A MULTI-SCALE COMPUTATIONAL FRAMEWORK FOR EVALUATING TECHNOLOGY IMPACTS ON FUTURE AIRCRAFT FLEETS

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Abstract

Future aircraft technologies promise significant improvements in efficiency, but their benefits cannot be fully understood through aircraft-level analysis alone. New aircraft enter service into mixed fleets, where legacy aircraft and operational constraints can mask the benefits of new technology. Additionally, the breadth of possible technologies, such as advanced aerodynamic concepts or novel propulsion systems, makes it difficult to prioritize the combinations with the greatest long-term impact. Early design decisions must therefore consider not only system-level performance changes but also how those changes propagate into long-term fleet behavior. This paper presents the Fleet Level Operations And Technology Integration Environment (FLOATIE) that integrates physics-based aircraft performance modeling with fleet evolution and scenario management to assess how new technologies influence individual aircraft, operational performance, and fleet fuel burn. In this paper we outline the methodologies and framework used to develop FLOATIE and present an illustrative A320neo-like fleet case study. At the aircraft level, a representative next-generation concept shows up to 32% mission fuel-burn reduction at long-range and maximum-passenger conditions compared with the notional A320neo baseline. However, under the assumed traffic growth and fleet adoption scenario, the aggressive technology fleet reduces fuel burn by 21% relative to a frozen-technology reference by 2060. The results demonstrate how mission-level benefits are diluted by fleet turnover and demand growth, supporting the use of multi-scale assessment during early design phases.

Keywords: operational fuel efficiency, fleet-level analysis, computational framework, future aircraft design

1. Introduction

Aviation plays a central role in the global economy, connecting people and goods across long distances. As air traffic continues to grow, decisions regarding aircraft design, technology investment, and operational strategy have long-term consequences for fuel burn, emissions, and fleet planning. Emerging aircraft technologies, including advanced composite structures, high-aspect-ratio wings, improved propulsion systems, hybrid-electric architectures, and more-electric aircraft systems, promise substantial aircraft-level efficiency improvements. However, the system-level benefit of these technologies depends not only on their performance on an individual aircraft, but also on how rapidly they enter service, how they interact with legacy aircraft in mixed fleets, and how operational constraints affect their utilization.

Several industry outlooks and climate roadmaps provide valuable high-level projections for aviation growth and decarbonization. The Boeing Commercial Market Outlook, Airbus Global Market Forecast, and Oliver Wyman Global Fleet and MRO Forecast provide long-term industry forecasts for traffic growth, fleet composition, aircraft demand, and market trends [1, 2, 3]. Based on industry forecasts aviation climate roadmaps from IATA and ICAO describe pathways for reducing the aviation industry's emissions through aircraft technology, operational improvements, sustainable aviation fuels, and market-based measures [4, 5]. These studies help identify sector-level trends and long-term decarbonization needs to provide high-level insight on aviation's potential future.

For looking at specific new aircraft technologies, prior work has shown that fleet turnover, retirement schedules, and adoption timing strongly influence the environmental benefit of these technologies. MIT's APMT-Economics framework links economic factors to aviation demand, fleet renewal, and emissions, demonstrating that future fleet composition is strongly shaped by market and economic drivers [6]. Dray's aircraft life-cycle analysis showed that even substantial aircraft-level performance improvements can produce limited system-wide benefits if new aircraft adoption is slow [7]. Related studies on aircraft retirement and fleet renewal further show that technology improvements set the potential lower bound on fuel burn and emissions, while fleet turnover determines how quickly those benefits are realized [8]. Carvalho's analysis on the effects of introducing new A320neos into an aging A320 fleet supported the claim that newer variants can reduce fuel burn and emissions in mixed fleets [9]. These findings motivate the need to evaluate emerging aircraft technologies within realistic fleet evolution dynamics to get an accurate understanding of the impact of adoption.

A number of aviation system and fleet-level models have been developed to examine future technology adoption scenarios impact. The Aviation Integrated Model (AIM) includes interacting modules for fleet evolution, emissions, and costs assessment, and has been used to study aviation emissions mitigation under different economic and regulatory conditions [10]. Boeing's Cascade Climate Impact Model provides a scenario-based tool for examining the relative contributions of fleet renewal, operational efficiency, alternative energy, and offsets to aviation decarbonization [11]. Other studies have examined future fleet emissions under technological and operational scenarios, including the effects of market penetration rates, traffic growth, and aircraft replacement timing [12, 13]. These tools demonstrate the importance of fleet-level assessment and are well suited for broad sector-level or policy-oriented analyses. In the context of early-stage aircraft technology assessment, there remains a need for frameworks that connect user-defined technology packages to traceable physics-based aircraft performance models for fleet-level evaluation.

The Fleet-Level Environmental Evaluation Tool (FLEET), for example, has been used to assess fleet-level fuel burn, emissions, and noise by combining aircraft performance modeling through FLOPS with airline operations represented as a resource allocation problem under technology availability and demand scenarios [14, 15]. Tetzloff further demonstrated that the environmental impact of new aircraft technologies depends on how those aircraft are introduced into future fleets, showing that aircraft-level improvements must be interpreted in the context of fleet adoption, market demand, and continued operation of legacy aircraft [16]. These studies provide an important foundation for fleet-level technology assessment.

Taken together, existing work highlights three important needs. First, sector-level and fleet-level models are needed because aircraft-level improvements are diluted by traffic growth, slow adoption, and legacy fleet operation. Second, physics-based aircraft modeling integration is needed because emerging technologies affect aircraft performance differently across mission conditions, and early design assumptions can strongly influence predicted performance. Third, flexible scenario tools are needed because technology packages, entry-into-service (EIS) years, adoption probabilities, and operational improvements are uncertain during early design. A gap remains between traceable physics-based conceptual aircraft modeling and flexible, technology-aware fleet evolution analysis.

This paper introduces the Fleet Level Operations and Technology Integration Environment (FLOATIE), which addresses this need through a complementary focus on early-stage aircraft technology evaluation. FLOATIE enables user-defined combinations of emerging technologies, including electrified propulsion concepts, to be translated into physics-based aircraft performance changes and propagated through fleet evolution. FLOATIE integrates the open-source Future Aircraft Sizing Tool (FAST) that combines historical data and physics-based performance analysis to size and evaluate conventional and electrified aircraft configurations [17]. Its use of the open-source design tool allows vehicle modeling assumptions and technology impacts to be inspected, modified, and propagated through mission-performance libraries before fleet-level evaluation. This is particularly useful when aircraft concepts are not fixed vehicles, but combinations of emerging technologies whose impacts may evolve during early design. In this way, FLOATIE connects physics-based aircraft modeling with fleet evolution analysis while preserving traceability in the aircraft-level assumptions used to generate fleet-level fuel burn outcomes.

The main focus of this work is a transparent, aircraft design-centered framework for evaluating how user-defined technology assumptions propagate from aircraft-level performance to long-term fleet-level fuel burn outcomes. This work makes three primary contributions:

(1) a FAST-based multi-scale framework that links traceable aircraft performance modeling with fleet evolution analysis;

(2) a technology impact database that allows user-defined construction of future aircraft concepts; and

(3) a fleet fuel-burn assessment method that uses mission-performance libraries to capture operational variability and decompose fleet-level fuel-burn reductions by source.

Rather than replacing existing sector-level aviation models, FLOATIE complements them by focusing on early-stage technology assessment, where vehicle modeling assumptions must be traceable and where technology packages may be modified as concepts mature.

An illustrative A320neo-like narrowbody fleet case study is used to demonstrate FLOATIE's capabilities. The case study evaluates conservative, moderate, and aggressive technology adoption scenarios from 2025 to 2060, showing how aircraft-level technology benefits propagate through mixed-fleet adoption and traffic growth. The results demonstrate that aircraft-level fuel burn reductions do not translate directly into equivalent fleet-level reductions, reinforcing the importance of multi-scale analysis for early-stage technology assessment.

