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An Investigation Into the Economic Useful Life of Commercial Aircraft as Impacted by Maintenance and Economic Variables

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AN INVESTIGATION INTO THE ECONOMIC USEFUL LIFE OF COMMERCIAL AIRCRAFT AS IMPACTED BY MAINTENANCE AND ECONOMIC VARIABLES

By

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This Dissertation was prepared under the direction of the candidate's Dissertation Committee Chairman, Dr. Michael J. Williams, and has been approved by the members of the dissertation committee. It was submitted to the College of Business and was accepted in partial fulfillment of the requirements for the
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ABSTRACT

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This research involved examining the economic useful life of commercial aircraft and the impact of maintenance and economic variables on the viability and longevity of the asset. The data sample consisted of the entire population of Boeing commercial aircraft produced between 1956 and 2021. The objective was to determine the effect of both maintenance and economic variables on the longevity and usefulness of commercial aircraft. As manufacturers work with issues such as service life, economic life, safety, and critical design features, those in the aviation community focus on the operational side of the equation—how long can one operate the asset, and at what point is it no longer effective to continue investing into the asset? The research presents an extensive review of the maintenance and technological advances in commercial aircraft over the last 60 years and an investigation of various aspects of the economic useful life concept in both use and application from an appraisal and industry perspective. The research focus is on the actual age at which an asset is removed from operational service and the underlying causes of such a decision.

Keywords: commercial aircraft, retirement, economic useful life

DEDICATION

To my wife Audrey, for without her love, devotion, encouragement, and understanding my life would be meaningless, who saw something that I failed to see within myself those many years ago. Her support, dedication, and perseverance throughout this roller coaster ride of life are constant and unwavering, always, and forever.

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To my grandchildren, Adriana, Ava, and Elena, education is an important undertaking, but learning is a lifelong process. Don’t waste opportunities and take advantage of what is given to you to make the best of your options. Never stop learning and never stop questioning.

To my parents and in-laws Joan, Ed, Anita, Ralph, and Carlo, you have given so much of your time and efforts in helping and guiding my life and making me understand that family is and always will be everything.

And to those who pursue a career in aviation always remember, it's not just a job, it's an adventure! Opportunity can come from many directions and in many forms.

AVIATION IS PROOF THAT GIVEN THE WILL WE CAN DO THE IMPOSSIBLE.

– Captain Eddie Rickenbacker, USA Air Service, G.M. Eastern Airlines

WE HAVE TO EARN OUR WINGS EVERY DAY.

– Colonel Frank Borman, USAF, Chairman, Eastern Airlines

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

On December 17, 1903, a cold windy day in Kitty Hawk, North Carolina, Orville Wright became the world's first man to achieve a successful controlled, powered, manned heavier-than-air flight. He and his brother Wilbur relied upon the mechanical aptitude of a machinist and bicycle mechanic named Charles E. Taylor, who served as their chief mechanic and designed and built the first engine for their flying machine in just 6 weeks. Mr. Taylor is considered to be the first aviation mechanic, a self-taught individual, inventor, machinist, and mechanic who put the Wright Flyer into the air and kept it flying. Aviation has grown and changed since then, adding complexities and regulatory guidelines that neither the Wrights nor Charles Taylor could have ever envisioned. None of the Wright cadres would have expected aircraft to enjoy the long life they have become known for nor for them to become the economic instrument into which they have developed.

In the Wright brothers' papers, the first mention of the environmental toll experienced by the machine was noted in a letter from Orville to his father dated November 15, 1903 (W. Wright et al., 1953). He stated the heat in the building where the glider was being stored had "so dried out the cloth and wood of the framework that the machine is now so rickety as to be unsafe" (p. 35). Today environmental concerns affect current aircraft safety and storage procedures from volcanic ash to heat and cold. Orville discussed the fact of the deterioration of the fabric again with Charles E. Taylor in a November 23, 1903, letter, speaking to the "dilapidated condition, which renders it [the machine] quite unsafe" (p. 385). It appears from the communication that the forward-looking concepts of maintenance and maintainability were on the Wrights' horizon. Maintenance of the machine becomes something of concern, as the original machines (i.e., aircraft) lasted approximately one flying season or about a year and obtained approximately 100 flights totaling about 25 hours of airborne time. Table 1 outlines a summation of the Wright brothers' initial flight durations.

Table 1

Summary of the Wright Brother's Hours, Cycles, and Equipment Ages

	Date	Fl	Pilot	Time of day	Duration aloft	Ground distance	Total time aloft
Wright Flyer (No. 1) Kitty Hawk, NC	12/17/1903	1	Wright, Orville	10:35 a.m.	12 sec.	12 ft.	≈ 1.62 mins.
	12/17/1903	2	Wright, Wilbur	11:20 a.m.	11 sec.	175 ft	
	12/17/1903	3	Wright, Orville	11:40 a.m.	15 sec.	200 ft	
	12/17/1903	4	Wright, Wilbur	12:00 p.m.	59 sec.	852 ft.	
	12/18/1903		The machine (Wright Flyer), damaged on the last flight, was torn down for packing and shipping back to Dayton, OH.				
			The engine (No. 1) had four cylinders of a 4 in. bore and a 4 in. stroke producing 11.81 HP at 1,090 RPM.				
No. 2 Huffman Prairie, OH	5/26/1904 12/9/1904		Approximately 100 flights were made within this period as well as the ability to fly a complete circuit (Racetrack Course).				≈ 45 mins.
	11/9/1904		Wright, Wilbur		5 min. 4 sec.	2.75 miles	
			The engine (No. 2) had four cylinders of a 4.125 in. bore and a 4 in. stroke producing 16.90 HP at 1,360 RPM.				
No. 3 Huffman Prairie, OH	6/23/1905 10/19/1905		Approximately 49 flights were made within this period as well as the ability to bank, turns, circuits, and figure eights.				≈ 3 hours
	10/4/1905		Wright, Wilbur		38 min. 3 sec.	24 miles	

Note. Adapted from W. Wright et al. (1953).

