)	These are non-fueling-related events in the vicinity that can ignite hydrogen if a leak occurs. Includes thunderstorms or nearby fire activities.
7. Latent Hydrogen Leakage from Aircraft Fuel or Cell System	4.12, 4.13: Fuel cell leakage 5.11, 5.12, 5.21, 5.22: Tank leakage or internal piping faults	These are non-tanking-specific hydrogen leaks that can occur onboard due to long-term degradation, fatigue, or fuel cell failures. May be analyzed in a separate scenario.
8. Other Skipped Hazards	10.33: Unauthorized access/sabotage 6.51: Foreign Object Debris 10.20: Incompatible materials	These are either too unlikely, already included in other categories, or not applicable to the defined scope (aircraft parked fueling operations). Excluded from this bow-tie.

Explanation of Choices:

- **Consolidation**: Hazards are grouped by cause type (e.g., equipment failure, human error, external impact) to reduce complexity in the bow-tie.
- **Scope Filtering**: Hazards irrelevant to the specific fueling operation context (e.g., fuel cell degradation during flight) are placed in a separate group or skipped.
- **HAZOP Referencing**: Original reference IDs are preserved for traceability in case you need to link back to HAZOP sheets.
- **Intended Use**: This classification feeds directly into the left (threat/prevention) side of a bow-tie diagram centered around the top event: **Hydrogen Leak during LH_2 Refuelling at Parked Aircraft**

1.2.5 Categorization of Hydrogen Leak Consequences

Notes:

- The HAZOP considers both mobile tanking (via LH_2 truck) and fixed infrastructure (cryogenic pipeline).
- Future expansions can include interactions with other systems (firefighting, terminal energy systems).
- This analysis should be updated as operational experience and system architecture mature.

Table 12: Categorisation of LH_2 refuelling hydrogen leak consequences and mitigations.

Category	Hazard	Explanation	Mitigation Options
A. Immediate Fire or Explosion	A.1 Flash fire	A dispersed hydrogen-air mixture ignites, causing a rapid combustion wave. Can occur if leaked hydrogen mixes with ambient air and finds an ignition source.	Intrinsically safe equipment, ignition source control, no-smoking policy, gas detection and emergency shutdown (ESD) systems.
	A.2 Jet fire	High-pressure hydrogen leak ignites at the release point, creating a continuous directional flame. Dangerous near personnel or critical infrastructure.	Use of pressure relief valves (PRVs), breakaway couplings, directional shielding, and emergency shutoff valves.
	A.3 BLEVE	Boiling Liquid Expanding Vapor Explosion: an external fire heats a liquid hydrogen tank, increasing internal pressure until the tank violently ruptures.	Fireproof insulation, passive fire protection (PFP), thermal sensors, tank siting in protected zones.
	A.4 Deflagration or detonation	Subsonic (deflagration) or supersonic (detonation) combustion in a confined space due to hydrogen-air accumulation. Can cause overpressure damage.	Eliminate confined spaces, ensure proper venting, hydrogen detection, and ignition control.
B Gas Dispersion Risks	B.1 Hydrogen accumulation	Accumulation in enclosed or poorly ventilated areas like hangars or under the aircraft. Can lead to undetected ignition risk.	Passive/active ventilation, hydrogen detectors mounted at high points, dispersion analysis, purge protocols.
	B.2 Asphyxiation hazard	In high concentrations, hydrogen displaces oxygen, creating a suffocation hazard in low-lying or stagnant air zones.	Oxygen sensors, ventilation, alarms for low oxygen levels, access control to enclosed zones.
	B.3 Invisible plume	Hydrogen is colorless and odorless; leaks may not be noticed visually or through smell.	Continuous monitoring, leak detectors, training on sensor-based alerts.
	B.4 Delayed ignition	Hydrogen leak may ignite after minutes, possibly after personnel or equipment have entered the area unaware.	Automatic purging, restricted access during venting, time-delayed isolation of leak zones.
C. Cryogenic Hazards (LH_2-specific)	C.1 Cryogenic burns	Exposure to liquid or cold vapor can cause severe frostbite or tissue damage. Inhalation may harm lungs.	Insulated transfer lines, PPE (gloves, face shield), operational training, and restricted zones.

Table 12: Categorisation of LH_2 refuelling hydrogen leak consequences and mitigations (continued).

Category	Hazard	Explanation	Mitigation Options
	C.2 Material embrittlement	Structural materials may become brittle at cryogenic temperatures, increasing fracture risk under stress.	Use of cryo-compatible alloys (e.g., SS316L), material aging checks, inspection of vulnerable parts.
	C.3 Thermal shock	Rapid temperature changes in pipes or tanks can lead to cracks or seal failures.	Pre-cooling steps, temperature ramp controls, thermal cycle monitoring.
	C.4 Frost formation	Condensation and frost from cold surfaces create slip hazards for personnel.	Anti-slip flooring, physical barriers, clear marking and signage, de-frost procedures.
	C.5 Oxyden Condensation	Air contacting very cold LH_2 surfaces can cause oxygen to liquefy and form oxygen-enriched condensate, which can soak materials (e.g., asphalt, clothing) and create extreme fire or detonation risk upon ignition	Use of vacuum-insulated lines, regular insulation integrity checks, purge protocols, avoidance of flammable surfaces near vent outlets, and signage to prevent access during venting.
D. Operational Disruption	D.1 Emergency shutdown	A hydrogen incident halts refuelling or apron activities, disrupting airport operations.	Emergency response protocols, ESD drills, alternate fueling plans.
	D.2 Aircraft ground stop	Neighboring aircraft may be unable to taxi or depart due to leak/fire risk in the vicinity.	Fueling zoning separation, reroute procedures, coordination with ATC.
	D.3 Area evacuation	A leak or fire triggers evacuation of the apron and nearby areas.	Clear evacuation plans, personnel briefings, signage and PA systems.
	D.4 Flight delays/cancellatio	Disruption cascades to schedule impacts and logistical problems.	Buffer time in flight plans, secondary ground handling teams.
E. Emergency Response Challenges	E.1 Invisible flame	Hydrogen flames emit little visible light and heat, making them hard to detect.	UV/IR flame detectors, visual indicators in fueling zones, training.
	E.2 Poor leak visibility	Same as above, can delay detection and increase risk of exposure.	Leak-detection lighting, increased sensor coverage.
	E.3 Sensor failure or delay	Hydrogen or flame sensors may fail to trigger in time due to environmental conditions or calibration errors.	Redundancy, regular testing and calibration, sensor validation protocols.

Table 12: Categorisation of LH_2 refuelling hydrogen leak consequences and mitigations (continued).

Category	**Hazard**	**Explanation**	**Mitigation Options**
	E.4 Miscommunication	Fueling crew, ATC, and fire teams may not coordinate correctly during an incident.	Standard operating procedures (SOPs), integrated communication systems, simulation exercises.
F. Personnel Hazards	F.1 Burn injuries	From fire or contact with hot surfaces during or after an incident.	PPE, flame-resistant clothing, safety zones.
	F.2 Frostbite / tissue damage	From cryogenic exposure to skin or eyes.	PPE, automatic cutoffs, training for emergency care.
	F.3 Psychological trauma	From experiencing or witnessing a near miss or actual hydrogen-related incident.	Post-incident debriefings, access to support services, safety culture promotion.
	F.4 Inhalation injuries	If hydrogen displaces oxygen, can cause suffocation or lung damage.	Respiratory protection, O_2 sensors, emergency evacuation procedures.
G. Damage to Infrastructure	G.1 Aircraft damage	LH_2 leaks or fires can damage fuselage, control surfaces, or fuel systems.	Separation of fueling and aircraft systems, physical barriers, automated cutoff.
	G.2 Truck or GSE damage	Fueling vehicles and support equipment may be damaged or destroyed.	Safe parking policies, shielding, emergency isolation procedures.
	G.3 Apron surface damage	Cryogenic spills or fire can damage tarmac or substructure.	Spill containment mats, fireproof surface coatings, structural inspection routines.
H. Regulatory, Financial & Reputational Impact	H.1 Regulatory investigation	Incident may trigger aviation or chemical safety investigation.	Safety documentation, traceable procedures, transparent reporting.
	H.2 Downtime	Aircraft or equipment taken offline for repairs or safety checks.	Redundancy, spares inventory, rapid inspection teams.
	H.3 Financial losses	Due to operational delays, damages, or penalties.	Risk-based financial planning, safety investment.
	H.4 Loss of public trust	Media coverage or stakeholder reaction may affect confidence in hydrogen systems.	Communication strategy, education on safety measures, engagement with regulators.

1.3 Bow–Tie Diagram

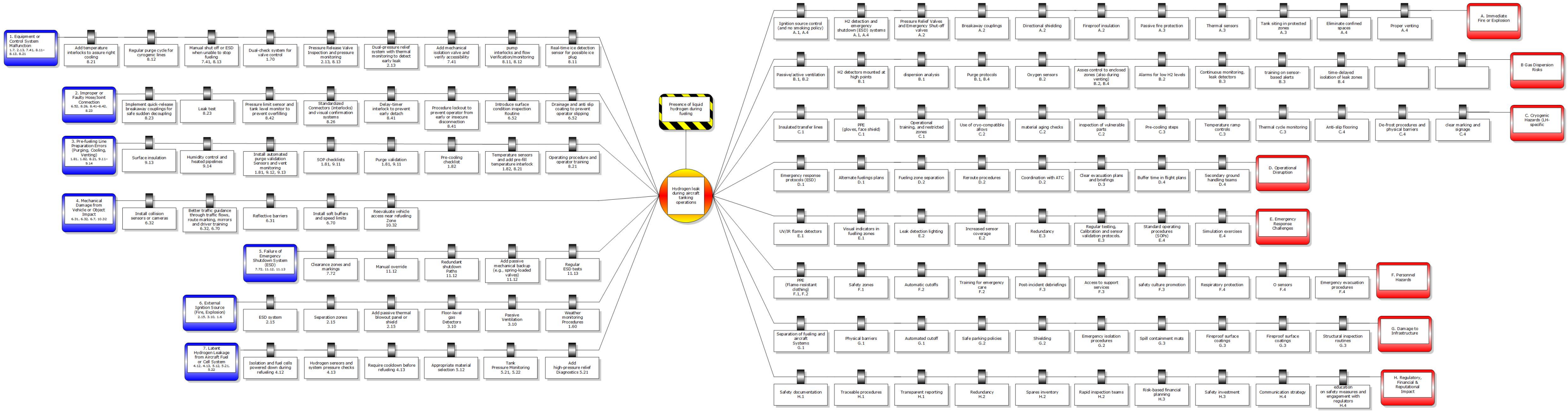


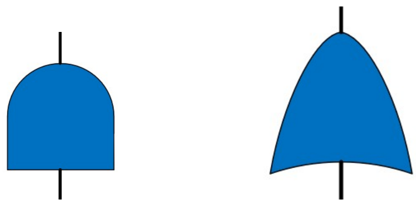
Figure 25: Bow–Tie diagram for the top event: LH_2 release during aircraft refuelling.

1.4 Fault Trees

Fault Tree Analysis (FTA) is a deductive, top-down safety assessment method that starts with a defined undesired event (the "top event") and works backwards to identify all credible combinations of failures that could lead to that event. In this case, the top event is a *Hydrogen Leak due to Residual Hydrogen After Failed Purge*.

The tree is constructed using a combination of:

- **OR-gates**, representing alternative failures, where the occurrence of any input leads to the output. These are the blue connectors with the bended underside.
- **AND-gates**, representing combined conditions, where all input failures must occur simultaneously to cause the next step. These are the blue connectors with the horizontally straight underside.



(a) AND gate (b) OR gate

Figure 26: Logic gates: AND and OR

These specific trees was developed based on failure modes identified in literature, engineering practice for cryogenic and hydrogen systems, and early results from the HAZOP study. All elements were mapped to logical groupings such as procedural failures, hardware malfunction, and environmental influences like moisture ingress or thermal gradients.

2 Key Hazard Selection

2.1 Methodology for Shortlisting Key Hazards

As the main reason for this safety assessment is to discover the impact on the safety distance and zones, it is important to take those hazards/consequences that have the most effect on this. Eventually there has to be made a well thought choice based on the likelihood and severity of a hazard to establish the right safety distances. Also only hazards that effect directly the safety distance or zone are considered, so this filters out B.2, C.2, C.3, C.4, D, E, F.3, F.4, G.3 and H.

That leaves: A1, A2, A3, B1 B3, B4, C.1, C.5, F1, F2, G1, G2. These hazards are examined for severtiy and likelihood in the following section and outlayed in table 13. Ofcourse these are the ultimate consequences of a sequence of faults and so for further research the fault sequence diagram should be made for these consequences together with their probabilities to get an accurate estimation of the likelihood.

The complete HAZID (Hazard Identification) list for LH_2 refuelling operations includes a wide spectrum of potential hazards, spanning mechanical, operational, thermal, electrical, chemical, and organizational failure modes. To focus the risk analysis and prioritize mitigation, a shortlist of the most critical hazards/consequences was extracted based on a structured filtering methodology:

1. **Operational Relevance Filter:** Hazards were first filtered to include only those directly applicable to the specific operation under study: ground-based refuelling of aircraft with liquid hydrogen (LH_2). Hazards linked exclusively to upstream production, in-flight use, vehicle crash scenarios, or unrelated hydrogen applications (e.g. fuel cells) were excluded.

2. **Risk Potential Prioritization:** From the operationally relevant hazards, those with the greatest risk contribution were selected. Risk was assessed as a combination of potential *severity* and *likelihood*, as outlined in Section 1.2. Hazards in the *high-risk quadrant* (i.e., high severity and medium likelihood, or catastrophic severity even with low likelihood) were prioritized. This includes explosion risks, major leaks, and static discharge ignition.

3. **Unique Hydrogen Characteristics:** Hazards that are uniquely exacerbated by hydrogens physical or chemical properties (e.g. low ignition energy, invisible flame, cryogenic behavior, oxygen condensation) were emphasized. These include invisible flame burns, static ignition, and oxygen enrichment hazards.

4. **Control Sensitivity / Bottleneck Identification:** Hazards where the system depends on a single or critical safeguard (a bottleneck) were retained. These include failure sensitive or maintenance critical elements like flame detectors, grounding systems, or relief valves, where failure could escalate minor issues into catastrophic events.

5. **Supporting Literature and Incident Data:** Preference was given to hazards frequently cited in hydrogen safety literature and prior accident investigations. Sources include [23, 10, 2, 14], which emphasize leak ignition, cryogenic contact, and pressure control failures as primary concerns.

2.2 Severity and Likelihood Assessment of Key Hazards

In this section, the consequence list on the right-hand side of the Bow–Tie is reduced to a shortlist of the most relevant hazards for liquid-hydrogen (LH_2) aircraft refuelling on an open apron. For each shortlisted hazard, we assign a qualitative severity class based on credible outcomes and a qualitative likelihood class based on the expected frequency under baseline controls.

Because empirical failure and incident data for LH_2 apron refuelling is limited, the ranking uses a structured qualitative approach. The assessments are supported by (i) hydrogen safety literature and guidance (standards, roadmaps, best-practice documents), (ii) evidence from analogous hydrogen and cryogenic handling applications, and (iii) expert judgement informed by operational and airport-safety perspectives (e.g., NLR and RTHA). Ratings are assigned for the open-apron refuelling context and assume baseline procedural and technical safeguards; where uncertainty remains, conservative classes are used. Severity reflects the credible consequence scale if the hazard occurs, while likelihood reflects how often the initiating conditions can occur under the assumed controls. Where a hazard requires enabling conditions (e.g., ignition or confinement), this is stated explicitly in the table rationale.

Table 13 summarises the key hazards with their assigned severity and likelihood and provides a short rationale for each rating, including the main drivers and controls. The highest-risk hazards are then discussed to identify the main safety bottlenecks, i.e., safeguards whose failure would strongly increase escalation potential.

2.2.1 Severity levels

Severity describes how serious the consequences can be if a hazard occurs during open-apron LH_2 refuelling. In this study, hazards are grouped into three severity tiers.

Catastrophic. Scenarios are rated Catastrophic when they can plausibly cause multiple fatalities and major asset loss, including destruction of the aircraft and critical ground equipment. This tier mainly covers loss-of-containment events followed by ignition (fire or explosion). The FAA notes that hydrogen is easy to ignite and has a wide flammability range, making fire and explosion hazards key concerns [10]. In confined or congested conditions, an ignited hydrogen–air cloud can also generate very high blast pressures [10]. In addition, flame acceleration can progress towards detonation under certain conditions [28], which supports a Catastrophic rating for large-release scenarios with credible escalation pathways.

Critical. Scenarios are rated Critical when severe injury or a single fatality is plausible and substantial equipment damage can occur, but outcomes are expected to remain more local than catastrophic events. Examples include jet-fire exposure near the leak source, asphyxiation due to oxygen displacement in a closed or partially enclosed space, and oxygen enrichment effects that can strongly intensify a fire if ignition occurs [2]. Hydrogen flames can be hard to detect in daylight and emit relatively little infrared heat [22], which can delay response and increase personnel exposure, worsening the outcome [22].

