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TURNAROUND SIMULATION AND ASSESSMENT OF FUTURE HYDROGEN AIRCRAFT CONCEPTS

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Abstract

Alternative fuels and novel aircraft designs are critical for enhancing aviation sustainability and reducing pollution. This work examines aircraft handling as a central interface between airlines, airports, and passengers, with the aim of evaluating the operational characteristics of future aircraft concepts as part of the aircraft design process. This study extends the turnaround simulation tool *TURNerate* by Bauhaus Luftfahrt through modular process structures and an integrated Liquid Hydrogen (LH_2) refueling model, employing CPACS-based geometry and mission data within the Bauhaus Luftfahrt Aircraft Design Environment (BLADE).

Validation against twelve conventional aircraft yields a mean deviation of only 5.4% from manufacturer reference turnaround times, underscoring the robustness of the methodology. Case studies demonstrate that geometry-sensitive processes, such as catering, vary substantially with cabin layout, thereby highlighting the importance of layout-driven modeling. For LH_2 concepts, the simulation illustrates that, while purge and chill-down steps add procedural complexity, the constant mass-flow fueling profile reported in literature enables turnaround durations that may even outperform kerosene. In contrast, scenarios involving distributed multi-tank architectures reproduce findings from prior studies, indicating that sufficiently high internal transfer rates are essential to avoid significant time penalties.

Overall, the proposed framework provides a validated and extensible basis for the early-stage operational assessment of hydrogen-powered aircraft, bridging the gap between conceptual design and airport integration. It demonstrates that hydrogen can be operationally competitive while identifying key infrastructural and safety-related challenges for future research.

Keywords

Turnaround; Airport; GSE; Hydrogen; Simulation; CPACS; Alternative Fuels; Future Aircraft Concepts

NOMENCLATURE

Abbreviations

BLADE	Bauhaus Luftfahrt Aircraft Design Environment
CO_2	Carbon dioxide
CPACS	Common Parametric Aircraft Configuration Schema
GSE	Ground Support Equipment
LH_2	Liquid Hydrogen
TAT	Turnaround Time

1. INTRODUCTION

Mitigation of climate change remains one of the greatest global challenges. Aviation contributes approximately 2.5% of global CO_2 emissions and around 4% of global warming effects [1]. In response, the European Green Deal sets the target of achieving climate neutrality by 2050, reinforcing the urgent need for sustainable propulsion technologies [2]. Among the possible alternatives, hydrogen is considered particularly promising for medium- and long-range aviation due to its high gravimetric energy density [3], especially in application domains where battery-electric propulsion remains infeasible [4].

At the same time, global air traffic is expected to grow steadily over the coming decades [5], further challenging airport infrastructure in terms of capacity, efficiency, and operational robustness. Turnaround time (TAT) is a central performance metric in this context, as it directly affects airline profitability, scheduling flexibility, and airport capacity utilization. Ensuring compatibility of novel aircraft concepts with established turnaround processes is therefore essential.

In this regard, future aircraft designs — particularly those relying on liquid hydrogen (LH_2) — require comprehensive evaluation not only in terms of aerodynamic and structural performance but also with respect to ground process integration. Early-stage operational assessment is key to identifying potential bottlenecks, evaluating the impact of alternative fuels on turnaround processes, and guiding the iterative aircraft design process.

This study addresses these challenges by extending an existing turnaround simulation environment to include geometry- and mission-dependent process modeling and

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by integrating a detailed LH_2 refueling process based on current research findings. Consequently, handling processes will be calculated based on the actual geometry of the cabin rather than solely on passenger capacity. Additionally, this research seeks to augment the evaluation methodologies by mapping the refueling process of liquid hydrogen in alignment with the latest research findings. The primary emphasis of this simulation is to examine the geometric dependencies of the various processes, thereby supporting aircraft designers in optimizing future concepts to optimize the operational turnaround performance.

The remainder of this paper is structured as follows: Section 2 briefly summarizes related work on turnaround operations and hydrogen applications in aviation. Section 2.2 discusses the integration of the turnaround simulation into the Bauhaus Luftfahrt Aircraft Design Environment (BLADE) [6], a multidisciplinary design framework. Section 3 describes the extended methodology, including geometry-based process modeling and the integration of hydrogen refueling. Section 4 presents case studies and validation against conventional reference aircraft. Section 5 reports the main findings on hydrogen fueling strategies, cabin layout sensitivity, and overall turnaround performance. Finally, Section 6 concludes the paper and outlines directions for future work.

2. RELATED WORK

2.1. Existing Approaches

Various approaches exist to simulate the aircraft turnaround process, differing in scope, level of detail, and objectives. One of the earliest airport-wide simulation frameworks was developed by the Airport Research Center (ARC) in the 1990s, where the Comprehensive Airport Simulation Tool (CAST) included ground handling and turnaround as subsystems within overall airport operations [7]. Airline-centric approaches emerged in the early 2000s, most notably the stochastic simulation model and analytical optimization framework developed by Wu and Caves [8, 9], which explicitly linked turnaround sequences to schedule punctuality and airline operating costs. In parallel, specialized tools began to investigate individual subprocesses in detail, with boarding and disembarkation models receiving particular attention as the longest critical-path activities [10, 11]. More recently, comprehensive reviews such as Picchi and Scardaoni [12] and Schmidt [13] have summarized the evolution of turnaround modeling environments and highlighted current methodological trends.