The early air transport industry proved to be extremely dangerous during its infancy. As aircraft developed, becoming faster and more complex, so did the individuals seeking to break records for the fastest, the longest, or the most aerobatic maneuvers; this was not for the light-hearted or weak individuals but rather those seeking fame and thrill. With the Air Mail Act of 1925, a level of organization became evident with the U.S.

Postal Service establishing an organized route structure as opposed to pilots following roads, rail lines, and barn fires to locations. Globally, regulation and legislation became the backbone of the industry, allowing for growth to occur in an organized manner. Domestically, the Federal Aviation Act of 1958 combined previous agencies and departments under one larger federal umbrella by repealing and replacing its predecessors, including the Air Commerce Act of 1926, the Civil Aeronautics Act of 1938, and the Airways Modernization Act of 1957. Internationally, through a series of aviation conventions such as the Chicago and Warsaw Conventions, aviation became an organized series of events. The industry from both an operational and regulatory standpoint worldwide has become safety oriented culture.

Maintenance, repair, and modification are the cornerstone of all aircraft, from both a usefulness and safety standpoint. The complexities of the operations and inspections have developed over time. The accomplishment and fulfillment of maintenance combined with the regulatory requirements are the tasks that support the safety of flights and the equipment that acts as a vehicle for aviation. From Airbus to Boeing and all the smaller companies in between, from the military to business aviation, from general aviation to the space program, are all supported by the maintenance and technical staff combined with their knowledge, dedication, and management of the process. As espoused by Dhillon and Liu (2006), global air transportation systems are dependent upon high-quality aircraft maintenance to provide safe, reliable aircraft to consumers and stakeholders. Manufacturers focus on reductions in the fuel used, aircraft weights, and maintainability as well as on incorporating technological changes into the production, design, and manufacture of equipment, or as some will call them assets. Yet, the maintenance personnel focus on accomplishing all those issues against a schedule.

Historical Background

It was not until 1938 that Boeing introduced commercialized passenger flight equipment using pressurized cabins with the Boeing Model 307 Stratoliner, a non-turbine powered aircraft. At approximately the same time (i.e., 1940), the Civil Aeronautic Authority was split into two separate agencies, the Civil Aeronautics Administration (CAA) and the Civil Aeronautics Board (CAB), each with different responsibilities. The CAA oversaw safety programs and the CAB focused on the safety rulemaking. Today, aircraft are built and designed with safety in mind under the control of one organization responsible for both safety aspects, the Federal Aviation Administration (FAA). Current aircraft fly at speeds just below that of the speed of sound (Mach). The industry is constantly advancing with new and emerging technologies. Over time, those in the industry have come to understand and accept that there are unique and specific factors involved in the maintenance and technical aspects of aircraft.

As aircraft get older, the related costs and expenses rise at a greater rate. Pyles (2003) discussed both the age and cost issues issue. He identified contributing factors such as workload and the required increases in manpower to maintain, inspect, and rectify discrepant items. Additionally, he pointed to material content and consumption of parts, component repairs, and the failure rates of specific hardware and software. He showed the interactions are related to the age of the system (aircraft) they support. Some may endeavor to rate the age of an aircraft in terms of categorical costs such as an appraiser may do for factory or plant. Others may examine the external factors found in operations such as a pandemic affecting global travel, an oil embargo, or the price increase in the barrel of crude oil as we are experiencing with the recent invasion of Ukraine to determine the economic costs associated with an aircraft asset. Still others look at the obsolescence of the asset, the need to replace a machine or equipment because it has just become worn out. There becomes a point where there is an inability to continue to finance the asset or there is a better version available and consumer confidence may have shifted away from the older version. Some, such as Hallerstrom and Melgaard (1998), believe the present value (PV) of all expected future cash flows represents the base value of an aircraft. However, according to the International Society of Transport Aircraft Trading (ISTAT), the base value is the appraiser's opinion of the underlying economic value of an aircraft in an open, unrestricted, stable market environment with a reasonable balance of supply and demand and the appraiser assumes full consideration of its "highest and best use."

There is always consideration given to safety and the aspect of risk and mitigation of the safety quotient as was witnessed in the B-737-800 Max grounding. In this case, consumer awareness was controlled by the constant beating of the media drum and discussion of accidents forcing a grounding of the fleet by President Trump and the FAA on March 13, 2019. Yet, each aircraft has a value component that is an economically tangible aspect. Every transaction, each purchase and sale, is a risk assessment that is directly tied to the magnitude of peril an investor is willing to accept or the exposure they are willing to take. Hatcher (2019) pointed out that successive generations of aircraft have benefited from design and configuration changes that have reduced cash direct operating costs and improved operational efficiencies. These concepts are the underlying goals of not only those who produce aircraft but also those who purchase and operate the equipment. Additionally, most would hope that consumers and the traveling public would benefit similarly from the collective improvements through safer more efficient transportation at reasonable prices.