Moderate. Scenarios are rated Moderate when consequences are typically limited to local injuries without expected fatalities or major asset loss. This tier includes cryogenic contact injuries and slip hazards caused by ice formation, which mainly affect personnel in the immediate vicinity of the refuelling equipment.

Table 13 assigns each key hazard a severity level based on these definitions and provides the case-specific reasoning.

2.2.2 Likelihood assessment

In contrast to severity, which can often be inferred from physical outcomes, the likelihood of hydrogen-related hazards is more difficult to quantify for aviation refuelling because empirical data is limited. Likelihood is therefore assessed qualitatively using defined frequency bands, supported by engineering judgement, literature on analogous systems (e.g., hydrogen vehicle fuelling stations and cryogenic infrastructure), and the assumed presence of mitigating measures.

Likelihood categories are defined as follows:

- **Very High:** expected to occur in nearly every fuelling cycle; likelihood exceeds 1 in 10 operations.
- **High:** occurs frequently (order 1 in 100 cycles); controls exist but are not consistently reliable or fail-safe.
- **Medium:** occurs occasionally, particularly under abnormal conditions or human error; order 1 in 1,000 to 1 in 10,000 operations.
- **Low:** unlikely under normal conditions, but possible under specific failure modes or combined faults; order 1 in 100,000 or less.
- **Very Low:** highly improbable and requires a rare combination of failures or external stressors; less than 1 in 1,000,000 fuelling cycles.

These qualitative thresholds are informed by best practices in hydrogen safety literature and are adapted to reflect the early-stage maturity of LH_2 ground handling operations [14, 2, 22].

Likelihood ratings are assigned by considering:

- failure mechanisms (e.g., thermal stress, overpressure, leak paths);
- evidence and trends from analogous hydrogen and cryogenic applications;
- hydrogen properties (e.g., diffusivity, low ignition energy, cryogenic temperature);
- baseline safeguards (e.g., venting, sensing, interlocks, grounding, and procedural controls); and

- operational factors, including human reliability and procedural complexity [16, 29].

Some scenarios (e.g., minor leaks or procedural errors) are inherently more likely and are therefore typically rated Medium to High, especially in early deployment phases where procedures and training may still be evolving. Other events, such as catastrophic rupture or severe overpressure failures, are rated Very Low, reflecting robust engineering controls and compliance with established design codes. Due to the potentially severe consequences of even low-probability hydrogen failures, conservative classes are used where uncertainty remains, and mitigation planning is considered for all credible hazards [33].

2.2.3 Shortlist Most Important Hazards

Table 13: Shortlist of most important hazards, with severity and likelihood estimates.

Hazard	Severity Level	Likelihood	Rationale and Notes
Large LH_2 Leak + Delayed Ignition B.4 (Vapor Cloud Explosion)	*Catastrophic* - could cause a powerful explosion, multiple fatalities, and destruction of aircraft and equipment.	*Low* - Requires major leak plus an ignition source after dispersion; all systems aim to prevent this, making it a rare scenario.	A major rupture or hose failure could release a large hydrogen cloud. If ignition is delayed until the cloud mixes with air in a confined or congested area, a deflagration or detonation can occur with devastating overpressure [10]. Hydrogens wide flammability range (475% in air) and low ignition energy (∼0.02 mJ) [10, 28] mean even a small spark can set off a large cloud. Controls (ventilation, leak detection, shutoff systems) make this outcome unlikely, but its severity is catastrophic and the worst-case accident in fueling.

Table 13: Shortlist of most important hazards, with severity and likelihood estimates (continued).

Hazard	Severity Level	Likelihood	Rationale and Notes
Immediate Ignition of Hydrogen Leak A.2 (Jet Fire)	*Critical* intense fire at leak source; can cause localized fatal burns, equipment damage; potential to escalate.	*Medium* Small leaks are not uncommon; ignition is possible if any spark or static discharge occurs.	If a leak ignites immediately, it forms a high-speed hydrogen flame (jet fire) instead of an explosion. This flame can burn through the refuelling apparatus or aircraft structure. Hydrogen flames have very high flame temperature and burn velocity [10], and are nearly invisible in daylight [23]. Personnel may not realize a fire is present until harm occurs, as the flame lacks smoke and radiant heat (little infrared radiation) [23]. This hazard is very dangerous (potentially lethal to anyone nearby) but usually more localized than a vapor cloud explosion. Given hydrogens extremely low ignition energy and ubiquity of ignition sources, the likelihood of a leak igniting (if a leak occurs) is moderate [2, 10].
Overpressure or Tank Rupture A.3 (Burst Release)	*Catastrophic* massive hydrogen release, possible BLEVE-type fireball or explosion; would likely be fatal to crew and destroy equipment.	*Very Low* Multiple safeguards (pressure relief valves, tank design codes) make a spontaneous tank failure highly improbable during normal operations.	Overfilling the aircrafts tank or an equipment failure could lead to over-pressurization of the LH_2 vessel. LH_2 has a large expansion ratio (1:845 from liquid to gas) [2], so even a small trapped volume can create huge pressures if warmed [23]. A tank or line rupture would release hydrogen violently. If ignited, this could produce a fireball or overpressure wave. Even without immediate ignition, a large release greatly increases the risk of subsequent ignition due to the volume of gas. This scenarios likelihood is extremely low (tanks are built to rigorous standards with relief valves), but the severity would be catastrophic.

Table 13: Shortlist of most important hazards, with severity and likelihood estimates (continued).

Hazard	Severity Level	Likelihood	Rationale and Notes
Cryogenic Liquid Contact C.1 (Cold Burns)	*Moderate* serious injury (frostbite, tissue damage) to personnel; not usually life-threatening to bystanders or immediately catastrophic to equipment.	*Medium* Handling LH_2 carries a notable risk of cold contact or splash, especially if procedures or PPE are inadequate.	LH_2 is stored at 20K (−253°C); skin contact with liquid or even cold gas can cause instant frostbite and tissue damage [2]. Cold metal surfaces (valves, couplings) can cause skin to stick and tear. Small LH_2 spills can happen (e.g. during hose disconnect or venting). Severity is typically limited to injuries to the immediate operator (hence moderate in the context of overall operation risk), but these injuries are severe on a personal level. The likelihood is non-negligible, without proper personal protective equipment (insulated gloves, face shields) and strict procedures, an operator might be exposed to cold burns [2]. History with cryogenic fuels (e.g. rocket fueling) shows that brief contact incidents do occur, so this hazard must be actively managed.
Oxygen Condensation & Enrichment on Surfaces C.5	*Critical* creates a fire/explosion amplification hazard; could lead to secondary fires or explosions if ignition occurs.	*Low* Requires prolonged exposure of equipment to cryogenic temperatures in air; mitigated by insulation and purge routines.	Air contacting very cold LH_2 equipment can liquefy. Nitrogen in air liquefies at 77K, oxygen at 90K; thus air condensation on uninsulated LH_2 lines can produce oxygen-rich liquid [2]. This liquid oxygen can soak materials (even asphalt or clothing) and make them extremely flammable, so much that even a minor spark can then cause a violent combustion of oxygen-saturated materials [23]. The presence of excess oxygen also increases flame speed and energy release. Severity: if oxygen-enriched condensate ignites, it can produce a severe fire or even detonation in confined spots. Likelihood: normally low, since designs use vacuum-insulated lines to prevent ice/oxygen formation [2, 23] and purge out air. It mainly becomes an issue if there is a failure in insulation or an uninsulated cold surface exposed to air for a long period.

Table 13: Shortlist of most important hazards, with severity and likelihood estimates (continued).

Hazard	Severity Level	Likelihood	Rationale and Notes
Accumulation of H_2 in Enclosed/Low Areas B.1 (Asphyxiation & Explosion Hazard)	*Critical* if an H_2 pocket forms in a confined space it can cause asphyxiation of personnel; if ignited, results in explosion.	*Low* (in open apron) / *Medium* (if partially enclosed space present) outdoor fueling dissipates H_2 effectively; confined pockets are unlikely unless ventilation is poor.	Although hydrogen is the lightest gas and normally rises and disperses quickly in open air [23, 22], a large release or a leak in a partially enclosed area (e.g. under an aircraft fairing, or in a maintenance trench/pit) could allow hydrogen to accumulate. Any gas in sufficient concentration can displace oxygen and act as an asphyxiant [23]. More critically, a trapped hydrogen layer (for instance, near a hangar ceiling or under a canopy) can reach flammable levels [23]. If ignited, the result is an explosion or intense fire overhead. For outdoor ramp operations, passive ventilation typically prevents significant accumulation [23], so risk is low. But the severity of a hydrogen build-up in a confined zone is high, warranting attention to ventilation design and H_2 detectors in any areas where gas could pocket.
Flash Fire A.1 (Immediate Combustion of Dispersed H_2)	*Critical* rapid combustion wave can cause burn injuries and ignite surroundings.	*Medium* hydrogens low ignition energy and wide flammability range make ignition of leaked gas likely in presence of spark.	A flash fire occurs when leaked hydrogen disperses and ignites without causing significant overpressure. This can happen quickly if gas-air mixture falls within flammable limits (475%) [2]. Though less destructive than an explosion, it can severely injure nearby personnel and damage exposed systems. The fire may go unnoticed initially due to hydrogens pale, near-invisible flame. Ignition source control, intrinsically safe equipment, and gas detection systems are primary mitigations [23].

Table 13: Shortlist of most important hazards, with severity and likelihood estimates (continued).

Hazard	Severity Level	Likelihood	Rationale and Notes
Invisible Hydrogen Plume B.3 (Undetected Leak)	*Moderate* unrecognized leak can escalate to fire or explosion.	*Medium* hydrogen is colorless and odorless; visual detection is unreliable.	Hydrogen leaks may go unnoticed as there is no visible or olfactory signal. Without gas detectors or sensor alarms, even experienced personnel may not detect a leak [23]. Training and reliance on monitoring systems (hydrogen sensors, alarms) is critical. This hazard is a precursor to several others, including flash fire and jet fire. Its severity is indirect but important: undetected hydrogen increases exposure time and chance of ignition [2].
Burn Injuries to Personnel F.1 (From Fire or Hot Surfaces)	*Critical* exposure to flame or superheated equipment can cause life-threatening injuries.	*Medium* occurs if personnel are near ignition zone or delayed in response.	Fire from hydrogen ignition can cause severe burns, especially if protective clothing is absent. Superheated metal parts (valves, couplings) retain heat even after a flame is extinguished. Flame-resistant PPE and clear safety zones reduce the risk. This hazard often arises as a consequence of jet or flash fires, but warrants separate identification due to its impact on human safety [23].
Cryogenic Frostbite or Tissue Damage F.2 (Cold Exposure)	*Moderate* contact with LH_2 or cold gas can cause frostbite or inhalation injury.	*Medium* possible during hose handling, disconnect, or small spills.	Accidental contact with LH_2 or extremely cold gas can instantly freeze skin or mucous membranes [2]. Inhalation of cold vapor can damage lungs. Protective equipment (insulated gloves, face shields), good procedure adherence, and fast automatic shutoff help mitigate this. Training for emergency response (first aid for frostbite) is also needed.

Table 13: Shortlist of most important hazards, with severity and likelihood estimates (continued).

Hazard	Severity Level	Likelihood	Rationale and Notes
Aircraft Damage G.1 (Structural or System Damage)	*Critical* leak or fire near fuselage can compromise structural integrity or avionics.	*Low* refuelling zones and safety buffers are designed to prevent direct exposure.	Hydrogen fires or uncontained leaks can damage control surfaces, composite structures, or wiring in the aircraft [29]. Even without ignition, prolonged exposure to cold gas or hydrogen embrittlement risk can impair sensitive components. Aircraft separation from fueling connection points and proper routing of fueling hoses minimize the likelihood. But the severity remains high due to safety-of-flight implications.
GSE / Truck Damage G.2 (Destruction of Fueling Equipment)	*Critical* fire or leak can destroy refuelling truck or ground support equipment (GSE).	*Medium* ignition of hydrogen near fueling truck is a known risk.	A hydrogen fire near or inside the fueling truck or cart can cause explosion, destroying the unit and posing risks to nearby aircraft or personnel. Vehicle shielding, safe standoff distances, and emergency shutdown features are key mitigations. For LH_2 refuelling, hydrogen is expected to be delivered by refuelling trucks and transferred via heavily insulated hoses; consequently, damage to the truckhose interface can have disproportionate operational and safety consequences.[15]

2.2.4

Excluded Hazards for Safety Distance Determination

While fire and explosion hazards drive the definition of fueling safety zones, several other hazards are relevant from an operational and personnel safety perspective. Their impact on fixed safety distance is generally secondary or localized. We summarize them below:

- **Gas Asphyxiation (B.2):** Hydrogen is non-toxic but can displace oxygen in enclosed spaces. On open aprons, buoyant dispersion minimizes this risk. Asphyxiation zones are local (e.g., pits, trenches) and mitigated by procedural exclusion and ventilation [14]. No large exclusion radius is added.
- **Cryogenic Cold Hazards (C.1, C.4):** Cold burns and frost hazards from LH_2 are confined to the immediate area near the fueling connection. These hazards justify PPE for fueling staff but do not affect general safety distances.
- **Material Embrittlement / Thermal Shock (C.2, C.3):** These are engineering-level concerns, addressed through material selection (e.g., stainless steel) [14]. They do not contribute to operational separation distances.

- **Invisible Flame (E.1):** Hydrogen flames are hard to see, increasing the risk of unknowingly entering a hazardous zone. While limited visibility does not reduce the physical hazard, it motivates conservative operational controls (e.g. an additional buffer) and reliance on flame detection instrumentation. .
- **Sensor Failure or Delayed Detection (E.3):** This increases uncertainty about leak duration and reinforces the use of conservative assumptions in setting zones (e.g., worst-case leak), rather than shrinking zones based on fast shutdown expectations.
- **Miscommunication (E.4):** Communication lapses can result in unsafe entries or delayed evacuations. This hazard affects zone enforcement rather than its physical size, justifying strict signage, procedural coordination, and clear area demarcation.
- **Operational Disruptions (D.1D.4):** These include fueling halts, stand closures, and flight delays during emergencies. They represent consequences of activating safety zones, not reasons to enlarge them. Emergency plans should anticipate such disruptions.
- **Personnel-Specific Hazards (F.1F.4):** These include burns, cold exposure, and inhalation trauma. They are addressed by keeping unprotected personnel outside the thermal zone and equipping workers with PPE. These concerns reinforce, but do not redefine, the safety distance.
- **Infrastructure Damage (G.1G.3):** Aircraft or GSE damage occurs within the same zone already defined for life safety. However, it supports ensuring that adjacent stands are unoccupied or unpowered during fueling, especially within 2030 m.
- **Regulatory / Financial / Reputational Impacts (H.1H.4):** These are secondary consequences but motivate conservative zoning. Emerging guidance (e.g. SAE AIR8466, EUROCAE ER034) will define reference values. Compliance supports stakeholder trust and avoids regulatory penalties [27, 9].

2.2.5 Implementation

Linking Safety Analysis to Airport Operations

The fault trees, event sequences, and bow-tie diagrams developed in this report identify a range of failure modes that can result in hydrogen leakage or ignition during LH_2 refuelling operations. These scenarios, although technical in nature, have direct consequences for the practical organization of airport ground operations. The identification of credible accident paths (e.g., failure of purge cycles, vent blockages, thermal shock) justifies a need for defined exclusion zones and refuelling protocols that influence where and how aircraft can be fueled.

Safety Distances and Zone Planning

Although the current analysis is qualitative, it forms a foundation for estimating minimum safety distances based on:

1. The maximum credible leak rate and duration (from fault/event trees)
2. Dispersion patterns under typical wind conditions
3. Jet fire length projections for full-bore PRV or connector failure
4. Required time to detection and emergency shutoff (based on system architecture)

Such assessments would eventually feed into quantitative risk assessments (QRAs), which inform:

- **Zoning of refuelling areas** relative to terminals, taxiways, and service routes
- **Limitations on simultaneous operations** (e.g., fueling and boarding/disembarkation)
- **Access control and surveillance systems** for hydrogen zones
- **Emergency response planning**, including egress routes and firefighting infrastructure

Explanation for Zoning Without Fixed Distances

At this stage, it is too early to define fixed safety distances for hydrogen refuelling operations with confidence. The actual size of the hazard area depends on many factors, such as the rate of hydrogen release, weather conditions (especially wind), and how the aircraft or ground equipment is shaped. While earlier studies (e.g. NASA-era work and Cryoplane) provide useful starting points for indicative distance estimates, safety zones and separation distances should be determined and validated for the specific operational context through a suitable risk assessment.[15]

Instead, a performance-based approach is recommended. This means defining safety zones based on realistic accident scenarios and modeling how far hazards like gas clouds, fires, or explosions might actually extend. This approach makes sure that safety distances reflect the real risks present on the apron. In many cases, such zoning also aims to meet widely accepted safety goals, such as keeping the chance of harm to any one person below one in a million per year ($<10^{-6}$/yr). By using scenario-based analysis and adjusting distances to match actual risk, the result is a safer and more practical fueling operation.

Operational Implications

Gate and Stand Configuration: Hydrogen-fueled aircraft may require dedicated or modified gate arrangements to ensure sufficient clearance from adjacent operations.

Turnaround Procedure: Fueling may need to occur in isolation, without concurrent boarding, catering, or baggage operations, potentially increasing turnaround duration.

