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From ground to sky: Exploring the dynamics of ground times in relation to future aircraft design and airline networks

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Abstract

Extended aircraft ground times between two flights are widely recognised to have the potential to increase costs, to generate network inefficiencies, and to diminish the attractiveness of both airports and airlines. As a result, minimizing ground times, and thereby maximising aircraft utilisation, has become an objective within airline operation planning. Furthermore, incorporating operational data such as ground times into scenario-based analyses has become relevant for identifying suitable design parameters in future aircraft concepts, such as the design of liquid hydrogen (LH_2) or electric aircraft. This study aims to explore the dynamics of ground times in relation to future aircraft design and airline networks. A dual approach is employed, combining both descriptive and analytical methods to analyse ground times across factors as aircraft types, regions, airports, and airlines. An openly available ADS-B data set to extract ground time information from flight operations between 2022 and 2024 is utilised. Additionally, flight schedules and passenger demand data are incorporated to conduct a network analysis from airport and network level, evaluating how ground times affect overall airline performance and connectivity.

The analysis of ground times across aircraft categories highlights the need for range- and operation-specific insulation strategies in future LH_2 aircraft to optimise hydrogen storage. Furthermore, the regression-based network analysis reveals that reduced ground times are associated with greater network robustness, higher passenger numbers, increased connectivity, enhanced centrality, and improved aircraft utilisation at the network level, with variations observed across regions and business models. Regional differences are more evident at the airport level, while business model variations became more apparent at the network level.

Keywords: Data analytics; ground times; network analysis; aircraft design

1. Introduction

The air transport system is a complex network in which each component has an influence on the overall efficiency. The dynamic of one of these components, namely aircraft ground times, will be the focus of this study. The term ‘ground time’ is defined as the time between ‘in block’ and ‘off block’. ‘In block’ refers to the time when the aircraft arrives at the destination gate and remains stationary, while ‘off block’ is used to denote the time when the aircraft

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departs from the gate. Per definition, ground time includes overnight stops and maintenance windows of aircraft. Conversely, the time during which an aircraft is airborne or taxiing is known as block time.

An environmental incentive to study ground times arises from the design of liquid hydrogen (LH_2) aircraft. LH_2 aircraft are currently discussed by industry and academia, e.g. Airbus (2020) and Adler and Martins (2023), as a more sustainable alternative to aircraft propelled by fossil or synthetic kerosene. However, a technical challenge of this aircraft type is that the LH_2 would need to be stored within the aircraft at a temperature of −253°C. Therefore, and in contrast to existing kerosene-based aircraft, a well-suited insulation would be required to minimize the evaporation of LH_2. This is not only relevant during the flight mission, but also during ground operation, since the LH_2 will remain in the storage vessel within normal operation. In this context, the concept of dormancy time becomes relevant: dormancy time refers to the maximum duration the storage system can remain on the ground without the need to vent hydrogen. Thus studying aircraft ground times can help to identify suitable dormancy time targets, informing insulation requirements and operational strategies for efficient LH_2 aircraft. While this study focuses primarily on the relevance of ground times for LH_2 aircraft design, the insights gained may also inform design decisions for electric aircraft. In electric aviation, ground times are extended by the comparatively long durations required for battery charging, though they may be shortened through battery swapping strategies, both of which have implications for airport operations and infrastructure (Doctor et al. (2022)). Designing electric aircraft that can operate within existing ground times therefore depends on access to operational data.

Extended ground times, which often are the result of delays or scheduled buffer times, have the potential to increase costs, to generate network inefficiencies, and to diminish the attractiveness of both airports and airlines. As such, reducing ground times has become an objective in airline operations planning. This focus is also reflected in academic research, with numerous studies proposing strategies aimed at reducing ground times, as reviewed in Hutter and Pfennig (2023). Eurocontrol (2025) revealed that in 2024, only 66.2% of European departures were on time, highlighting the current operational challenges the industry faces. Furthermore, ground times are a competitive factor in airline networks, as aircraft generate revenue solely while airborne transporting passengers or cargo (Hutter and Pfennig (2023)). Given the operational and economic incentives, this study focuses on understanding the dynamics of ground times in relation to airline networks. The goal of this study is to provide valuable insights for both academia and industry by contributing to the identification of requirements for future aircraft design, while also closing the gap between network measures and ground times in academic literature.