The concepts of economic life, economic useful life (EUL), and residual values present issues for lessors, financiers, and operators of equipment when there is no straight line that describes the depreciation method used to model the values and longevity of an asset. Aviation or aircraft appraisers approach the processes of evaluating aircraft values from multiple tangential aspects such as the concept of useful life, economic life, or remaining life. Each aspect depends upon one major facet—the obsolescence of the asset. It is difficult to determine the useful life with any degree of reliability and reasonableness. Combined with a set of various concepts and underlying thoughts, there emerges a problematic situation without a solution—How do we determine the economic useful life?

Significance of the Study

Placing aside exogenous events that can affect the aviation industry, such as fuel prices, wars, pandemics, disease, and the occasional fear of flying, in the current study, the focus was on the maintenance aspects of aircraft. The aerospace industry designs and produces aircraft with consideration given to the lifespan of that product. Along with that time frame is the technical support process and how long the manufacturer will support the equipment. All of these considerations go into the specifications and are included within their design concept. Over the design and manufacturing time frame, such benchmarks may change, causing changes in the original assumption process used to determine such life. The impact of these findings contributes to changes or amendments in actions required to align with production targets and completions within the production cycles. Manufacturers and designers begin the process of development already considering changes in aspects such as gross weight increases, ranges, stretches of the aircraft, and possible passenger to freighter conversions. The life of an aircraft is also of concern to maintenance personnel, planners, schedulers, fleet managers, and appraisers looking to the aircraft design and maintenance schedule over the longer-term horizon of about 20 years.

In this study, the researcher explains several aspects that affect the life of an aircraft as viewed from a maintenance and technical perspective and as applied to the decision-making process used when trying to predict the point at which an aircraft may become uneconomical to continue at its highest and best use. Some refer to this as economic service life (ESL) or economic useful life (EUL), whereas others point to a more defined concept, indicating individual aircraft must be evaluated using factors such as historical cyclic utilization, environmental basing history, and previous maintenance history to provide an accurate snapshot of today’s economic assessment (Rice, 1998) and how that aircraft continues in future service. This dissertation moves through the processes from safe-life and fail-safe design to limits of validity (LOV) and all the aspects and programs in between. The researcher endeavored to identify issues that could, if handled incorrectly, jeopardize the continuing airworthiness of aircraft, making it ineffective to keep them in continued operations as an asset of a company. The effectiveness of the applied logic and fundamental technical understanding is key to the asset reaching its true EUL and earning potential.

It is understood that market conditions and economics play a significant role in the extent to which aircraft remain in service, in some cases well beyond the original economic design goals of the manufacturers. There are also periods such as those pointed out in an article in *Airfinance Journal* (“Analysis: The end of history,” 2012), where it was believed that the “perfect storm” existed where the overproduction of aircraft combined with the widespread availability of export credit finance was affecting values. Issues such as these were shifting aircraft life to less than the 25-year model, which would consider an obsolescence factor for the technology involved in the equipment. There are two basic types of obsolescence as defined by the American Society of Appraisers (ASA, 2020):

> economic obsolescence. A form of depreciation where the loss in value or usefulness of a property is caused by factors external to the property. These may include such things as the economics of the industry; availability of financing; loss of material and/or labor sources; new legislation or ordinances; increased cost of raw material, labor, or utilities without a compensatory increase in product price; reduced demand; increased competition; inflation or high-interest rates; or similar factors.
>
> functional obsolescence. A form of depreciation in which the loss in value or usefulness of a property is caused by the inefficiencies or inadequacies of the property itself when compared to a more efficient or less costly replacement property that new technology might not allow. (pp. 48–49)

Additionally, there are always underlying issues related to costs as impacted by maintenance, both as current costs and future costs (planning). These expected future costs become a sustained part of the decision to keep or replace the economic strategies undertaken in aviation.

It was identified by the FAA and industry steering groups in the late 1980s that the aging fleet of Boeing aircraft was not adequately protected by its then-current maintenance programs. As the aircraft aged, fatigue damage increased and corrosion was becoming more widespread and severe. Corrosion, combined with poor repairs and the compounding of multiple repairs on top of each other, was degrading and compromising the fatigue life of the structures. The industry became united in seeking a comprehensive understanding of its problems combined with a path and goals to be implemented to continue to fly the aircraft. This became a philosophical change to maintenance planning and control programs that has been incorporated into current production models.

Two basic constructs affect aircraft life or age, one being related to the traditional and progressive approach to the age and longevity of the asset as viewed historically by the industry and the second being a modification that may be accomplished on aircraft. However, it should be noted that analysis is not specifically related to an individual or specific modification to a small select group of aircraft but rather large-scale modifications to a fleet such as that of a passenger-to-freighter (PTF) conversion. Additionally, the concept of an entire fleet re-engine program to meet an imposed regulatory event such as the Rolls Royce Tay installation on 727s for UPS or the similar program of a re-engine of a fleet type as the B727 and MD80 aircraft with the JT8D-200 series was not considered in the analysis. These modification decisions are specific and timed to extraneous events that drive a decision variable unforeseen outside the regulatory construct.