However, most existing simulations are limited to conventional kerosene-powered aircraft and do not account for the specific challenges introduced by hydrogen as an alternative fuel. In particular, LH_2 handling differs due to increased safety requirements, additional process steps, and sensitivity to achievable mass flow rates. To address this gap in aircraft design approaches, the present study incorporates the following aspects into a holistic turnaround simulation:

1) **Fuel Safety Zones.** Hydrogen refueling requires significantly larger exclusion areas compared to Jet A-1. While the International Air Transport Association (IATA) defines a 3 m radius for conventional refueling [14], FlyZero estimates safety zones of up to 8 m, and as much as 20 m during hose coupling for LH_2 [15]. These restrictions may initially be more stringent and gradually relaxed toward the future. A case study at Rotterdam The Hague Airport showed that efficient ground handling of Airbus ZeroE concepts is only feasible if parts of the workforce are permitted to enter the safety zone [16]. Otherwise, access restrictions would severely constrain parallel processes.
2) **Simultaneous Ground Processes.** In kerosene operations, multiple processes such as catering and boarding can often proceed in parallel with fueling, subject to safety regulations. For LH_2, stricter exclusion zones and higher safety standards could prohibit simultaneous operations, potentially extending the critical path. Existing studies highlight the need for systematic evaluation of such process interdependencies.
3) **Liquid Hydrogen Refueling Processes.** Compared to Jet A-1 fueling (truck positioning, coupling, fueling, uncoupling, removal), LH_2 requires additional cryogenic-specific procedures such as line purging and hose chill-down prior to fueling [17].
   Different coupling technologies and purge strategies (e.g. helium vs. nitrogen) have been proposed in the literature, leading to significant variations in assumed process times [18, 19].
   Typical purge durations are reported between 1.5 minutes (helium-based) and considerably longer when additional GH_2 flushing is required [17]. Similarly, chill-down procedures depend on hose length, material properties, and cooling strategy, and are a major source of operational uncertainty.
   Regarding achievable mass flow rates, published values span a range from 13 [20] to 20 [17] kg/s, depending on hose diameter and system design. Mangold [17] therefore recommends 20 kg/s as a practical design assumption.
   These discrepancies underline the importance of clearly stating assumptions when analyzing turnaround times of LH_2-fueled aircraft.
   Unlike kerosene fueling, where decreasing pressure in the aircraft tank causes an exponential reduction of the mass flow towards the end of the process, LH_2 fueling typically maintains a constant flow by returning vaporized hydrogen to the ground system and therefore maintaining constant internal tank pressure. This constant flow profile has the potential to shorten refueling times for large fuel quantities, even if conservative flow rate assumptions are applied.
4) **Fuel Distribution Systems.** Hydrogen aircraft concepts often rely on distributed multi-tank configurations, necessitating internal cross-feed and redistribution [21].
   Recent simulation studies highlight that such internal flows can substantially extend the effective refueling duration. According to Brewer, the minimum

internal mass flow rate required is 0.397 kg/s for an LH2 engine during takeoff. For a hose diameter of five inches, Brewer calculates a flow rate of 2.23 kg/s. [20]

These limitations highlight the need to critically examine both external and internal distribution processes when assessing the throughput performance of LH_2 aircraft.

2.2. Integration into BLADE

BLADE is a Python-based framework developed to support multidisciplinary aircraft design processes [6]. It enables designers to couple aerodynamic, structural, and operational assessments within a unified workflow. At its core, BLADE employs the Common Parametric Aircraft Configuration Schema (CPACS) [22] as a standardized input and output format, allowing seamless data exchange between different disciplinary modules. This integration facilitates iterative design loops in which novel configurations can be evaluated holistically with respect to performance impact and operational feasibility. Within this framework, the turnaround simulation presented in this study provides an operational perspective that complements the technical design evaluations (see Fig. 1).

In the previous state of TURNerate [13], the model relied primarily on static input values and modeled process times as functions of passenger numbers. In contrast, the present work extends the methodology by directly linking process durations to CPACS-based geometric and mission-specific parameters. This enables the calculation of process times based on the actual cabin arrangement and the positioning within the cabin. This enables a more precise operational consideration of unconventional aircraft concepts.

A central novelty of this integration is the implementation of LH_2 refueling processes. These are represented as modular process elements, including purging, chill-down, and internal tank distribution, which were not previously covered by TURNerate. Embedding this functionality into BLADE ensures that future hydrogen-powered aircraft concepts can be evaluated consistently within the same design cycle as conventional kerosene aircraft. In doing so, the methodology supports the assessment of novel aircraft also with respect to their ground handling and operational performance.

3. METHODOLOGY

3.1. Simulation Architecture and CPACS Data

Building on the TURNerate framework [13], the simulation was re-implemented in Python to improve flexibility and facilitate integration with multidisciplinary design tools like the BLADE environment.

A CPACS file serves as the standardized input format for aircraft configuration and mission data. By automatically parsing CPACS files, the simulation extracts key geometric and operational parameters, such as cabin layout, galley positioning, number and location of service doors, tank configuration, and passenger capacity. This enables process durations to be calculated not only from statistical assumptions but also from geometry-dependent relationships, ensuring applicability to unconventional aircraft concepts.

Each ground handling process is represented as an independent module, executed within a critical-path logic that accounts for positioning, execution, potential repositioning, and removal of ground support equipment (GSE). Boarding and deboarding times are obtained via coupling with the PAXelerate [23] tool, while other processes (catering, refueling, water exchange, cargo handling, cleaning) are parameterized directly within the simulation. The liquid hydrogen refueling approach includes additional process steps such as purging and chill-down, as well as alternative strategies for fuel distribution between multiple tanks.

Overall, the architecture enables consistent assessment of both kerosene and hydrogen concepts within the CPACS design loop, thereby forming the methodological basis for the process design and validation steps outlined in the following sections.

