

LOSS OF RELIABILITY OF NEW GENERATION ENGINES: THE CASE STUDY OF THE PW1100G ENGINE RECALL ON MEXICAN AVIATION AS A SYSTEM OF SYSTEMS

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Abstract

The loss of reliability of new generation engines has created a unique scenario in the commercial aviation industry. A manufacturing issue that originated from the manufacturing of life limited parts led to disruptions in airline operations, saturation in the capacity of engine maintenance, repair and overhaul and airframe manufacturer part scarcity. This paper presents the case study of the PW1100G engine recall and its impact on Mexican aviation from a System of Systems Engineering perspective. It reconstructs the series of events that led to the recall, quantifies its impact on the availability of the fleet for the Mexican airline, and frames the analysis from an evolutionary perspective of how emergent behaviours transcended to set the context upon which the two largest Mexican low-cost airlines merged.

Keywords: Air transportation, Aviation safety, System of Systems

1. Introduction

In Mexico, the two most important low-cost airlines, Viva, (Aeroenlaces Nacionales, S.A. de C.V., formerly Viva Aerobus) and Volaris (Concesionaria Vuela Compañía de Aviación, S.A.P.I. de C.V.) had selected the PW1100G engine for their A320neo aircraft since 2013 and 2014 [1] [2]. This would play an essential role in their fleet renewal plans in the medium and long term. However, since July 2023, RTX Corp (formerly Raytheon), holding Pratt & Whitney, informed about a rare powder metal defect that could lead to the cracking of some engine components. This called for accelerated inspections that led to the issuance of AD 2023-16-07 in August 2023 and the grounding of a large number of aircraft due to this loss of reliability.

The objective of this work is to present and discuss the case study of the factors that represented the loss of reliability of the PW1100G and its repercussion on the two most important low-cost airlines in Mexico.

The study provides insights on the coupled and evolving behavior of a complex ecosystem that is not only responsible for the design of an engine, but also for its manufacturing, supply chain and maintenance.

2. Background

2.1 System of Systems Engineering

While Systems Engineering (SE) has matured as the standard approach for developing complex products, the deployment of such systems in an operational environment introduces new interactions that together can be considered as a larger entity that exhibits system-like behavior. Studying these

https://doi.org/10.71945/icas2026_0822

entities at a higher level of abstraction has led to the emergence of System of Systems Engineering (SoSE) as a growing field of research.
Contrary to a single complex system where multiple subsystems interact to perform a function, a System of Systems (SoS) is a system whose elements are managerially or operationally independent self-sufficient Constituent Systems (CS), whose interactions produce emergent behaviors unattainable by the CS alone [3]. For the complete categorization and characteristics of a SoS, the interested reader is invited to consult Walden [4] and Maier [5]. One particularly relevant characteristic for this study is the evolutionary nature of a SoS. This means that over time CSs are free to reorganize, enter or exit the SoS, potentially altering the overall structure and behavior of the SoS itself. By understanding the interconnected context, interfaces and relationships where aerospace systems are expected to function, the expanded perspective helps understand the product in an overreaching context that goes beyond the traditional system boundaries of SE.
Civil aviation can be categorized as an acknowledged SoS [6], its CS consisting of aircraft, airports, air traffic management, airlines, Maintenance Repair and Overhaul (MRO) facilities, Original Equipment Manufacturers (OEMs), suppliers, etc., all adhering to central standards and regulations. Constituent systems while remaining managerially and operationally independent, together producing the emerging capabilities of efficient and safe global air transport. Examples of SoS applications in aviation include wildfire firefighting [7], search and rescue operations [8], urban air mobility [9], financial enterprises operating in collaborative constellations [10] and multi-organization civil aviation impact assessment frameworks [11].

3. Method

This paper's objective is to provide a descriptive view and interpretation in the light of the System of Systems Engineering basis of the PW1100G engine recall and its impact in the Mexican aviation environment. To do that, it adopts an exploratory, instrumental single-case study design, with the case selected using a paradigmatic sampling strategy [12].
The data used for the case presentation include quantitative data of affected aircraft, regulatory documents issued by governmental institutions, official corporate press releases and news articles. A summary is presented in Table 1. The quantitative data of the aircraft affected was retrieved based on *airfleets.com* and *flightradar24.com*, from September 1, 2023, to April 30, 2025. The flight codes of Viva, Volaris and its subsidiaries (VB, H2, Q4 and EL) were retrieved and compared with the data published by Agencia Federal de Aviación Civil (AFAC), the Mexican Civil Aviation authority, to provide information consistency. This comparison corroborated 99.2469% of the available flight hours (FH), with the remaining data excluded due to inconsistencies.

Table 1 – Summary of data sources

Data type	Source	Purpose in the study
Quantitative data	Airfleets.com, Flightradar24.com, AFAC	Measurement of fleet availability, flight hours, identification of affected aircraft and its geographical position
Regulatory documents	FAA, AFAC	Definition of recall scope, validation of technical issues, and timeline of regulatory actions
Industry and corporate communications	OEM communications, airline institutional communications, press releases	Identification of decisions, explanations, responses and changes in structure within the system
Relevant events and contextual information	Secondary sources like news articles (e.g., Reuters, aviation media)	Reconstruction of the timeline of events and contextualization of operational and economic impacts

3.1 The A320neo and the PW1100G Geared Turbo Fan

The A320neo family is the most advanced A320 aircraft family from European aircraft manufacturer Airbus [13]. Officially launched on December 1, 2010, the abbreviation “neo” stands for "New En-

gine Option", which replaces the previous generation of CFM56 and IAE V2500 engines with new-generation CFM LEAP and PW1100G, which are more efficient and have at least the same operational expectations as their predecessors [14]. Pratt & Whitney's PW1100G Geared Turbo Fan (GTF) design aims at increasing the engine's propulsive efficiency by reducing the speed of the bypass airflow around the core. This can be achieved by using higher Bypass Ratios (BPR) coupled to lower Fan pressure ratios (see left of Fig. 1).

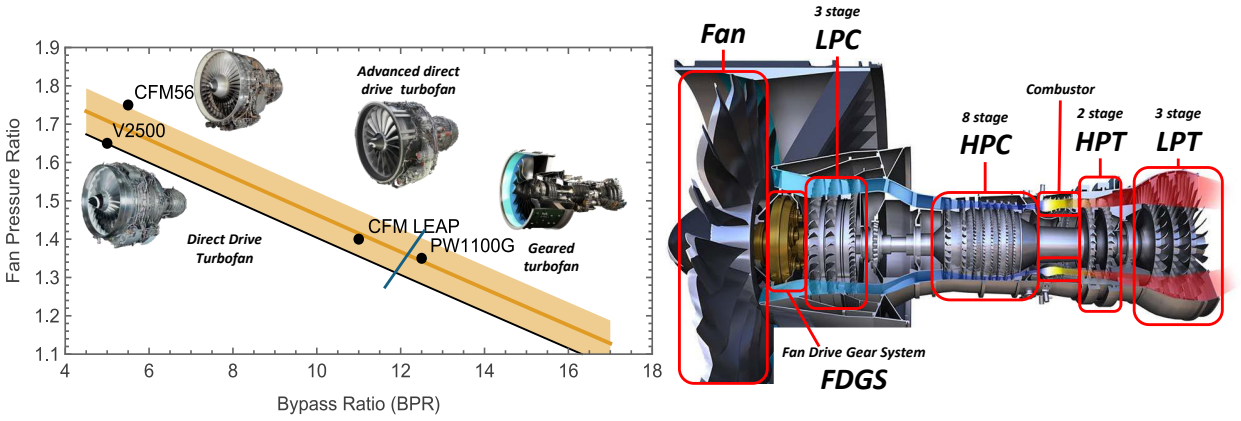


Figure 1 – Left: Approximated turbofan engines for the Airbus320 family. Right: Architecture of the PW1100G based on [15] and [16]