Statement of the Problem

Aircraft are capital-intensive assets that are placed into operational service to earn profits for the operator and the owner, which may not be the same entity. One of the key issues is the understanding that all aircraft are not created equal. Each comes with its own set of variables and differences, whether in terms of operational weight, payload capacity, specific engine type, or model specifics that will fit a set of circumstances defined by an operator. Aircraft are evaluated from multiple directions in an attempt to optimize the potential of the asset. The economic value can be assessed by revenue-producing ability, return on investment of capital, life expectancy, or actual monetary investment, all of which may present a different set of answers related to asset. The economic worth of an investment is influenced not only by the amount of the investment and its economic life but also by the time, shape, and pattern of its earning potential (Radnoti, 2002). To assess an aircraft, many unique and individual aspects combined with multiple practical paradigms must be studied, analyzed, and researched. In this paper, the researcher explores the quantitative conditions and discusses some of the methods to make such determinations based on the age, maintenance, and technical aspects of aircraft.

In its purest sense, the ability to finance an asset based on its ability to have an economically viable useful life, which is generally considered to be the amount of time an asset can be used in a cost-effective manner for its original purpose. Yet another concept comes into play, that of the LOV of the engineering data that supports the structural maintenance programs of the aircraft’s physical attributes. In fixed-wing as opposed to rotor-wing aircraft, there are differences in views as some claim that “because it [a helicopter] is just a frame with components attached, it has no fixed economic useful life" (Desfor, 2008, p. 8). What Desfor (2008) did not say until later on is that there is no economic useful life *restriction* imposed on the aircraft, indicating there is no LOV associated with this type of aircraft as with other commercial products produced under 14 Code of Federal Regulations (CFR) Part 25. This misleads the reader into a sense that EUL does not exist, which is not factual. Ghoshal and Kim (2006) also discussed rotorcraft, stating

> the economic useful life of an NDE (Non-Destructive Evaluation) technique is the period in which the technique fulfills the requirement for which it is employed at the lowest achievable cost compared with alternative techniques, again signaling another and fundamentally different opinion as to the issue of "life." (p. 1676)

These discussions appear to have conflicting ideas although both speak to the concept of EUL of the roto-wing aircraft but use two distinct measurements.

A recent rating action commentary by Fitch Ratings (2022) related to Vista Global indicated each aircraft could be fully repaid in 7 years or fewer (versus a useful economic life of around 25 years). Standard & Poor's (2010) stated, "We view capital intensity as a limiting rating factor for airlines, as for some other industries, particularly given the long lives (around 25 years) and high cost of aircraft" (p. 13). PricewaterhouseCoopers (2013) noted an oversupply of aircraft at that time (i.e., 2013) and indicated "we are seeing a trend towards a shortening in the average life of an aircraft from the traditionally accepted 25 years" (p. 16), concluding that the standard 25 years is no longer valid. Yet, Aviation Capital Group, LLC, in their financial statements for Q2-2021 stated, "We generally assume a 25-year estimated economic useful life for aircraft" (p. 14). Air Lease Corporation, in its Annual Report for 2014, discussed the aircraft life cycle and indicated their preference "is generally to own an aircraft for approximately the first third of its expected 25-year useful life" (p. 21). The RAND Corporation, under the Project AIR FORCE (PAF; Dixon, 2006) study, noted U.S. commercial aircraft are generally retired before reaching an age of 20 years (p. 37). The Financial Crisis Inquiry Commission (2011) leveled a critique of placing and managing investments and placed partial blame on the financial services industry by stating

> the accepted wisdom among many investment banks, investors, and rating agencies was that the wide range of assets had contributed to the problem; according to this view, the asset managers who selected the portfolios could not be experts in sectors as diverse as aircraft leases and mutual funds. (p. 130)

Yet, lenders invested in such assets, lacking a comprehensive understanding of both the industry and terms such as "life" and only looking on a basis of a forecasted cash flows and not considering the aircraft and its technical limitations. In the Aviation Industry Leaders Report (KPMG, 2022), executives discuss "mid-life" aircraft approximately 22 times, yet if the mid-life paradigm is present, then should we not understand what a total life is as an asset?

As the concept of EUL is used in the underlying assessment of aircraft, their value, and longevity, we see how practitioners may apply the term. As the term EUL is used it becomes different in terms of concepts to different individuals and organizations at different times. The term EUL as a period of an asset's ability to perform tasks influences the financability of that asset and the understanding of such a term is imperative. Leaders in the industry should insist that the ambiguity be removed and a consistent term be established and applied.

As an industry, if we can comprehend the term EUL, then we should be able to make decisions concerning the term and thus the end-of-life or the actual life of an asset. Both age and condition should be a cornerstone in our ability to make comprehensive decisions about such factors as the life of an asset. Additionally, changes in regulations could affect the economic life of aircraft and engines as proposed in the European Union's Emission Trading Scheme from the 2013 time period, depending on operating limitations.

Purpose Statement

This investigation uniquely contributes to both practical and business knowledge by improving awareness for various stakeholders. This quantitative investigation was designed to increase the understanding of the decisions and actions undertaken by airlines, lenders, banks, and financiers regarding commercial aircraft assets in producing and determining what factors play a role in the decision matrix of aircraft retirements.