2. Methods

FLOATIE is organized as a modular, multi-scale framework that links aircraft-level performance modeling with long-term fleet evolution analysis. The framework consists of three primary modules: (1) aircraft-level performance modeling, (2) fleet evolution modeling, and (3) fleet fuel burn assessment. These modules exchange information through standardized data structures so that aircraft technologies, mission assumptions, and fleet adoption scenarios can be varied independently.

The following subsections describe the FLOATIE architecture, aircraft-level modeling process, fleet evolution model, technology impact database, and fleet fuel burn assessment.

2.1 FLOATIE Architecture

The FLOATIE architecture couples bottom-up aircraft performance modeling with top-down fleet evolution analysis to propagate aircraft-level technology impacts into fleet-level outcomes. The overall architecture flow is given in Fig. 1.

In the bottom-up direction, technology improvements are first represented as changes to aircraft weight, aerodynamic efficiency, propulsive efficiency, or supplemental power demand. These changes are evaluated to generate mission fuel burn estimates over a range of payload, range, and holding conditions and stored in a mission-performance library.

In the top-down direction, the fleet evolution module applies traffic growth, retirement schedules, EIS dates, and technology adoption probabilities to determine the composition of the fleet in each year of the analysis period. The aircraft mission-performance library is combined with the fleet evolution results to estimate how aircraft performance improvements affect long-term fleet fuel burn under traffic growth, retirement, and technology adoption assumptions in the fleet fuel burn assessment.

This structure allows individual technology improvements to be evaluated not only by their isolated aircraft-level benefit, but also by their influence on long-term fleet outcomes. For example, a technology with a large mission-level fuel burn reduction may have a limited fleet-level effect if it enters service late, has a low adoption probability, or replaces legacy aircraft slowly. Conversely, a moderate aircraft-level improvement may produce meaningful fleet-level benefits if it is adopted broadly and early.

2.2 Aircraft-Level Performance Modeling

Aircraft-level performance in FLOATIE is evaluated using the Future Aircraft Sizing Tool (FAST), which provides physics-based performance assessment and mission analysis capabilities for con-

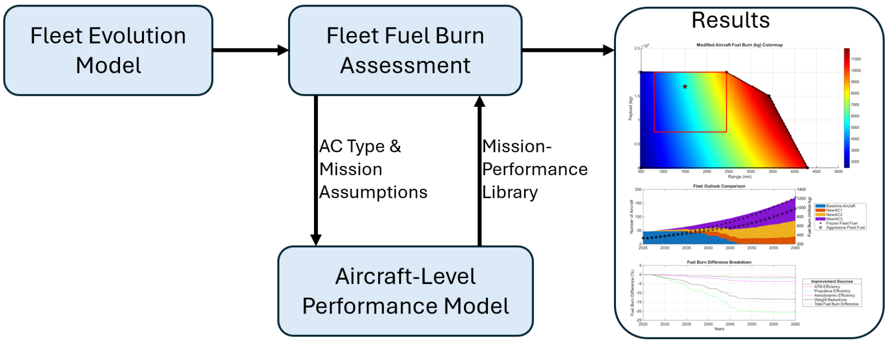

Figure 1 – FLOATIE Architecture Block Diagram

ventional and electrified aircraft configurations [17]. In this work, FAST is used to generate a baseline narrowbody aircraft model, apply technology-driven performance changes, and construct mission-performance libraries for each aircraft group used in the fleet analysis.

The aircraft-level workflow is shown in Fig. 2. A baseline aircraft is first sized to match the target level aircraft requirements (TLARs) and representative specifications of a current narrow-body aircraft. Technology impact factors are then applied to create modified aircraft groups. Depending on the type of technology change, the modified aircraft is either re-sized in FAST or evaluated directly using off-design mission analysis. Weight and aerodynamic changes trigger aircraft re-sizing in FAST, while TSFC corrections and holding-time assumptions are applied for mission performance analysis without re-sizing the baseline aircraft. The resulting mission-level fuel burn values are stored in a mission-performance library that is later used by the fleet fuel burn assessment.

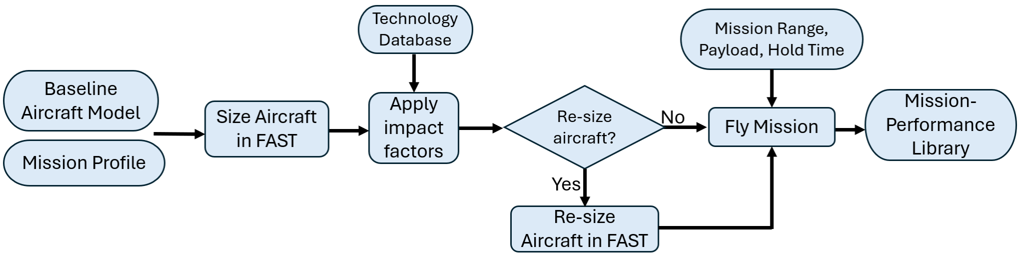

Figure 2 – Aircraft performance analysis block diagram.

2.2.1 Baseline Aircraft Model

The baseline aircraft model used for this study is based on the A320neo narrowbody aircraft and is used to represent current state-of-the-art single-aisle technology. The aircraft is sized using representative A320neo design requirements and engine specifications, summarized in Table 1.

The design mission used for sizing is shown in Fig. 3 which includes the main design mission portion with a step climb and a reserve mission consisting of a 100 nmi diversion and 30 minute hold. The reserve mission is used as a modeling assumption representative of final-reserve holding fuel for turbine-engine air-carrier operations under selected dispatch rules. This mission profile is used for the rest of analysis with the range and reserve times adjusted to match the designated mission length and hold assumptions.

Once the aircraft is initially sized, FAST is used to evaluate off-design mission performance over the payload–range envelope shown in Fig. 4, made to match the A320neo payload–range diagram [18]. For each payload–range point, FAST computes mission fuel burn and checks mission feasibility. A mission is considered feasible if the aircraft can complete the mission without exceeding the maximum takeoff weight constraint of the baseline aircraft. The resulting payload–range fuel burn map provides the aircraft-level reference case against which all modified aircraft groups are compared.

Group	Specification	Value
TLARs	Design Range (km)	6,300
	Max Passengers	194
	Thrust-to-Weight Ratio	0.331
	Cruise Mach	0.78
	Wing Loading (kg/m^2)	624.5
	Cruise L/D	18.23
	Max RC (m/s)	11.43
Model Specs	MTOW (kg)	80,619
	Empty Weight (kg)	45,092
	Block Fuel (kg)	19,252
	SLS Engine Thrust (kN)	125.5
	Wing Area (m^2)	129.1
	Avg Climb/Cruise Engine TSFC [kg/(kN·h)]	49.2

Table 1 – Baseline aircraft model design parameters and specifications.