3.2. Correction Factors

To ensure consistency with empirical turnaround data, selected processes are scaled by correction factors. These factors were derived from Original Equipment Manufacturer (OEM) reference values and depend primarily on aircraft size, represented by three passenger-capacity categories (small, medium, and large aircraft). The general formulation is

$$t_{ex,\,corr} = t_{ex} \cdot f(N_{pax}), \tag{1}$$

where t_{ex} denotes the modeled execution time, N_{pax} the number of passengers, and $f(N_{pax})$ the size-dependent correction factor.

The correction factors are mainly applied to the positioning and removal phases of ground service equipment, which scale with aircraft size. Larger aircraft typically require longer driving distances on the ramp as well as more complex attachment procedures at service interfaces. By calibrating these subprocesses across modules such as catering, refueling, and cargo handling, the correction factors ensure that the model reproduces realistic turnaround durations for conventional aircraft while maintaining sensitivity to novel configurations.

3.3. Modular Process Design

3.3.1. General Process Logic

Each turnaround process in the simulation is decomposed into four potential steps: positioning (t_{pos}), execution (t_{ex}), repositioning (t_{rep}), and removal (t_{rem}). The total process duration is therefore expressed as

$$t_{proc} = t_{pos} + t_{ex} + t_{rep} + t_{rem}. \tag{2}$$

This modular formulation allows different ground handling processes to be represented in a consistent

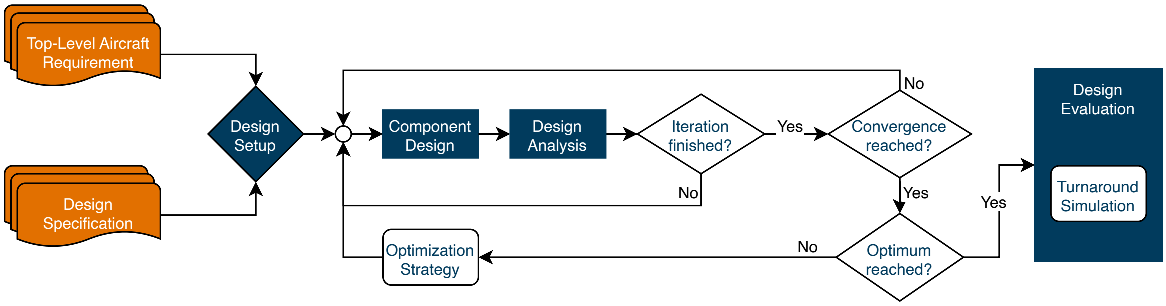

FIG 1. Turnaround Simulation module within the BLADE design evaluation loop. Own adaptation based on [6].

structure while retaining the flexibility to account for geometry-dependent parameters and varying GSE configurations. Repositioning times are calculated whenever a vehicle must serve multiple interfaces on the aircraft, using a generic expression that accounts for positioning, removal, and travel time between interfaces.
The overall turnaround duration is determined through a critical-path analysis. Processes can run in parallel or sequentially depending on physical and operational constraints, with the longest chain of dependent processes defining the minimum achievable turnaround time. This logic builds upon the initial TURNerate structure [13], but was extended in this work to support variable numbers of vehicles, multiple service interfaces, and geometry-dependent execution times. The consistent breakdown into process modules and the integration into a critical-path framework provide the methodological basis for the subsequent implementation of individual passenger, service, and refueling processes.

3.3.2. Passenger Processes

Passenger handling is a major determinant of turnaround duration, with boarding typically representing the single longest cabin-related process. To capture geometry-dependent effects, two different modeling approaches were considered. A simplified method assumes constant passenger flow rates per boarding device (bridge or stairs), but this approach was discarded due to its limited sensitivity to cabin layout variations.
Instead, an agent-based simulation was integrated by coupling the turnaround framework with the PAXelerate tool [23]. PAXelerate evaluates boarding times directly from the CPACS-defined cabin layout, accounting for parameters such as seat abreast, number and location of service doors, and deck configuration. The resulting ingress times are provided on a per-door basis and imported into the turnaround simulation. This enables realistic differentiation between conventional single-aisle layouts and unconventional wide-body or multi-deck concepts.
Deboarding is not explicitly modeled in PAXelerate. Following empirical findings, deboarding is assumed to be faster than boarding, mainly due to the unidirectional flow of passengers and the absence of luggage stowing. Consistent with industry practice, the simulation therefore applies an empirical correction factor to boarding times, typically around 0.6 for conventional aircraft [24, 25]. This default approach ensures robust results while maintaining consistency with the PAXelerate-based boarding simulation. In addition, a literature-based regression using layout-specific coefficients [26] was adopted from the TURNerate simulation as an optional method. This provides users with a manual control option to evaluate sensitivity or to account for unconventional cabin configurations, even though the geometry dependence is already largely captured by the boarding model itself.
Overall, the integration of PAXelerate establishes a geometry-driven modeling of passenger flows that replaces earlier statistical assumptions. This extension represents a key improvement of the simulation framework, as it allows passenger processes to directly reflect innovative cabin architectures and multi-deck configurations.

3.3.3. Catering Process

In the initial TURNerate implementation, catering time was modeled exclusively as a function of passenger numbers [13]. In this work, this approach is extended by incorporating aircraft geometry and cabin layout parameters. All galleys are extracted directly from the CPACS file, including their size and longitudinal position within the cabin. Each galley is assigned to the nearest available catering door, and catering trucks are allocated accordingly. The number of galley trolleys is determined from the galley area rather than passenger numbers, enabling a more realistic estimation of catering demand.
The catering process duration is computed as

$$t_{cat} = t_{pos} + t_{trolley} + t_{walk} + t_{rep} + t_{rem} \quad (3)$$

where t_{pos} and t_{rem} denote truck positioning and removal times, $t_{trolley}$ is the cumulative refill time per trolley, and t_{walk} represents crew walking time between doors and galleys. If multiple catering vehicles are assigned, their operations are synchronized. For the critical path, only the truck with the longest service time is considered, since parallel processes are constrained by the slowest individual operation.
For long-haul aircraft, where OEM specifications assume higher service times per trolley, a correction factor is ap-

plied to adjust the model accordingly. This calibration ensures consistency with manufacturer assumptions and provides a robust basis for subsequent validation.