In this study, the researcher compared the varied definitions that currently exist in the aviation industry. During the course of this analysis and investigation, the researcher examined the variables that have become commonplace and are grounded in both the regulatory and maintenance aspects of management of the engineering functions found within the aviation industry. These various intervals are used throughout the course of maintenance and inspection that are identified in the maintenance program and planning data, and an aircraft's instructions for continued airworthiness. Additionally, the U.S. Federal Aviation Administration (FAA) approved Certification Maintenance Requirements (CMRs), Type Certificate Data Sheet (TCDS), and all other documentation established by the requirements of FAR 25.571, FAR 25.1529, and Advisory Circular (AC) 25-19 in making such detailed maintenance action mandatory were reviewed.

Within the bounds of this examination, the researcher attempted to determine the impact, if any, of maintenance variables (e.g., corrosion prevention and control programs, repair assessment programs, supplemental structural inspections, aging aircraft programs, and hard time replacement concepts) in determining the useful life of commercial aircraft. Through the application of these independent variables at specific points in the aircraft life cycle, the researcher wanted to quantify their role in the decision to retire an aircraft asset.

Scope of the Study

This study involved analyzing information related to maintenance events that may affect the life cycle of commercial jet aircraft. Some industry experts believe the maintenance activities related to aircraft affect their useful life. Looking through the lens of technically astute individuals and examining the various age-life paradigms and regulatory environments that were present, the researcher designed the study to measure the independent variables that have played important roles in aircraft maintenance philosophies. The researcher examined the historical trends and independent program implementations as they pertain to retirements of aircraft. This analysis was accomplished using data on aircraft from the inception of the modern jet era (i.e., 1958 to 2021). The researcher endeavored to identify what future performance may look like for planning purposes based upon a historical review.

Research Questions and Hypotheses

This research involved studying the effects of maintenance, regulatory, production, technological, and program factors on the useful life assets that have been retired using their technical attributes. Some other variables that influence the EUL of commercial aircraft and, by extension their values, are also discussed. The analysis was intended to identify historical trends and attempt to forecast the life, age, and EUL of commercial aircraft given the current and expected state of technological innovations and the regulatory environment by looking historically at the shifts and changes that have occurred throughout the jet era. This research was guided by the following questions.

R1: Do aircraft cycles, hours, maintenance, regulatory inputs, and macroeconomic variables influence the EUL of an aircraft asset?

$H1_0$: There are no statistically significant maintenance or technical variables that influence the EUL of the asset.

$H1_a$: There is a statistically significant relationship between the independent variables and the EUL of the asset.

R2: Does the age of the aircraft (DV) exceed the required LOV?

R3: Is there a predominant group of IVs that has the largest effect on the EUL outcome?

R4: Is there a specific model Boeing aircraft that is more susceptible to earlier retirement due to shorter EUL?

R5: Based upon Maintenance Steering Group (MSG) program development, has there been an impact on retirements and a shorter EUL?

Delimitations

In this study, the researcher did not focus on any qualitative aspects of the industry or attempt to research underlying corporate goals and assumptions related to aircraft industry investors' mindsets or stakeholder input. Additionally, the construct of FAA AC 120-16G and its European Union Aviation Safety Agency (EASA) counterparts placed bounds upon the investigation by its regulatory requirement. It should be noted that the individual boundaries imposed were not specifically investigated under the individual maintenance programs of hard time, MSG-1, -2, or -3 concepts and are therefore under the all-encompassing construct of maintenance programs as a generalization.

Delimitations in particular to this study were bound by the Boeing Company, their airplanes, types, and models defined within this document as produced by the manufacturer. The key concepts are discussed herein in relation to the CFR and by statute are mandatory. These laws and therefore the discussions within this paper are consistent with a U.S.-centered approach to aircraft in which the FAA is the regulatory authority. This study did not include an examination of modifications to a group of aircraft such as the installation of a cargo door and their particular impact on age. It also did not include examining the possibilities of changes in a regulatory requirement such as noise, alternative fuels, or emissions or the impact of such on the aircraft population.

Issues such as the cost of ownership were not addressed in this study as an independent concept. However, the study was designed with a focus on the implications of the age of an aircraft and the maintenance and overall economic life of an asset. This study was quantitative in nature as the researcher was seeking to predict outcomes based on previous statistical information. This research involved using a quantitative design to assess statistics to accept or reject a stated hypothesis as discussed by Tumele (2015) to answer the questions and expand upon relevant theories in the field. The researcher in this study did not seek to forecast or predict issues such as profitability or the earning potential of airlines, banks, finance companies, or lessors.

Assumptions

Although the focus in this study was on the current aircraft of the Boeing Company, the reader must realize that currently, Boeing includes the companies formerly known as the Douglas Aircraft Company and the McDonnell Aircraft Corporation. The two organizations combined in 1967 to form McDonnell Douglas Aircraft Company and subsequently in 1997 were acquired and merged into present-day Boeing. The data analyzed and reviewed represent all three organizations under the current Boeing head banner. This research included only Boeing Commercial Airplanes and therefore eliminated aircraft under Boeing Defense and military products.