2. Literature review

Past research has examined ground times from various perspectives, which will be explored sequentially in the literature review, beginning with descriptive analysis and subsequently considering dynamics of ground times. Additionally, a brief overview of network theory will be provided, as the study employs this framework.

Burschyk et al. (2023) examined ground times for short-range aircraft across two regions, North America and Europe, focusing on two business models: low-cost carriers (LCCs) and full-service-network carriers (FSNCs). Their findings indicate, first, that LCCs generally have shorter ground times than FSNCs, and second, that the yearly operating ground time for short-range aircraft is lower in North America than in Europe, partly due to longer average flight distances. The present study extends this research by including a more varied set of aircraft categories in addition to short-range aircraft. Similarly, Lange et al. (2019) analysed ground times across different airline business models, demonstrating a trend of increasing ground times from LCCs to hybrid carriers to FSNCs.

Beyond descriptive analysis, a small number of studies have explored the operational and economic impacts of ground times. Plötner et al. (2015) examined the indirect impact of ground times on airline yields by analysing the effects of varying cruise speeds and the resulting changes in block times on passenger demand and revenue using discrete choice theory. Their findings indicate that reductions in block times lead to moderate increases in average yields, while extended block times result in decreasing yields, with effects varying by market characteristics and available alternatives. A more in-depth study was undertaken by Habsari et al. (2023) who utilised linear regression to analyse the impact of ground times on flight departure punctuality for one Indonesian airline. Luo et al. (2021) proposed a machine learning approach to predict ground times based on turnaround sub-processes such as deplaning, cleaning, and boarding, aiming to reduce delays and their propagation. While these sub-processes are not the focus in this study, overlapping factors include airline affiliation and aircraft type.

This study additionally employs network theory to explore the dynamics of ground times in relation to airline networks. Network theory has already been widely used in the analysis of air transportation networks for the past two decades. A recent comprehensive review is provided by Zanin and Wandelt (2023). This review considers three network levels: airport, city, and multi-airport region. Complementing the review, an empirical study covering twelve years is conducted which identified correlations between different network measures. A broader temporal perspective is offered by Kölker et al. (2025), who examined the intra-European air transport network from 2010 to 2023. At the global level, Sun et al. (2024) analysed the development of the worldwide air transport network over a ten-year period, showing that a small number of highly developed countries in Western Europe and North America continue to dominate the system. However, this dominance has gradually declined due to the emergence of major hubs in the Middle East and China's growing influence as an Asian hub. While a diverse set of literature on airline connectivity exists, the interplay between ground times and airline connectivity remains an area of interest, with no studies known to the authors that explicitly link ground times with network measures. This research gap, which was also identified by Lange et al. (2019) will be addressed within this study.

3. Methodology

This section presents the methodological framework of the study, comprising both the preprocessing of ground time data in Subsection 3.1 and the subsequent analytical procedures in Subsection 3.2.

3.1. Preprocessing

Ground times are derived from ADS-B signals captured by the OpenSky Network (Schäfer et al. (2014)). ADS-B is a surveillance technology that tracks aircraft, with each aircraft identified by a 24-bit ICAO address. Unfortunately, the OpenSky Network has limited regional coverage, as ADS-B receivers are deployed in specific areas. The coverage is illustrated in Figure 1, where Subfigure 1(a) visualises the geographical distribution of valid ground time observations per airport, as collected and generated in this study. The node size corresponds to the number of valid ground times, with larger nodes indicating more valid ground times. Subfigure 1(b) visualises the combined structural network of all airlines, in which edges are weighted according to the normalised capacity from each route, representing the airline schedule network. The observed variation in number of ground times arises both from disparities in data coverage and from differences in the operational scale of individual airports, as reflected in the schedule network. Due to the restricted geographical reach of OpenSky data, the analysis may introduce biases requiring a focus on specific regions. Nevertheless, as illustrated in Figure 1(a), OpenSky provides a wide coverage across a range of regions.