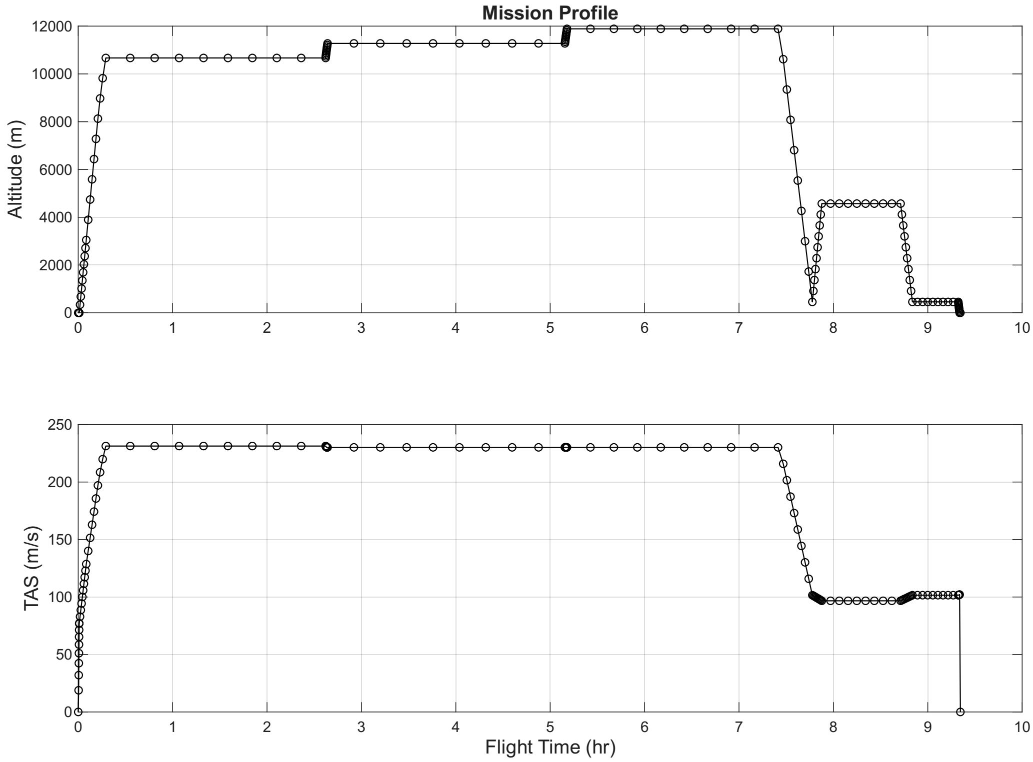

Figure 3 – Baseline model design mission for model sizing.

2.2.2 Technology Impact Database

A technology impact database is used to translate emerging aircraft technologies into quantitative aircraft-level changes. Each technology is characterized by its estimated effect on one or more aircraft performance categories: operating empty weight, lift-to-drag ratio, supplemental power demand, and fuel burn. These impact factors are derived from literature values and are expressed as percent changes relative to the baseline aircraft.

For a given technology group, the weight impact factor ΔW_{OEW} is applied to the baseline operating empty weight $W_{\mathrm{OEW,base}}$ as

$$W_{\mathrm{OEW,mod}} = W_{\mathrm{OEW,base}} \left(1 + \Delta W_{\mathrm{OEW}}\right), \tag{1}$$

A negative value of ΔW_{OEW} corresponds to a weight reduction.

Aerodynamic improvements are represented through changes in the aircraft lift-to-drag ratio,

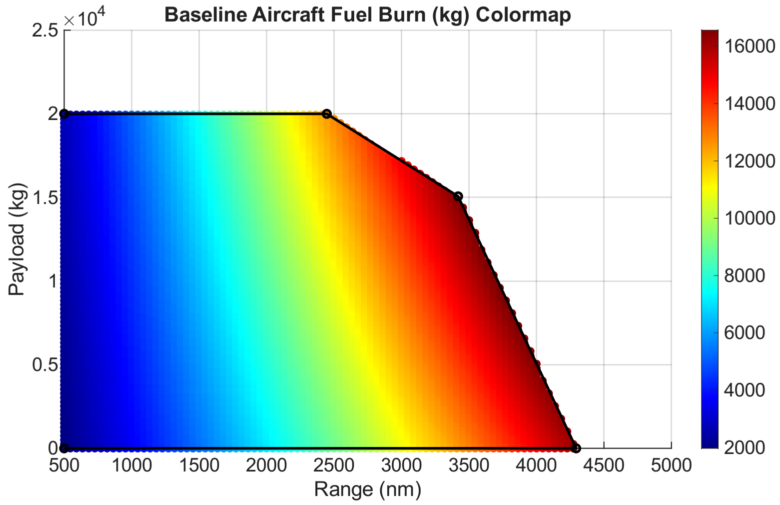

Figure 4 – Baseline aircraft model fuel burn across payload-range capabilities.

$$\left(\frac{L}{D}\right)_{\text{mod}} = \left(\frac{L}{D}\right)_{\text{base}} \left(1+\Delta_{L/D}\right), \tag{2}$$

where $\Delta_{L/D}$ is the fractional improvement in aerodynamic efficiency. Technologies such as folding wingtips or high-aspect-ratio wings are represented through this term when their primary effect is an increase in aerodynamic efficiency.

Changes in supplemental power demand Δ_{Ps} are applied to the baseline supplemental power value Ps_{base} as

$$Ps_{\text{mod}} = Ps_{\text{base}} \left(1+\Delta_{Ps}\right), \tag{3}$$

Propulsive-efficiency improvements are represented as a change in thrust specific fuel consumption (TSFC),

$$TSFC_{\text{mod}} = TSFC_{\text{base}} \left(1+\Delta_{f}\right), \tag{4}$$

where Δ_f is the fractional fuel burn impact associated with the propulsion technology. A negative value represents a lower TSFC value which leads to a reduction in fuel burn.

The individual technology assumptions and impact factors are summarized in Tab. 2. The values were estimated from the cited public literature and should be interpreted as illustrative case-study inputs for a narrow-body class aircraft rather than definitive predictions of future technology performance. Each technology is assigned a Technology Readiness Level (TRL) to represent its approximate maturity. The TRLs were estimated by the authors based on available public information. A qualitative confidence rating is also assigned by the authors to reflect the reliability of the impact estimate based on the amount of available evidence and the maturity of the technology.

When multiple technologies are included in the same aircraft group, the impact factors are combined by category before being applied to the aircraft model. For the present study, the combined impact in each category is computed as the sum of the individual fractional impacts,

$$\Delta_j^{(g)} = \sum_{i\in g} \Delta_{j,i}, \qquad j \in \{W_{\text{OEW}}, L/D, P, f\}, \tag{5}$$

where $\Delta_j^{(g)}$ is the total impact for category j in aircraft group g, and $\Delta_{j,i}$ is the impact of technology i on category j. The summed values define the total aircraft-level impact factors for each modified aircraft group.

In addition to aircraft technology impacts, FLOATIE can represent operational efficiency assumptions. In this study, ATM efficiency improvements are modeled as reductions in holding time. Holding time is treated as an additional mission segment that increases fuel burn. Therefore, ATM efficiency does

Category	Technology [Source]	Impact Category Weight	L/D	Power	Fuel	TRLs	Impact Value Confidence
Airframe	Composite Fuselage [19]	-15%	–	–	–	9	High
	Composite Wings [20] [21]	-5%	–	–	–	9	High
	Composite Tail [19]	-1%	–	–	–	8	High
Wings	Folding Wingtips [21]	1%	3%	–	–	9	High
	Thin, High Aspect Ratio Wings [22]	2%	10%	–	–	6	Med
Engine	Boundary Layer Ingestion [23]	–	–	–	-9%	4	Low
	Ultra High Bypass Turbofan [24]	–	–	–	-5%	6	Med
	Geared Turbofan [25]	–	–	–	-10%	9	High
Cabin	Lightweight Seats [26]	-5%	–	–	–	9	High
Other	High Voltage Power Lines [27]	-2%	–	-1%	–	7	Med
	Electric Actuators [28] [29]	-0.5%	–	1%	–	8	Med
	Electric Landing Gear [30]	-2%	–	1%	–	7	Med
	Fly-by-Wireless [31]	2%	–	–	–	5	Low
	Wireless Avionics Networks [31]	0.5%	–	–	–	6	Low
	Active Flow Control [32]	2%	1%	–	–	3	Low

Table 2 – New technology impact factors compared to current narrowbody aircraft.

not directly modify the aircraft model; instead, it reduces operational fuel burn by decreasing the amount of time aircraft spend in holding conditions.

2.2.3 Mission-Performance Library

For each aircraft group, a mission-performance library is generated over a range of payload, range, and holding-time conditions. The library stores the mission fuel burn for each sampled operating condition, only including feasible missions. This lookup-table structure allows the fleet-level analysis to repeatedly evaluate aircraft fuel burn without re-running the full aircraft performance model for every flight in every fleet year.

Mission conditions are sampled based on prescribed minimum, maximum, and representative mean values for each mission variable. Sampling is biased toward representative mean operating conditions while still spanning the prescribed minimum and maximum values. This ensures that the mission-performance library emphasizes typical operations but still includes off-nominal missions near the operating bounds.