The first assumption was the addition of a block of aircraft categorized as being “stored.” It should be made clear that just because the term “stored” is applied it does not mean the aircraft is in fact being correctly stored or maintained to keep the asset in a serviceable condition. The term stored has wide ranging possibilities from aircraft abandoned to aircraft maintained in pristine condition in accordance with the manufacturer’s instructions for continued airworthiness. Clearly, this action peaked during the pandemic and aircraft were being returned to service. As to the interim “stored,” it is logical that aircraft stored without the utilization of a storage maintenance program will require excessive costs to return to service; therefore, the term stored should have been replaced with “parked aircraft.” It should also be clear to the industry that storage may be being used as a term of art where owners are not forced to write off the asset or completely remove it from their balance sheet. This could affect the financial performance of a business unit and in such cases business leaders may choose to classify the asset as being stored. We assume based on the current status of the industry that any aircraft at the 20-year age mark would be hard-pressed to find its way back into operational status. Aircraft at this cutoff were presumed retired in this analysis and research.

As current production and later model aircraft within the MSG-3 time frame have adopted for the most part heavy maintenance visits tied to calendar intervals, earlier aircraft were not developed under such constraints. Faced with this aspect of changes in the measurement units, the researcher decided to convert such data to fit the current intervals. As these aircraft for the most part have been permanently retired or at a minimum stored and with the fleet/model sizes having been diminished, the researcher was moved to use older data available from the manufacturer that were of a general nature and non-specific to some of the model variants.

With these data points, the researcher was able to confirm the aircraft D check/ structural inspection (SI) or heavy maintenance visit (HMV) to a period of corresponding months approximately equal to the flight hour/flight cycle requirements that the aircraft experienced during their operational life. Within this research, the researcher used the terminology of D Check, HMV, 4C Check, and SI as synonymous and to carry the same weight and inference in this product.

The last of the challenges with these model-specific aircraft is that there were no data available as to the original hard time interval for the 707 aircraft to determine the interval period for the D check equivalent, as during that period individual air carriers developed programs based upon experience with the product. The repository for all of the Pan Am technical data was contacted at the “Cradle of Aviation” Museum in Long Island New York and this aspect was researched by the staff who placed the researcher in contact with some retired maintenance planners who agreed with the researcher’s analysis of the situation.

A supplemental structural inspection program is the outgrowth of the 707/720 reassessment (Goranson & Hall, 1980). The authors claimed as Boeing engineers that the supplement does not replace ongoing operator maintenance programs that are effective in maintaining the damage tolerance built into the aircraft. As such and due to the association and combination of the programs, the researcher assigned the same threshold for check intervals as the 707 aircraft that was verified.

Limitations

The major limitation of this research is that there is no specific repository for maintenance, engineering, and technical data on a global level. As such, the ability to triangulate using limited external data and some very general data can produce less-than-desirable results. As each civil airline acts individually and reports to various state regulatory agencies, the data sets are inconsistent. The researcher also did not investigate any effects of ownership on the decision-making process nor was any investigation undertaken to examine the profitability, revenue, or capitalization cost of aircraft whether operated by an airline, bank, or financial institution.

Definitions of Terms

The majority of the terms and definitions were taken from 14 CFR § 1.1 unless otherwise noted by an asterisk (*) after the term for the reader's understanding.

Administrator means the Federal Aviation Administrator or any person to whom they have delegated their authority in the matter concerned.

Aircraft means a device that is used or intended to be used for flight in the air.

Airplane means an engine-driven fixed-wing aircraft that is heavier than air and is supported in flight by the dynamic reaction of the air against its wings.

Civil aircraft means aircraft other than public aircraft.

Air transportation means interstate, overseas, or foreign air transportation or the transportation of mail by aircraft.

Configuration, Maintenance, and Procedures (CMP) document means a document approved by the FAA that contains minimum configuration, operating, and maintenance requirements; hardware life limits; and master minimum equipment list (MMEL) constraints necessary for an airplane-engine combination to meet Extended-range Twin-engine Operations Performance Standards (ETOPS) type design approval requirements.

Approved, unless used with reference to another person, means approved by the FAA or any person to whom the FAA has delegated its authority in the matter concerned, or approved under the provisions of a bilateral agreement between the United States and a foreign country or jurisdiction.

Foreign air carrier means any person other than a citizen of the United States, who undertakes directly, by lease or other arrangement, to engage in air transportation.

Foreign air commerce means the carriage by aircraft of persons or property for compensation or hire, or the carriage of mail by aircraft, or the operation or navigation of aircraft in the conduct or furtherance of a business or vocation in commerce between a place in the United States and any place outside thereof; whether such commerce moves wholly by aircraft or partly by aircraft and partly by other forms of transportation.

Foreign air transportation means the carriage by aircraft of persons or property as a common carrier for compensation or hire, or the carriage of mail by aircraft, in commerce between a place in the United States and any place outside of the United States, whether that commerce moves wholly by aircraft or partly by aircraft and partly by other forms of transportation.

Large aircraft means aircraft of more than 12,500 pounds with a maximum certificated takeoff weight.

International Civil Aviation Organization (*) (ICAO) is part of the United Nations and is funded and directed by 193 national governments to support their diplomacy and cooperation in air transport as signatory states to the Chicago Convention of 1944.

Maintenance means inspection, overhaul, repair, preservation, and the replacement of parts, but excludes preventive maintenance.

Design Service Goal (DSG) refers to the flight cycle, flight hours, and calendar time goals used in the design of the airplane. Other common terms used in the aircraft industry are design service objective (DSO) and design life goal (DLG; FAA, 2013).