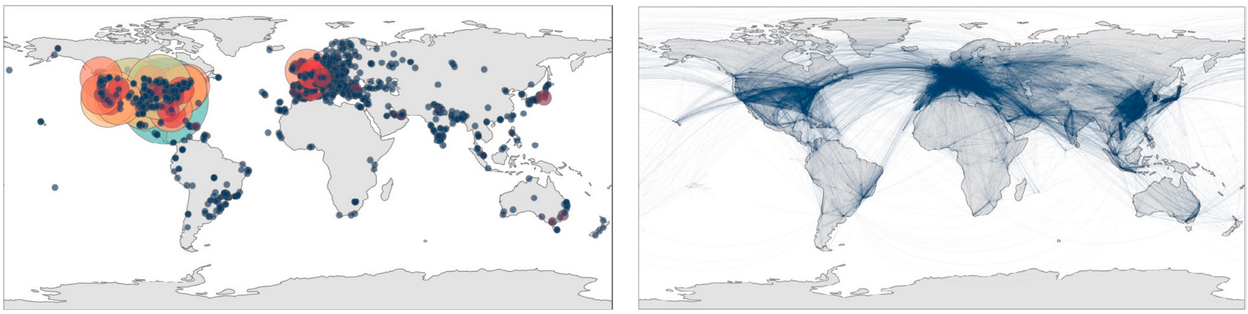

Fig. 1: (a) visualisation of the geographical coverage of valid ground times data, (b) visualisation of the airline network structure.

The data of ground times consists of a sequential list of flights for each aircraft, based on ADS-B signals. The completeness, continuity, and accuracy of the data are not guaranteed. To ensure reliable ground time measurements, a filtering method was applied to exclude invalid data. Only sequences of two consecutive valid flights operated by the same aircraft are considered, for which additionally the arrival airport of the previous flight matches the departure airport of the subsequent ensuring continuity. Flights are considered valid if and only if the block time is larger 15 minutes and origin and destination are distinct. Flights with unknown airports are excluded. This method ensures that the block times of flights preceding and following the ground time are known. The scaled block time to total time ratio, also used as aircraft utilisation, is calculated using the subsequent flight's block time, with adjustments made for percentage data coverage to ensure comparability across aircraft. Aircraft coverage denotes the proportion of time each aircraft is tracked during the study period, calculated as the sum of valid ground and block time divided by the total period. Flights that depart without recorded preceding arrival time at the same airport are flagged as invalid, as they likely result from erroneous signals. For all valid recordings, the ground time is determined as the time difference between the last recorded ADS-B signal of the previous flight and the first recorded signal of the next flight. Small uncertainties, arising from not knowing the exact moment the ADS-B signal was turned off relative to landing, taxiing, or being in-block, are accepted. For the following analysis, only valid ground time observations from aircraft with a minimum coverage of at least twenty percent of the observation period are taken into account. Additionally, only ground times with a maximum duration of 72 hours are taken into consideration, resulting in the exclusion of 0.2% of the data. This threshold covers all basic and frequent maintenance events, such as A-checks and B-checks (Rhoades et al. (2005)), as well as operational standstills due to curfew restrictions. Longer maintenance events, including C- and D-checks, typically lasting up to several weeks (Rhoades et al. (2005), are excluded. This approach also excludes irregularities caused by longer seasonal fleet groundings, ensuring the analysis focuses on regular operations.

3.2. Analytical framework

To analyse the relationship between ground times and aircraft design, the data is clustered by aircraft type using average number of seats and average operational flight distance in all valid data. Four categories are defined and shown in Figure 2(a). This combined classification is used to avoid distortions that would arise from relying solely on seat capacity or maximum range. For example, in some regions long-haul aircraft are often operated on short-haul routes, which would lead to misleading classifications if only a single parameter were applied.

The data of ground times covers the period from 2022 to 2024 and is summarised in Table 1. In total, the data comprises more than 17 million ground times of 12,592 aircraft during three years of operation. As demonstrated in Table 1, the majority of aircraft categories across different regions possess a sufficient number of aircraft and valid ground time observations to facilitate meaningful analysis. However, for a number of categories, indicated by values in parentheses, the number of ground time records falls below the threshold of 10,000 and is therefore excluded from further analysis. The data encompasses a global sample of aircraft from 90 airlines, 6 regions and 3 business models, which were chosen according to their fleet size. In addition to FSNC and LCC, regional carriers (RC) are included.