For long-haul aircraft, where OEM specifications assume higher service times per trolley, a correction factor is introduced to align simulation outputs with manufacturer data. Using this adjustment, deviations from Airbus reference values were reduced from 46.7% in the original TURNerate model to 7.6% with the new method. This improvement demonstrates the robustness of the geometry-based approach across a wide range of aircraft categories.

In contrast to passenger-based approaches, the geometry-driven method is designed to remain applicable also to unconventional cabin layouts.

3.3.4. Cargo and Service Processes

Cargo handling is modeled via two distinct modules: unit load device (ULD) container loading and bulk cargo loading. Both processes follow the generic four-step logic of positioning, execution, repositioning, and removal, with equipment numbers defined in CPACS or set as tool-specific defaults. Execution times are parameterized through handling rates per container or per bulk position, while positioning and removal are scaled by correction factors to capture aircraft-size dependencies. Only the slower of the two cargo modules contributes to the critical path, as both can operate in parallel.

Potable water and wastewater exchange are treated as separate service modules, each executed by dedicated trucks. Due to missing OEM reference values for wastewater, its duration is calibrated using the potable water correction factor. Since both potable and wastewater exchange were never found to be part of the critical path in any of the analyzed cases, their validation was not the primary focus of this study. Both processes are positioned at the aft fuselage in accordance with empirical layouts [27].

The ground power unit (GPU) is modeled as an auxiliary service required at the beginning and end of every turnaround. Its positioning precedes all other processes, while its removal concludes the turnaround.

Cabin cleaning is implemented as an independent process linked to passenger egress and preceding boarding. Execution times scale with passenger capacity and cabin size, ensuring applicability to both conventional and non-standard layouts.

Together, these cargo and service processes complement the passenger, catering, and refueling modules, forming the operational baseline against which novel hydrogen-related extensions are integrated.

3.3.5. Refueling Processes

This section discusses the differences between conventional Jet A-1 and LH_2 refueling from a simulation perspective, with particular emphasis on the additional process steps and the extended fuel safety zones (see Fig. 2).

Conventional Jet A-1 refueling is modeled as a sequence of truck positioning, hose coupling, fueling, uncoupling, and truck removal [14].

According to recent studies and infrastructure assessments, LH_2 refueling requires several additional steps. Prior to fueling, the transfer lines must be purged with inert gas to remove residual gases, followed by a chill-down phase to cool the cryogenic lines to operating temperature. Only then does the actual fueling take place, after which the lines are disconnected and safely vented. [17]

The corresponding refueling time t_{LH2} is expressed as (4)

$$t_{LH2} = t_{con} + 2 \cdot t_{purge} + t_{chill} + \frac{m_{fuel}}{\dot{m}_{LH2}} + t_{rep} + t_{discon}$$

where m_{fuel} is the required fuel mass and $\dot{m}_{LH2}$ the effective mass flow rate. The coupling process t_{coup} is preceded by the positioning of the fuel truck, and after the disconnect t_{discon}, the vehicle is removed.

Different fueling strategies were implemented to reflect alternative aircraft tank configurations. In cases where no hydrogen tanks are specified in the CPACS model, the required LH_2 mass can be estimated by converting the Jet A-1 fuel mass into its hydrogen energy equivalent [17]. This simple method enables early-stage assessments, where the aircraft and tank geometry are not yet defined, by assuming a *single virtual tank* that contains the entire hydrogen mass.

$$t_{LH2,singleTank} = \frac{m_{LH2}}{r_{LH2} \cdot n_{trucks}} \tag{5}$$

Although this approach neglects internal distribution effects, it provides a practical first-order estimate and comparison to the Jet A-1 fueling time.

If CPACS models already include LH_2 tanks with defined capacities and locations, more realistic strategies are applied. The first is an *internal cross-feed configuration*, in which the fuel truck stays connected to a single interface, and cryogenic pumps distribute the liquid hydrogen from one feeder tank to all other tanks. This process is typically limited by the lower internal transfer rates between tanks, which can extend the overall refueling time compared to a single-tank assumption.

Alternatively, a *repositioning strategy* is considered, where the fuel truck sequentially docks at multiple tank interfaces. In this case, the external truck mass flow is maintained, but the overall duration increases due to repositioning and recurring coupling steps.

By covering these three cases, energy-equivalent estimation, internal cross-feed, and truck repositioning, the model remains applicable across early design phases with limited data, as well as detailed CPACS configurations with multiple distributed hydrogen tanks.