For a generic mission variable $x \in [x_{\min}, x_{\max}]$ with representative mean value x_{avg}, the sampling interval is divided into left and right regions around x_{avg}. A nonlinear mapping is then used to cluster grid points near the representative value:

$$x_L(t_L) = x_{\min} + \left(x_{\text{avg}} - x_{\min}\right)\left[1 - (1 - t_L)^2\right], \qquad t_L \in [0,1], \tag{6}$$

$$x_R(t_R) = x_{\text{avg}} + \left(x_{\max} - x_{\text{avg}}\right) t_R^2, \qquad t_R \in [0,1]. \tag{7}$$

This deterministic biased sampling approach provides denser coverage near expected operating conditions while preserving the full admissible range of each mission variable. The resulting mission-performance library is used as the aircraft-level input to the fleet fuel burn assessment described in Section 2.4.

2.3 Fleet Evolution Model

The fleet evolution module determines the yearly fleet composition over the analysis period based on traffic growth, aircraft retirement, aircraft utilization, and technology adoption assumptions. The purpose of this module is to represent how aircraft-level technology improvements enter a mixed fleet over time rather than assuming that all aircraft are replaced by a new design.

The fleet evolution workflow is shown in Fig. 5. The model starts with a baseline fleet and traffic demand. Each aircraft type has a set assumed annual utilization given in revenue passenger kilometers

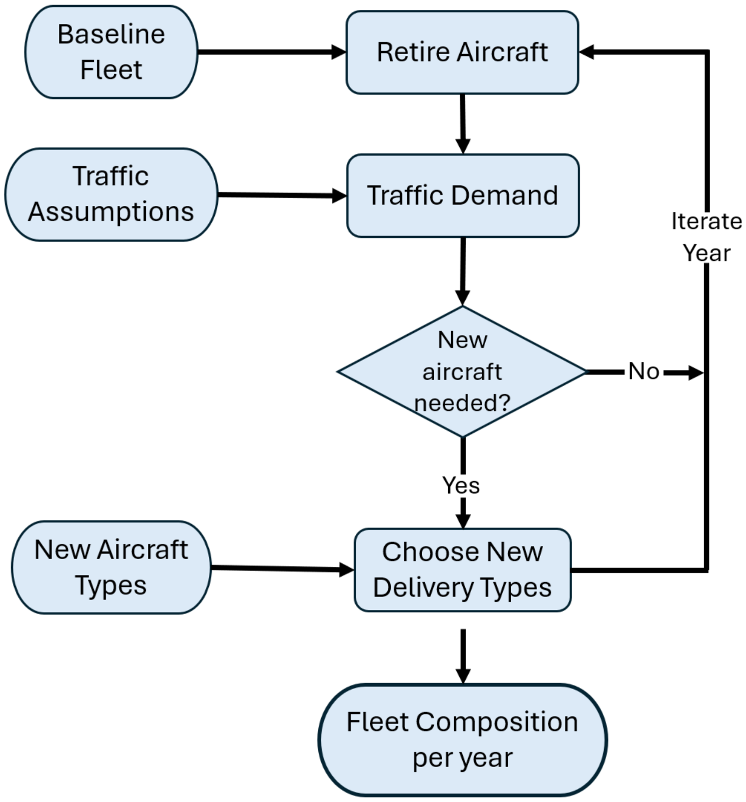

Figure 5 – Fleet Evolution Model Block Diagram

(RPKs) based on payload capacity and typical ranges flown. For each year in the analysis period, the total traffic demand is updated according to an assumed annual growth rate. Aircraft that exceed the specified retirement age are removed from the fleet, and additional aircraft are introduced as needed to satisfy the updated traffic demand. New aircraft are selected from the available types according to their EIS years and adoption probabilities.

The yearly traffic growth rate D_y is calculated based on Eq. 8, where D_0 is the base-year traffic demand, r is the annual traffic growth rate, and y_0 is the base year.

$$D_y = D_0\,(1+r)^{y-y_0}, \tag{8}$$

The number of aircraft required to serve this demand N_y is estimated based on the assumed aircraft type annual RPKs RPK_{ac}, given in Eq. 9. This ensures that the modeled fleet has sufficient capacity to meet the prescribed traffic demand.

$$N_y = \left\lceil \frac{D_y}{RPK_{\text{ac}}} \right\rceil, \tag{9}$$

At the beginning of each year, the age of each aircraft in the fleet is incremented. Aircraft are removed from the fleet when their age exceeds their specified retirement age. Then, new aircraft are added to meet the total needed aircraft for that year from Eq. (9). Aircraft are available for new deliveries if their EIS year has passed. Among the available aircraft types, new deliveries are assigned based on defined adoption probabilities. The probability of selecting aircraft type g in year y is defined as

$$P_g(y) = \frac{p_g I_g(y)}{\sum_{h=1}^{n_g} p_h I_h(y)}, \tag{10}$$

where p_g is the adoption weight for type g, $I_g(y)$ is an availability indicator equal to one if $y \geq y_{\text{EIS},g}$ and zero otherwise, and N_g is the number of candidate aircraft groups. This normalization ensures that only aircraft types available in a given year can be selected for new fleet additions. The adoption weight for each aircraft type p_g is assigned by the user for each fleet scenario to represent which aircraft types are more favorable for new deliveries.

2.4 Fleet Fuel Burn Assessment

The fleet fuel burn assessment module computes the yearly fuel burn of the modified fleet and compares it to the baseline scenario. For each aircraft type included in the modified fleet scenario a mission-performance library is created from the aircraft performance model. For each aircraft group, the mission-performance library contains precomputed fuel burn values over varying mission types, simulating typical commercial operations. Mission fuel burn m_f is selected uniformly at random from the precomputed library. Because the library itself is biased toward representative mission conditions, this procedure samples typical operations more frequently while retaining coverage of off-nominal missions. For a given aircraft type g in year y, the total annual fuel burn $M_{f,g,y}$ is computed by summing the fuel burn of the sampled missions $m_{f,g}^{(s_{k,\ell})}$ for each aircraft in that group $N_{g,y}$, Eq. 11. The full fleet annual fuel burn $M_{f,y}$ is the sum of all the groups in year y, Eq 12.

$$M_{f,g,y} = \sum_{i=1}^{N_{g,y}} \sum_{s=1}^{n_{\text{flights},i}} m_{f,g}^{(s)}, \tag{11}$$

$$M_{f,y} = \sum_{g=1}^{n_g} M_{f,g,y}, \tag{12}$$

The number of annual flights assigned to each aircraft is determined from the assumed annual aircraft utilization, expressed in RPKs. For each sampled mission, the passenger load factor is estimated from the mission payload as

$$LF_s = \frac{W_{\text{payload},s}}{W_{\text{payload,max}}}, \tag{13}$$

where $W_{\text{payload},s}$ is the payload of sampled mission s and $W_{\text{payload,max}}$ is the maximum payload of the aircraft. The RPK associated with the sampled mission is then computed as

$$RPK_s = LF_s R_s N_{\text{pax,max}}, \tag{14}$$

where $N_{\text{pax,max}}$ is the maximum passenger capacity of the aircraft and R_s is the mission range in kilometers. Missions are sampled uniformly at random from the mission-performance library until the cumulative RPK assigned to aircraft i reaches the assumed annual aircraft RPK, RPK_{ac}:

$$\sum_{s=1}^{n_{\text{flights},i}} RPK_s \geq RPK_{\text{ac}}. \tag{15}$$

The number of sampled missions required to satisfy Eq. (15) defines the annual number of flights for aircraft i, denoted $n_{\text{flights},i}$. For the assumptions used in this study, this procedure results in an average utilization of approximately three flights per aircraft per day.
Fleet-level technology impacts are evaluated relative to a frozen-technology reference fleet. In this reference case, traffic growth and retirement dynamics are retained, but all new aircraft deliveries are the baseline aircraft type to represent a worst case scenario.