In a conventional two-spool Direct Driven turbofan (DDTF), the Fan, the Low Pressure Compressor (LPC) and Low Pressure Turbine (LPT) use the same shaft and therefore rotate at the same speed. Operating at the desired lower Fan speeds to achieve lower Fan pressure ratios also forces the LPC and LPT to operate at lower rotational speeds. This requires additional compression stages to compensate the lower speeds, resulting in a larger and heavier engine. The Geared Turbo Fan (GTF) solves this by decoupling the Fan from the low speed spool by means of a Fan Drive Gear System (FDGS) that reduces the speed at an approximately 3:1 ratio. Thus, the FDGS allows the LPC and the LPT to run at higher speeds closer to the design optimal, reducing the number of stages, engine length and weight [16]. Challenges associated with this configuration include the increased weight penalty of the gearbox, drag generated by its casing, gear friction, and the integration problems on engine dynamics from adding more weight on the shaft line.
The GTF produces a BPR of approximately 12:1, compared to up to 6:1 for the CFM56 (the engine it aims to replace) and compared to the 11:1 BPR of its direct competitor the CFM International's LEAP [17]. P&W reported savings of up to 20% in fuel efficiency, and 50% less NOx emissions [18], in line with the aviation industry's growing environmental expectations. However, while higher operational efficiencies were guaranteed, several reliability deficiencies became apparent that significantly impacted this high-value indicator, even in the short term as detailed in later sections.

4. Case presentation

A detailed account of the Geared Turbofan (GTF) engine recall is now presented.

4.1 First in-service issues

In March 2017, initial in-service issues were identified since engines were experiencing combustor-lining degradation and oil leaks from the no. 3 bearing compartment carbon seal. This was mostly due to their operation in high-particulate, low air-quality environments [19].
In December 2017, engineering changes were introduced into new-production GTF engines, which included a new design of the knife-edge seal on the High Pressure Compressor (HPC) aft hub [20]. Unintentionally, this caused several engine In-Flight Shut-Downs (IFSD) and rejected take-offs. This prompted the European Aviation Safety Agency (EASA) to issue the emergency Airworthiness Directive (AD) 2018-0041-E (later corrected to 2018-0041R1) on February 18, 2018 [21]. It affected 43

PW1100G-JM engines already installed on wing and another 55 delivered to Airbus. The issue was quickly solved in less than a month for new production engines by reverting the design changes to the previous versions [22].
This type of setbacks is expected for the introduction of a new highly complex technological product, and in December 2020 P&W reported the admirable technical dispatch reliability rate of 99.98 percent for the PW1100G-JM [23].
In 2022 an uncontained failure of an HPT 1st-stage disk resulted in debris penetrating the engine cowling of an aircraft flying with an International Aero Engines AG V2533-A5 turbofan. For that, on November 7, 2022, the Federal Aviation Administration (FAA) issued AD 2022-19-15 [24] which required Angled Ultrasonic Inspection (AUSI) of the HPT's 1st and 2nd-stage disks and, depending on the results of the inspections, replacement.
In June 2023, RTX Corp (formerly Raytheon), holding Pratt & Whitney (which was acquired in 2020), told the Paris Airshow audience that they were experiencing supply chain issues involving a part that a supplier wrongly installed on a number of GTF engines [25]. This increased engine turnaround times from the expected 100 days to 120 days per engine [26].

4.2 The Powder Metal issue

The powder metal issue is the manufacturing event that cascaded into the massive recall that currently affects the industry. In July 2023, RTX informed about a rare powder metal defect that could lead to the cracking of some engine components and called for accelerated inspections initially affecting 200 [27]. The manufacturing issue is now explained in greater detail.
P&W has used Powder Metallurgy (PM) manufacturing in its engines' components since the 1960's. In this process, metal powders are compacted into a solid billet, which is then forged and machined to the required part specification. If foreign particles enter the powdered metal, these contaminants get scattered at random, causing improper bonding that creates weak zones in the piece. Since these pieces are subjected to extremely high temperatures, fatigue and mechanical forces, these weak spots could lead to crack development and, in the worst cases, catastrophic failures. That is why the presence of contaminants during the manufacturing process drastically affect the life of the component, the module it belongs to and the engine itself [28].

4.3 The massive recall

On July 25, 2023, RTX informed that 1,200 of 3,000 engines manufactured between 2015 and 2021 had to be taken off and inspected for micro cracks [25]. RTX initially predicted that the accelerated inspection would take 60 days [29].
On August 28, 2023 the FAA issued AD 2023-16-07, providing 30 days to perform an ultrasonic inspection of the HPT's 1st and 2nd stages hubs to determine their serviceability [30].
On September 11, 2023, the number of engines affected increased from the original 200 to 600, and so did the predicted inspection times now projected to last up to 300 days per engine [31]. This affected the global Maintenance Repair and Overhaul (MRO) capacity, which was already reported to have been working close to saturation [32].
On September 29, 2023 the FAA issued the Notice of Proposed Rulemaking (NPRM) FAA 2023-1989 regarding potentially degraded knife-edge seals (unrelated to the powdered metal issue). The pieces had been cleaned in alkaline solution without proper masking, and this would affect the HPC's 2nd and 4th stage disks.
In October 31 2023, Volaris announced a plan to counter the GTF engine recall crisis. It included extending the leasing of aircraft for 18 more months, adding 24 new Airbus aircraft to their fleet in the next 2 years and the layoff of 200 employees [33]. One day later, on the 1st of November of 2023, FAA issued AD 2023-20-11. It required replacement of the HPC's rear hub with a part eligible for installation [34].
On November 17, 2023, the Mexican Federal Civil Aviation Agency (AFAC) authorized Viva to employ wetleasing from Avion Express Malta to counter the engine recall situation [35] [36]. After 3 months of negotiations, Volaris secures economic compensation from P&W on December 5, 2023 [37]. On December 28, 2023, NPRM FAA–2023–2401 was issued affecting the HPC's 7th and 8th-stage disks and hubs, as well as the HPT's 1st and 2nd stage hubs, air seals, and blade retaining plates [38].

On April 11, 2024, this NPRM became the infamous AD 2024-05-11 (superseding both 2022–19–15 and 2023–16–07), which is the AD that has kept most of the engines on the ground until the time of writing. It demanded an AUSI (and replacement if necessary) of the HPT's 1st and 2nd stage hubs, the HPC's 7th and 8th-stage integrally bladed rotor (IBR) 7 and 8 as well as the HPC's rear hub [39].
On June 3rd, 2024, the FAA issued AD 2024-06-14 (superseding NPRM FAA 2023-1989) regarding the degraded knife-edge seals that were improperly cleaned [40].
On July 31st, 2024, Viva announced reaching an undisclosed economic compensation agreement with P&W for the GTF recalls [41].