In addition, safety considerations play a more prominent role for LH_2. Whereas conventional kerosene fueling requires a fuel safety zone around the fueling interface of approximately 3 m [14], recent hydrogen studies recommend safety distances of 8 m during normal fueling and up to 20 m during coupling operations [15, 16]. In the present implementation, these zones are visualized around the aircraft to highlight potential conflicts with other ground support equipment (see Fig. 2). However, no direct process coupling has been enforced in the critical-path logic, as regulatory guidelines for simulta-

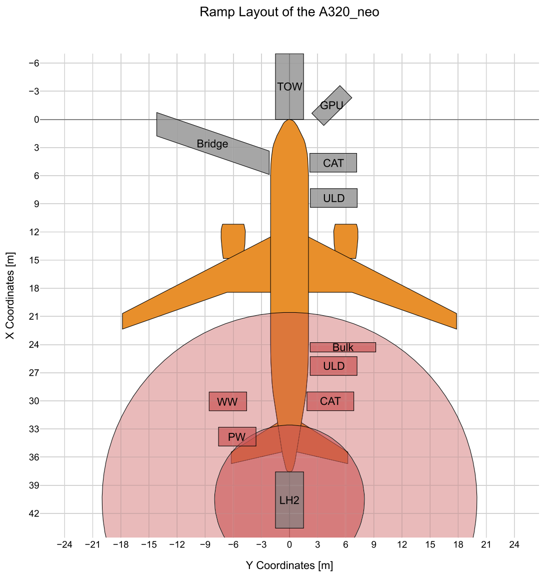

FIG 2. LH_2 truck positioned in the aft fuselage area - circle radius: dark red (8m), light red (20m).

neous operations during LH_2 fueling are not yet defined. Consequently, the fueling process is currently modeled to run in parallel with all other services except passenger handling, analogous to conventional Jet A-1 operations, while generating a visual warning if overlaps with the safety zone occur.

By embedding these additional subprocesses, fueling strategies, and safety constraints into the same modular framework as conventional refueling, the simulation allows for a consistent assessment of LH_2 aircraft within the overall turnaround process.

3.3.6. Visualization and Postprocessing

To enhance the interpretability of the simulation results, two complementary postprocessing tools were developed. First, a *ramp layout* (see Fig. 2) is generated based on CPACS geometry. The aircraft is displayed in planform together with all ground support equipment (GSE) at their respective service positions. Door coordinates and service interfaces are directly taken from CPACS where available, while missing data (e.g., cargo door positions) are approximated using empirical offsets from reference studies [27]. This visualization also allows the overlay of hydrogen-specific safety zones, providing a geometric check of potential conflicts between refueling and parallel processes.

Second, a *Gantt chart* representation is automatically created for each simulation run (see Fig. 3). All subprocesses are arranged along a common timeline, with the critical path highlighted. The graphical style is aligned with OEM documentation from Airbus and Boeing, facilitating direct comparison of maximum and minimum turnaround times. Processes are grouped into pax-, cabin-, and sub-process-related tasks, enabling rapid identification of bottlenecks and sensitivities across different design configurations.

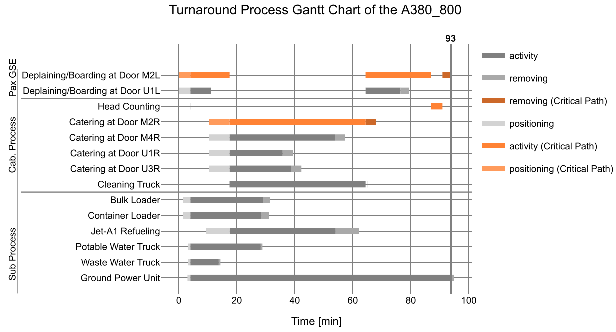

FIG 3. Automatically generated Gantt chart of an A380-800.

Together, these visual outputs complement the numerical results by providing both a spatial and temporal perspective on aircraft ground operations, thereby supporting the iterative design evaluation within BLADE.

4. CASE STUDIES AND VALIDATION

The validation of the developed framework was performed at both the process and system levels. The central metric for the overall turnaround is the *critical path*, defined as the longest chain of dependent processes. Figure 4 illustrates the sequencing logic: certain tasks, such as passenger and cargo handling, can proceed in parallel (indicated by curly brackets), while others, such as deboarding before fueling and subsequent boarding, are strictly sequential (physically or by regulatory requirements). Within each bracket, the longest process determines the continuation of the critical path.

Some standard parameters are not specific to the aircraft and are therefore not available in the CPACS files. Table 1 provides an overview of the cross-aircraft parameters embedded in this simulation. These are adjusted by a correction factor depending on the size of the aircraft (see chapter 3.2).

At the level of individual ground handling processes, the following observations were made:

- **Passenger boarding** is directly taken from the validated PAXelerate simulation, which computes boarding times as a function of cabin geometry, seat layout, and door usage.
- **Passenger deboarding** is not explicitly modeled in PAXelerate. Based on OEM data, deboarding is assumed to be faster than boarding, and is represented as 60% of the corresponding boarding time for conventional aircraft.
- **Cargo handling** as well as **potable and waste water exchange** are parameterized according to Schmidt [13]. Their durations are scaled with correction factors to capture aircraft size dependencies, ensuring realistic values across both single-aisle and twin-aisle aircraft.
- **Catering** exhibited the largest improvement compared to the original TURNerate framework. Whereas earlier models estimated catering demand from passenger