List of Acronyms

14 CFR	Code of Federal Regulations, Aeronautics, and Space; contains Federal Aviation Regulations issued by the FAA

49 U.S.C	United States Code Title 49, Formerly Federal Aviation Act of 1958
AC	FAA Advisory Circular that provides guidance such as methods, procedures, and practices acceptable to the Administrator
AD	Airworthiness Directive; U.S. FAA mandatory action to correct a safety problem or issue
ARAC	Aviation Rulemaking Advisory Committee
ASA	American Society of Appraisers
ATA	Air Transport Association of America
AWL	Airworthiness Limitation
CAA	Civil Aviation Authority
CFR	Code of Federal Regulations
CIC	Corrosion Inhibiting Compound
CMP	Configuration, Maintenance, and Procedures
CMR	Certification Maintenance Requirement
CPCP	Corrosion Prevention and Control Program
DFDR	Digital Flight Data Recorder
DOC	Direct Operating Cost
DOM	Date of Manufacture
DSO	Design Service Objective
DSG	Design Service Goal
DLG	Design Life Goal
DTR	Damage Tolerance Rating
EASA	European Union Aviation Safety Agency
EPNdB	Effective Perceived Noise Decibels

ESG	Environmental, Social, Governance
ESL	Economic Service Life
EUL	Economic Useful Life
EWIS	Electrical Wiring Interconnection System
FAA	Federal Aviation Administration (United States of America)
FAR	Federal Aviation Regulation
HMV	Heavy Maintenance Visit
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ISTAT	International Society of Transport Aircraft Trading
LOV	Limit of Validity
MEL	Minimum Equipment List
MPD	Maintenance Planning Document
MRB	Maintenance Review Board
OEM	Original Equipment Manufacturer
PSE	Principal Structural Element
RAP	Repair Assessment Program
RL	Remaining Life
RUL	Remaining Useful Life
S/N or C/N	Serial Number
SB	Service Bulletin
SSID	Supplemental Structural Inspection Document
SSIP	Supplemental Structural Inspection Program
STC	Supplemental Type Certificate
TC	Type Certificate

TCDS	Type Certificate Data Sheet
WFD	Widespread Fatigue Damage
YOM	Year of Manufacture

CHAPTER II

REVIEW OF THE RELEVANT LITERATURE

Chapter II consists of an overview of the extraneous issues in the airline industry that caused a shift in operations. It also covers the concept of the life of an aircraft or the economic life of an asset pointing to various constructs not all remaining consistent, thus causing conflict depending upon the specific application. The chapter concludes with a discussion of the variables and constructs employed in the analysis and why they are relevant to the research and industry from a technical perspective. The literature review addresses concepts and considerations in no particular order; the listings do not signify a level of importance as there is no weighted assessment related to the topic areas. Also, on any given day the situation could become a very fluid aspect of the decision-making process, with importance shifting from technical to geopolitical to economic in mere hours.

Aircraft or assets are an investment strategy either for an airline or financier. As explained by Woods and Hollnagel (2017) in their discussion critique of investments and initiative-taking decisions management may fall short of the goals because they make their decisions only considering a short-term horizon. Maintenance professionals must make short-term immediate decisions that have to be viewed in a longer-term decision paradigm looking far over the horizon, not in weeks, months, or a year but out for the life of an aircraft. Woods and Hollnagel stated, “In the case of research, i.e., activities that take place at academic institutions rather than in industries and are driven by intellectual rather than economic motives, the effects of hindsight ought to be less marked” (p. 1). Research should by its very nature be looking to problems that go beyond the immediate practical needs, and hence address issues that are of a more principal and applied nature. This paper was intended to accomplish that goal by bridging the gap between the two camps of academics and practitioners into a commonplace understanding grounded in reality and practice but bounded by academic theory.

Technical decisions and the aspects surrounding them require some type of assessment or action to be undertaken and tend to find their way to the desk of the technical managers and senior maintenance management staff, whether at an airline, leasing company, or financial investment organization. These individuals are usually challenged to make determinations as to the asset and its longevity and applicability to the organization's use of the equipment both technically and financially. At this point, the complexities inherent in each of the variables discussed are for the most part at a level of detail beyond the reach of laypersons. When trying to assess the condition of an asset, a team may apply terms that are inserted into the discussion such as life, economic life, useful life, fleet life, and service life as different terms may apply to different situations. Many, both in research and conversation, use these terms, which are specifically defined, sometimes interjecting them in a colloquial sense, sometimes being interchangeable in their mind but rarely clearly defined. They may not understand the terms due to their subjectiveness and their encompassing application in various literature.

Decisions are made by staff that affect multiple aspects of maintenance that can have a large swing with dramatic or devastating results for an incorrect move or act. Sometimes these decisions are undertaken as an immediate answer to what is a much longer life view. As technical managers consider economic life, they may see the term used by others within the organization in a different context. For many, the term is applied as an estimate to determine a period, in some cases depreciation, and in others some period in which actions are to transpire, and in some cases to plan for future actions of residuals at the termination of such life. In many instances, the term applies to fixed assets yet some may not consider aircraft as such in the true sense of the term.

Therefore, we end up at a juncture where the practicality of these variables and questions becomes, why is maintenance important, and does it affect the overall age that we retire aircraft? Does the accomplishment of that maintenance have an economic impact, and does it change and vary the life of an asset? The simple answer as to why the industry accomplishes maintenance may be that the regulators require that they perform maintenance, preventative maintenance, and inspection of aircraft. However, the more constructive and disciplined answer is that they wish to assure the operational safety and reliability of the flight equipment so the maintenance group can provide a product, the aircraft to stakeholders to fly the equipment and make money. In simple terms, reliability equals availability.