Ground Support Equipment (GSE): Only hydrogen-safe or intrinsically safe equipment should be allowed within the exclusion zone. Conventional diesel-powered GSE must remain outside the high-risk area unless risk mitigations are in place.

Coordination with Neighboring Aircraft: Adjacent aircraft operations, including fueling or pushback, may need to be delayed during hydrogen fueling. Sequencing of activities must be coordinated with ground operations control.

Incident Management: Safety zones transition into evacuation zones during abnormal events. Emergency response must be adapted to hydrogen-specific hazards, including invisible flames, cryogenic risks, and high flammability. Appropriate equipment and training for fire crews and ground personnel are essential.

Justification for Hazard Focus

- Flash fire and jet fire scenarios represent credible, high-severity events with moderate probability and therefore form the basis of zone planning.
- BLEVE, while catastrophic, has an extremely low likelihood due to engineering controls (e.g., insulation, pressure relief devices) and is not used to define routine exclusion zones.

- Smaller-scale hazards (e.g., cold burns, embrittlement, sensor failure) are either managed by engineering design or mitigated via local procedural controls and PPE.

A tiered safety zoning concept is recommended for LH_2 aircraft fueling operations, driven by high-severity, credible fire scenarios. Exclusion and buffer zones must be defined based on hazard characteristics and validated through modeling and risk analysis. Operational adjustments in stand allocation, GSE deployment, and emergency preparedness are necessary to support safe hydrogen integration into airport fueling operations. Refinement of zone sizes should follow site-specific risk assessments, consistent with evolving standards and best practices.

3 Input Assumptions en Data

3.1 Aircraft fuel vs trailer capacity

For the assessment of apron loading, logistics, and refuelling infrastructure it is important to relate the fuel capacity of liquid hydrogen (LH_2) aircraft concepts to the capacity of currently available LH_2 road tankers. Commercially available cryogenic LH_2 transport trailers from Chart and Heil provide a useful indication of the present state of the art: typical models offer a geometric tank volume of approximately 66–75 m^3 and a maximum LH_2 payload of roughly 4–5 t per trailer [6, 13, 34]. In this work, a representative trailer payload of

$$m_{\text{trailer}} \approx 4.5 \text{ t} \tag{2}$$

is assumed for capacity and scaling analyses.

Recent literature provides fuel capacity estimates for several classes of LH_2 aircraft. The ICCT white paper on evolutionary hydrogen-powered aircraft defines two liquid-hydrogen concepts: a regional turboprop of about 70 passengers and a narrow-body aircraft of about 165 passengers [20]. For a typical design mission, the turboprop concept requires approximately 1,190 kg of LH_2 (about 1.2 t), while the narrow-body concept requires around 5,050 kg (about 5.1 t) of LH_2 [20].

ZeroAvia report an 80-seat regional turboprop hydrogen-electric concept with a cryogenic tank sized for about 8,450 L of LH_2, which, assuming a density of roughly 70 kg/m^3, corresponds to roughly 0.6 t of LH_2 [36]. Mangold et al. analyse the refuelling process of an A320-like LH_2 aircraft and consider a maximum refuelling mass of 5,350 kg LH_2, chosen as the energy-equivalent of the maximum kerosene volume of a conventional A320-class aircraft [19]. At the long-range end of the spectrum, Xisto and Lundbladh size a year-2050 EIS LH_2-fuelled wide-body for a 414-pax, 7,500 NM design mission.[35, p. 8, Table 5] The corresponding LH_2 fuel mass including reserves is 41.6 t.[35, p. 10, Table 7]

To relate these aircraft fuel capacities to the current LH_2 trailer technology, the required number of trailers N_{tr} to fully supply the aircraft fuel load can be estimated as

$$N_{\text{tr}} = \left\lceil \frac{m_{\text{fuel}}}{m_{\text{trailer}}} \right\rceil, \tag{3}$$

where m_{fuel} is the total LH_2 fuel mass carried by the aircraft and $\lceil \cdot \rceil$ denotes the ceiling operator. Table 14 summarises the key literature concepts and the corresponding trailer counts based on $m_{\text{trailer}} = 4.5$ t.

Table 14 highlights that a single present-day LH_2 trailer can easily support multiple regional LH_2 aircraft turns, while even evolutionary LH_2 narrow-body concepts already require more than one full trailer load to cover the maximum fuel capacity. For future long-range LH_2 wide-body aircraft, the equivalent of roughly ten current trailers would be needed to fill the tanks from empty. In practice, aircraft will not arrive empty and will typically land with on the order of 10–20% of the fuel capacity remaining on board, so the average uplift per turnaround

Table 14: Overview of LH_2 aircraft fuel capacities from the literature and the equivalent number of LH2 tankers required to supply a full tank, assuming $m$trailer $= 4.5$ t per trailer [6, 13, 34, 36, 20, 19, 35].

Study / concept	Segment	m_{fuel} [t]	N_{tr} [-]
ZeroAvia (2024) [36]	80-seat regional turboprop	≈ 0.6	1
ICCT (2022) turboprop [20]	$\sim$ 70-seat regional	≈ 1.2	1
ICCT (2022) narrow-body [20]	$\sim$ 165-seat narrow-body	≈ 5.1	2
Mangold et al. (2022) [19]	A320-like LH_2 aircraft	≈ 5.35	2
Xisto & Lundbladh (2022) [35]	414-seat wide-body, 7,500 NM	≈ 41.6	10

will be smaller than the full tank capacity. Nevertheless, the comparison clearly illustrates that trailer-only supply becomes operationally unattractive for larger aircraft classes, and that dedicated on-airport LH_2 storage and hydrant/dispenser systems will be required for large-scale LH_2 aviation [34, 20, 19, 35].

3.2 Refuelling Rates and Trailer Capacities

A key input parameter in modelling liquid hydrogen (LH_2) ground operations is the *refuelling time* per aircraft. Early-stage modelling in this work adopted a broad range of 10–60 minutes. Upon closer inspection of available flow-rate data and trailer technology, this range appears overly conservative.

Current conceptual designs for aviation-scale LH_2 fuel trucks often assume a mass flow rate on the order of 5 kg/s per vehicle for airport operations.[12, 31] This is substantially higher than the 0.1–0.2 kg/s flow rates of todays automotive LH_2 dispensers [8], and reflects the requirement to maintain competitive turnaround times in commercial aviation. Other studies, most notably Mangold et al. [19], demonstrate that cryogenic transfer through a 6 in. (152 mm) hose can reach mass flow rates of up to 20 kg/s, highlighting the significant technological headroom and uncertainty in future LH_2 refuelling systems.

Trailer capacity is another important source of variability. Commercially available LH_2 transport trailers typically carry 4–5 t of LH_2 [6, 13, 34], whereas smaller conceptual aviation-dedicated refuelling trucks in the literature range from 2–3 t per vehicle [12]. If a 3 t trailer is assumed and each aircraft requires approximately 1 t of uplift, a single trailer could serve three aircraft before returning to storage. At a nominal refuelling flow rate of 5 kg/s, the pure liquid transfer time for a 1,000 kg uplift is

$$t = \frac{m}{\dot{m}} = \frac{1000 \text{ kg}}{5 \text{ kg/s}} = 200 \text{ s} \approx 3.3 \text{ min.} \tag{4}$$

Including pre-cooling, purging, connection and disconnection activities, literature suggests that a total process duration of approximately 10–15 minutes per LH_2 refuel cycle is realistic for narrow-body aircraft [19]. This is substantially lower than the upper limit of the previously assumed 60 minutes, indicating that the operational range can be narrowed considerably.

Nevertheless, the uncertainty in the flow rate remains large: values between 1.5 and 20 kg/s are reported across studies, with corresponding impacts on refuelling duration of nearly an order of magnitude. Similarly, LH_2 trailer capacities vary by more than a factor of two. Tables 15 and 16 summarize the flow-rate and trailer-capacity figures identified in the literature to provide a consolidated overview for scenario development.

In summary, both the LH_2 mass-flow rate and trailer capacity exhibit substantial uncertainty, which has a pronounced effect on aircraft turnaround modelling. Future work should parameterise refuelling times explicitly as a function of (i) achievable cryogenic mass flow, (ii) hose diameter, (iii) pump technology, and (iv) on-airport storage and replenishment strategies.

Table 15: Overview of LH_2 refuelling mass flow rates reported in the literature.

Source / System	**Flow Rate [kg/s]**
Automotive LH_2 dispensers (Elaflex) [8]	0.1–0.2
GOLIAT concept: 5–6 t/h (converted) [3]	1.4–1.7
Minimum aviation refuelling requirement (TU Delft) [12]	≥ 5
TULIPS operational modelling [31]	≈ 10
Cryogenic 6-inch hose limit (Mangold et al.) [19]	up to 20
PRESLHY cryogenic test-stand [34]	10–25

Table 16: LH_2 trailer capacities reported in literature and industry specifications.

Source / Manufacturer / Concept	**Capacity [t]**
Small conceptual aviation fuel truck (TU Delft) [12]	2–3
TULIPS LH_2 airport truck [31]	3
Chart Industries LH_2 trailer [6]	≈ 4.3
Heil LH_2 trailer [13]	4–5
PRESLHY white paper (max payload) [34]	up to 5

Given that high-flow systems ($\dot{m} \geq 10$ kg/s) appear technically feasible, the operational bottleneck is likely to shift from fluid transfer to logistical management of trailer movements and storage replenishment rather than the cryogenic refuelling process itself.

3.3 Reference Aircraft Fuel Capacity

In order to model liquid hydrogen (LH_2) refuelling operations for a future regional hydrogen-powered aircraft at airports, it is necessary to make a justified assumption about the on-board LH_2 storage capacity. Since Airbus has not published any technical specifications for the ZEROe turboprop concept (expected for ~70–100 passengers), assumptions must be grounded in peer-reviewed or industry modelling studies.

A suitable reference is the performance analysis conducted by the International Council on Clean Transportation (ICCT), which models an LH_2 turboprop aircraft based explicitly on the Airbus ZEROe design envelope (i.e. rear-fuselage cryogenic tank, 70–100 passengers, regional mission lengths). The ICCT model constrains the cylindrical LH_2 tank to a maximum structural length of 3.5 m to limit mass growth, and finds that the required hydrogen mass for nominal regional missions is:

$$m_{\mathrm{LH_2}} \approx 1190 \text{ kg} \tag{5}$$

This corresponds to a tank volume of approximately:

$$V_{\mathrm{tank}} = \frac{m_{\mathrm{LH_2}}}{\rho_{\mathrm{LH_2}}} \tag{6}$$

where the density of liquid hydrogen at cryogenic storage conditions is $\rho_{\mathrm{LH_2}} \approx 71 \text{ kg m}^{-3}$ [22, 33]. Thus:

$$V_{\mathrm{tank}} \approx \frac{1190}{71} \approx 16.7 \text{ m}^3. \tag{7}$$

This value is consistent with independent LH_2 storage scaling analyses for aircraft, which generally place regional aircraft tank volumes in the range of 15–20 m^3 for 1000–1500 kg LH_2 [32].

Justification for Selecting a 1200 kg LH_2 Tank
Given:

- the ICCT modelling basis,
- the mission profile of regional aircraft (500–1500 km),
- the volumetric and gravimetric constraints of cryogenic storage,
- and the similarity to the Airbus ZEROe turboprop architecture,

a nominal tank capacity of:

$$m_{\text{tank}} = 1200 \text{ kg LH}_2 \tag{8}$$

is a defensible engineering assumption for simulation of operational and safety processes.

This mass is large enough to support typical regional missions while remaining compatible with the structural and volumetric limits of a turboprop-sized fuselage.

3.4 Average Refuelling Requirement per Turnaround

In airport operations, an aircraft is rarely refuelled from empty. This is true for both kerosene aircraft and future LH_2 aircraft, because:

- reserve fuel from the previous flight remains on board,
- not every mission requires a full tank, a safety margin must remain in the tank at landing,
- operators optimise fuel loading to minimise weight penalties.

Empirical data from kerosene operations shows that commercial aircraft typically land with 5–20% of their fuel capacity still on board (contingency, alternate, final reserve). Although LH_2 aviation does not yet exist, similar operational logic will apply since safety and reserve requirements are driven by flight rules rather than fuel chemistry.

For a 1200 kg LH_2 tank, assuming a conservative landing reserve of 15%:

$$m_{\text{reserve}} = 0.15 \times 1200 \approx 180 \text{ kg}. \tag{9}$$

Thus, the fuel *used* per typical regional mission (and therefore requiring replenishment) is:

$$m_{\text{used}} = m_{\text{tank}} - m_{\text{reserve}} \approx 1200 - 180 = 1020 \text{ kg}. \tag{10}$$

Aircraft also do not necessarily refuel to full every turnaround, particularly for short sectors. If operators refuel to 90% of maximum capacity on average (leaving headroom for thermal management and operational flexibility), the typical refuel mass becomes:

$$m_{\text{refuel}} = 0.90\, m_{\text{tank}} - m_{\text{reserve}}. \tag{11}$$

Substituting:

$$m_{\text{refuel}} = 1080 - 180 = 900 \text{ kg}. \tag{12}$$

Thus, for operational modelling:

$$\boxed{m_{\text{refuel,avg}} \approx 900 \text{ kg LH}_2} \tag{13}$$

This value represents:

- a realistic operational load,
- compatible with regional sector fuel burn,
- aligned with hydrogen density and tank volume,
- and suitable for refuelling simulations, safety zone analysis, and mass-flow modelling.

3.5 Implications for LH_2 Refuelling Operations

An average per-turnaround refuelling load of approximately 900 kg LH_2 directly informs:

- sizing of refuelling hoses and couplings,
- expected mass-flow rate requirements,
- cooldown time of the fueling line,
- thermal stratification and boil-off management,
- safety zoning (flash fire and jet fire modelling),
- vehicle scheduling and ground operations planning.

Given a typical LH_2 refuelling mass flow rate of 20–60 kg/min (based on industrial LH_2 transfer systems [33]), the refuelling duration for 900 kg would be:

$$t_{\text{refuel}} = \frac{900}{20 \dots 60} = 15 \dots 45 \text{ min.} \tag{14}$$

This is directly compatible with typical regional aircraft turnaround times (25–40 minutes), indicating that a 1200 kg LH_2 tank and 900 kg average refuelling requirement are plausible within operational constraints.

Refuelling Flow-Rate Assumptions

For the simulation of LH_2 refuelling operations, not only the onboard tank capacity (here taken as 1200 kg LH_2 with an average refuelling quantity of approximately 900 kg) is relevant, but also the achievable mass flow rates during refuelling. At present, there is no certified standard for liquid hydrogen aircraft refuelling, and literature values span a relatively wide range depending on aircraft size, hose diameter and the design objective (e.g. matching kerosene turnaround times versus minimising thermal stresses).

This section summarises representative LH_2 refuelling mass flow rates from the literature and related standards, and translates them into indicative refuelling times for the reference load of

$$m_{\text{refuel,avg}} \approx 900 \text{ kg } LH_2. \tag{15}$$

High flow concepts: 13–20 kg/s

Mangold et al. analyse the turnaround procedures of LH_2 aircraft and compile reported LH_2 refuelling mass flow rates in the range of 13–20 kg/s for large aircraft classes [19]. Based on a simplified Reynolds-number constraint and a hose inner diameter of 152.4 mm, they demonstrate that a mass flow rate of 20 kg/s is achievable with suitably sized cryogenic equipment.

Similarly, Ten Damme et al. consider an LH_2 refuelling rate of 20 kg/s for a hydrogen-powered aircraft in order to maintain refuelling times comparable to conventional kerosene aircraft of similar size [7]. These values are mainly motivated by medium to large narrow-body or wide-body aircraft and assume that the refuelling system is deliberately sized for very short fill times.

For the regional turboprop-sized aircraft considered in this thesis, a flow of 13–20 kg/s would technically reduce the pure filling time for 900 kg LH_2 to well below two minutes:

$$t_{\text{fill}}(13 \text{ kg/s}) \approx \frac{900}{13} \approx 1.2 \text{ min,} \tag{16}$$

$$t_{\text{fill}}(20 \text{ kg/s}) \approx \frac{900}{20} = 0.75 \text{ min.} \tag{17}$$

In practice, such high flow rates may be undesirable for regional aircraft due to increased complexity (larger hoses, more demanding chill-down, higher instantaneous heat loads) and the fact that turnaround time is usually constrained more by passenger and baggage handling than by refuelling alone.

Historic and conceptual wide-body reference: ∼13 kg/s

A classic NASA airport requirements study for LH_2-fuelled wide-body aircraft (400 passengers, 10 192 km range) reports a required refuelling flow of approximately 762 kg/min in order to load 27 942 kg of LH_2 in 38 minutes (including a 5% allowance for boil-off) [4]. This corresponds to:

$$\dot{m} \approx \frac{762\ \text{kg/min}}{60} \approx 12.7\ \text{kg/s}, \tag{18}$$

which is consistent with the upper range reported by Mangold et al. for large aircraft refuelling [19].

While this historic design study targets a much larger aircraft class than the regional turboprop in this work, it provides an upper benchmark for what has been deemed technically and operationally acceptable in terms of refuelling flow rate.