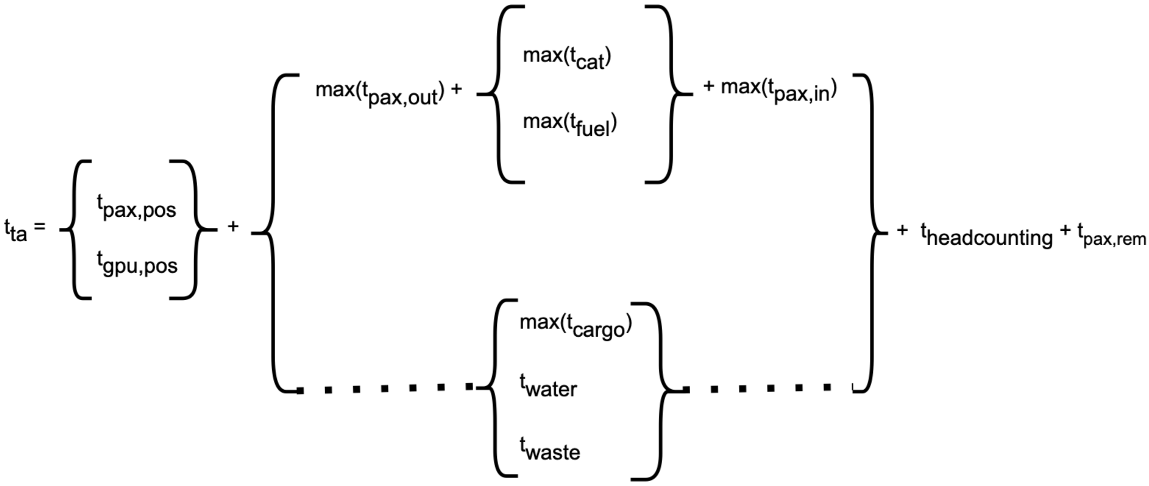

FIG 4. Critical path logic. Each set of curly brackets represents processes that are executed in parallel. For the determination of the critical path, only the longest process within each bracket is considered.

TAB 1. Default values for all turnaround parameters not directly provided by CPACS. Most values are adopted from [13], while the boarding/deboarding ratio and head-counting assumptions are based on OEM documentation [24].

	Default Value	Unit
Passenger Handling		
Deboarding/Boarding Ratio	0.6	[-]
Positioning	120	[s]
Removal	78	[s]
Head Counting Rate	92	[pax/min]
GPU		
Positioning	60	[s]
Removal	60	[s]
Cargo		
Positioning	120	[s]
Removal	78	[s]
Refueling		
Positioning	54	[s]
Removal	72	[s]
Catering		
Positioning	63	[s]
Removal	69	[s]
Movement time	24	[s]
General Service		
Positioning	48	[s]
Removal	36	[s]
Potable Water	0.34	[l/pax]

numbers, the present approach derives galley capacity directly from CPACS, accounting for the higher galley area per passenger in premium cabin classes. As a result, average deviations from OEM reference times were reduced from 46.7 % to 7.6 % (see Table 2). Beyond calibration, the geometry-based method also increases sensitivity to innovative cabin layouts. Case studies of modified cross-sections [28] confirmed significant differences in catering times, while the passenger-based model produced constant results independent of geometry. This capability is essential for evaluating unconventional concepts such as wide but short cabins or multi-deck configurations.

TAB 2. Comparison of catering process times.

Aircraft	Airbus [24]	Schmidt [13]	Fiege	Unit
A320neo	13.5	15.0	14.9	[min]
A350-900	67.5	25.0	59.2	[min]
A380-800	122.5	41.7	122.8	[min]
Deviation		**46.7**	**7.6**	[%]

Finally, the full turnaround simulation was compared to OEM reference times across different aircraft categories. Table 3 presents the results for representative Airbus and Boeing aircraft, showing that the model reproduces the planned turnaround times with high accuracy, from short-range single-aisle to long-range wide-body aircraft.

In summary, the validation confirms that the extended simulation environment significantly reduces deviations from OEM specifications compared to earlier approaches, while simultaneously increasing sensitivity to geometry-dependent effects. This ensures that the model provides a reliable foundation for the assessment of conventional aircraft. Validation for hydrogen-powered concepts is not yet possible due to the absence of real-world reference data; nevertheless, the implemented framework already enables their consistent simulation and comparison in early design phases.

5. RESULTS

5.1. Operational Comparison: Jet A-1 vs. LH_2

While conventional refueling consists of positioning, coupling, fueling, uncoupling, and removal, the LH_2 process includes additional purge and chill-down steps, which extend the overall fueling process.

TAB 3. Validation of the full servicing turnaround time between simulation and manufacturer data. [24, 25]

Aircraft	TAT OEM [min]	TAT Fiege [min]	Deviation from OEM	TAT Schmidt [min] [13]	Deviation from OEM
Airbus					
A319	37	43	16.2 %	39	5.4 %
A320neo	44	44	0.0 %	43	2.3 %
A321neo	52	50	3.8 %	47	9.6 %
A330-300	59	56	5.1 %	38	35.6 %
A340-300	62	58	6.5 %	41	33.9 %
A340-600	68	71	4.4 %	43	36.8 %
A350	61	61	0.0 %	47	23.0 %
A380	90	93	3.3 %	75	16.7 %
Boeing					
B737-8	36	36	0.0 %	44	22.2 %
757-2	39	43	10.3 %	47	20.5 %
767-2	40	42	5.0 %	51	27.5 %
767-4	53	58	9.4 %	55	3.8 %
Average			**5.3 %**		**19.8 %**

Figure 5 compares Jet A-1 and LH_2 refueling processes for three different representative aircraft categories.

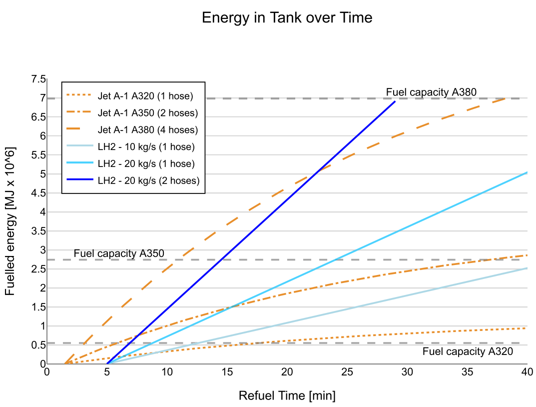

FIG 5. Comparison between Jet A-1 and LH2 refueling processes over time for different aircraft; LH2 process starts after purging + chill-down. Adapted from Mangold [17].