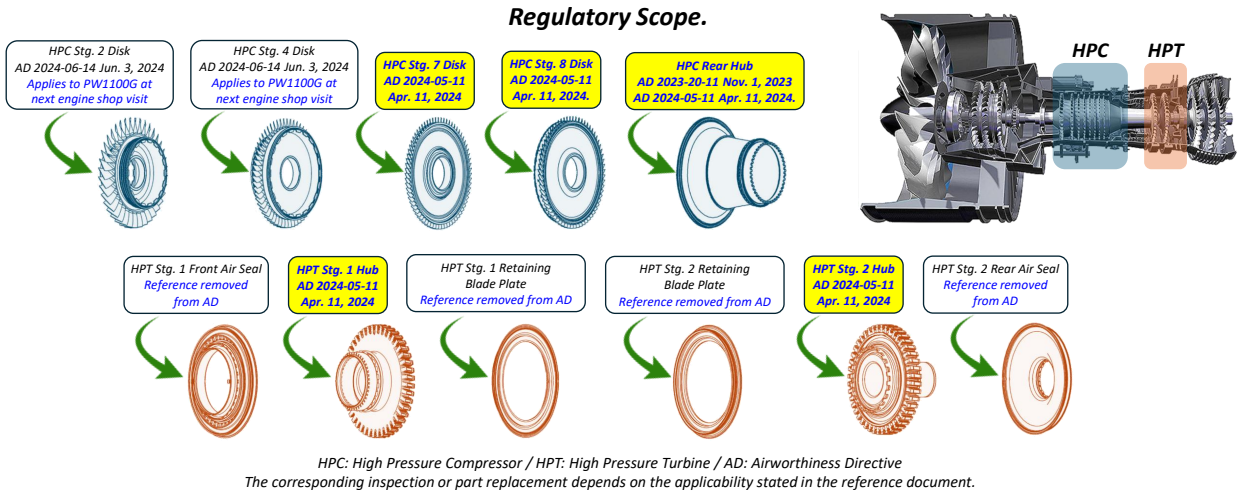


Figure 2 – Regulatory scope of Life Limited Parts (LLP) involved in GTF engine recall of the PW1100G and PW1400G series.

On the 21st of October of 2024, shortages of component availability and labor in the supply chain of the engines was reported. Specifically, MRO shop capacity and availability of cast and forged metal parts were limiting the pace of the recall-related work [42].
During this period of time, P&W had been working on the new version of the GTF called *Advantage*, which delivers 4-8% more takeoff thrust with redesigned LLPs and technology enhancements to maximize time-on-wing [43]. On February 27, 2025 the new GTF Advantage engine obtained FAA type certification in a program with more than twice the amount of testing compared to the previous GTF engine [43].
On April 8 2025 RTX announced the implementation of additive manufacturing solutions to speed up engine maintenance turnaround times [44]. Increases of between 10-18% of supply chain part production along with a 40% increase in MRO output have only produced a 15% decrease of aircraft on the ground [45].
On June 16, 2025 RTX announces the introduction of the Hot Section Plus (HS+), a fully interchangeable upgrade option from the GTF Advantage that can be used in current GTFs as a retrofit. It can be incorporated during maintenance visits and is expected to nearly double the time-on-wing [46].

After more than two years of dealing with this situation, at the end of November 2025, Volaris decided to contract additional capacity through wet lease with Avion Express and Heston Airlines for approximately 45 days starting on December 1, 2025. Once again, Mexican aviation regulations became the focus of attention. AFAC stated that this permission was granted to avoid the suspension of 20 national routes, which would have affected 200,000 passengers and the national economy [47]. This triggered protests and strikes from Mexican pilots against operations with foreign crew in Mexico City [48].
On December 18, 2025, in a momentous decision, Volaris and Viva jointly announced their merger

into a holding company called “Grupo Mexicano de Aerolíneas,” which would continue to operate both companies independently and is expected to receive regulatory approval by the end of 2026 [49].
This year, on February 20, Airbus announced a revision of their output expectations for 2026, and mentioned possible legal action against P&W for supporting airlines and MROs more than the airframe manufacturer [50].
On April 28th, 2026, Volaris withdrew its 2026 forecasts amid geopolitical uncertainty and volatile fuel prices. The airline expects to close the year with 25 inactive units due to the GTF recall [51].
On April 30, 2026 Volaris rescheduled A320neo family deliveries from 2027 to 2028 to receive the new aircraft with the P&W GTF Advantage. They expect to have up to 70% of their fleet composed of neo aircraft, as compared to the 52% in 2025 [52].
By April 26th, 2026 P&W reported an overall 40% increase in MRO output for the PW1100G through facility upgrades and new equipment across three U.S. maintenance sites. Regarding the supply chain, the company has increased production of structural engine castings by 10% and forged components by 18% year over year. This has collectively reduced the number of grounded aircraft due to GTF issues by 15% during the first quarter of 2026 [45].
Figures 3 shows Volaris’ and Viva’s fleet of aircraft and the percentage of aircraft marked as “Parked”, which in this context means an aircraft that has not made a commercial flight for at least 70 days. Figure 8 and 9 present the Volaris and Viva flight hours (FH) per fleet.

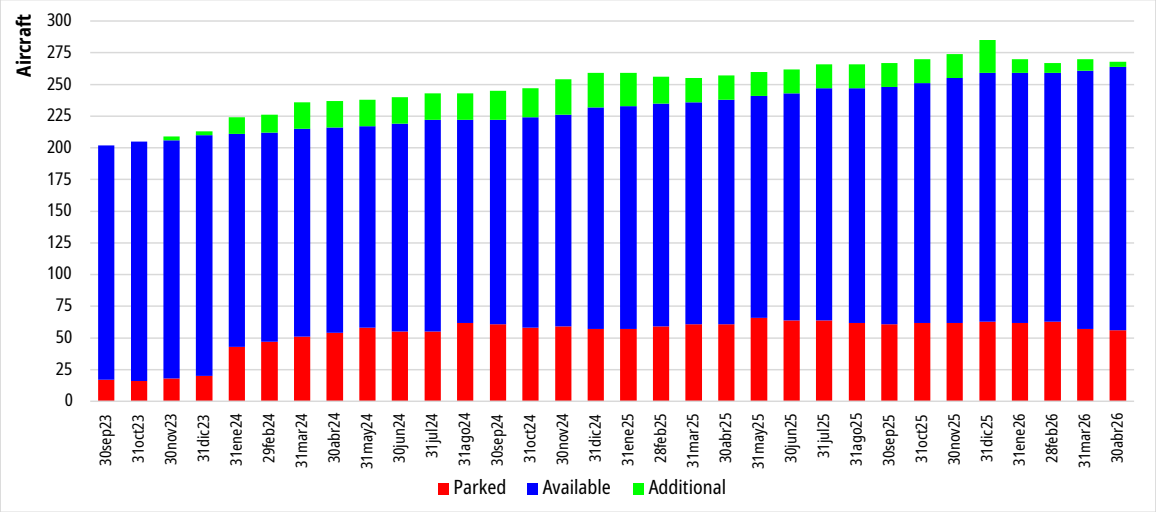


Figure 3 – Volaris and Viva fleet scenario facing GTF engines recall. Each column presents the summary at the end of the month.

5. Analysis and Discussion

The analysis of the GTF engine recall from the SoS perspective is now presented.

5.1 Discussion on the impact on Mexican aviation

The two low-cost airlines approached the crisis in a different way. While Volaris chose to optimize its network of destinations and its operating fleet, Viva chose to contract additional capacity through a wet lease with Avion Express, a situation that brought Mexican aviation legislation into the media spotlight. Under certain interpretations, the fact that a foreign pilot operates a domestic flight for a Mexican airline violates Article 32 of the Mexican Constitution. However, by the end of 2025, Volaris also started wet leasing operations with Avion Express and Heston Airlines.
At this point, it is important to refer to the scope of the impact of this highly disruptive scenario which is expected to be completed in mid-2027. The direct impact on aircraft availability when engines are classified as “unserviceable” is that the aircraft remains inoperative on the ground immediately reducing the airline’s available seating capacity. The financial impact can be classified into short- and medium-term impacts. In the short term, contracting additional aircraft capacity, either through wet lease or dry lease, may become a necessity to continue with the planned operation.

In the medium term, the technical and financial conditions of the affected leased fleet as well as the engine maintenance contract are impacted. From a global financial perspective, it is important to note that this entire situation has led to two significant financial changes: a substantial increase in the value of engines, and a loss in value of the affected airframes. It should also be noted that aircraft leasing is the norm rather than the exception in the Mexican aviation market. At the time of writing, approximately 95.5% of the Volaris fleet and 95.3% of the Viva fleet are leased. A complete timeline of the events is shown in Fig. 7 at the Appendix.