Medium flow concepts for future regional / narrow-body aircraft: 1.4–2.0 kg/s

More recent studies and industrial roadmaps suggest significantly lower, but still relatively high, flow rates for future hydrogen aircraft compared to the 13–20 kg/s concepts. Importantly, EUROCAE ER-034 (2024) introduces a dedicated regional aircraft connector class (Category C), specifying a nominal LH_2 refuelling capacity of 84 kg/min (1.40 kg/s). This provides an emerging standards-based reference point that sits at the lower end of the medium-flow range.

The ICCT discusses future "quick pit stops for zero-emission aircraft and, in the absence of established LH_2 protocols, assumes an illustrative LH_2 volumetric flow of 1560 L/min for a narrow-body aircraft scenario [30]. Using a density of approximately 71 kg/m^3 for liquid hydrogen [22, 33], this corresponds to:

$$\dot{m} \approx 1560\ \text{L/min} \times 0.071\ \text{kg/L} \approx 111\ \text{kg/min} \approx 1.85\ \text{kg/s}. \tag{19}$$

Airbus, in its recent GOLIAT (Ground Operations of LIquid hydrogen AircrafT) study, targets LH_2 refuel flow rates of 5–6 t/h for mobile refuelling units [3]. This yields:

$$\dot{m} \approx \frac{5000 \ldots 6000\ \text{kg/h}}{3600\ \text{s/h}} = 1.39 \ldots 1.67\ \text{kg/s}. \tag{20}$$

For the 900 kg average refuelling quantity assumed in this thesis, these medium flow concepts lead to filling times of the order of 8–11 minutes:

$$t_{\text{fill}}(1.4\ \text{kg/s}) \approx \frac{900}{1.4} \approx 10.7\ \text{min}, \tag{21}$$

$$t_{\text{fill}}(1.85\ \text{kg/s}) \approx \frac{900}{1.85} \approx 8.1\ \text{min}. \tag{22}$$

This is consistent with typical regional aircraft turnaround times (25–40 minutes) when additional time is accounted for pre-cooling, purging and connection procedures, and therefore constitutes a realistic design range for regional LH_2 aircraft.

Low to moderate flows: small aircraft and cross-sector analogies

SAE guideline AIR8547 on liquid hydrogen aircraft fueling performance and safety provides scenarios for small aircraft (SAE AIR8999 Types A and B) with refuelling rates up to 10 kg/min [26], i.e.:

$$\dot{m} \approx \frac{10 \text{ kg/min}}{60} \approx 0.17 \text{ kg/s}. \tag{23}$$

At such a rate, refuelling 900 kg of LH_2 would require roughly 90 minutes and is therefore not suitable for commercial regional operations, but it does illustrate practical lower bounds for cryogenic fuelling systems.

Cross-sector experience from heavy-duty vehicle hydrogen systems also indicates typical LH_2 refuelling rates of 8–10 kg/min (0.13–0.17 kg/s) for truck-scale storage systems [1]. These figures are technologically conservative and driven by current hardware, not by the more stringent time constraints of aviation.

Summary and choice of design range

Table 17: Representative LH_2 refuelling mass flow rates from literature and corresponding fill times for 900 kg LH_2.

Source / context	Mass flow	Class	Fill time for 900 kg
SAE AIR8547 small aircraft	∼ 0.17 kg/s	small aircraft	∼ 90 min
HDV LH_2 systems [1]	0.13–0.17 kg/s	trucks	90–115 min
EUROCAE ER-034 Category C (2024)	84 kg/min ≈ 1.40 kg/s	regional aircraft	∼ 10.7 min
Airbus GOLIAT [3]	1.39–1.67 kg/s	regional / narrow-body	9–11 min
ICCT narrow-body example [30]	∼ 1.85 kg/s	narrow-body	∼ 8 min
NASA wide-body study [4]	∼ 12.7 kg/s	long-range wide-body	∼ 1.2 min
Mangold / Ten Damme [19, 7]	13–20 kg/s	medium–large aircraft	0.75–1.2 min

For the regional turboprop aircraft considered in this thesis, the following conclusions are drawn:

- very high flows (13–20 kg/s) are technically plausible but unnecessarily aggressive for a 900 kg refuelling load;
- flows below 0.5 kg/s would lead to impractically long refuelling times;
- the medium range of approximately 1.4–2.0 kg/s, as suggested by Airbus and ICCT concepts, yields refuelling times of 8–11 minutes that integrate well into typical regional turnaround windows.

Therefore, the subsequent simulations in this thesis will adopt a baseline LH_2 refuelling mass flow rate in the order of 1.5–1.8 kg/s for the 1200 kg tank / 900 kg average refuelling case, with sensitivity analyses performed over a wider range (e.g. 1–5 kg/s) to capture potential design variations in future LH_2 ground infrastructure.

3.5.1 Overview of Commercial LH_2 Trailer Capacities

Liquid hydrogen (LH_2) distribution to airports is typically performed using vacuuminsulated cryogenic tanker trailers. Current market availability shows a clear capacity range between approximately 2 t and 4.6 t LH_2 per trailer, depending on manufacturer, tank geometry and insulation design. Table 18 provides an overview of representative commercially available LH_2 trailers and their payload capacities.

Table 18: Representative commercial LH_2 trailer / container capacities from accessible manufacturer and workshop sources.

Source / manufacturer	**Capacity [kg LH_2]**	**Volume [L]**	**Notes**
Chart Industries ST-18600H trailer [5]	4 608	70 632	Current high-end commercial LH_2 road trailer (large bulk delivery)
Linde Engineering LH_2 trailer (Europe) [18]	3 900	–	European bulk LH_2 delivery (large payload road transport)
Gardner Cryogenics LIN-Shielded ISO (40 ft) [11]	∼2 600	∼41 600	Larger ISO-container variant; scalable bulk LH_2 distribution for industrial/aerospace supply
Gardner Cryogenics LIN-Shielded ISO (30 ft) [11]	∼2 400	∼37 900	ISO-container-based LH_2 logistics unit; suited for flexible supply chains and demonstrations
Small / mobile LH_2 trailers (airport-oriented) [24]	∼2 000	–	Smaller mobile units discussed for early airside refuelling concepts / airport demonstrations

Commercial options therefore support the use of 2–4 t LH_2 trailers for airport operations. In line with discussions with Rotterdam The Hague Airport and observations from ongoing projects such as GOLIAT (Ground Operations of LIquid hydrogen AircrafT), the lower end of this range (2 t) is considered more practical for airside manoeuvrability, whereas the upper end (4–4.6 t) reflects the maximum payload achievable with current market technology.

4 Operational simulation supporting material

4.1 DES model

4.1.1 Model Extention Overview

Table 19: Delta summary: extensions relative to the baseline apron DES of Janssen [17].

Extension	Model hook (DES terms)	New parameters	Operational effect pathway
LH_2 phased refuelling model (B3)	Refuelling service event logic (A3)	LH_2 scenario (S1–S5), phase times, aircraft-per-trailer	Changes LH_2 service time and therefore truck occupancy and the duration of active safety restrictions.
Time-varying safety closures (B1)	Stand and link availability state	Safety mode (0/1/2), actor-specific rules, optional EKCC edges	Imposes temporary closures of stands and route segments during LH_2 refuelling, reducing stand capacity and access.
Actor-specific routing under closures (B2)	Vehicle travel-time computation	Directed GSE graph, undirected truck graph, closure sets	Changes travel times and effective service times through detours; affects dispatch timing and GSE task completion.
Explicit GSE subsystem (B4)	Additional resource and FIFO queue	GSE fleet size, tasks per aircraft, task time range	Adds GSE queueing and travel. Aircraft departure requires completion of both refuelling and GSE tasks.
Boundary conditions and fuel assignment	Initial state and per-flight attributes	Backlog/overnighters, penetration rate (PR)	Sets initial stand occupancy and assigns fuel type per flight using a Bernoulli draw at the PR level.
LH_2 post-service exit rule	Truck return event logic (A4)	`lh2_exit_mode` (direct/right_detour)	Changes return routing and local interference near the refuelling stand, affecting truck availability and congestion.

4.1.2 Turnaround Process Definition

Table 20: Turnaround DES overview, aligned with blocks in Figure 7.

Block	Purpose (I/O)	Inputs (I)	Controls (C)	Mechanism & Outputs (M/O)
A1	Assign aircraft to stand; record stand waiting	Aircraft arrival event; fuel-type label; initial stand occupancy	Stand availability; assignment rule; retry interval; active stand closures (B1)	Stand resources + stand holding. Outputs: aircraft at stand; stand-assignment waiting time.
A2	Dispatch refuelling truck + trailer	Aircraft at stand requiring refuelling	Fuel demand; truck availability; trailer availability	Dispatch logic + truck fleet + trailer inventory + routing (B2). Outputs: dispatched truck+trailer; truck arrives at stand.
A3	Perform refuelling service and generate start/end triggers	Truck+trailer at stand; aircraft ready	Jet-A1 refuel-time model; active LH_2 scenario (B3); safety mode (B1)	Truck as server; on-stand service. For LH_2: phased service time from B3. Outputs: refuel complete; trailer state updated; refuel start/end events (trigger B1); refuel ETA/end times for B4 gating.
A4	Return/reassign truck and update supply state	Service complete; vehicle location	Trailer refill/replacement time; parking/return logic; active route closures (B1)	Truck–trailer cycle + routing (B2). Outputs: truck availability/location; trailer availability/state.
B1	Safety zoning enforcement (time-varying closures)	LH_2 refuel start/end events; refuelling stand location	Safety mode rules; actor access rules; front-row taxiway rule (modes 1–2); adjacent-stand rule (mode 2); optional EKCC edges	Restriction manager. Outputs: stand closures; node/edge closures per actor; blockage counters.
B2	Routing under closures (actor-specific)	Trip request (O–D); current closure set (B1)	Actor type; shortest-path rule; no-path rule	Actor-specific routing graphs. Outputs: feasible route + travel time; detour/waiting when blocked.
B3	LH_2 refuel model (phases + scenarios S1–S5)	LH_2 scenario selection	`lh2_scenario`; `aircraft_per_tra`; phase-time settings; scenario transfer time	Phase scheduler. Outputs: LH_2 service time; trailer consumption; restriction duration input to B1 (via A3).
B4	GSE service (queue + travel), gated by LH_2 refuelling window	GSE task requests; (modes 1–2) refuel ETA/end time	`gse_fleet_size`; tasks per aircraft; task-time model; `gse_service_time`; safety mode	Pooled GSE fleet + FIFO queue + routing (B2). In modes 1–2, tasks are deferred if they would overlap refuelling. Outputs: GSE completion times; GSE waiting; utilisation.

Main couplings: $A1→A2→A3→A4 defines the primary turnaround flow. A3 triggers B1 (closures), which feeds back into A1 (stand availability). B1 modifies feasible routing for A2/A4 and B3 through B2. B3 runs in parallel with refuelling and contributes to turnaround completion through GSE task completion.

4.1.3 Simulation Control Logic (Pseudocode)

```
# ============================================================
# A-BASELINE: CORE OPERATIONAL LOGIC (IDEF0-aligned pseudocode)
# ============================================================

INPUTS:
  schedule: list of flights with (arr_time, dep_time, fuel_demand)
  stands: set of stands (capacity = 1)
  trucks[fuel]: fleet per fuel type (JetA1, LH2)
  trailers[fuel]: inventory per fuel type with remaining_fuel
  (or remaining_refuels)
  network: distances / travel times between locations
  params: speeds, connect_time, refuel_time_dist[fuel], refill_time,
  retry_interval=1 min

STATE:
  stand_occupancy[stand]  {free, occupied}
  truck_state[truck]  {idle, traveling, fueling, parked}
  trailer_state[trailer]  {available, assigned, refilling}
  truck_location[truck], trailer_location[trailer]
  stats (delays, utilisations, etc.)

# ------------------------
# A1  Stand assignment
# ------------------------
ON_EVENT AircraftArrival(flight):
  WHILE True:
    available_stands = {s  stands | stand_occupancy[s] == free}
    available_stands = available_stands \ blocked_stands[aircraft]

    IF available_stands  :
      stand = StandAssignmentRule(available_stands)
      AssignFlightToStand(flight, stand)
      stand_occupancy[stand] = occupied
      SCHEDULE_EVENT RefuelRequestReady(flight)
      BREAK
    ELSE:
      WAIT retry_interval
      CONTINUE

# ------------------------
# A2  Truck + trailer dispatch
# ------------------------
ON_EVENT RefuelRequestReady(flight):
  fuel = DetermineFuelType(flight)
  truck = WaitAndAssignAvailableTruck(fuel)
```

```
  IF TruckHasTrailerConnected(truck) == False:
    candidates = {t  trailers[fuel] |
                  trailer_state[t] == available AND
                  TrailerHasSufficientFuel(t, flight)}
    trailer = SelectTrailer(candidates)  # e.g., "most empty" policy if defined

    travel_time = TravelTime(truck_location[truck],
                             trailer_location[trailer], network, params.speed)
    MoveTruck(truck, trailer_location[trailer], travel_time)
    WAIT params.connect_time
    ConnectTrailerToTruck(truck, trailer)
    trailer_state[trailer] = assigned
  ELSE:
    trailer = GetConnectedTrailer(truck)

  PickupTrailerIfNeeded(truck, trailer)

  stand = flight.assigned_stand
  travel_time = TravelTime(truck_location[truck],
                           stand.location, network, params.speed)
  MoveTruck(truck, stand.location, travel_time)
  SCHEDULE_EVENT StartRefuel(flight, truck, trailer)

# -------------------------
# A3  Refuelling at stand
# -------------------------
ON_EVENT StartRefuel(flight, truck, trailer):
  refuel_time = Sample(params.refuel_time_dist[fuel])
  truck_state[truck] = fueling
  WAIT refuel_time
  UpdateTrailerAfterRefuel(trailer, flight)
  truck_state[truck] = idle
  SCHEDULE_EVENT PostServiceLogic(flight, truck, trailer)

# -------------------------
# A4  Turnaround completion + return + refill + statistics
# -------------------------
ON_EVENT PostServiceLogic(flight, truck, trailer):
  PerformRestOfTurnaround(flight)
  WHEN TurnaroundComplete(flight):
    stand_occupancy[flight.assigned_stand] = free
    RemoveAircraftFromStand(flight)

  IF ExistsQueuedRefuelRequestForFuel(fuel) AND TruckAssignable(truck):
    next_flight = SelectNextFlight(fuel)
    SCHEDULE_EVENT RefuelRequestReady(next_flight)
  ELSE:
    park_loc = SelectTruckParkingLocation()
    travel_time = TravelTime(truck_location[truck], park_loc,
                             network, params.speed)
```

```
    MoveTruck(truck, park_loc, travel_time)
    ParkTruck(truck)

  IF TrailerNeedsRefillOrReplacement(trailer):
    trailer_state[trailer] = refilling
    trailer_loc = SelectTrailerParkingLocation()
    travel_time = TravelTime(trailer_location[trailer],
                             trailer_loc, network, params.speed)
    MoveTrailerToParking(trailer, trailer_loc, travel_time)
    WAIT params.refill_time
    RestoreTrailerSupply(trailer)
    trailer_state[trailer] = available

  UpdateOperationalStatistics(flight, truck, trailer)




# ==============================================================
# B-EXTENSIONS: SAFETY, ROUTING, LH2 PHASES, AND GSE (B1B4)
# (aligned with Figure: B1B4 only; no extra B-blocks)
# ==============================================================

ADDITIONAL INPUTS:
  safety_mode  {0,1,2}
  lh2_scenario  {S1..S5}
  lh2_exit_mode  {direct, right_detour}
  EKCC_edges (optional): list of edges blocked for non-emergency traffic
  gse_graph: directed routing network (with vertical connectors)
  truck_graph: undirected routing network

ADDITIONAL STATE:
  blocked_stands[actor]         # actor  {aircraft, trucks, gse}
  blocked_edges_dir[actor]      # directed edge blocks per actor
  taxiway_blocked_for_aircraft
  # set of taxiway links/nodes blocked during LH2 refuel
  refuel_window[flight] = (t_start, t_end)
  transfer_window[flight] = (t_start, t_end)
  # used only for mode-2 adjacent blocking
  closure_metrics (time active, wait-for-path, detour time)

# ------------------------
# B1  Safety zoning (time-varying restrictions)
# ------------------------
ON_EVENT LH2RefuelStart(flight, stand):
  # activate restrictions for the selected mode;
  # they remain linked to A3 service
  mode = safety_mode

  # front-row (taxiway) blocking for aircraft in modes 12
  IF mode in {1,2}:
```

```
    front_set = FrontRowClosureSet(stand)   # stand-indexed lookup
    blocked_stands[aircraft] += front_set
    # or block the corresponding taxiway links/nodes

  # existing closures
  ApplyStandClosures(mode, stand, blocked_stands[aircraft])
  ApplyTaxiwayClosures(mode, stand, taxiway_blocked_for_aircraft)
  ApplyVehicleLinkClosures(mode, stand,
                           blocked_edges_dir[gse],
                           blocked_edges_dir[trucks])

  # 1) stand and taxiway restrictions (aircraft access / stand availability)
  ApplyStandClosures(mode, stand, blocked_stands[aircraft])
  ApplyTaxiwayClosures(mode, stand, taxiway_blocked_for_aircraft)

  # 2) service-vehicle link restrictions (GSE and trucks)
  ApplyVehicleLinkClosures(mode, stand,
                           blocked_edges_dir[gse],
                           blocked_edges_dir[trucks])

  # 3) optional keep-clear corridor edges
  IF EKCC_edges not empty:
    blocked_edges_dir[gse]   += EKCC_edges
    blocked_edges_dir[trucks]+= EKCC_edges

  # 4) mode-2 adjacent stands:
  # only during LH2 transfer window (not full on-stand time)
  IF mode == 2:
    SCHEDULE_EVENT StartTransferBlocking(flight, stand)

ON_EVENT StartTransferBlocking(flight, stand):
  IF safety_mode == 2:
    adjacent = AdjacentStandsSameRow(stand)      # immediate left/right
    blocked_stands[aircraft] += adjacent
    blocked_stands[gse]      += adjacent
    blocked_stands[trucks]   += adjacent
    SCHEDULE_EVENT EndTransferBlocking(flight, stand)

ON_EVENT EndTransferBlocking(flight, stand):
  IF safety_mode == 2:
    adjacent = AdjacentStandsSameRow(stand)
    blocked_stands[aircraft] -= adjacent
    blocked_stands[gse]      -= adjacent
    blocked_stands[trucks]   -= adjacent

ON_EVENT LH2RefuelEnd(flight, stand):
  # remove all closures that were added for this LH2 refuelling instance
  RemoveClosuresForFlight(flight)

# NOTE (baseline connection):
# Stand assignment in A1 stays deterministic (lowest-ID).
```

```
# B1 only reduces the set of stands considered available
# while LH2 refuelling restrictions are active.

# ------------------------
# B2  Routing under restrictions (aircraft/trucks/GSE)
# ------------------------
FUNCTION Route(actor, origin, destination):
  graph = (actor == gse) ? gse_graph : truck_graph

  # build actor-specific feasible network
  feasible_graph = graph
  feasible_graph = RemoveBlockedStands(feasible_graph, blocked_stands[actor])
  feasible_graph = RemoveBlockedEdges(feasible_graph, blocked_edges_dir[actor])

  path = ShortestPath(feasible_graph, origin, destination)

  IF path exists:
    travel_time = PathLength(path) / Speed(actor)
    RETURN (path, travel_time)
  ELSE:
    RETURN (None, None)

# used by:
# - A2 dispatch travel (truck to trailer, trailer to stand)
# - A4 return/reassign travel (truck/trailer back to parking or next job)
# - B4 GSE travel (base to stand and back)
# if no path exists: vehicle waits and retries after closures change

# ------------------------
# B3  LH2 refuelling phases and scenarios (S1S5)
# ------------------------
ON_EVENT StartRefuel_LH2(flight, truck, trailer):
  scenario = lh2_scenario
  transfer_time = ScenarioTransferTime(scenario, flight)    # from S1S5

  # fixed or configured auxiliary phases
  t_dock   = docking_time
  t_purge  = purge_time
  t_chill  = chilldown_time
  t_disc   = disconnect_time

  total_lh2_time = t_dock + t_purge + t_chill + transfer_time + t_disc

  refuel_window[flight] = (now, now + total_lh2_time)
  transfer_window[flight] = (now + t_dock + t_purge + t_chill,
                             now + t_dock + t_purge + t_chill + transfer_time)

  # trigger B1 at start and end of the full LH2 on-stand service
  SCHEDULE_EVENT LH2RefuelStart(flight, flight.assigned_stand)

  # run phases (can be modelled as waits; phase events optional)
```

```
  WAIT t_dock
  WAIT t_purge
  WAIT t_chill

  # mode-2 adjacent blocking is tied
  # to the transfer window (B1 Start/EndTransferBlocking)
  IF safety_mode == 2:
    SCHEDULE_EVENT StartTransferBlocking(flight, flight.assigned_stand)
  WAIT transfer_time
  IF safety_mode == 2:
    SCHEDULE_EVENT EndTransferBlocking(flight, flight.assigned_stand)

  WAIT t_disc

  UpdateTrailerConsumption(trailer, scenario)
  # aircraft_per_trailer logic
  SCHEDULE_EVENT LH2RefuelEnd(flight, flight.assigned_stand)

# -------------------------
# B4  GSE service (queue + travel) gated by LH2 refuelling windows
# -------------------------
ON_EVENT CreateGSETasks(flight):
  for i in 1..tasks_per_aircraft:
    EnqueueFIFO(gse_queue, (flight, task_i))

ON_EVENT TryStartGSE():
  WHILE gse_unit available AND gse_queue not empty:
    task = DequeueFIFO(gse_queue)
    flight = task.flight
    stand  = flight.assigned_stand

    (path_in, t_in) = Route(gse, GSE_BASE, stand.location)

    IF path_in == None:
      # no feasible access under current closures: wait and retry later
      RequeueFront(gse_queue, task)
      WAIT until closures change
      CONTINUE

    # overlap rule for modes 12, LH2 flights only
    IF safety_mode in {1,2} AND flight.fuel == LH2:
      t_refuel_eta = refuel_window[flight].start
      # in implementation: ETA estimate
      IF now + t_in + tserv_max > t_refuel_eta:
        DeferUntil(task, refuel_window[flight].end)
        CONTINUE

    # execute task (travel + service + return), routing uses B2 both ways
    TravelAlong(path_in, t_in)
    WAIT SampleGSEServiceTime(8..15 min)
    (path_out, t_out) = Route(gse, stand.location, GSE_BASE)
```

```
    IF path_out != None:
      TravelAlong(path_out, t_out)
    ELSE:
      WAIT until closures change
      RETRY return trip

    MarkTaskComplete(task)

# -------------------------
# Additional traffic rule (kept within A4 + B2, not a new block)
# -------------------------
# After LH2 refuel completion, the truck return trip in A4 is routed via B2.
# If lh2_exit_mode == right_detour, the truck first moves to the right-adjacent
# stand (if feasible) before routing back to the tanking point/parking.
```