3. Results

This section demonstrates FLOATIE using an illustrative A320neo-like narrowbody fleet case study. The purpose of the case study is not to forecast a specific airline fleet, but to demonstrate how FLOATIE can connect aircraft-level technology impacts, operational assumptions, and fleet evolution dynamics to estimate long-term fleet fuel burn. The results are presented in three parts. First, the new aircraft technology groups and fleet outlook scenarios are defined as case-study inputs. Second, the aircraft-level effects of the selected technology groups are compared across the payload–range envelope. Third, new aircraft performance is propagated through the fleet evolution within mixed fleets model to evaluate future fuel burn outcomes.

3.1 Case Study Setup

The case study compares three fleet outlook scenarios varying aircraft technology improvements and maturity, aircraft types introduced into the fleet, and how quickly the baseline fleet is aged out. This study uses the A320neo baseline aircraft described in Section 2.2.1. The three representative future aircraft are defined by applying technology impact groupings to the baseline aircraft, with increasing levels of performance improvement and different levels of technology maturity. These groups are not fixed FLOATIE inputs; rather, they are user-defined technology packages selected for this demonstration, and the framework could be applied to any aircraft type that FAST can model.

3.1.1 Technology Group Definitions

Three technology groups were defined representing three potential new aircraft types considered for the fleet scenarios. NewAC1 represents a near-term technology package composed of relatively mature technologies with modest aircraft weight reductions. NewAC2 represents a more advanced aircraft concept that combines larger structural weight reductions with aerodynamic improvements. NewAC3 represents low maturity technology with higher potential benefits. The individual technology impact factors used to construct these groups are summarized in Table 2, and the resulting combined impact factors are summarized in Table 3.

		Total Impacts				Average	
Aircraft	**Technologies**	**Weight**	**L/D**	**Power**	**Fuel**	**TRLs**	**Confidence**
NewAC1	Electric Landing Gear Electric Actuators Lightweight Seats	-7.5%	0%	1%	0%	8	High
NewAC2	Composite Airframe Electric Landing Gear Folding Wingtips Fly-by-wireless	-19%	3%	1%	0%	7	High
NewAC3	Composite Airframe Thin Wings Ultra High Bypass Turbofan High Voltage Power Lines Electric Actuators	-21.5%	10%	-1%	-5%	6	Med

Table 3 – New aircraft technology groups with total impact factors compared to the baseline.

3.1.2 Fleet Evolution Scenarios

The aircraft technology groups are then combined with the baseline aircraft in three fleet evolution scenarios: conservative, moderate, and aggressive. These scenarios are intended to represent bounding cases for technology adoption and operational efficiency rather than specific airline procurement forecasts. All scenarios begin from the same baseline fleet and are evaluated under the same traffic assumptions, given in Tab 4. The scenarios differ in the new aircraft types available, their EIS years, their adoption probabilities, and the assumed air traffic management (ATM) efficiency improvements. The traffic growth assumed for all scenarios is plotted in Fig 6, showing the 3.6% annual growth used in the fleet traffic assumptions.

The conservative scenario represents limited technology adoption and includes the baseline aircraft and NewAC1 as new aircraft options. This case isolates the effect of modest near-term aircraft improvements entering a mixed fleet with aging aircraft. The moderate scenario includes NewAC1 and NewAC2, aging out the baseline fleet immediately as new aircraft are introduced, and assumes minor improved ATM efficiency relative to the conservative case. The aggressive scenario includes NewAC1, NewAC2, and NewAC3, representing earlier and broader adoption of more advanced aircraft technologies and substantial hold time reductions. NewAC3 offers the highest aircraft-level improvements and is adopted with the highest probability in the aggressive case. The aircraft tech-

Category	**Value**
Start Year	2025
End Year	2060
Base Year Traffic (RPKs)	2.3e10
Average Aircraft Yearly RPK	4.9e8
Traffic Growth Rate	3.6%
Aircraft Retirement Age	25
Max Pax	180
Pax Load Factor	0.5 - 1
Mission Ranges (nmi)	800 - 2500

Table 4 – Fleet traffic, utilization, and mission assumptions based on typical commercial narrowbody trends.

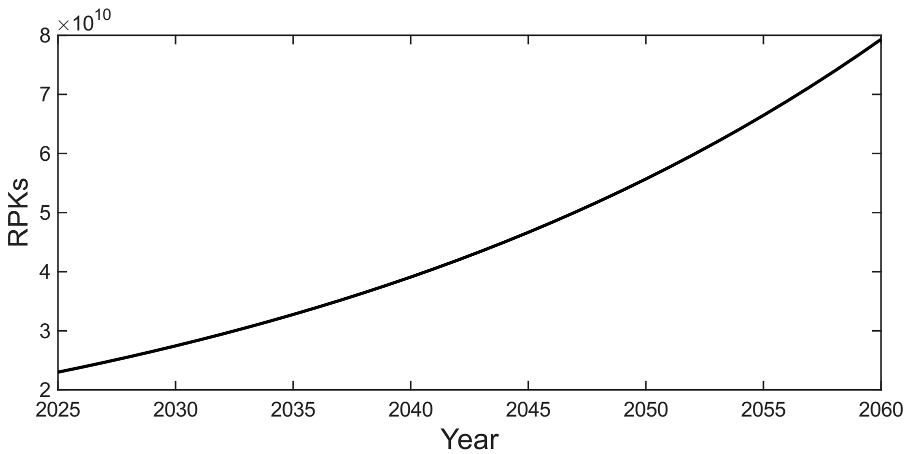

Figure 6 – Fleet traffic growth in revenue passenger kilometers.

nology groups, EIS years, adoption probabilities, and ATM holding-time assumptions used in each scenario are summarized in Table 5.

Table 5 – Fleet outlook scenario aircraft types, EIS years, adoption probabilities, and ATM hold-time assumptions.

	Conservative		**Moderate**		**Aggressive**		
Fleet AC Types	Baseline	NewAC1	NewAC1	NewAC2	NewAC1	NewAC2	NewAC3
EIS	2016	2025	2025	2030	2025	2028	2030
Adoption Probability	0.5	0.5	0.4	0.6	0.2	0.3	0.5
ATM Hold Times [min, max, mean]	[0, 30, 20]		[0, 30, 10]		[0, 15, 3]		

The initial baseline fleet used in the case study is provided in Appendix Tab. 6.

3.2 Aircraft-Level Technology Comparison

Figures 7–9 show the aircraft-level mission fuel burn maps for the three modified aircraft groups across payload–range operating limits and their percent differences relative to the baseline aircraft. These plots demonstrate that the aircraft-level benefits of the selected technologies are not uniform across the payload–range envelope. The relative benefit also varies with the type of aircraft-level improvement considered. Each plot has the region of mission operating conditions considered for the fleet evolution case studies outlined in red. These bounds were selected to match typical commercial domestic flights for a narrowbody aircraft.

NewAC1 provides the smallest fuel burn reduction, shown in Fig. 7, because it is composed primarily of near-term technologies with modest weight impacts. Across representative mission conditions, NewAC1 reduces mission fuel burn by approximately 5–7% relative to the baseline aircraft. The fuel burn percent improvements are relatively constant with respect to range.