5.2 The Geared Turbo Fan production framed as a System for Systems

The engine operation ecosystem depends on a collaboration between three main actors: the Engine Original Equipment Manufacturer (OEM), Maintenance, Repair and Overhaul (MRO) facilities, and the aircraft operator. Figure 4 shows an abstraction of the drivers for each actor and the relationships between them. One important aspect to highlight is the fact that the MRO can be either a business unit within the OEM, an external contractor or a business unit of an airline. This introduces operating decisions that imply different levels of managerial independence.

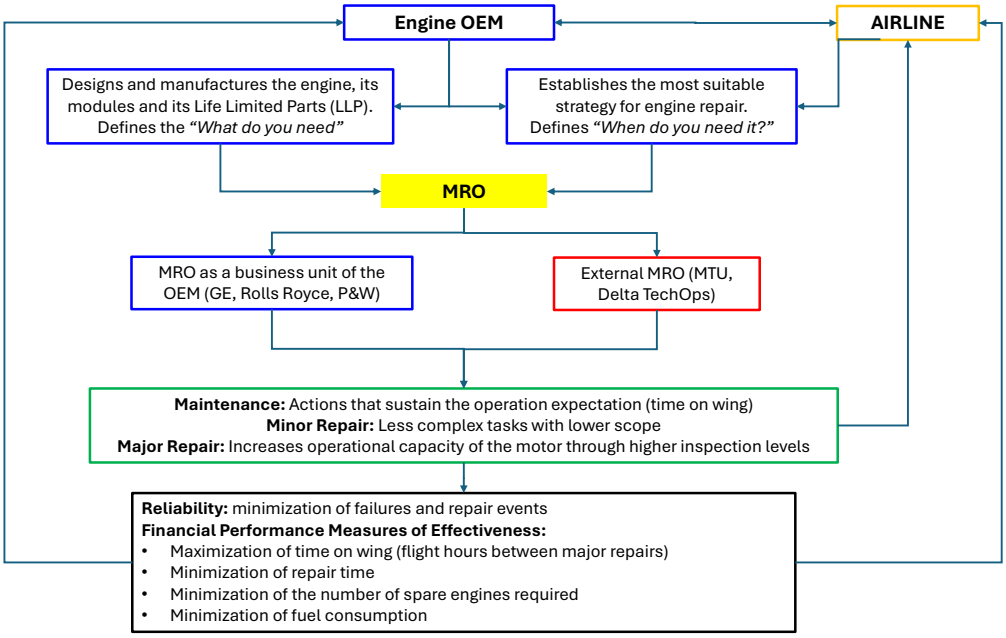


Figure 4 – The engine operation ecosystem including Original Equipment Manufacturer (OEM), Maintenance Repair and Overhaul (MRO) and the airline

This ecosystem, as well as the engine recall event and its impact on Mexican aviation from Sec. 4. can be analyzed from the System of Systems Engineering (SoSE) perspective to provide insights on the coupled and emergent behavior. SoSE can bring perspectives and tools to evaluate design and operational decisions according to their effect on downstream systems.

This SoS can be modeled within the System for System (S4S) subcategory proposed by Donelli, which describes the relationship between the System of Interest (SoI) and the Enabling Systems (ES) [53]. In her approach, an aircraft is defined as the System of Interest (SoI), whose development relies on the manufacturing, supply chain and MRO systems that operate as Enabling Systems (ESs). These ES facilitate the development, production, deployment, operation or disposal of a SoI; but do not necessarily contribute directly to its operational capability. Similarities with the development of new generations of aero engines are evident.

When the gas turbine is considered as the SoI, its development is supported by the coordinated interaction of the manufacturer and supply chain as well as the MRO as ES. In this approach, airlines act as an ES within the overall SoS and together with the S4S define the operational context [54], as shown in Fig. 5. It is worth noting that an enabling system in its own right can be modeled as an SoS.

For example, Atasoy et al. [55] proposed an SoS methodology for engine maintenance and repair alone while excluding the engine OEM and other spare part suppliers in the aftermarket.

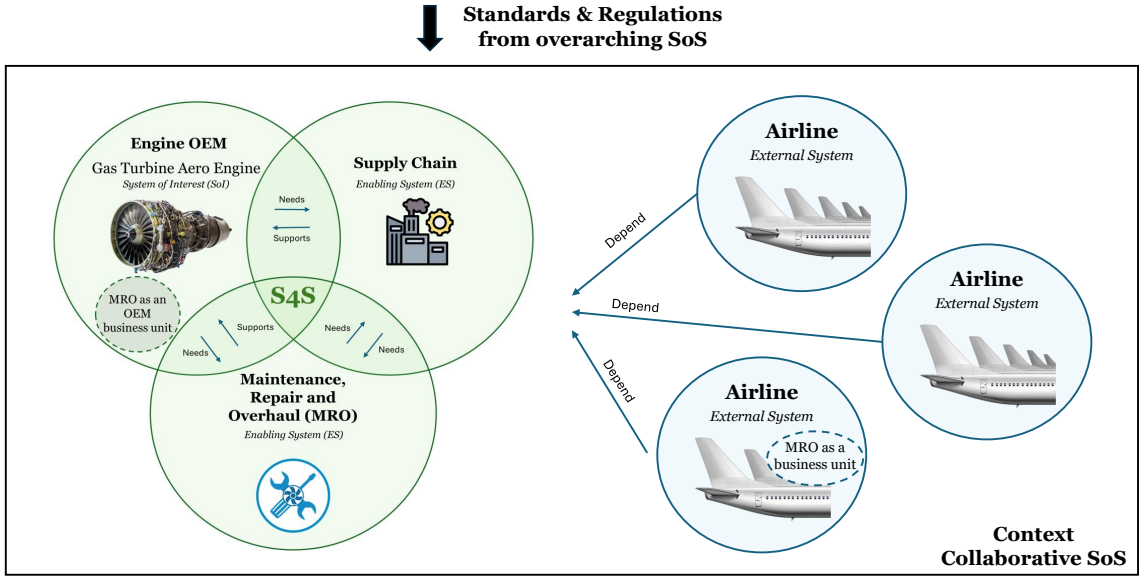


Figure 5 – The PW1100 GTF engine recall scenario modelled as a System for Systems (S4S).

Subsequently, this S4S could be cataloged as a SoS operating within an acknowledged Air Transport SoS. Within the collaborative SoS the central purpose of providing and operating the engine efficiently and safely is attained through agreements between the collaborating partners - all the while adhering to standards and regulations set in the overarching acknowledged SoS - but each actor still retains its own strategic orientation. Collaboration is achieved through agreements between the partners at the SoS level, and one central challenge is to ensure efficient collaboration for a set goal while maintaining autonomy and organizational independence between the entities [56].

The emergent SoS behavior produced by the rare powder metal defect can be analyzed along three axes: engine SoI-level, its propagation to SoS-system levels, and its evolution through time. The rare powder metal defect propagated throughout the engine sub-system, affecting the life of entire modules rather than a single component. This eventually escalated to the impact propagation into the described S4S, affecting the connected ES. The fact that the modules that needed inspections were in the central part of the core (HPC and HPT) also influenced engine maintenance. This required costly major repairs that were at least performance restoration, if not overhaul. Had it been a more easily accessible component, inspection and maintenance schemes would have been less intrusive. The resulting higher demand for necessary but unscheduled maintenance and material flow constraints resulted in longer times between engine removal and induction into the MRO workshops, leading to additional downtime for each engine. Longer downtime than expected also likely displaced the already scheduled maintenance of other engine types, with carriers competing not only for market share on routes but also for shop capacity.