4.2 GSE Subsystem Specification

This section describes the modelling of Ground Support Equipment (GSE) within the simulation framework, including task generation, routing behaviour, interactions with LH_2 refuelling safety constraints, and the performance indicators used to evaluate GSE operations.

GSE Entities and Task Handling

For every arriving flight, a predefined number of GSE tasks, determined by the parameter `gse_per_aircraft`, is generated and added to a central GSE queue as soon as the aircraft is assigned to a gate. Each GSE entity represents an independent vehicle with:

- a home location at the Trailer Parking (TP) area,
- a fixed driving speed (`gse_speed`),
- a service duration drawn uniformly between `gse_service_time_min` and `gse_service_time_max`,
- an internal state tracking travel time, service time, and total waiting time.

Once a GSE task is dequeued, the assigned vehicle travels to the corresponding gate using the shortest available path. After completing the service, the vehicle returns to TP and becomes available for future tasks. Throughout the simulation, GSE vehicles record their waiting time, including queue delays and any LH_2-related obstructions, and their utilisation, defined as the proportion of time spent travelling or servicing an aircraft.

Departure from a gate is constrained by the GSE completion condition: a flight may only depart when all its associated GSE tasks have reached the `gse_done_state`. This ensures that ground handling processes precede every take-off, consistent with real-world operational practice.

For simplicity, the GSE pool is modelled as centrally available: vehicles do not maintain individual parking locations, but are assumed to be accessible from a common pool at the Trailer Parking (TP) area. Assignment follows a first-come logic: if insufficient units are available when a flight requires handling, the task is queued until enough resources are freed. The number of required GSE units per aircraft is fixed throughout the simulation, defined by the parameter `gse_per_aircraft`, and does not vary across aircraft types. Sensitivity analyses conducted in dedicated scripts (`gse_sweep.py`) vary the total number of GSE units (`num_gse_units`) to assess how resource constraints influence operational performance.

4.2.1 GSE Performance Metrics

Two key performance indicators are computed for GSE operations and included in the simulation output dictionary:

- `gse_mean_wait`: the average total waiting time of GSE vehicles, comprising queue delays and blockage-related delays,
- `gse_mean_utilization`: the mean utilisation rate, measuring the fraction of time vehicles spend servicing or travelling.

By combining queue-related delays with blockage-induced waiting, the model provides a comprehensive representation of how LH_2 safety constraints influence ground-handling performance and broader turnaround efficiency.

4.2.2 Blockages During LH_2 Refuelling

LH_2 refuelling introduces temporary safety restrictions that affect both GSE movements and, depending on the safety mode, nearby aircraft operations, as explained before. Three blockage modes are implemented:

Mode 0 (No Blockages). No restrictions are applied. This mode represents current Jet-A1 operations and serves as the baseline scenario. Only restriction is that the GSE have to enter the stand from above while refuelling is happening.

Mode 1 (Local Gate Blockage). During LH_2 refuelling, the serviced gate becomes inaccessible to GSE. Additionally, the left-turn direction along the gate row is closed to both GSE vehicles and LH_2 trucks (e.g., movement from A3 to A2 or A1 is prohibited, whereas right-hand routing remains available). Aircraft taxiways remain fully operational.

Mode 2 (Extended Blockage). In addition to the restrictions in Mode 1, adjacent gates are blocked for both GSE and aircraft during LH_2 refuelling. The left-turn direction in the gate row remains closed for the entire duration of the refuelling process. Blockages are activated at the start of refuelling and lifted immediately once refuelling is completed. This mode represents conservative early-stage hydrogen safety procedures.

4.2.3 Routing Logic and Detour Behaviour

Two distinct routing graphs are used in the model:

- **GSE Directed Graph (gse_digraph)**: Contains dedicated vertical gate–gate links that allow GSE to manoeuvre efficiently within the stand rows. Shortest-path calculations account for blocked nodes (gates) and blocked directed edges (left-turn closures in Mode 1 and Mode 2).
- **LH_2 Truck Grid**: LH_2 trucks operate on the regular airport grid, but experience blockages on undirected edges when left-turn movements are restricted. As a result, trucks may need to take longer detours around safety zones during refuelling operations.

This separation enables realistic differences between GSE operations, which occur close to stands, and LH_2 truck movements, which span the wider airport layout.

4.2.4 LH_2 Exit Routing Behaviour

After completing an LH_2 refuelling service at a stand, the truck must vacate the immediate stand area and return to the apron access grid. In current operations for conventional fuels, this departure is typically unconstrained and the vehicle simply exits via the shortest available route. For LH_2, however, several concept studies and early operating assumptions treat the post-refuelling phase as operationally sensitive and therefore consider more prescriptive vehicle movements in the first tens of metres after disconnection. Such prescriptions are not modelled as additional service time, but as a routing rule that can change which stand-adjacent links are used and where potential conflicts occur. In the simulation, this is captured by a dedicated exit-behaviour parameter.

The parameter `lh2_exit_mode` determines how an LH_2 truck departs from a serviced stand:

- **direct**: the truck leaves the stand and immediately rejoins the main grid (default),
- **right_detour**: the truck first moves to the right-adjacent stand (if available) before rejoining the grid, representing a conservative routing protocol directing trucks toward predefined safe zones.

Two motivations underlie this behaviour:

1. **Directional evacuation toward predefined "safe" corridors.** Concept designs for hydrogen-ready apron layouts (e.g., from ATI, ACI Europe, and operational safety studies by DLR and Hamburg Airport) propose routing strategies that guide LH_2 vehicles away from the refuelling zone along a controlled direction. Direct left-hand turns are often discouraged during or immediately after cryogenic operations, due to the potential interaction with neighbouring stands, GSE clusters, or passenger flows.
2. **Minimising crossing conflicts near the refuelling zone.** The departure phase immediately after LH_2 refuelling is one of the periods with heightened hazard sensitivity. A short lateral detour to the right reduces the likelihood that the truck crosses in front of newly arriving GSE vehicles or aircraft taxiing toward adjacent stands. This behaviour mirrors conservative routings proposed in safety assessments where hydrogen vehicles are temporarily guided along a clean outbound corridor before resuming normal navigation through the apron.

Although the exact operational standard for LH_2 refuelling has not yet been finalised at the regulatory level, such routing concepts recur in multiple feasibility studies and risk assessments. The inclusion of the `right_detour` mode therefore provides a flexible mechanism to evaluate how directional safety routing influences traffic flow, stand accessibility, and truck utilisation. It enables stress-testing of more restrictive early-adoption procedures compared to the unconstrained `direct` exit path that resembles conventional Jet-A1 refuelling operations.

5 Model Credibility and Statistics

5.1 Replication Adequacy Diagnostics

This appendix documents how the number of replications was chosen and provides supporting diagnostics. Because the simulation is stochastic, KPI estimates contain Monte Carlo error that decreases with the number of independent replications.

5.1.1 Sequential Confidence-Interval Half-Width Test

For each scenario (safety mode × penetration rate, PR), we run n independent replications and compute the sample mean $\bar{y}$ and sample standard deviation s. A two-sided 95% confidence interval (CI) for the mean is

$$\bar{y} \pm h, \qquad h = t_{0.975,\,n-1}\,\frac{s}{\sqrt{n}},$$

where h is the CI half-width and $t_{0.975,\,n-1}$ is the Student-t critical value [21].

We apply an absolute precision target $\epsilon = 2.0$. For each scenario, replications are added until

$$h \leq \epsilon,$$

or until a predefined maximum number of runs is reached. Where useful, we also report the relative half-width $h/\bar{y}$ to indicate uncertainty when mean values are small.

5.1.2 Diagnostics and Convergence Highlights

Table 21 provides snapshot checks at small run counts (e.g., $n = 10$ and $n = 20$). Some scenarios show substantial uncertainty at low n, particularly when the mean KPI value is small, which inflates $h/\bar{y}$.

Table 21: Snapshot of CI-width diagnostics for selected scenarios. Relative half-width is $h/\bar{y}$.

Scenario	PR	Runs	Mean	CI half-width h	$h/\bar{y}$
Mode 0	0.20	10	5.356	1.835	0.343
Mode 0	0.50	10	5.707	1.801	0.316
Mode 0	1.00	10	15.638	1.210	0.077
Mode 1	0.20	10	3.683	2.783	0.756
Mode 1	0.20	20	3.541	1.450	0.409
Mode 1	0.80	10	11.995	2.389	0.199
Mode 1	0.80	20	12.240	1.764	0.144
Mode 1	1.00	10	19.544	1.674	0.086
Mode 2	0.20	10	7.522	3.065	0.407
Mode 2	0.20	20	6.683	1.865	0.279
Mode 2	0.50	10	11.243	1.758	0.156

Table 22 illustrates representative convergence trajectories. Some scenarios converge slowly and require many replications to meet the absolute target, while others reach the target with fewer runs.

Table 22: CI-width convergence examples (first vs. last reported run count). Relative half-width is $h/\bar{y}$.

Scenario	PR	Runs	Mean	h	$h/\bar{y}$
Mode 0 (start)	0.80	10	13.827	8.854	0.640
Mode 0 (end)	0.80	210	15.784	1.984	0.126
Mode 1 (start)	0.50	10	12.940	6.730	0.520
Mode 1 (end)	0.50	280	15.331	1.967	0.128
Mode 2 (start)	0.80	10	41.747	9.821	0.235
Mode 2 (end)	0.80	140	32.225	1.938	0.060
Mode 2 (start)	1.00	10	46.584	8.237	0.177
Mode 2 (end)	1.00	200	48.112	1.954	0.041

Across all scenarios, the half-width target $h \leq 2.0$ is achieved within the available replication budget. The slowest case required approximately 280 replications, which motivates the use of 300 replications for all scenarios in the main analysis to ensure consistent precision and comparability.

5.2 Statistical Tests (Mode Comparisons)

Statistical comparison framework

This section tests whether zoning mode choice leads to different delay outcomes. The operational hypothesis is that more restrictive safety-zone implementation can increase departure delays by reducing effective apron capacity through stand and access restrictions. We combine ANOVA (overall test), Tukey HSD (pairwise comparisons), and Vargha & Delaneys A (effect size) to quantify both statistical evidence and practical magnitude.

5.2.1 ANOVA and Tukey HSD (Statistical Significance)

We use ANOVA and Tukey HSD to determine whether differences in delay metrics between Mode 0/1/2 are systematic effects of the safety-zone implementation, rather than random variation across stochastic replications. For each KPI and for each penetration rate (PR) and test day, ANOVA tests whether the three modes have the same mean KPI and reports an F-statistic with a corresponding p-value. A significant ANOVA implies that at least one mode differs, but it does not specify which modes. We therefore apply Tukeys Honestly Significant Difference (HSD) as a post-hoc test to identify which specific mode pairs (0–1, 0–2, 1–2) differ while controlling the familywise error rate (FWER), reporting mean differences, confidence intervals (CI), and adjusted p-values. In the results section, ANOVA is used to establish overall mode effects and Tukey HSD supports pairwise mode ranking at each penetration rate.