Table 1: Overview over number of aircraft and number of valid ground times (GT) by airline region and aircraft category.

Region	Cat I		Cat II		Cat III		Cat IV	
	Aircraft	GT	Aircraft	GT	Aircraft	GT	Aircraft	GT
Africa	61	12,331	198	49,087	74	12,425	34	(4,419)
Asia Pacific	52	(4,875)	892	321,127	525	251,415	354	124,424
Europe	354	772,449	1,492	2,746,380	322	195,853	296	155,043
Latin America	193	19,460	822	136,569	60	23,459	51	12,756
Middle East	7	(296)	413	104,167	183	48,226	458	209,115
North America	2,056	4,901,658	3,106	6,455,673	410	377,743	179	159,834
$\sum$	2,723	5,711,069	6,923	9,813,003	1,574	909,121	1,372	665,591

The network analysis follows the approach of Kölker et al. (2025), which is adapted and extended to analyse airline connectivity, focusing on different airlines and linking ground time data with structural and functional network data, sourced from Sabre GLBL Inc. (2025). The following measures are calculated and analysed: accessibility measures (number of airports, number of passengers, seat capacity, shortest path length, network density), centrality measures (degree centrality, closeness centrality, betweenness centrality, eigenvector centrality), competition measures (ticket price, airline market share, variants of the Herfindahl-Hirschman Index (HHI), leg utilisation) and robustness measures (clustering coefficient, density robustness, degree assortativity). While the measures themselves are not originally introduced in the study, their application and descriptions in Kölker et al. (2025) serve as the basis. The library 'Networkx' (Hagberg et al. (2008)) was used to calculate the network measures. Additionally, the 'airportsdata' Python library was used for airport-related data processing, as well as fleet analyser data from Cirium (2025) for aircraft information. To assess the dynamics of ground times on airline networks, a standardised regression analysis is conducted between network measures as dependent variables and ground time as explanatory variable. To ensure comparability across measures with different scales, all variables were standardised. This can be approached from two aggregation levels, either evaluating metrics at the airport level or across entire networks. At the network level, some measures are aggregated from measures calculated at the airport level, while others yield a single value per network and, consequently, do not require aggregation. The analysis takes an operational viewpoint, considering all aircraft types from multiple airlines. A diverse selection of 15 airlines per region, encompassing different business models, enables an analysis of variations in operational strategies and regional differences. The focus is primarily placed on North America and Europe. These two regions were selected because they are best covered by Opensky and are dominating the network structure of the aviation system (Sun et al. (2024)), which can also be seen in Figure 1(b). The selected airlines include 5 LCCs, 6 FSNCs, and 4 RCs in North America, and 5 LCCs and 10 FSNCs in Europe.

4. Results

The findings are derived from two different perspectives. Subsection 4.1 examines the dynamics of ground times in relation to aircraft design, while Subsection 4.2 investigates the dynamics between ground times and airline networks.

4.1. Dynamics in relation to aircraft design

The understanding of ground times can be utilised to improve preliminary aircraft design, e.g. new aircraft configurations such as LH_2 aircraft. To illustrate this, specific operational requirements for LH_2 aircraft that arise from insulation types are examined to identify threshold values for ground times that are considered in the subsequent analysis. As demonstrated by Burschyk et al. (2023), the hydrogen ground consumption is influenced by the duration of ground time, the insulation quality and the dormancy time. Ground consumption is defined as all hydrogen losses that occur during periods when the aircraft is on the ground. Such losses may include boil-off resulting from parasitic heat input, venting to prevent overpressure, and additional losses during handling or other ground-based operations. Burschyk et al. (2023) demonstrated that, under constant tank pressure, hydrogen losses begin to occur during ground times as short as one hour in tanks insulated with closed-cell foam, particularly when employing thinner insulation layers. Increasing the thickness of the insulation reduces and delays the hydrogen ground consumption rate but also adds weight to the tank, potentially increasing fuel consumption in flight. In contrast, vacuum-insulated tanks do not demonstrate measurable hydrogen losses until ground times exceed 10 hours, with hourly hydrogen loss rates significantly lower than those observed in foam-insulated tanks. Based on these findings, a ground time of approximately two hours can be identified as a critical threshold beyond which hydrogen losses become operationally significant for most insulation types. This value, however, is not universal and depends on several factors, including permissible tank pressure, fill level, and ambient conditions. Using the predefined threshold, the distribution of ground times across different aircraft clusters is analysed.