These issues cascaded to yet another External Dependent System, in this case the airframe manufacturer Airbus. P&W had to balance allocation of scarce engine components between the used GTF that needed maintenance and the new powerplants needed for Airbus' production [42]. This had (unofficially) raised tensions between P&W and Airbus, with the prospect of legal action emerging between the OEMs [57]. This gets aggravated when considering the evolutionary nature of the effect, since the disruption not only affects the near-term deliveries, but also the ramp-up trajectory predicted in the years to come [58].

Finally, the third time axis is typical of the SoS's evolutionary behavior. Actions and consequences unfolded over time, eventually circling back and forth, in and out ES and dependent systems. While

causality cannot be assured, the recall event set the context upon which two major airlines merged and redefined the business environment in a whole country as shown in Fig. 6.
It also did so at different timescales of the problem propagation and the solution implementation. After its discovery, the manufacturing impact on other systems escalated in a matter of a few months (or even weeks), while ramping up MRO capacity and supply chain production needed time on the scale of years. The same happened to the sensitivity of the solution implementation vs. its impact on aircraft grounding. While causality cannot be directly assigned, it is not clear if this major ramp-up on MRO capability was part of a planned incremental upgrade or an unexpected emergency action.

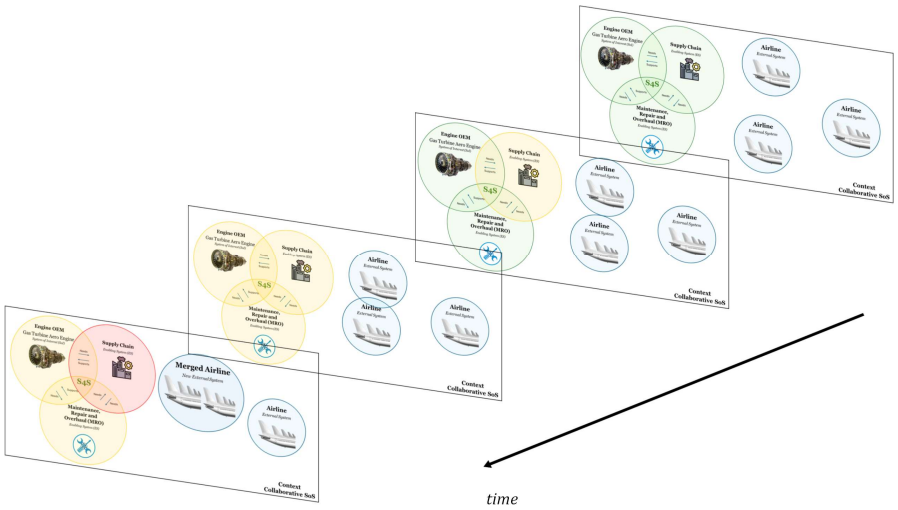


Figure 6 – Notional view of how emergent behavior cascades on the same system level, across system levels and propagates over time.

When an Original Equipment Manufacturer decides to start an ambitious project like a new engine with a new architecture, it cannot be designed as an isolated system. Reliability and risk should be analyzed not only constrained to the technical frame of the SoI (i.e., engine level), but also considering the holistic system on which it operates at the SoS level. Otherwise, the technical gain obtained from fuel consumption reductions stands the risk of being outweighed by issues such as reliability not directly related to the SoI's design but to its ES. Effects and impacts cascading out of the SoI towards ES and other systems within the overarching SoS, as this work presents, should be taken into account at early design stages with appropriate SoS tools and methods.
A SoSE framework would most likely not have been decisive in predicting a "Black Swan" kind of an event like the rare powder metal contamination. Instead, it could provide tools for decision making and impact assessment by analyzing "what if scenarios" to locate possible vulnerable points in the process, risk analyses or to develop contingency measures and strengthen SoS recovery capabilities in case of disturbances. The trade-off between the lower costs of an optimized, lean product development line must be balanced against its SoS-wide emergent effects on resilience against major, unexpected disruptions.
Other decisions that could be explored using SoSE include having single or multiple suppliers, evaluation of "what if" scenarios during maintenance contract negotiations to define shop workscopes, spare pool sizes (parts and engines), maintenance reserves, make or buy decisions, end of lease adjustments and the evaluation of single vs. diversified product usage. Additionally, the airline competition, market shares and revenues during uptake of the new engines and during the chain of MRO and grounding events described in chapter 4 could be modeled with SoS methods. Methods like Agent Based Modeling (ABM), Discrete Event Simulation (DES) and System Dynamics (SD) could be utilized to capture emergent SoS behaviors, potentially paired with Game Theoretical approaches to incorporate market equilibrium during disturbances and broaden the understanding of adaptive

strategies and flexible positioning [59].
Cost for on-boarding new suppliers (both in certification, time for negotiation and possible impact on other existing contracts that may penalize) need to be balanced with the fact of having fewer points of failure [53]. The same goes for the resources allocated for spare parts and engines. In normal conditions these expensive assets will be used scarcely, representing capital that is not flowing. However, if the buffer is too low, they may still be insufficient in an emergency condition. After this case, the 5 to 10 % spare buffer is getting challenged.
A similar evaluation follows diversification of products for the SoS. While having a diversified product family could generate a more resilient system, it also increases planning complexity since that could mean different removal timing and off-wing expectations that need to fit the operational schedules. Air operators that diversified their A320neo's powerplants between the PW1100G and the CFM LEAP are in a better position than the ones who decided to go altogether for the PW alone. This generates a change of paradigm for the lessors too, since the industry is no longer evaluating a single engine family because it could become a single point of failure. This increases complexity in the management and prediction not only for operators but also for lessors, investors and MRO providers [60].
The case study also highlights a possible change of paradigm between the most important Measures of Performance (MoP) of a complex product, with analysts highlighting that product reliability (at the complete life cycle and SoS level) has become as important as fuel savings. This could mean that approaches similar to Concurrent Engineering [53] may become imperative to assure not only a competitive product at the system level, but fulfilling the commercial expectations of its stakeholders in the relevant operational context.

6. Conclusions

The case study of the PW1100G GTF engine recall and its framing as a SoS was presented. While there exists no conclusive evidence that the rare powder metal effect was a direct cause of the two airlines merging, it did set the context upon which the holding was created.
Analyzing an entity as a single system or as a SoS is a modeling decision that depends on which perspective provides better insights for a particular problem. In that context, the study proposes a case study that could be analyzed using the SoSE framework to obtain valuable lessons learned and to enable studies of emergent SoS behavior subsystem to SoS and vice versa.
It is conceivable that had stakeholders known the magnitude of a disruption like this, they would have spent considerably more resources on a more robust SoS and invested in strengthening cross SoS recovery capabilities. Highlighting the importance of SoS-level collaboration within the air transport SoS including all stakeholders involved. Product diversification, higher engine and spare part counts, more robust maintenance contracts; these all have high associated costs to justify preparing for an event that had such a low probability of occurrence. Nevertheless, the SoSE framework could provide the stakeholders with the necessary tools to evaluate and perform these trade-offs and to showcase impacts and magnitudes for decision makers in the future. This could also enable (sub-)system impact assessments in an SoS at early stages of design.