5.2.2 Vargha & Delaney's A (Effect Size)

Because the simulation results are random and may not follow a normal distribution, we measure the size of pairwise differences using Vargha and Delaney's A:

$$A_{XY} = P(X > Y) + \tfrac{1}{2}P(X = Y).$$

Here, $A = 0.5$ indicates no difference; $A > 0.5$ implies X tends to be larger than Y; and $A < 0.5$ implies X tends to be smaller than Y. For magnitude interpretation we use the symmetric separation

$$A^* = \max(A, 1 - A),$$

so that values further from 0.5 correspond to stronger separation regardless of direction. As a rule of thumb, we interpret Vargha & Delaney's A^* following Sandora et al., where A^* values of 0.56–0.64 indicate a small effect, 0.64–0.71 a medium effect, and $A^* > 0.71$ a large effect [**Sandora2021_OASIS_ODSIS_CZ**]. In this study, for each penetration rate (PR) and test day, we compute A for each mode pair on key KPIs (e.g., average delay), complementing Tukey's significance with an interpretable magnitude and direction.

Table 23: Role of each statistical method in the safety-mode comparison.

Method	What it answers in this study
ANOVA	Do the three safety modes differ overall for a KPI at a given PR/day?
Tukey HSD	Which specific mode pairs differ (0–1, 0–2, 1–2), while controlling FWER?
Vargha & Delaney's A	How strong is the pairwise difference, and in which direction, without distributional assumptions?

5.2.3 Statistical Comparison of Delay Across Penetration Rates

The statistical outcomes show a clear and consistent pattern. At low penetration (PR 0.00–0.05), there is no evidence of differences between safety modes: ANOVA is non-significant, Tukey HSD rejects no pairwise comparisons, and A values remain close to 0.5 (negligible practical differences). From PR = 0.10 onward, Mode 2 becomes distinguishable: ANOVA turns significant and Tukey HSD identifies Mode 2 as significantly worse than both Mode 0 and Mode 1, while Mode 0 vs. Mode 1 remains non-significant. From PR $\approx$ 0.15 and higher, differences between Mode 2 and the other modes persist with very small adjusted p-values and confidence intervals entirely above zero, indicating substantially higher mean delay under Mode 2.

Table 24: Representative ANOVA, Tukey HSD, and Vargha & Delaney A results for the delay KPI across penetration rates. For brevity, only the Mode 2 comparisons are shown; Mode 0 vs. Mode 1 is non-significant at all PR values in this series.

PR	ANOVA	Tukey HSD (mean diff [95% CI], p_{adj})		A (Vargha–Delaney)	
	F, p	0 vs 2	1 vs 2	$A(0,2)$	$A(1,2)$
0.00	0.047, 0.954	−0.021 [−0.192, 0.151], 0.957	−0.018 [−0.189, 0.154], 0.968	0.503	0.499
0.05	0.633, 0.532	0.083 [−0.127, 0.292], 0.624	0.091 [−0.119, 0.300], 0.567	0.505	0.476
0.10	6.127, 0.0023	0.298 [0.065, 0.531], 0.0079	0.304 [0.071, 0.537], 0.0065	0.414	0.425
0.15	25.442, 2.49×10^{-11}	0.670 [0.430, 0.909], $< 10^{-3}$	0.582 [0.342, 0.821], $< 10^{-3}$	0.327	0.359
0.30	45.811, 3.10×10^{-19}	1.188 [0.859, 1.517], $< 10^{-3}$	1.134 [0.805, 1.464], $< 10^{-3}$	0.320	0.328
0.50	86.226, 1.27×10^{-33}	2.904 [2.323, 3.486], $< 10^{-3}$	2.716 [2.134, 3.297], $< 10^{-3}$	0.217	0.248
0.80	122.217, 3.24×10^{-45}	6.315 [5.271, 7.360], $< 10^{-3}$	5.674 [4.629, 6.718], $< 10^{-3}$	0.187	0.242
1.00	133.252, 1.42×10^{-48}	8.364 [6.997, 9.730], $< 10^{-3}$	8.075 [6.709, 9.442], $< 10^{-3}$	0.256	0.270

Vargha & Delaney's A corroborates practical relevance: $A(0 \text{ vs } 2)$ and $A(1 \text{ vs } 2)$ drop below 0.5 as PR increases, meaning delays under Mode 2 are typically larger than under Modes 0/1. In contrast, $A(0 \text{ vs } 1)$ stays near 0.5, consistent with the absence of statistically significant differences between Modes 0 and 1.

Taken together, these results indicate threshold behaviour: below PR $\leq$ 0.05 the safety mode has no detectable impact on delay, whereas from PR $\approx$ 0.10–0.15 onwards, Mode 2 yields consistently higher delays than both Mode 0 and Mode 1. The gap widens with PR (increasing mean differences and strictly positive CIs), while Mode 0 and Mode 1 remain statistically and practically similar.

6 Additional Results Operational Modelling

6.1 Heatmap mode 0

This section provides the delayed-flight heatmap for safety mode 0 referenced in Section 9.3. Heatmaps for modes 1 and 2 are included in the main text (Figures 12 and 13).

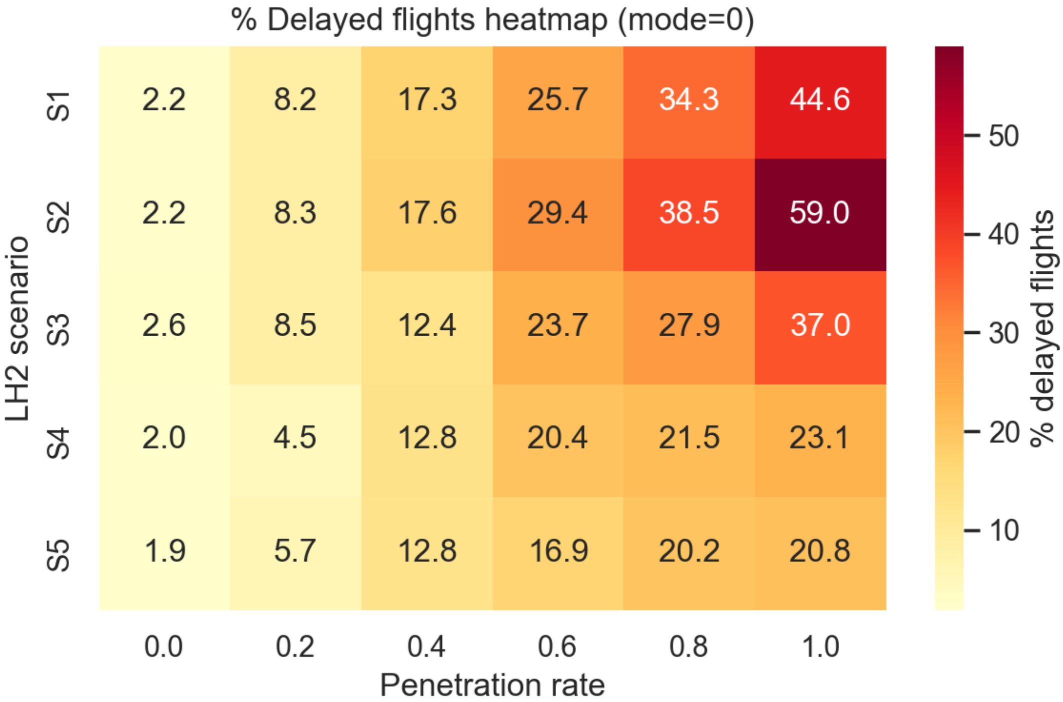


Figure 27: Percentage of delayed flights for different LH_2 refuelling configurations (mode 0).

6.2 KPI Comparison Figures

This section presents additional visualisations of the model outputs for the different future scenarios analysed in this study. Each figure provides a detailed comparison of the key performance indicators (KPIs) across multiple years, penetration rates, and safetyzone configurations. All results are based on 300 simulation replications with a fleet consisting of two Jet-A1 trucks and three LH_2 trucks. he figures present results across three safety modes, corresponding to safety-zone diameters of <20 m, 20-40 m, and >40 m (mode 0/1/2). For safety zone, results are shown for four representative operational days: Average Summer (11-05), Peak Summer (26-08), Average Winter (20-02), and Peak Winter (31-10). The truck fleet is set on 2 Jet-A1 and 3 LH_2 trucks.

KPI Comparison for 2040 with Safety Zone $< 20\,\mathrm{m}$

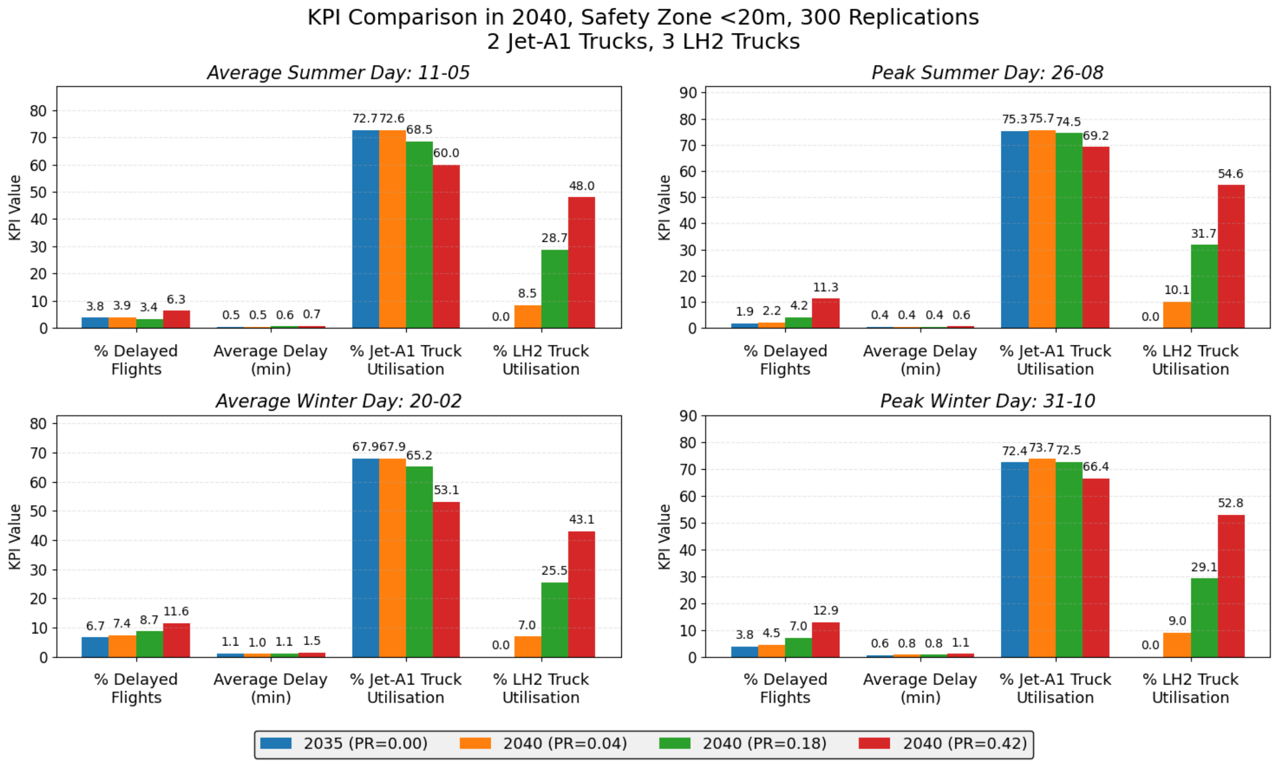


Figure 28: 2040 scenario KPI comparison, Mode 0 (baseline configuration)

Figure 28 in Supporting Work provides the full 2040 KPI comparison for Mode 0 and serves as the reference case for the future-horizon analysis.

KPI Comparison for 2050 with Safety Zone $< 20\,\mathrm{m}$

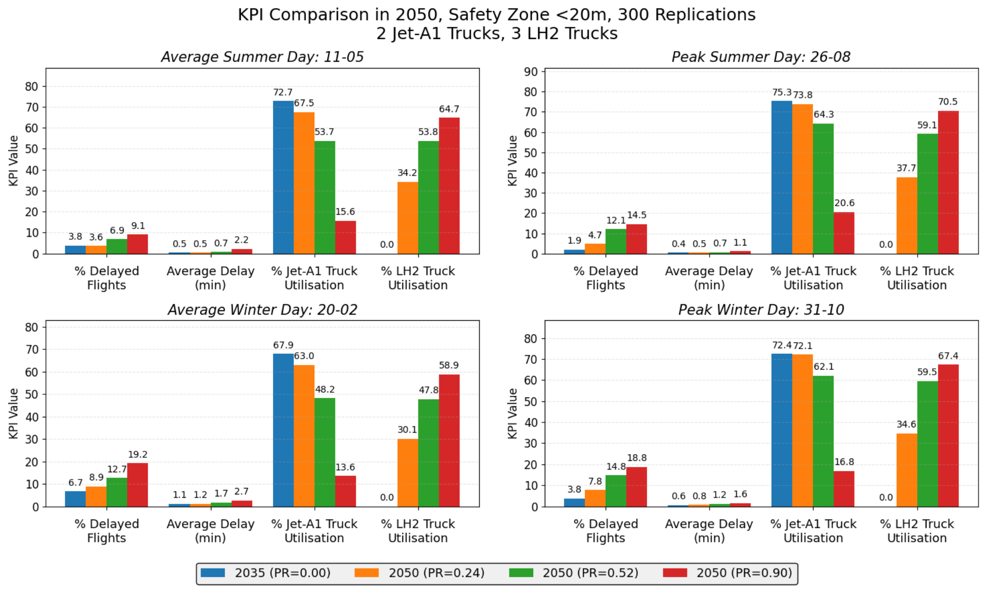


Figure 29: 2050 KPI comparison: <20 m safety zone on four different days, 2 Jet–A1 and 3 LH_2 trucks and 300 reps

Figure 29 shows the KPI results for the 2050 high-demand scenario under a safetyzone diameter below 20 m. Jet-A1 truck utilisation remains consistently high, while LH_2 truck utilisation increases sharply with penetration rate. The percentage of delayed flights remains limited in low-penetration cases but increases noticeably under the highest penetration level. Average delays per flight follow similar trends and remain modest in absolute terms.

KPI Comparison for 2040 with Safety Zone > 40 m

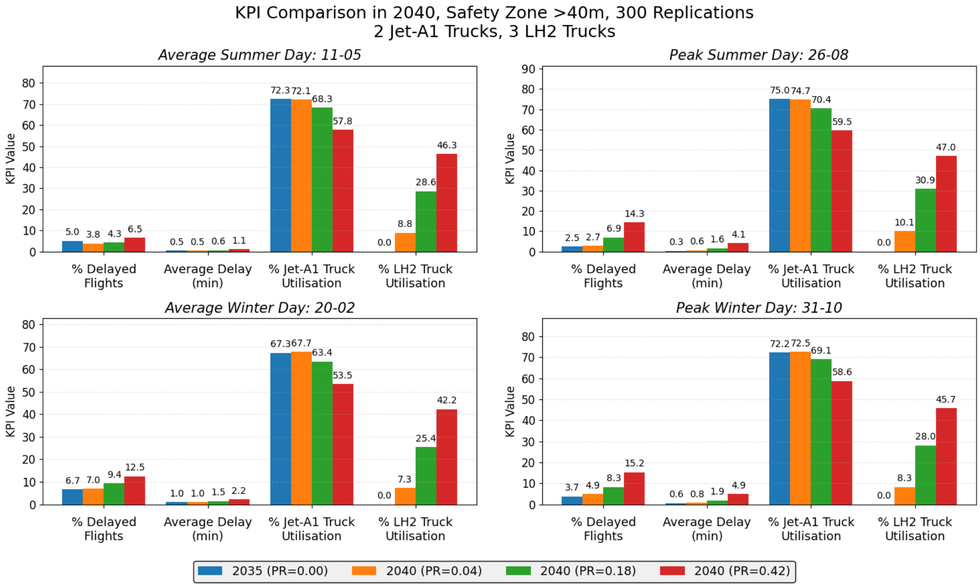


Figure 30: 2040 KPI comparison: >40 m safety zone on four different days, 2 Jet–A1 and 3 LH_2 trucks and 300 reps. Results shown for all four representative operational days, based on 300 replications.

Figure 30 presents the results for 2040 under the most restrictive safetyzone configuration (> 40 m). Larger exclusion zones reduce stand availability and increase competition for apron space, leading to more frequent delays and higher average delay values. LH_2 truck utilisation increases even at low penetration levels due to longer wait times and blocked stand access, while Jet-A1 utilisation gradually declines as hydrogen penetration increases.