The linear mass flow of LH_2 offers a distinct advantage over the progressively flattening profile of kerosene fueling, particularly for larger aircraft. Even at a conservative flow rate of 10 kg/s [17], hydrogen refueling achieves shorter durations than kerosene for small and medium aircraft despite the additional purging step. For long-range configurations, one LH_2 truck at 15 kg/s achieves comparable times to two Jet A-1 trucks (35.8 vs. 35.3 minutes for the A350), and outperforms them at 20 kg/s. Refueling very large aircraft such as the A380-800 requires two LH_2 trucks at 20 kg/s each, which still completes faster (30.3 minutes) than kerosene refueling with four trucks (36.6 minutes).
Overall, the linear fueling profile allows hydrogen to match or undercut kerosene turnaround times even with the additional required coupling steps, which reflects the state of the art of Mangold [17].

5.2. Impact of Tank Configurations

To investigate the influence of tank configurations on refueling performance, four A320-range-equivalent aircraft concepts [28] with LH_2 tanks were analyzed (see Table 4).

TAB 4. Quantities of liquid hydrogen (LH2) and number of tanks for four A320-range-equivalent aircraft concepts [28].

Aircraft Model	Quantity of LH2 [kg]	Number of Tanks
Dynamic Aft	7730.9	2
Front and Aft	5520.8	2
Over Cabin	5230.3	3
Over Cabin and Aft	7011.3	4

Two strategies were implemented. In the *cross-feed configuration*, the fuel truck remains connected to a single interface while cryogenic pumps distribute the liquid hydrogen internally across multiple tanks. This approach avoids repeated positioning but is limited by the lower internal transfer rates, which prolong the overall fueling time.
In the *repositioning strategy*, one truck sequentially connects to each fueling interface. Therefore, the mass flow between truck and aircraft is maintained for every tank, but additional coupling and positioning times are added to the process chain. Figure 6 shows the refueling times for the four hydrogen concept aircraft depending on the refueling method compared to the A320neo kerosene refueling time. For all refuel methods, an LH2 truck is used, which provides a mass flow of 20 kg/s to the aircraft interface. These plots can be used within the design validation process (described in chapter 2.2) to find the most efficient type of refueling logic for the selected tank configuration. Suppose the corresponding point is below the red reference line of the A320neo (kerosene version). In that case, the selected refuel logic and/or internal mass

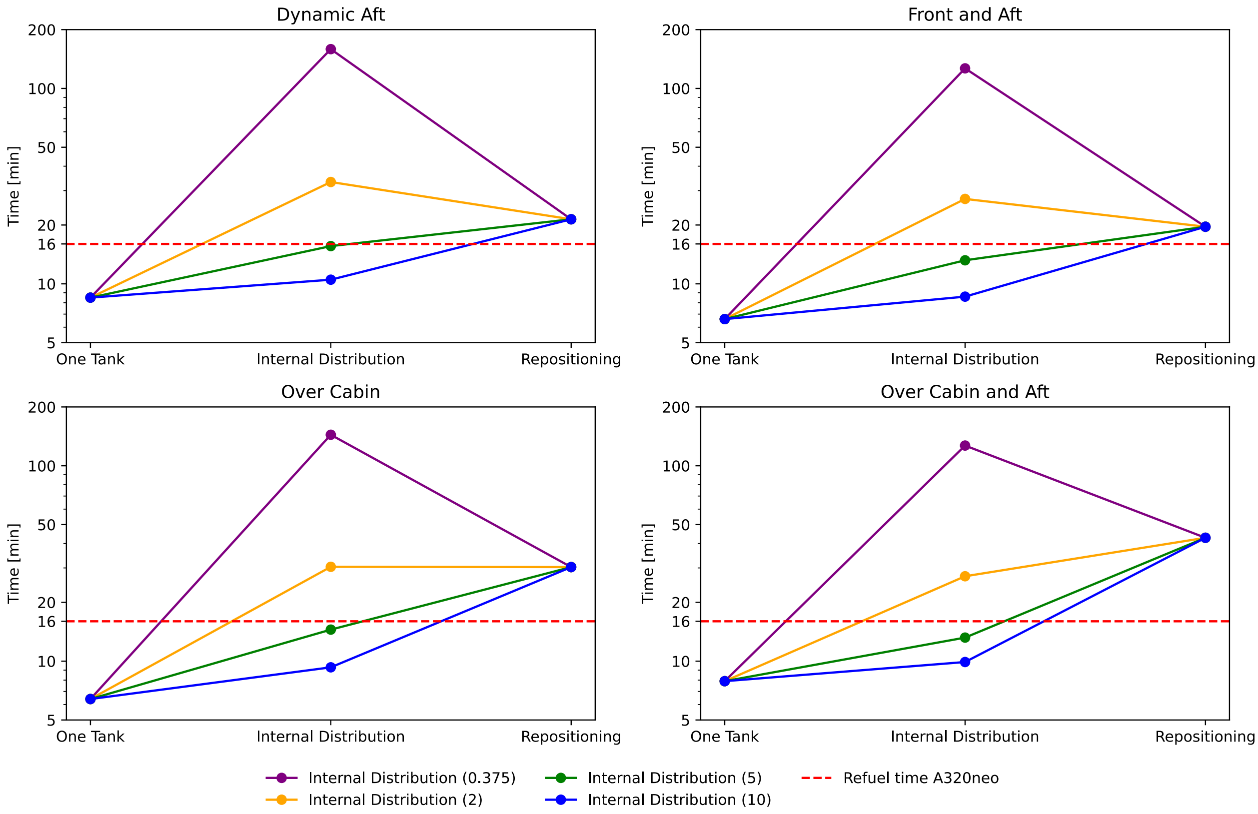

FIG 6. Refueling times of LH2 for four different hydrogen aircraft models, compared to the A320neo kerosene refueling time.

flow is superior to the kerosene process in terms of time. From Figure 6, it becomes clear that an internal mass flow from the main tank in the direction of the additional tanks of 2 kg/s is faster for some models (*Over Cabin*, *Over Cabin and Aft*) than repositioning the truck, but in order to achieve comparable or even shorter refueling times than for the kerosene process, mass flows of at least 5 kg/s must be realized, which is probably a very optimistic value according to Brewer's calculations [20]. These findings demonstrate that hydrogen fueling strategies cannot be assessed independently of the underlying tank geometry and must therefore be considered in early design phases to ensure operational feasibility.