The primary findings are illustrated in Figure 2(b), which shows the relative distribution of ground time events clustered by aircraft categories, as defined by mean number of seats and operational range in Figure 2(a). It is notable that there are substantial differences in the frequency distribution of ground times across the categories. For both Cat I and Cat II, the frequency initially increases, followed by a decline, then rises again with a secondary peak in the 7–10 hour interval, before decreasing once more. This pattern is primarily attributed to reduced night-time demand and the influence of airport curfews imposed by night-time noise mitigation regulations, particularly affecting aircraft with shorter flights. In contrast, Cat III and Cat IV exhibit a more continuous increase and subsequent decrease in frequency, assuming uniform interval widths. The share of ground times belonging to the 0 to 2 hour interval is highest for Cat I (67.4%), and decreases across Cat II (60.9%), Cat III (19.5%) and Cat IV (6.8%). The interval from 10 to 72 hours, associated with potential hydrogen losses for all insulation types, accounts for a relatively small share of ground time events: 8.9% for Cat I, 8.6% for Cat II, 14.2% for Cat III and 14.0% for Cat IV. The majority of these events occur within the 10–24 hour subinterval. Although the frequency of events in the 10–72 hour range is limited, this interval contributes disproportionately to the total accumulated ground time. Specifically, it accounts for 39.5% of total ground time in Cat I, 36% in Cat II, 48.4% in Cat III, and 45.8% in Cat IV.

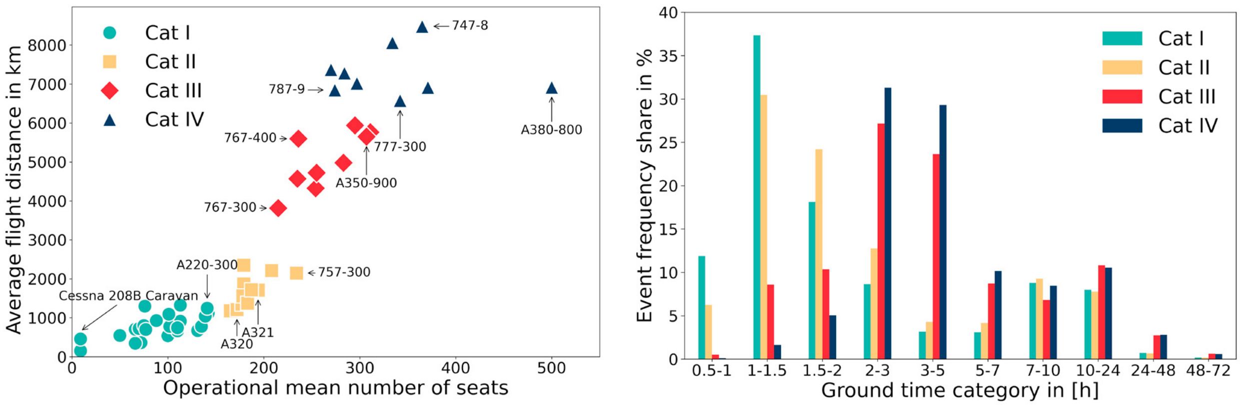

Fig. 2: (a) aircraft categories by mean number of seats and flight distance, (b) results of ground time analysis for different aircraft categories.

These findings suggest that the aircraft category is an important factor in determining the suitability of insulation, given the substantial variations in the proportion of ground times falling below and above critical thresholds. A cost-benefit analysis is necessary to derive specific insulation design recommendations. However, preliminary insights can be drawn from the observed ground time distributions. For Cat I and Cat II aircraft, insulation systems with moderate performance may be adequate, given that a significant proportion of the ground times remains below the predefined two-hour threshold for hydrogen losses. In contrast, aircraft in Cat III and Cat IV more frequently exceed this threshold, indicating a need for higher performance insulation capable of limiting hydrogen losses over longer durations. Additionally, Cat III and Cat IV aircraft not only have longer ground times but also operate on longer flight segments, where the benefits of lightweight insulation are more pronounced due to the increased fuel savings achieved by reducing aircraft mass over extended flight durations. This creates a trade-off between minimizing insulation weight during flight and ensuring thermal performance on the ground.