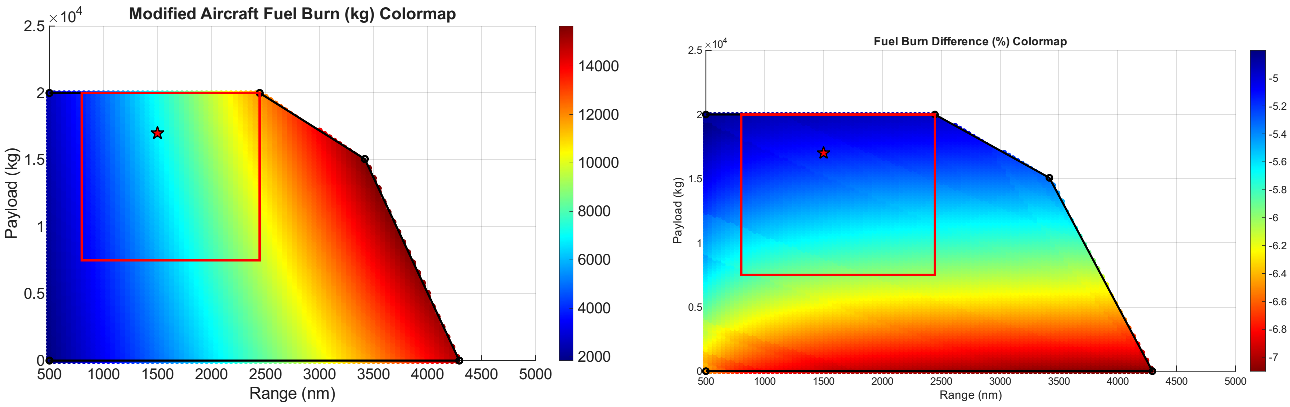

Figure 7 – Payload–range fuel burn heatmap for NewAC1 (left) and percent difference for fuel burn compared to baseline aircraft (right). Mission-performance library values outlined in red. Mean range and payload marked with star.

NewAC2 produces a larger aircraft-level benefit because it combines substantial weight reduction with an aerodynamic improvement from the selected wing technology, displayed in Fig. 8. The resulting fuel burn reduction is approximately 14–20% across much of the payload–range envelope. The relative fuel-burn reduction increases with range because aerodynamic efficiency improvements have a larger cumulative effect on longer missions.

Finally, NewAC3 provides the largest aircraft-level fuel burn reduction, as shown in Fig. 9, because it combines the most aggressive weight reductions with both aerodynamic and propulsive-efficiency improvements. Across the payload–range envelope, NewAC3 reduces mission fuel burn by approximately 22–32% relative to the baseline aircraft. In contrast to NewAC1 and NewAC2, whose relative fuel-burn reductions are comparatively uniform with range after the shortest missions and vary primarily with payload, NewAC3 exhibits substantially stronger variation across the full operating envelope.

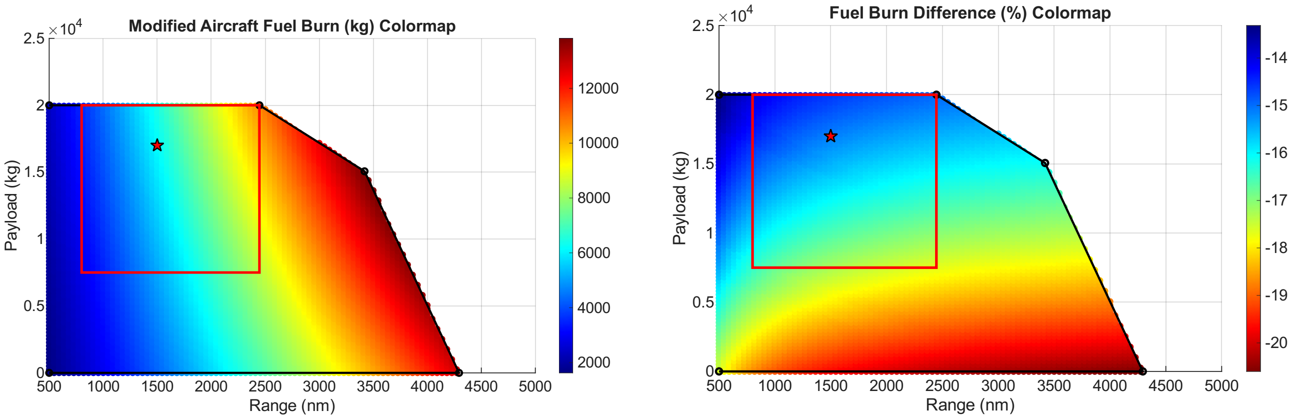

Figure 8 – Payload–range fuel burn heatmap for NewAC2 (left) and percent difference for fuel burn compared to baseline aircraft (right). Mission-performance library values outlined in red. Mean range and payload marked with star.

In particular, the NewAC3 improvements vary meaningfully with both payload and range, with larger reductions observed at longer-range conditions. This stronger dependence on operating condition demonstrates the importance of using the full mission-performance library in FLOATIE rather than applying a single fixed fuel-burn reduction factor across all missions.

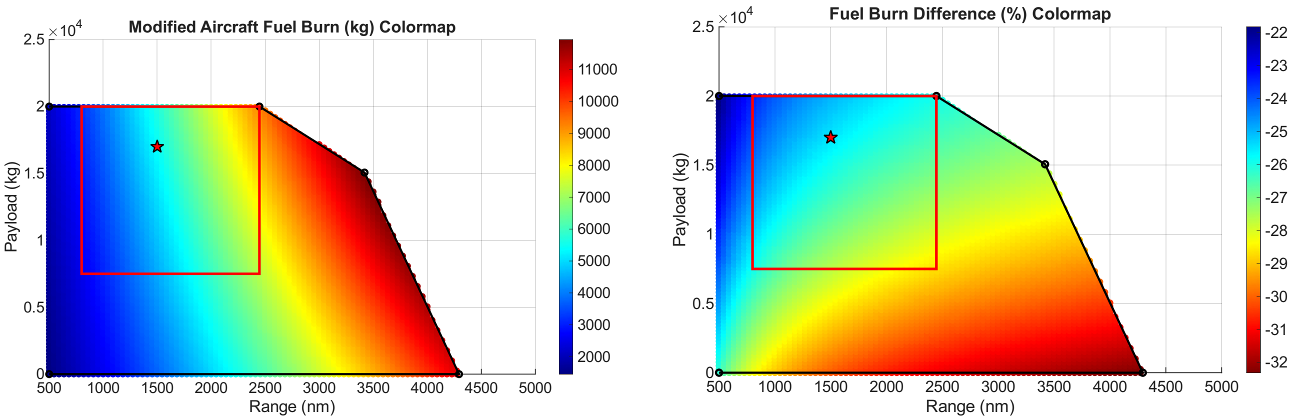

Figure 9 – Payload–range fuel burn heatmap for NewAC3 (left) and percent difference for fuel burn compared to baseline aircraft (right). Mission-performance library values outlined in red. Mean range and payload marked with star.

Overall, the aircraft-level comparison shows that technology benefits depend on both the selected technology package and the mission condition. This motivates the use of payload–range mission-performance libraries as inputs to the fleet-level analysis, because a single representative mission would not capture the variation in technology benefit across the operating envelope.

3.3 Future Fleet Fuel Burn Outlook

The technology groups and fleet evolution scenarios are propagated through the fleet fuel burn assessment to evaluate long-term outcomes. Figures 10–12 compare the modified fleet scenarios with the frozen-technology reference fleet. The frozen-technology fleet retains the same traffic growth and fleet replacement assumptions as the modified scenarios, but all new aircraft deliveries use the baseline aircraft technology and no ATM hold-time improvements are applied.

The conservative scenario is shown in Fig. 10. Although NewAC1 provides approximately 5–7% mission-level fuel burn reduction for representative missions, the fleet-level fuel burn reduction reaches only about 2.9% by 2060. The aircraft-level benefit is reduced at the fleet-level because NewAC1 enters gradually into a mixed fleet, while baseline aircraft remain in operation and continue to be delivered in the conservative scenario. The conservative case demonstrates how fleet turnover and partial adoption can dilute aircraft-level technology benefits.