5.3. Sensitivity to Cabin and Layout Configurations

The geometry-based modeling of service processes enables the simulation to capture effects that passenger-based approaches neglect. Catering provides a representative example. In the original TURNerate model, catering demand was approximated solely from the number of passengers, leading to identical process times for all layouts with the same seating capacity. In contrast, the present method derives catering times directly from galley areas extracted from CPACS, thereby accounting for the larger galley-to-seat ratio in premium classes such as business or first class.
Figure 7 compares alternative cabin configurations [28] with the same total number of passengers. While the passenger-based model yields constant catering

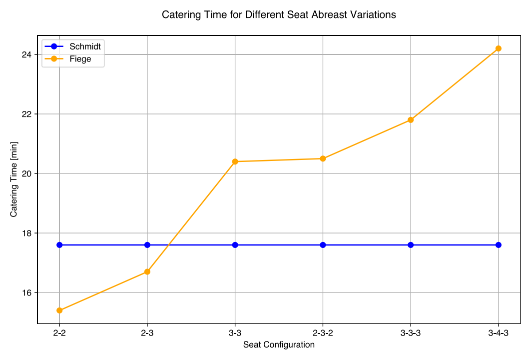

FIG 7. Catering time for different seat abreast variations, passenger-based (Schmidt) and layout-based (Fiege).

durations, the geometry-driven approach results in significant differences, with premium-heavy layouts requiring markedly more time than economy-dense configurations. This increased sensitivity is particularly relevant for unconventional concepts such as wide but short cabins or multi-deck arrangements, where service requirements deviate substantially from conventional single-aisle references.
These results highlight the importance of geometry-based modeling for assessing turnaround performance, as cabin configuration can substantially alter the process time even when passenger capacity remains unchanged. Passenger boarding and deboarding, derived from

PAXelerate and empirical ratios, remain the dominant contributors to turnaround time but show little variation across layouts.

5.4. Robustness and Limitations

The validation results indicate that the simulation framework accurately reproduces OEM turnaround specifications for various aircraft categories, showing single-digit deviations. This robustness is further enhanced by the modular process structure, which ensures applicability from short-range single-aisle aircraft to long-haul wide-body configurations. The consistent integration of CPACS data enables geometry-dependent sensitivities to be captured, allowing the framework to assess not only conventional designs but also unconventional layouts such as multi-deck or short-wide-body aircraft. Moreover, the explicit inclusion of liquid hydrogen fueling extends the scope of turnaround analysis to future propulsion concepts, incorporating purge and chill-down steps in a consistent simulation framework.
At the same time, several limitations remain. Fuel safety zones for hydrogen are currently implemented only as a visual overlay in the ramp layout and not yet coupled to the critical path, since regulatory guidance is still evolving. The absence of real-world data prevents empirical validation of LH_2 fueling processes, which at present can only be modeled using assumptions from recent research studies. Furthermore, correction factors derived from reference aircraft are applied to some values, such as positioning and deposition, to meet the different OEM specifications (see Table 1). These correction factors are currently calibrated only for three size categories, distinguished by passenger capacity, and therefore do not yet account for additional parameters such as mission range or maximum take-off weight, for example. Finally, parallelization rules for ground handling processes remain simplified, as interactions between service vehicles have not yet been modeled in full operational detail.
Overall, the framework provides a robust foundation for comparative assessments and design studies, while highlighting areas where future research and operational data are needed to improve predictive accuracy.

6. CONCLUSION

Short turnaround times are of considerable importance to both airlines and airport operators. The economic viability of hydrogen-powered and unconventional aircraft configurations critically depends on their ability to achieve competitive turnaround durations. It is therefore essential to assess turnaround performance early in the design process, accounting for both fuel type and cabin geometry.
This study introduced a simulation framework capable of calculating turnaround times based on geometry- and mission-specific parameters from a CPACS file. The model extends conventional kerosene-based approaches by incorporating liquid hydrogen fueling according to the current state of research, including additional purge and chill-down steps, and by capturing geometry-dependent service processes such as catering and boarding. In this way, the framework supports the identification of impractical design solutions at an early stage and facilitates the integration of operational requirements into aircraft design.
The simulation was benchmarked against reference turnaround times from Airbus and Boeing across short-, medium-, and long-range aircraft, showing single-digit deviations. Furthermore, applications to conceptual hydrogen aircraft demonstrated the model's ability to handle unconventional tank and cabin layouts, even though empirical validation for cryogenic fueling remains pending.
Future work may integrate optimization routines and extended input parameters to enhance process fidelity and enable systematic design-space exploration. Improved geometric modeling and refined aircraft classification could further support collision analysis and increase robustness. Advancing the hydrogen refueling logic to better reflect operational constraints and safety requirements will be essential once empirical data become available.
In summary, the proposed framework provides a validated and extensible basis for incorporating operational feasibility into aircraft design, bridging the gap between conceptual studies and practical ground operations in the transition toward sustainable aviation.

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