Table 2: Aircraft utilisation by airline region, category, and business model; $\sum^*$ denotes the weighted sum.

Region	Cat I				Cat II			Cat III	Cat IV
	FSNC	LCC	RC	$\sum^*$	FSNC	LCC	$\sum^*$	FSNC	FSNC
Africa	–	–	–	–	48.9%	41.2%		53.6%	–
Asia Pacific	–	–	–	–	38.8%	49.2%		48.4%	56.4%
Europe	27.0%	31.7%	–		32.5%	39.6%		59.2%	60.0%
Latin America	–	–	–	–	50.3%	54.4%		55.8%	–
Middle East	–	–	–	–	51.0%	56.3%		61.8%	59.7%
North America	31.3%	33.9%	24.3%		36.8%	38.5%		51.1%	58.0%
$\sum^*$	30.1%	33.7%	24.3%	28.6%	37.2%	40.3%	38.3%	53.4%	58.7%

In addition to the event frequency and total ground time share, the aircraft utilisation rate across different categories is also relevant, as it directly affects the trade-off between insulation quality and aircraft mass: the higher the utilisation, the more critical the aircraft's performance becomes. Table 2 presents the aircraft utilisation by airline region, category, and business model, though with some limitations. FSNCs operate aircraft across all four categories, while RCs are restricted to Cat I aircraft, and LCCs primarily utilise aircraft within Cat II. A clear trend emerges in the data, with utilisation rates increasing as the aircraft category progresses from Cat I to Cat IV. Although most ground times in Cat I (61.8%) fall within the uncritical interval, the utilisation rate is the lowest. This may be partly attributed to the shorter operational range and shorter block times characteristic of this category. Nevertheless, the importance of improved insulation properties should not be overlooked for Cat I aircraft. Additionally LCCs exhibit higher utilisation rates compared to other business models in Cat II, except in Africa, where FSNCs show slightly higher utilisation. This deviation may be attributable to limited data availability for smaller airports in Africa, potentially biasing the results.

4.2. Dynamics in relation to airline networks

A standardised regression analysis is provided in Figure 3, illustrating the dynamics between mean ground time and network measures in Subfigure 3(a) at the airport level and in Subfigure 3(b) at the network level, with results grouped by business model and region. Only statistically significant coefficients are visualised. An initial observation is the heterogeneity in both the strength and direction of the regression coefficients, with variations across regions and business models, as illustrated by the distribution of the bar charts for each measure. Notably, RC North America stands out as an outlier, possibly due to the absence of an European counterpart.

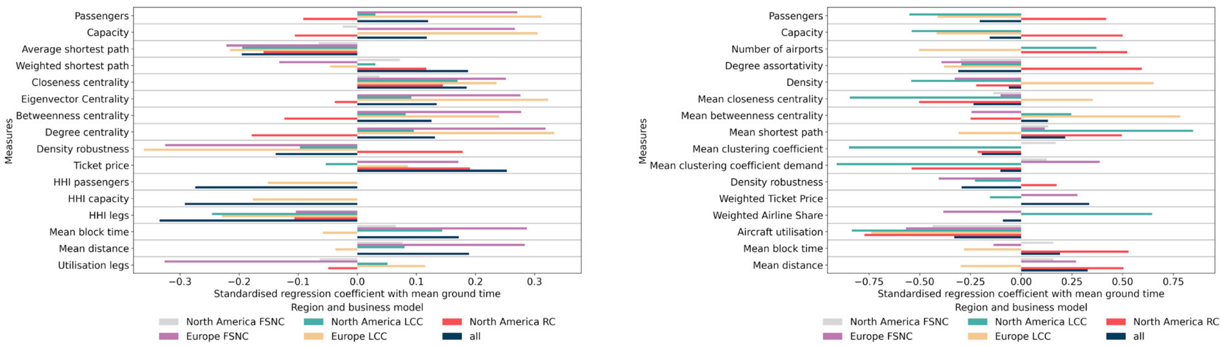

Fig. 3: Regression between mean ground time and measures at (a) airport level and (b) network level, grouped by region and business model.