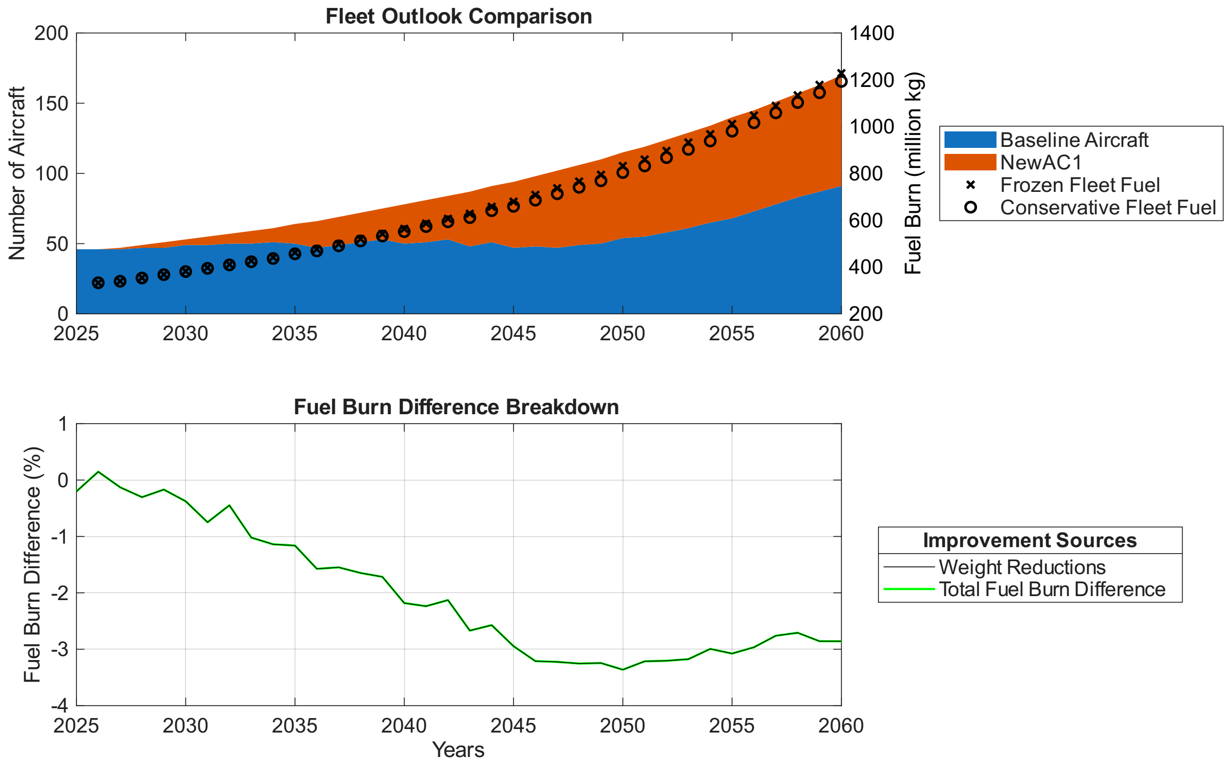

Figure 10 – Conservative technology adoption fleet outlook and fuel burn percent difference comparison to frozen fleet.

The moderate scenario is shown in Fig. 11. In this scenario, the introduction of NewAC2 and the reduction in holding-time assumptions lead to a larger fleet-level fuel burn reduction than in the conservative case, up to 13%. The fuel burn breakdown shows that weight reduction provides the largest contribution, while aerodynamic efficiency and ATM efficiency provide additional reductions. This indicates that combining aircraft-level improvements with operational efficiency assumptions can produce larger fleet-level benefits than aircraft technology alone.

The aggressive scenario yields the largest fleet-level fuel burn reduction because NewAC3 is introduced with the highest adoption probability and the most favorable ATM holding-time assumptions are applied. As shown in Fig. 12, NewAC3 accounts for approximately 50% of the fleet by 2060, resulting in a 21% reduction in fleet-level fuel burn. The mission-performance library for NewAC3 indicates aircraft-level fuel burn reductions ranging from 22% to 28%, suggesting that accelerating the retirement of older aircraft and prioritizing substantial technology improvements can help mitigate the limitations associated with operating in a mixed fleet. Under the assumed technology package and decomposition approach, weight reduction is identified as the largest estimated contributor, reflecting the aircraft-level improvements incorporated into NewAC3. Overall, the aggressive scenario represents the upper-bound behavior of the case study, demonstrating that broader adoption of advanced technologies can produce substantially larger fuel burn reductions relative to the frozen-technology fleet.

Across all scenarios, the fleet-level reductions are smaller than the largest aircraft-level fuel burn reductions because aircraft improvements are introduced gradually and operate within a mixed fleet. In addition, total fleet fuel burn continues to increase over the analysis period because traffic growth increases the number of aircraft required to meet demand. This result highlights the importance of evaluating emerging technologies at the fleet level: aircraft-level improvements alone do not directly translate into equivalent fleet-wide reductions.

The results demonstrate three main capabilities of FLOATIE. First, the framework quantifies how technology impacts vary across aircraft-level mission conditions. Second, it propagates those impacts through fleet turnover, traffic growth, and adoption dynamics. Third, it decomposes fleet-level fuel

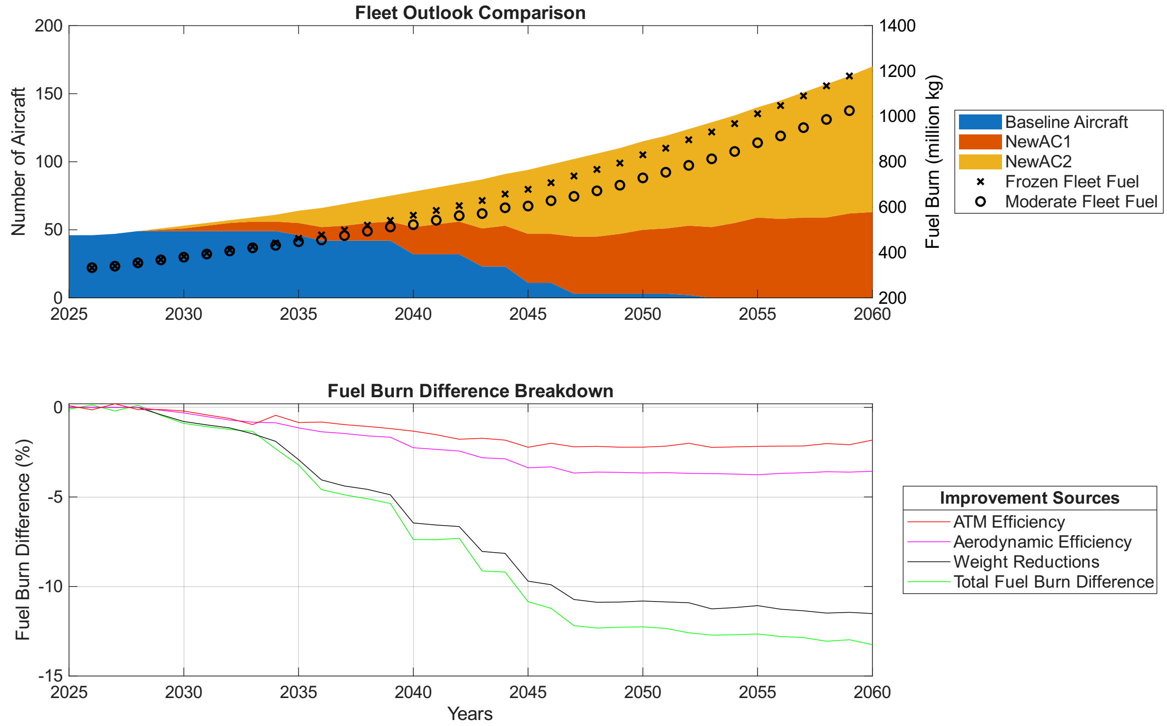

Figure 11 – Moderate technology adoption fleet outlook and fuel burn percent difference comparison to frozen fleet.