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9. Appendix

9.1 Timeline of events

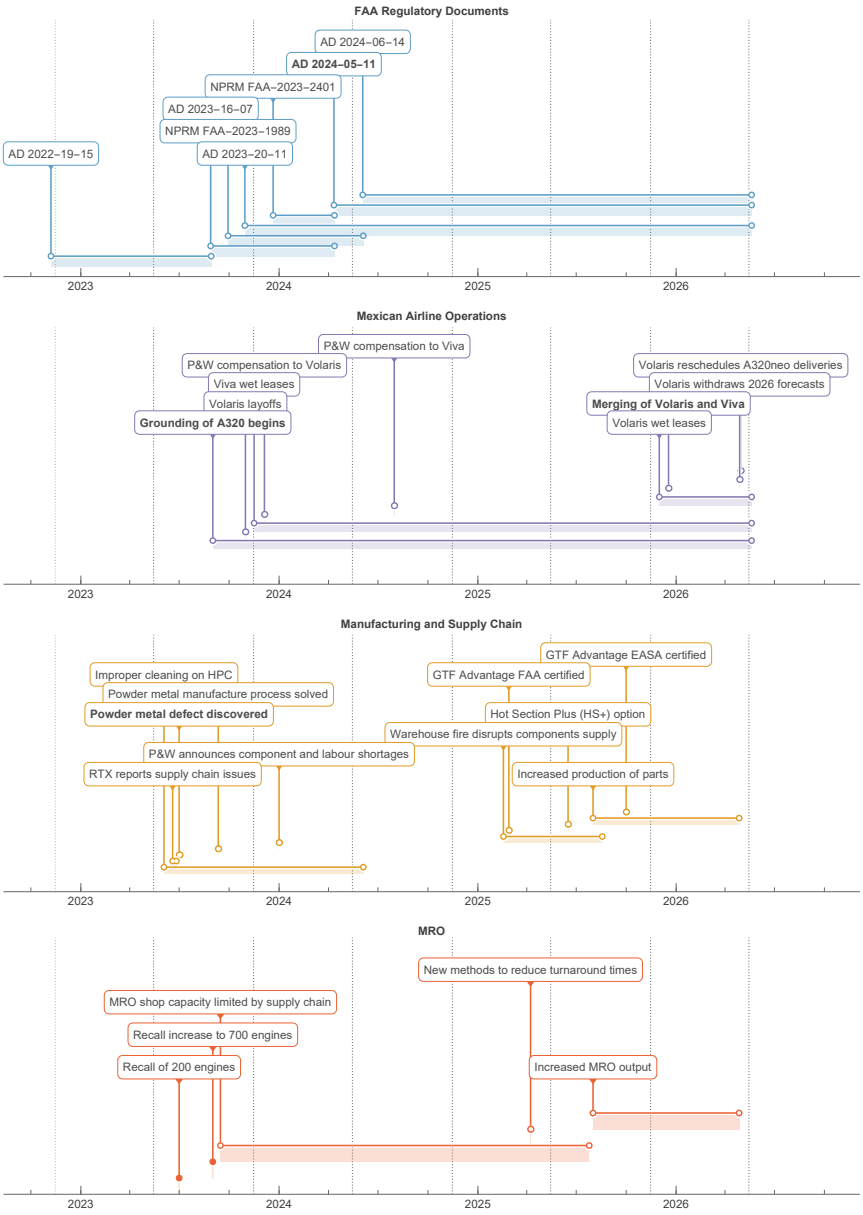


Figure 7 – Timeline of events at the different SoS levels of the PW1100G engine recall and its impact on Mexican aviation