Subfigure 3(a) shows that, for RC North America, higher airport centrality, measured by eigenvector, betweenness, and degree centrality, is associated with shorter ground times, as indicated by negative regression coefficients. This contrasts with the pattern observed in other airline groups, where more central airports tend to exhibit longer ground times. The latter may be explained by operational practices at major hubs, particularly among FSNCs, where extended ground times result from factors such as maintenance activities or passenger transfers. A similarly heterogeneous pattern is observed for the variables passengers and capacity. For RC North America, a moderate negative coefficient indicates that fewer passengers and lower capacity are associated with longer mean ground times at airports. In contrast, for other airline groups, airports with higher passenger numbers generally have longer ground times as indicated by a positive coefficient. Furthermore, regional differences emerge at the airport level. In Europe, the relationship between most measures and mean ground times is significantly stronger. For example, the coefficient between closeness centrality and ground times is 0.25 for European FSNCs compared to 0.04 for North American FSNCs. This discrepancy reflects the stricter airport regulations and more limited availability of slots in Europe, leading to more closely coordinated operations and thus a stronger relationship between airport measures and ground times.

While airports with higher passenger volumes generally exhibit longer ground times, networks with greater overall passenger numbers tend to be associated with shorter ground times. This divergence in direction, also observed for capacity, shortest path, and closeness centrality, can be attributed to the composition of networks, which generally comprise a greater number of airports with fewer departures or passengers, in addition to a smaller number of high-traffic airports. At the network level, RC North America again emerges as an outlier. However, Europe LCC also deviates from the overall pattern for some measures. For all other airline categories, a negative coefficient is observed between mean ground times and network measures such as passenger volume, capacity, degree assortativity, and density robustness, indicating that larger passenger volumes and more robust networks are generally associated with shorter ground times. Furthermore, there is a negative coefficient between mean ground times, and density and centrality measures. In contrast, RC North America exhibits a positive coefficient, indicating that higher passenger volumes and increased network robustness are associated with longer ground times. This suggests that for RC North America greater passenger volume and network strength are linked to reduced operational efficiency. Subfigure 3(b) further indicates that LCCs in both North America and Europe exhibit a stronger negative relationship between mean ground time and network metrics such as passenger numbers, capacity, and utilization rate compared to FSNCs. This pattern aligns with the operational strategy of LCCs, which aim to maximise aircraft utilisation.

5. Conclusion and outlook

This study explores the dynamics of ground times in relation to aircraft requirements for future aircraft design and airline networks. The analysis of ground times across aircraft categories, formed by clustering aircraft types according to their average number of seats and average operational flight distance, reveals distinct ground time patterns between the categories. From an aircraft design perspective, this result emphasises the need for range- and operation-specific tank configurations and insulation strategies to optimise hydrogen storage in future LH_2 aircraft, particularly considering the variation in ground time distributions relative to critical thresholds across aircraft categories. Understanding the dynamics between ground time and airline networks is more complex due to the number of measures, the two levels of analysis and the heterogeneity of regression patterns. Regional disparities are more evident at the airport level, where operational factors are influencing the strength of the regression parameters. In contrast, differences between business models become more evident at the network level. This can be explained by the higher variability of airport-level measures across individual airports, as compared to aggregated data. By aggregating the data, the impact of business models becomes more evident at the network level. Furthermore a negative coefficient between mean ground time and network robustness, passenger numbers, density, centrality and aircraft utilisation are revealed at the network level. Several limitations should be acknowledged, which could be addressed in future research. The regional focus of the data on North America and Europe and its limited scope constrain the generalisability. Temporal trends and seasonality were not analysed, as the inclusion of multiple years primarily aimed to enlarge the sample size and enhance statistical reliability. Furthermore, a dynamic network systems approach could be used to examine the dynamics of airline characteristics, operational parameters, and aircraft features with ground times. This would provide a more detailed understanding of the dynamics that goes beyond the limitations of a linear regression analysis.

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