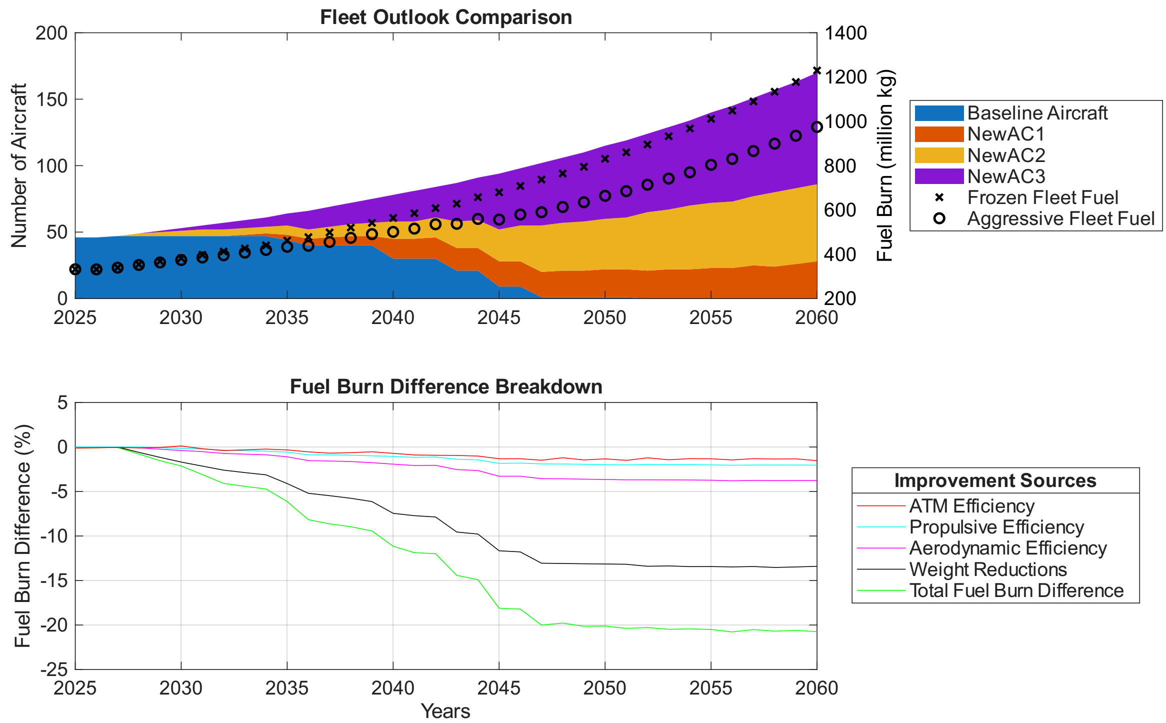

Figure 12 – Aggressive technology adoption fleet outlook and fuel burn percent difference comparison to frozen fleet.

burn reductions into contributions from weight, aerodynamic efficiency, propulsive efficiency, and ATM operational improvements. Together, these capabilities allow FLOATIE to evaluate not only whether a technology improves aircraft performance, but also whether that improvement produces meaningful long-term fleet-level benefits.

4. Conclusion

This paper introduced FLOATIE, a modular framework for connecting physics-based aircraft performance modeling with fleet evolution analysis. The framework enables user-defined technology packages to be translated into mission-performance libraries and propagated through future fleet scenarios. This allows early-stage aircraft technologies to be assessed not only by their isolated mission-level performance, but also by their ability to produce meaningful fleet-level fuel-burn reductions over time.

An illustrative A320neo-like narrowbody case study was used to demonstrate the framework. At the aircraft level, the three representative technology packages produced progressively larger mission fuel-burn reductions relative to the baseline aircraft. NewAC1 reduced mission fuel burn by approximately 5-7% across representative operating conditions, NewAC2 reduced mission fuel burn by approximately 14-20%, and NewAC3 reduced mission fuel burn by approximately 22-32% over the feasible payload-range envelope. These results show that the benefit of a technology package depends on mission range, payload, and the specific combination of weight, aerodynamic, and propulsion changes.

When these aircraft-level benefits were propagated through fleet evolution, the realized fleet-level reductions were smaller than the largest aircraft-level reductions. Under the assumed 3.6% annual traffic growth, 25-year retirement age, adoption probabilities, and ATM holding-time assumptions, the conservative, moderate, and aggressive scenarios reduced 2060 fleet fuel burn by approximately 2.9%, 13%, and 21%, respectively, relative to the frozen-reference fleet. Total fleet fuel burn nevertheless increased over the study period because traffic growth increased the number of aircraft required to meet demand. This demonstrates that fleet turnover, adoption timing, and demand growth can substantially dilute aircraft-level technology benefits.

The counterfactual source breakdown indicates that, under the selected technology packages and scenario assumptions, weight reduction is the largest isolated source of fleet fuel-burn reduction, with aerodynamic efficiency, propulsive efficiency, and ATM holding-time reductions providing additional benefits. Because these categories interact through aircraft performance and fleet evolution, this ranking should be interpreted as case-study-specific rather than universal.

This study also has several limitations. The technology impact factors used in the case study were derived from publicly available sources, where detailed information on aircraft-level effects is often limited. Therefore, the selected technology groups should be interpreted as illustrative examples for demonstrating the FLOATIE workflow rather than definitive predictions of future aircraft performance. More detailed proprietary or experimentally validated technology data would improve the accuracy of future assessments. In addition, this study considered a single narrowbody baseline aircraft type and assumed the same utilization, passenger capacity, and traffic growth assumptions across all scenarios. In practice, future aircraft may differ in utilization, route suitability, passenger capacity, operating constraints, or airline deployment strategy. Future extensions of FLOATIE should therefore include additional aircraft classes, alternative propulsion systems, and more operationally detailed deployment assumptions, including hybrid-electric aircraft concepts.

Future work will expand FLOATIE by incorporating uncertainty metrics into the results and performing sensitivity studies on key assumptions, including technology impact factors, adoption probabilities, retirement schedules, traffic growth, mission variability, utilization, and air traffic management improvements. These studies will help identify the factors that most strongly influence fleet-level performance benefits and the interactions that can either enhance or reduce fuel-burn savings.

Overall, the results show that linking aircraft-level design changes to fleet-level evolution provides a more informative basis for early technology prioritization than aircraft-level analysis alone. FLOATIE therefore provides a transparent decision-support capability for assessing how emerging aircraft technologies may translate into practical long-term fleet-level fuel-burn benefits.

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Appendix

Table 6 – Baseline fleet assumptions used for analysis.

Aircraft Type	Tail No.	Year EIS	Retire Age	Retire Year
A320neo	N102UW	2010	25	2035
A320neo	N103US	2010	25	2035
A320neo	N104UW	2010	25	2035
A320neo	N105UW	2011	25	2036
A320neo	N107US	2011	25	2036
A320neo	N108UW	2011	25	2036
A320neo	N109UW	2011	25	2036
A320neo	N110UW	2015	25	2040
A320neo	N111UW	2015	25	2040
A320neo	N112UW	2015	25	2040
A320neo	N114UW	2015	25	2040
A320neo	N117US	2015	25	2040
A320neo	N118US	2015	25	2040
A320neo	N119US	2015	25	2040
A320neo	N121UW	2015	25	2040
A320neo	N122US	2015	25	2040
A320neo	N123UW	2015	25	2040
A320neo	N124US	2018	25	2043
A320neo	N125UW	2018	25	2043
A320neo	N126UW	2018	25	2043
A320neo	N127UW	2018	25	2043
A320neo	N128UW	2018	25	2043
A320neo	N647AW	2018	25	2043
A320neo	N649AW	2018	25	2043
A320neo	N650AW	2018	25	2043
A320neo	N651AW	2018	25	2043
A320neo	N652AW	2020	25	2045
A320neo	N653AW	2020	25	2045
A320neo	N654AW	2020	25	2045
A320neo	N655AW	2020	25	2045
A320neo	N656AW	2020	25	2045
A320neo	N657AW	2020	25	2045
A320neo	N658AW	2020	25	2045
A320neo	N659AW	2020	25	2045
A320neo	N604AW	2020	25	2045
A320neo	N660AW	2020	25	2045
A320neo	N662AW	2020	25	2045
A320neo	N661AW	2020	25	2045
A320neo	N663AW	2022	25	2047
A320neo	N664AW	2022	25	2047
A320neo	N665AW	2022	25	2047
A320neo	N667AW	2022	25	2047
A320neo	N668AW	2022	25	2047
A320neo	N669AW	2022	25	2047
A320neo	N601AW	2022	25	2047
A320neo	N673AW	2022	25	2047

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