KPI Comparison for 2040 with Safety Zone 20–40 m

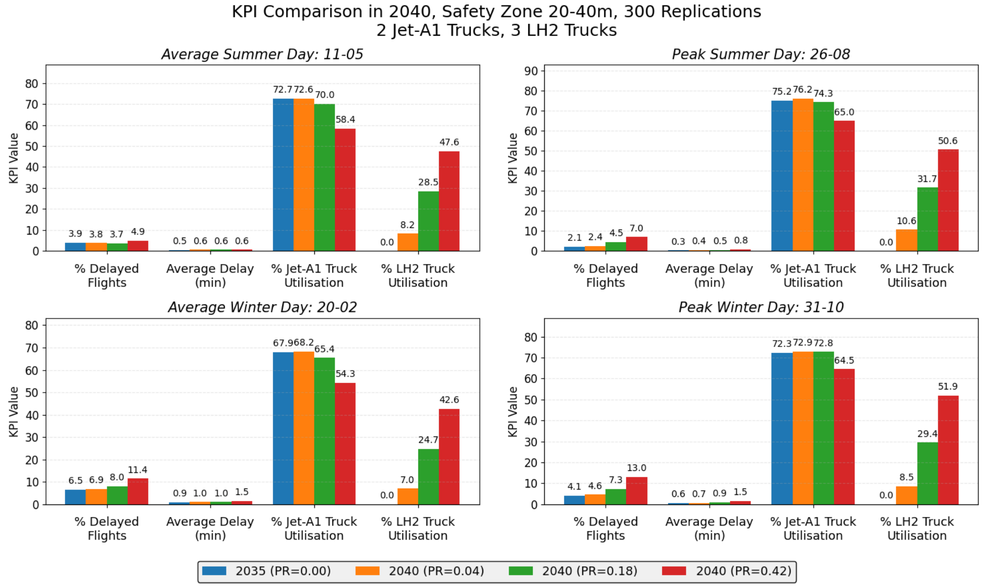


Figure 31: 2040 KPI comparison: 20-40 m safety zone on four different days, 2 Jet–A1 and 3 LH_2 trucks and 300 reps

Figure 31 shows the results for the intermediate safetyzone configuration of 20–40 m. Compared with the > 40 m case, delay percentages and average delays are significantly reduced, especially during peak-demand periods. Jet-A1 truck utilisation remains high across all penetration levels, while LH_2 truck utilisation increases proportionally with hydrogen adoption. This configuration demonstrates the most balanced operational performance among the three tested safetyzone ranges.

KPI Comparison for 2050 with Safety Zone 20–40 m

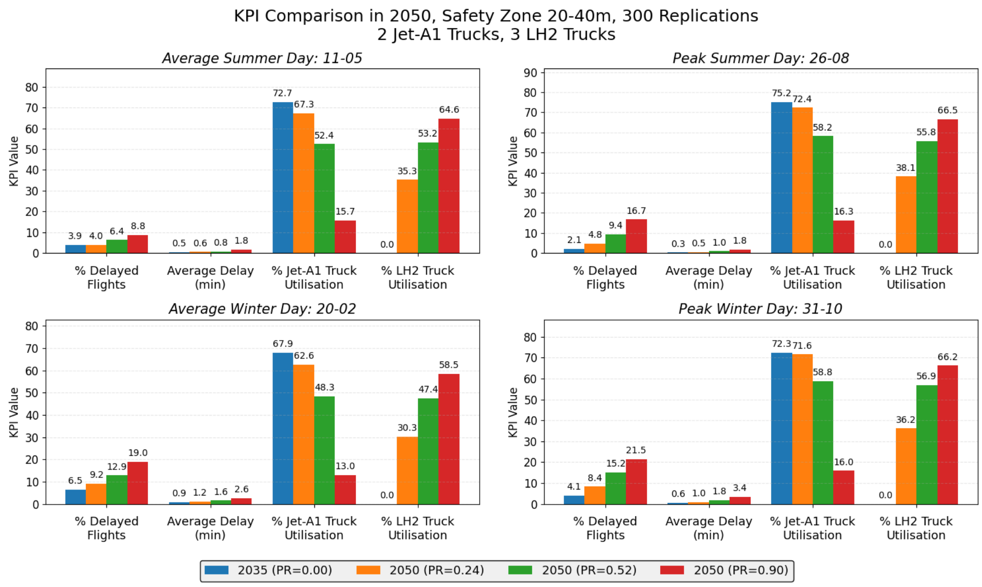


Figure 32: 2050 KPI comparison: 20-40 m safety zone on four different days, 2 Jet–A1 and 3 LH_2 trucks and 300 reps

Figure 32 displays the KPI results for 2050 under the intermediate safetyzone size. As penetration rates increase, LH_2 truck utilisation becomes the dominant operational bottleneck, reaching utilisation levels above 60% in high-penetration cases. Delay percentages also rise in the most demanding scenarios, particularly during winter operations where multiple stand conflicts occur. Despite this, the 20–40 m safetyzone remains operationally viable for medium penetration rates, though future infrastructure expansion may be required in high-demand scenarios.

6.3 Violin Plot

Figure 33 extends the fleet-sizing sensitivity analysis by including configurations with up to four LH_2 trucks for the peak summer day (26–08) at PR = 0.7. The figure shows the resulting departure-time distributions for Jet-A1 and LH_2 flights across the tested Jet-A1/LH_2 fleet combinations, together with the maximum planned departure time (blue) and maximum allowed departure time (red).

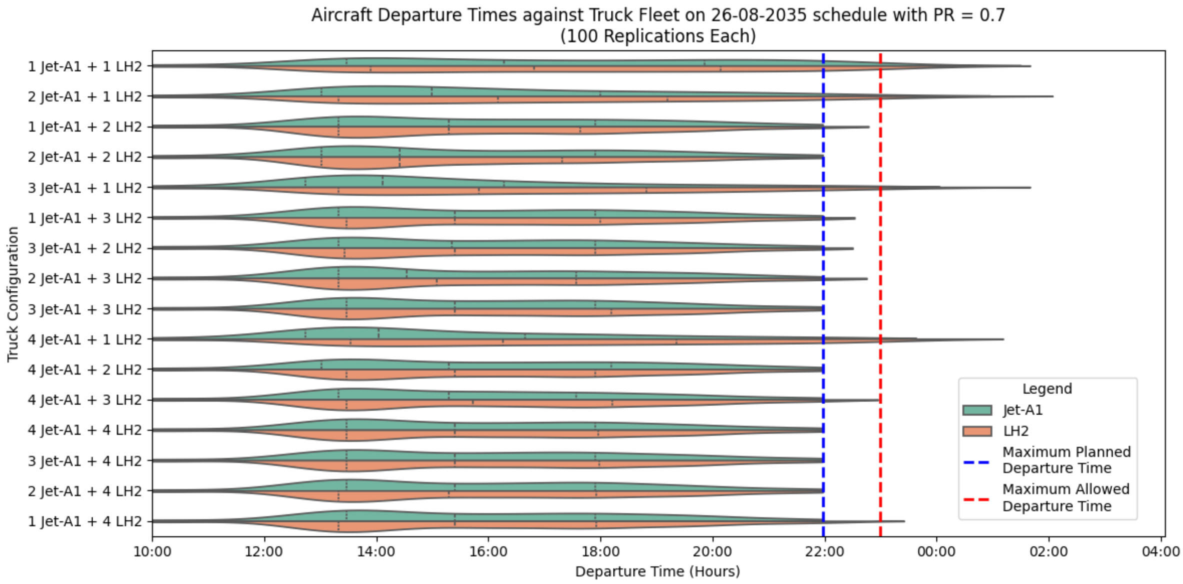


Figure 33: Departure-time distributions for PR = 0.7 on the peak summer day (26-08) for different truck configurations (up to four LH_2 trucks).

6.4 LH2 scenarios

6.4.1 Departures after 20:00

Interestingly, Figure 34 shows that the share of departures occurring after 20:00 remains relatively stable across penetration rates and modes. While scenario S2 with mode 2 at 100% penetration shows a slight increase (up to 12%), most scenarios fluctuate within a narrow band between 6% and 8%. This is notable, as one might expect that higher penetration rates would lead to more stands being occupied in the evening by hydrogen-fueled aircraft requiring overnight parking. However, the evening stand occupation does not appear to significantly affect departure timing on the same day, suggesting that delayed flights earlier in the schedule are the primary driver of cumulative delays.

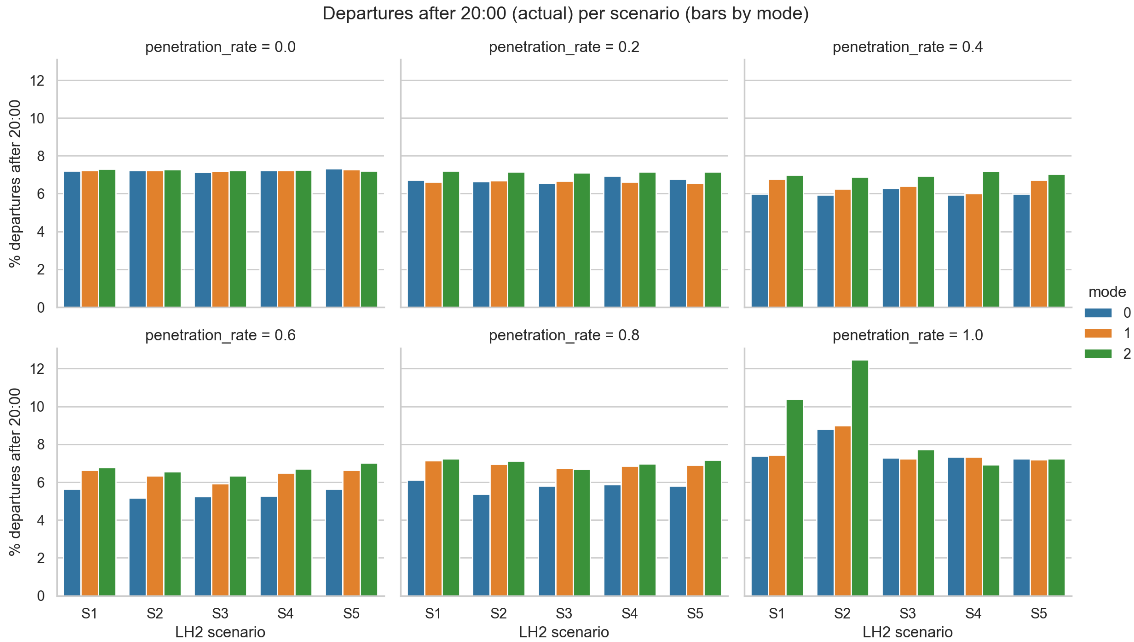


Figure 34: Departures percentage after 20:00 by LH_2 refuel scenario, penetration rate, and mode

6.4.2 LH2 truck utilisation

Figure 35 shows the average utilisation of LH_2 trucks across various LH_2 scenarios and safety modes, segmented by penetration rate. At lower penetration rates, utilisation levels increase progressively, consistent with rising refuelling demands. However, a notable saturation occurs around a penetration rate of 0.6, beyond which truck utilisation plateaus or even slightly declines in some scenarios. This effect is visible across all modes and LH_2 scenarios and suggests that the two LH_2 trucks used in these simulations are operating at or near capacity from PR = 0.6 onwards. Consequently, the data indicate that at higher penetration rates, the available LH_2 fleet may become a bottleneck, and deploying an additional LH_2 truck could b

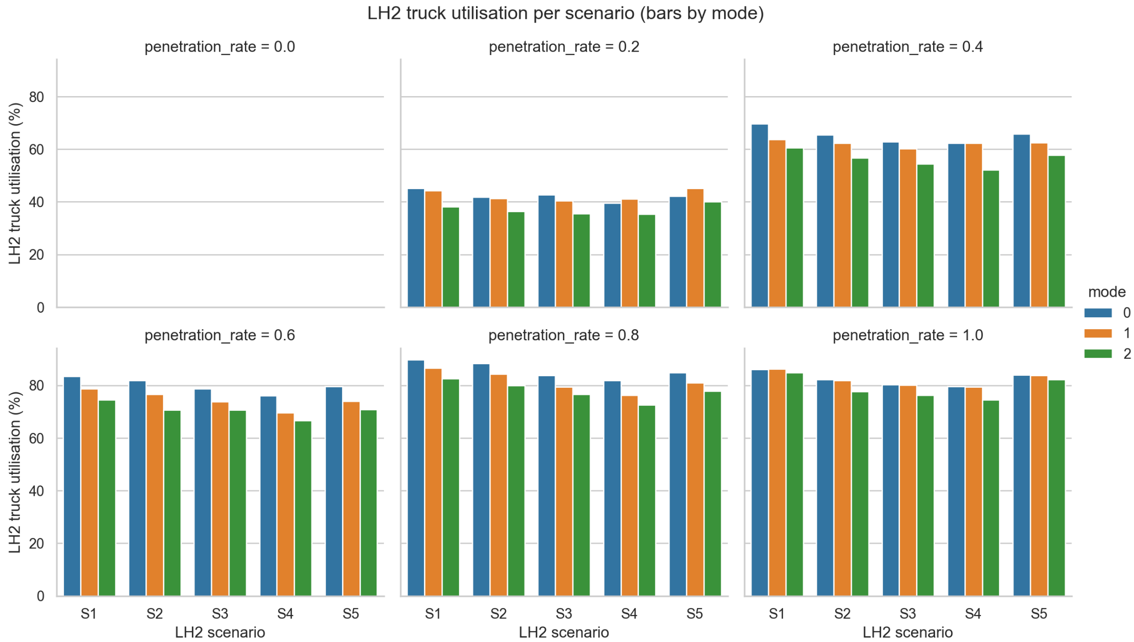


Figure 35: LH_2 truck utilisation per LH_2 refuel scenario across modes, split by penetration rate.

6.4.3 Total stand assignment wait

Figure 36 displays the total stand assignment wait time across different LH_2 scenarios and penetration rates, disaggregated by safety mode. All results are based on a peak summer day operation with a fixed fleet of two LH_2 and two Jet-A1 refuelling trucks.

As expected, Mode 2 (the most restrictive safety configuration) exhibits significantly higher cumulative stand wait times, particularly from a penetration rate (PR) of 0.4 onwards. For instance, at PR = 1.0, Mode 2 results in stand waits exceeding 1200 minutes in Scenario S2equivalent to over 35 minutes per flight assuming 34 departures that day.

In contrast, Mode 1despite introducing safety-related blockagesmaintains relatively modest wait times, even at high penetration levels. This indicates that the additional constraints of Mode 2 (blocking adjacent stands and access lanes) are the primary drivers of congestion, rather than general hydrogen safety zoning.

Interestingly, even at PR = 0.6, Mode 2 already results in delays of around 400500 minutes, while Mode 1 remains well below 100 minutes in all scenarios. These results suggest that, under constrained truck resources, excessive spatial restrictions around LH_2 operations can trigger substantial stand assignment inefficiencies. A less conservative approach like Mode 1 may offer a more viable balance between safety and operational throughput in practice.

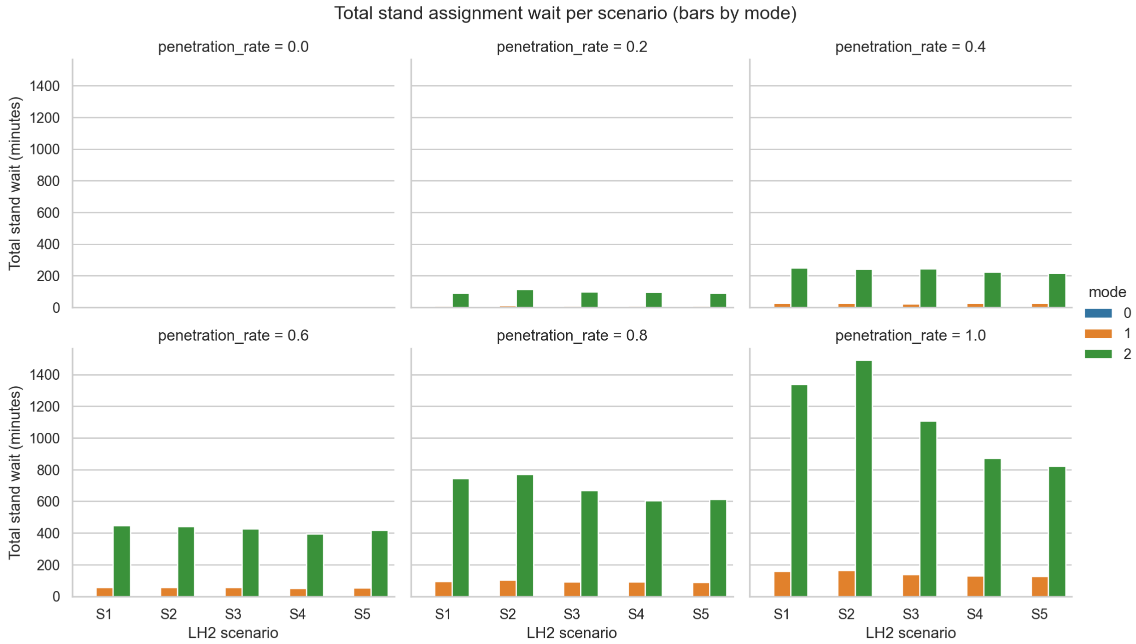


Figure 36: Total stand-assignment wait time by LH_2 refuel scenario and penetration rate on peak summer day

6.5 GSE Count, Wait and General Effect

6.5.1 GSE Mean Wait and Count Effect

Figure 37 shows the effect across penetration and safety zone related to GSE mean wait time, delayed flights percentage and the number of GSE. The figure shows that increasing the number of GSE units significantly reduces average wait times up to about 15 units, with the steepest gains between 6 and 9 units. Beyond this point, saturation occurs and additional units yield minimal benefit. While the waiting time varies slightly across safety modes and penetration rates, the percentage of delayed flights remains nearly constant, indicating that more GSE does not translate to fewer delays.