9.2 Flight hours per fleet per airline

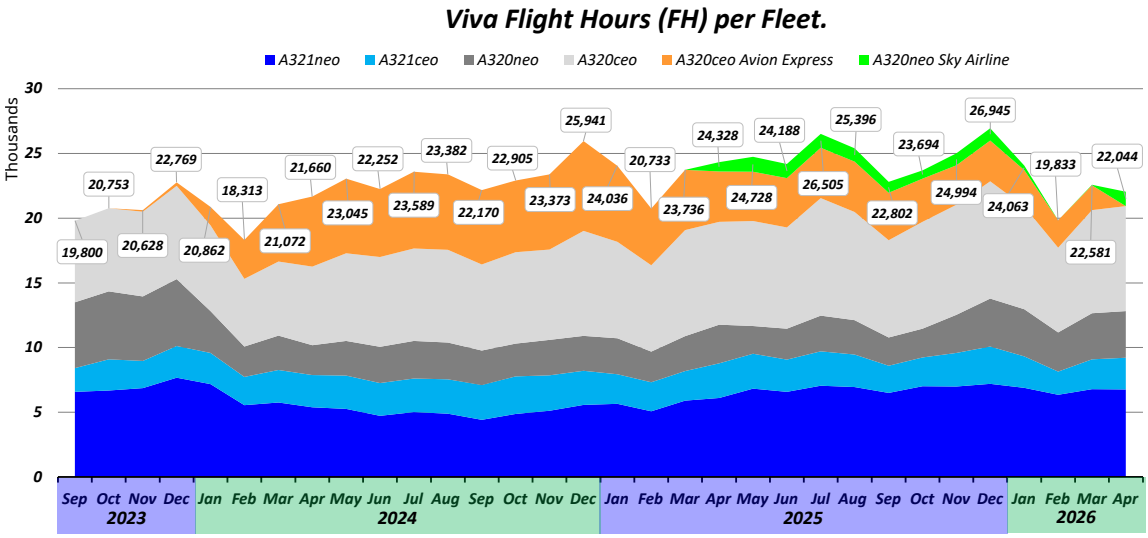


Figure 8 – Viva flight hours (FH) per fleet

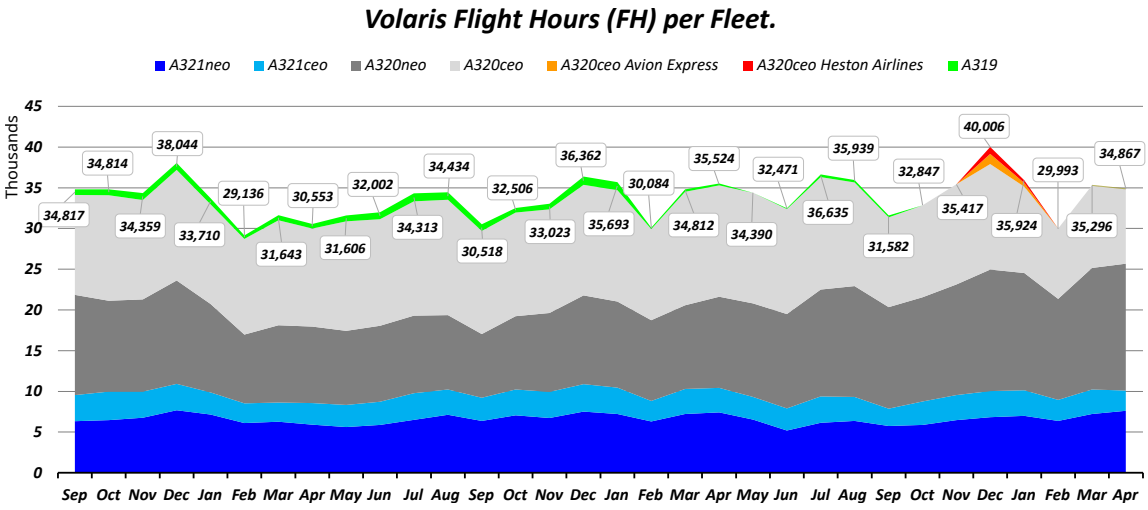


Figure 9 – Volaris flight hours (FH) per fleet

9.3 Viva parked and additional wet leased aircraft

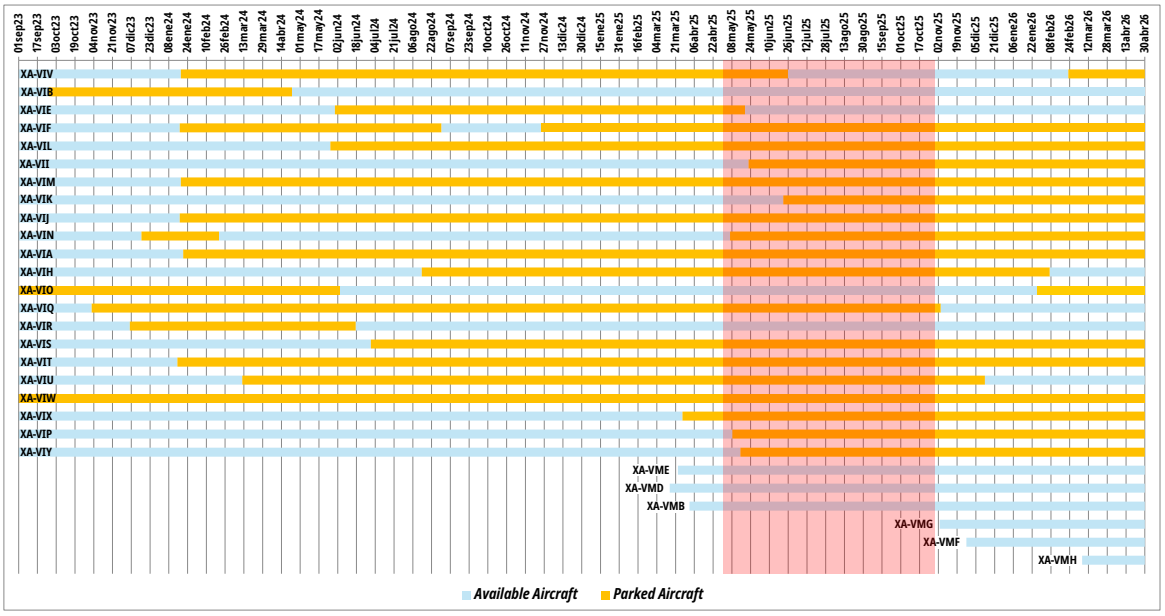


Figure 10 – Parked Viva A320neo

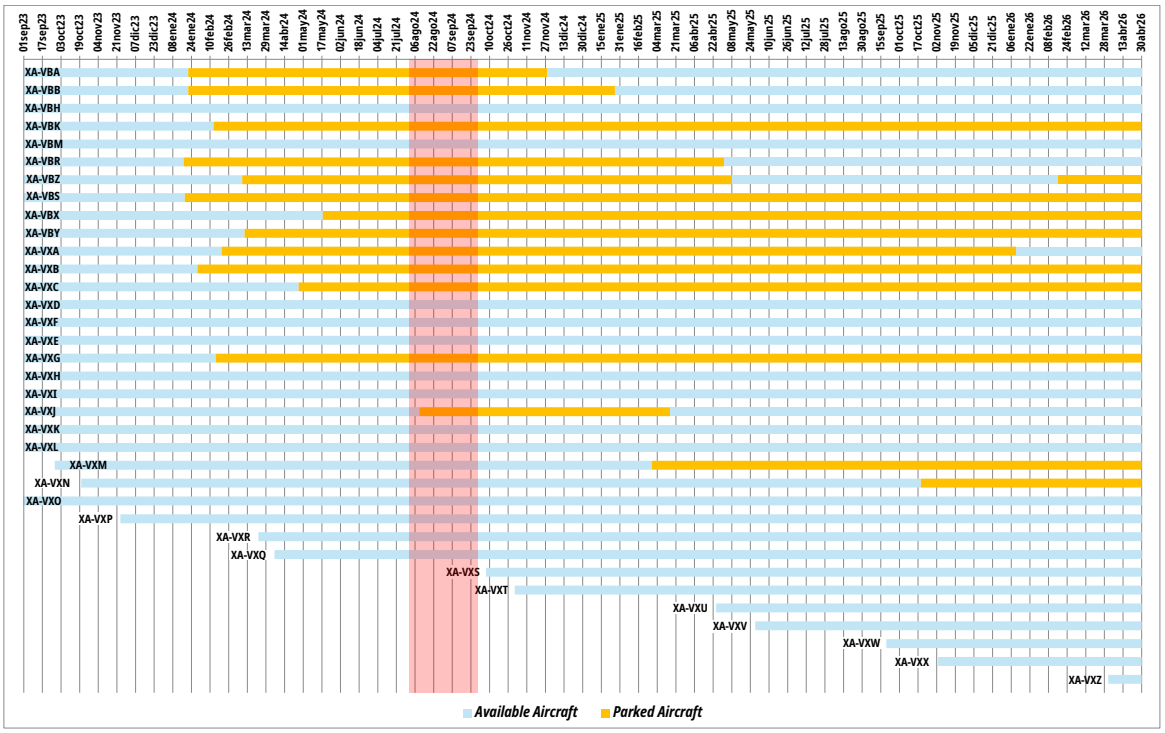


Figure 11 – Parked Viva A321neo

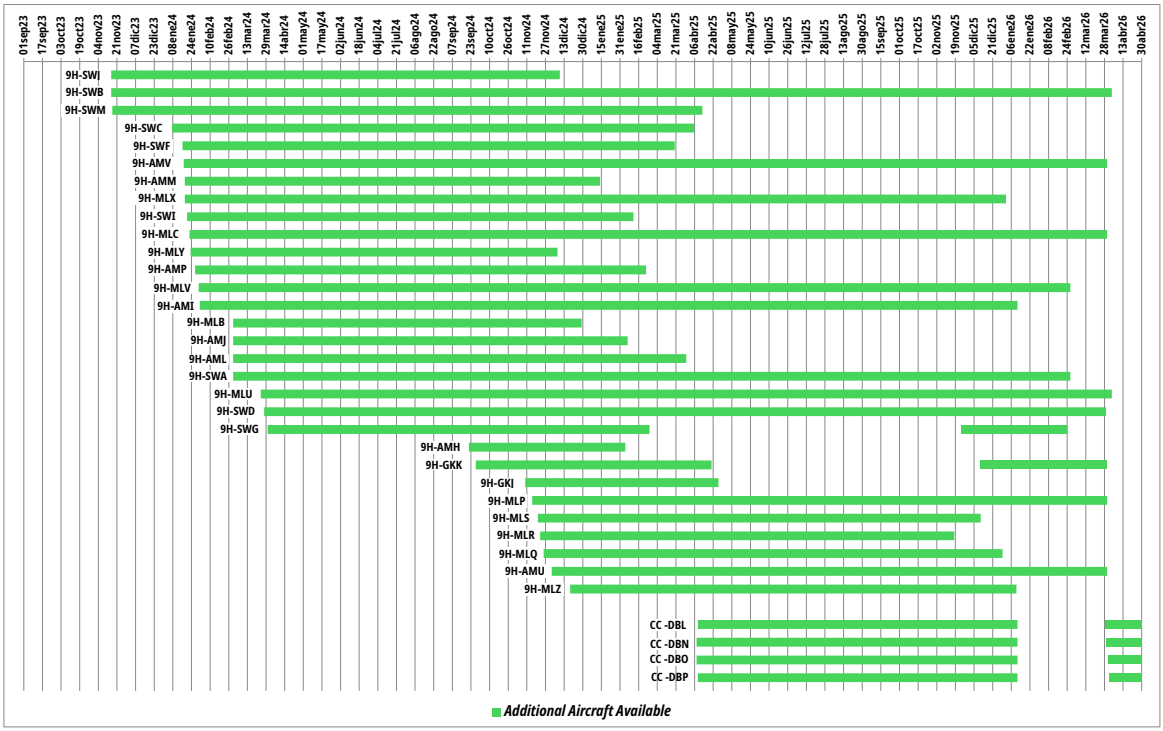


Figure 12 – Viva additional wet leased aircraft

9.4 Volaris parked and additional wet leased aircraft

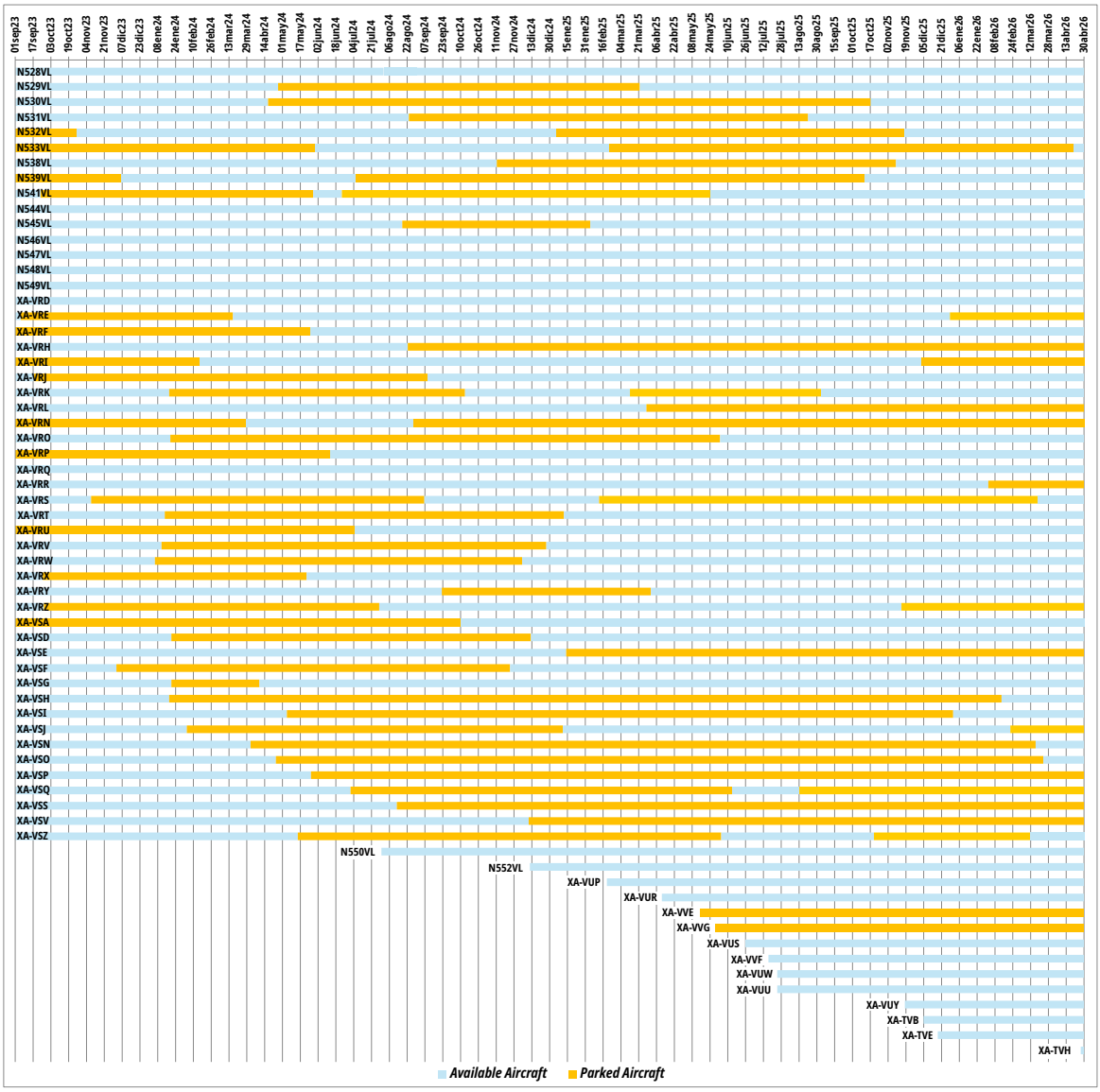


Figure 13 – Parked Volaris A320neo

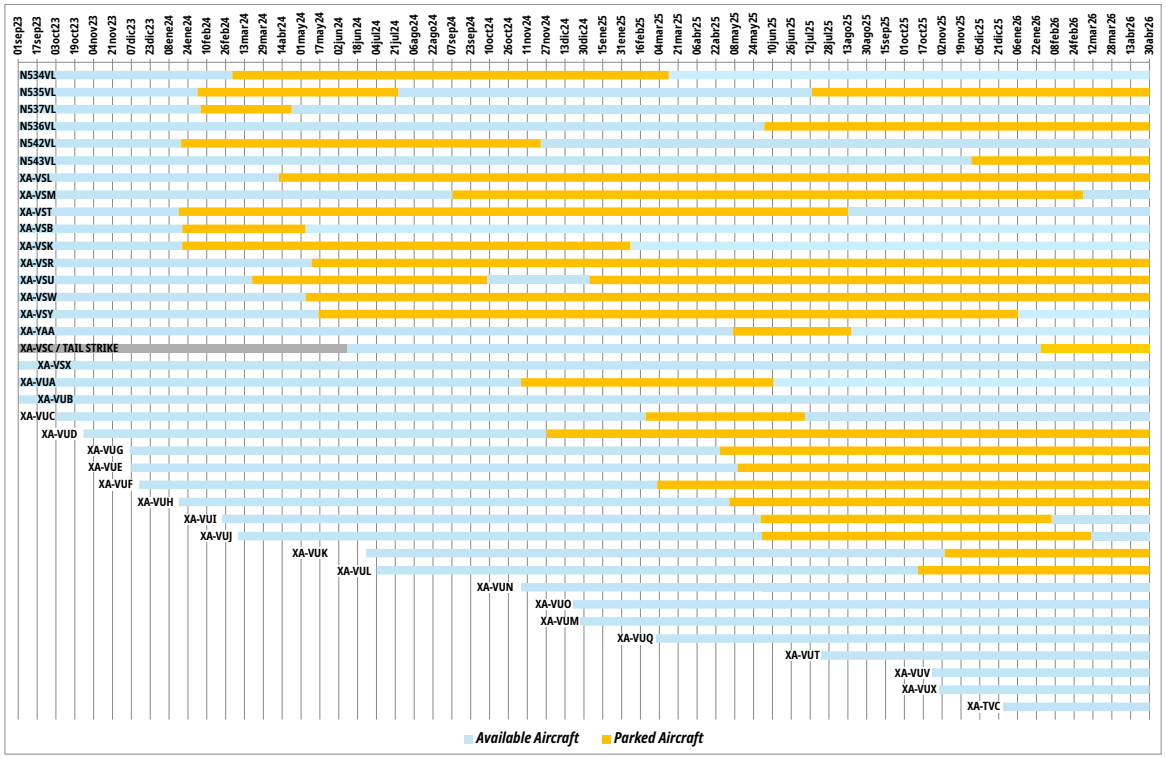


Figure 14 – Parked Volaris A321neo

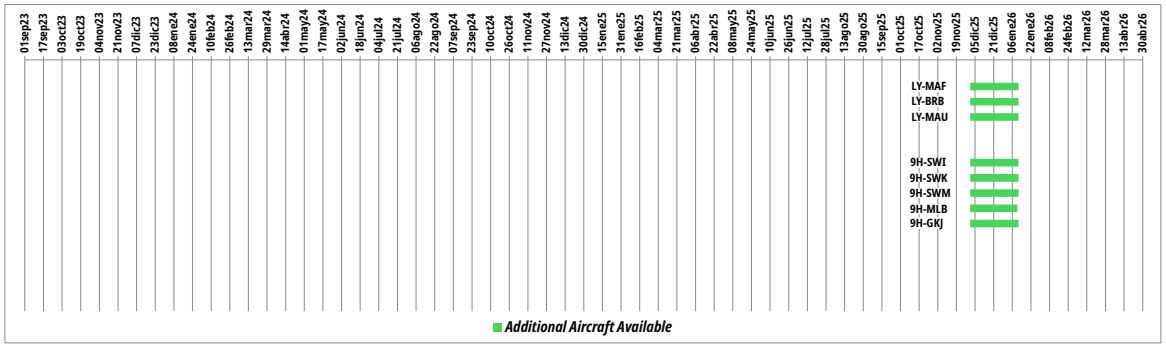


Figure 15 – Volaris additional wet leased aircraft