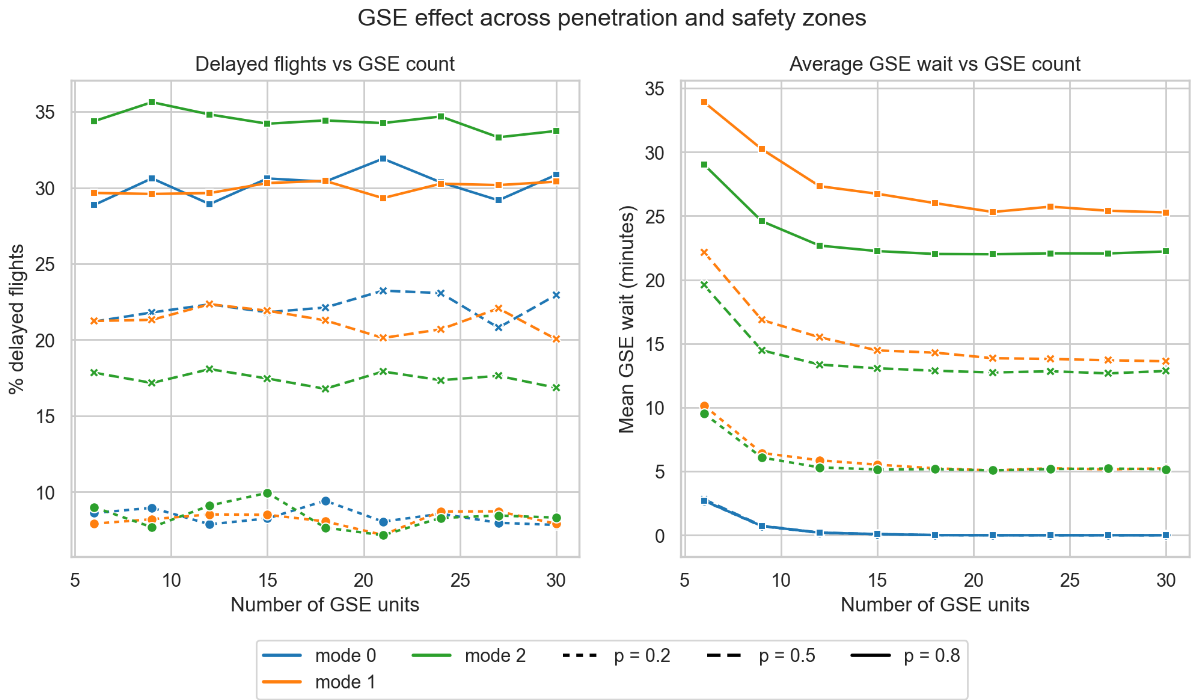


Figure 37: Effect of GSE fleet size on average wait time (right) and delayed flights (left) across safety zone modes and hydrogen penetration rates.

6.5.2 Effect of GSE Rerouting

Figure 38 compares the percentage of delayed flights across penetration rates for the three safety modes, with GSE rerouting switched on and off. The curves largely overlap for Modes 0 and 1, indicating that enabling the rerouting logic does not meaningfully change the delayed-flight share over the tested penetration range. The dominant driver remains the zoning mode: Mode 2 produces a substantially higher delayed-flight percentage at moderate to high penetration, and the difference between GSE on/off remains small relative to the Mode 2 increase. This supports the interpretation that, in this apron layout, stand-availability effects dominate over GSE access detours in determining whether flights become delayed.

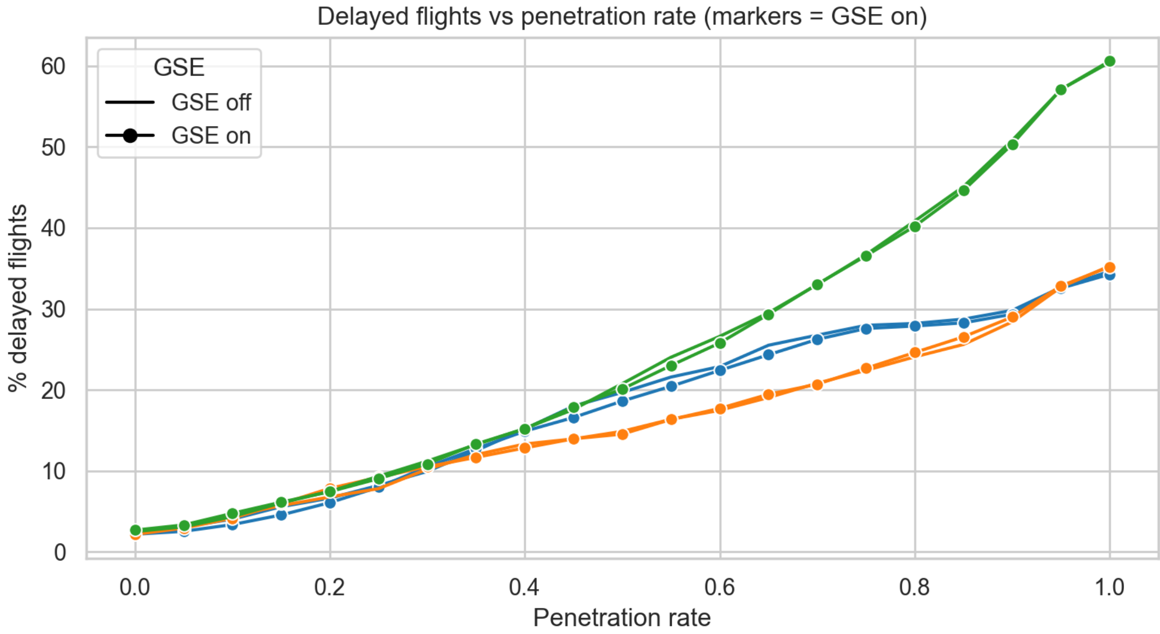


Figure 38: Impact of the implemented GSE routing logic on delayed-flight percentage across LH_2 penetration rates

7 Verification tests

Table 25: Verification log for the operational simulation model.

Test ID	Setup (scenario + setting)	Expected behaviour	Evidence and outcome
V1	Penetration rate PR = 0 (no LH_2 flights scheduled); all other inputs unchanged.	No LH_2 refuelling events occur; no LH_2 trucks/trailers are dispatched; KPIs reduce to the non-hydrogen baseline.	Event log shows zero LH_2 refuelling starts; LH_2 resource utilisation is zero; KPI values coincide with the non-hydrogen baseline within Monte Carlo variation.
V2	Safety mode 0 (safety-zone blockages disabled) with non-zero penetration (e.g. PR = 20%).	No nodes, stands, or routes are blocked by safety zones; the simulation remains feasible and completes.	Blockage event count is zero; network availability is unchanged; the model completes without deadlock or infeasible states.
V3	Single-aircraft trace run (one LH_2 flight) with verbose event logging enabled.	Refuelling phases occur in the prescribed order (docking, purge, chill, transfer, disconnect). Safety-zone blockages activate at refuelling start and release at completion.	Trace confirms the phase order and associated durations; blockage-on timestamps align with refuelling start and blockage-off timestamps align with refuelling completion.
V4	Routing stress tests under forced network blockage: (a) an alternative path exists, (b) no alternative path exists.	(a) Vehicles reroute via a feasible alternative path. (b) Vehicles queue/wait until a path becomes available.	(a) Planned routes switch to an alternative path and vehicles still reach the destination. (b) Vehicles enter a waiting/queue state and resume movement once the blockage is released.

References (Supporting Work)

[1] R. K. Ahluwalia et al. *Cost Assessment and Evaluation of Liquid Hydrogen Storage for Medium- and Heavy-Duty Transportation Applications.* Tech. rep. U.S. Department of Energy Hydrogen Program Annual Merit Review (Project ST223), 2021. URL: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review21/st223_ahluwalia_2021_o-pdf.pdf.

[2] Air Products and Chemicals, Inc. *Safetygram #9: Liquid Hydrogen.* PDF; hosted on U.S. Department of Energy (EERE) website; accessed 15 Dec 2025. 2007. URL: https://www.energy.gov/eere/fuelcells/articles/safetygram-9-liquid-hydrogen.

[3] Airbus. *Ground Operations of LIquid hydrogen AircrafT (GO-LA).* Project brochure. 2025. URL: https://mediaassets.airbus.com/pm_38_747_747228-ni0nsggi79.pdf.

[4] G. D. Brewer. *LH2 Airport Requirements Study.* Tech. rep. NASA, 1976. URL: https://ntrs.nasa.gov/api/citations/19770003090/downloads/19770003090.pdf.

[5] Chart Industries. *LH2 Transport Trailer ST-18600H 155 Pressure Transfer System – Specification Sheet*. PDF. 2023. URL: https://files.chartindustries.com/LH2TransportTrailerSpecSheet.pdf.

[6] Chart Industries. *Liquid Hydrogen Transport Trailer ST-17600H-155*. Product Datasheet. 2021. URL: https://files.chartindustries.com/21746492_LH2Trailer.pdf.

[7] L. ten Damme et al. "Simulation of the Refuelling Process for an LH_2-Powered Aircraft". In: *International Journal of Hydrogen Energy* (2025). Online first. URL: https://www.sciencedirect.com/science/article/pii/S0360319925051717.

[8] Elaflex. *H2 Hydrogen & Carbon Capture News 2023 – Information 9.22*. Product information sheet (PDF). Reports an LH_2/sLH_2 nozzle flow rate of 150 L/min (640 kg/h). Rev. 8/2023. 2023. URL: https://elaflex.de/dokumente/download/ElaflexInformation/ELAFLEX_Information_9.22.pdf.

[9] EUROCAE. *ER-034: Hydrogen Fueling Stations for Airports in both gaseous and liquid form*. Tech. rep. Developed jointly with SAE (AE-5CH). EUROCAE, 2024. URL: https://www.eurocae.net/product/er-034-hydrogen-fueling-stations-for-airports-in-both-gaseous-and-liquid-form/.

[10] Federal Aviation Administration (FAA). *Hydrogen-Fueled Aircraft Safety and Certification Roadmap*. DOT/FAA publication. Key properties of hydrogen fuel and associated hazards are discussed on pp. 5–7, highlighting wide flammability, low ignition energy, and fire/explosion risk. Dec. 2024.

[11] Gardner Cryogenics and U.S. Department of Energy. *Current Practices to Transfer and Deliver Liquid Hydrogen*. Workshop slides (PDF), Liquid H2 Workshop (Feb 24, 2022). 2022. URL: https://www.energy.gov/sites/default/files/2022-03/Liquid%20H2%20Workshop-Gardner%20Cryogenics.pdf.

[12] L. Gijzen. "Exploratory Analysis of Future LH2-Powered Aircraft Ground Operations at a Regional Airport". MA thesis. Delft University of Technology, 2024. URL: https://repository.tudelft.nl.

[13] Heil Trailer International. *18,000 Gallon Liquid Hydrogen Trailer – Specification Sheet*. 2024. URL: https://heiltrailer.com.

[14] HyResponder Consortium. *Hydrogen Emergency Response Training for First Responders BLEVE Risk and Mitigation*. EU HyResponder Project Report. 2023. URL: https://www.hyresponder.eu.

[15] International Air Transport Association (IATA). *Concept of Operations of Battery and Hydrogen-Powered Aircraft at Aerodromes*. PDF. 2025. URL: https://www.iata.org/globalassets/iata/publications/sustainability/concept-of-operations-of-battery-and-hydrogen-powered-aircraft-at-aerodromes.pdf.

[16] Z. Jaffary and M. Wiedemann. "Towards net-zero aviation: Exploring safe hydrogen refuelling at airports". In: *Journal of Air Transport Research Society* 4 (2025), p. 100048. URL: https://www.sciencedirect.com/science/article/pii/S2941198X24000599.

[17] Gijs Janssen. "Modelling Hydrogen Refuelling Operations at Airports". Accessed 2025. MSc Thesis. Delft, The Netherlands: Delft University of Technology, 2023. URL: https://repository.tudelft.nl/.

[18] Linde Engineering. *Liquid Hydrogen Transport Trailer for the European Market*. PDF. 2025. URL: https://assets.linde.com/-/media/celum-connect/2025/07/14/13/25/le_staticequipment_trailer_emea_broschure_a4_rz_144dpi_lbs180_194174.pdf.

[19] D. Mangold et al. "Refueling of LH2 AircraftAssessment of Turnaround Procedures and Aircraft Design Implication". In: *Energies* 15.7 (2022), p. 2475. DOI: 10.3390/en15072475.

[20] Jayant Mukhopadhaya and Dan Rutherford. *Performance analysis of evolutionary hydrogen-powered aircraft*. Tech. rep. White paper. International Council on Clean Transportation (ICCT), 2022. URL: https://theicct.org/wp-content/uploads/2022/01/LH2-aircraft-white-paper-A4-v4.pdf.

[21] NIST/SEMATECH. *NIST/SEMATECH e-Handbook of Statistical Methods: Critical Values of the Student's t Distribution*. Accessed 2026-01-06. n.d. URL: https://www.itl.nist.gov/div898/handbook/eda/section3/eda3672.htm.

[22] Pacific Northwest National Laboratory. *Hydrogen Compared to Other Fuels*. Online resource; accessed 2025. n.d. URL: https://h2tools.org/bestpractices/gaseous-gh2-and-liquid-h2-fueling-stations/hydrogen-compared-to-other-fuels.

[23] Pacific Northwest National Laboratory (PNNL). *Gaseous (GH_2) and Liquid Hydrogen (LH_2) Fueling Stations – Best Practices*. https://h2tools.org/bestpractices. Covers hydrogen fueling station design, hazards, and mitigation measures such as detection, ventilation, and materials. 2022.

[24] Rotterdam The Hague Airport (RTHA) hydrogen experts. *Indicative LH2 mobile trailer capacity range for airport-oriented concepts*. Personal communication. 2025.

[25] Royal Netherlands Aerospace Centre (NLR). *NLR Impact Report 2024*. Tech. rep. Describes NLR researchers substantive contributions in areas such as airport infrastructure, hydrogen design requirements, and safety (EUROCAE WG80 context). NLR, 2024. URL: https://www.nlr.org/wp-content/uploads/2025/06/NLR_impact_report_2024.pdf (visited on 12/16/2025).

[26] SAE International. *AIR8547: Liquid Hydrogen Aircraft Fueling Performance & Safety Guideline*. Aerospace Information Report. 2024. URL: https://www.sae.org/standards/air8547-liquid-hydrogen-aircraft-fueling-performance-safety-guideline.

[27] SAE International and EUROCAE. *AIR8466 / ER-034: Hydrogen Fueling Stations for Airports, in Both Gaseous and Liquid Form*. Defines safety/performance requirements for hydrogen fueling stations at airports. 2024. URL: https://www.sae.org/standards/air8466-hydrogen-fueling-stations-airports-gaseous-liquid-form.

[28] S. Shen et al. "Risk Assessment of Hydrogen-Powered Aircraft: An Integrated HAZOP and Fuzzy Bayesian Network Framework". In: *Sensors* 25.10 (2023), p. 3075. DOI: 10.3390/s25103075.

[29] L. Simonetto. *Operational Risk Management for Cryogenic Fuel Handling in Aviation*. Master Thesis, TU Delft. In preparation. 2025. URL: https://repository.tudelft.nl/.

[30] A. Tan et al. *Quick pit stops: A challenge for zero-emission planes?* International Council on Clean Transportation, accessed 2025. 2023. URL: https://theicct.org/quick-pit-stops-a-challenge-for-zero-emission-planes/.

[31] TULIPS Consortium. *Hydrogen Airport Ground Operations Deliverable Report*. Tech. rep. European Union Horizon Project, 2024. URL: https://tulips-greenairports.eu/wp-content/uploads/2024/12/TULIPS_Deliverable_D2.4_final.pdf.

[32] U.S. Department of Energy. *Overview of Hydrogen Safety, Codes and Standards*. Tech. rep. Washington, DC: DOE/EERE, 2014. URL: https://www.energy.gov/sites/prod/files/2014/03/f12/overview_final.pdf.

[33] K. Verfondern et al. *Handbook of Hydrogen Safety — Chapter on Liquid Hydrogen*. PRESLHY Deliverable D3.9, European Hydrogen Safety Panel. 2021. URL: https://hysafe.info/wp-content/uploads/sites/3/2021/04/D39_2021-01-PRESLHY_ChapterLH2-v3.pdf.

[34] K. van Wingerden et al. *Safety of Liquid Hydrogen: PRESLHY White Paper*. Tech. rep. HySafe / PRESLHY Project, 2021. URL: https://hysafe.info/wp-content/uploads/sites/3/2021/06/PRESLHY_D6_4_WhitePaper_202101505_V2p1.pdf.

[35] C. Xisto and A. Lundbladh. "Design and Performance of Liquid Hydrogen Fuelled Aircraft for Year 2050 EIS". In: *33rd Congress of the International Council of the Aeronautical Sciences (ICAS)*. Accessed 2025. 2022. URL: https://research.chalmers.se/publication/532872/file/532872_Fulltext.pdf.

[36] ZeroAvia. *Scaling Hydrogen–Electric Propulsion for Large Aircraft*. Tech. rep. White paper, accessed 2025. ZeroAvia, Aug. 2024. URL: https://zeroavia.com/wp-content/uploads/2024/08/ZeroAvia-Whitepaper-Scaling-hydrogen-electric-propulsion-for-large-aircraft-d.pdf.