Airlines, Aircraft, and Economics

Aircraft are complex arrangements of parts that interact with each other to produce a result—flight. Systems depend upon components that depend upon structure to house and organize the parts into a workable conglomerate of assets. Additionally, economic theory encompasses a broad range of topics and inputs as do the economic characteristics of commercial air travel. A fundamental turning point in the airline industry was the Airline Deregulation Act of 1978 when the Civil Aeronautics Board encouraged new entrant airlines and the opening of markets to interstate air transportation. The theme of the Act was that maximum reliance on competition would bring about the objectives of efficiency, innovation, low prices, and service options while still providing the needed air transportation system (Baldwin, 2016). At the same time the industry was encountering a deluge of new entrants, technical management was also undergoing fundamental changes. These were not the old guard that maintained aircraft in a particular way because they had always accomplished tasks in similar constructs based on learned experiences and fixed time intervals. New airlines had new personnel with different experiences and ideas and a more in-depth understanding of the underlying issues and who were concerned with making profits and applying sound management techniques to their decisions. Prior to 1982, the major carriers had in place what was known as the Mutual Aid Pact. This agreement allowed for member airlines to "strike" and the other operators all to raise their fares in support of the airline not flying. The excess in fares, because they were regulated at the time by the government, was distributed to the airline on strike. This created situations for labor to settle as there was no real burden imposed to the carrier involved in the labor dispute.

An analysis by Dempsey (1995) at the time that deregulation was being considered by Congress showed the Airline Deregulation Act when initially examined by Stephen Breyer, now Justice Breyer during his tenure working on a congressional committee as an aid found that he [Breyer] concluded that the Act would only cause airlines to adjust prices only using variable costs and not fixed. How incorrect that analysis was when viewed today. Such a limitation as to only viewing the cost issue was incorrect and when looked at now would suggest a lack of understanding of the market as it has currently evolved or what the Act was fundamentally doing to the industry. Not only did the cost structure change, the industry encountered radical shifts as to how work was accomplished. As pointed out by Benson (2004), there was a time when Pan American Airways was known as the U.S. “chosen instrument” for international commercial aviation, showing a close governmental symbiotic relationship between the two and projecting political clout. The early expansion of airlines such as Pan Am was intended to develop and own the seaplane bases to which they operated and thus control the entrance into a market sector. There were ownership interests between airlines and hotels such as those between United and TWA and the control of catering corporations such as Sky Chefs and American (Cunningham & Khandekar, 1985). Airlines focused on being the sole provider or all-encompassing owner of assets in the travel industry. We tend not to focus on these shifts and how they influenced today’s aviation environment where airlines have become the provider of transport services from point to point, which also is a derivative of the Act. Yet today we find that for most airlines, a major portion of maintenance and repair work is done outside the corporate structure, having been shifted to outside labor and Maintenance and Repair Organizations (MROs). The huge in-house capabilities of airlines have diminished, and gone are the hangars at every airport a company served. The industry has witnessed predatory pricing that developed in the sector and the impetus to cut and control fixed costs such as maintenance that remain in place currently. An example would be the recently proposed merger of Frontier and Spirit Airlines, combining two smaller operations to be in a position to use the economy of scale to better position themselves as a business entity. However, this possibility did not move ahead as these negotiations were terminated as Jet Blue decided to enter the discussions. It is now understood that air carriers such as these that do not find ways to adjust and curtail their high fixed costs are no longer present in today's grouping of airlines.

Today, airlines operate in an increasingly competitive environment caused by the globalization of air transport networks and therefore a necessary condition for airlines to be commercially successful is the reduction of direct operating costs, which mainly depends on the technological and design characteristics of the aircraft used. Technological development is occurring at a rapid rate and we can effectively make use of this technological revolution to reduce the fuel consumption of commercial aircraft. Moreover, the fuel consumption of air transport can be reduced through a variety of options, such as increased aircraft efficiency, improved operations, the use of alternate fuels, socioeconomic measures, and improved infrastructure, but most of the gains so far have resulted from technological improvements to the aircraft themselves.

There is a direct tie between the airlines and the underlying economic conditions present both in the industry and in the overall economy of a society. Airlines in general barely make a profit. Low-cost carriers also put additional pressure on network carriers' operating costs by offering flights at reduced fares (Franke, 2004). Research conducted by Zuidberg (2014) indicated the ownership costs (i.e., depreciation and leasing costs) of new aircraft outweigh the increasing maintenance costs of old aircraft. A comparison of other industries to air transportation demonstrated airlines have a high fixed cost structure and low variable costs (Pompl, 2006; Wells & Wensveen, 2004). Air transportation has always been an extremely capital-intensive industry requiring high dollar investments in assets, which creates high entrance barriers (Joppien, 2006). The predominant reason for this high-cost structure is the investments by original equipment manufacturers (OEMs) that must develop and produce new products. Airlines face the need to provide financing or lease streams for such new aircraft whereas airports that have to be available are mostly public entities that have to develop and provide the infrastructure necessary to operate, all in support of a consumer who must have the disposable income and need to travel. The model becomes almost circular in each trying to make their little bit of profitability. Table 2 shows the utilization as it relates to U.S.-based carriers filing Form 41 data as required by the government.

Table 2

Passenger Air Carriers Filing Schedule P-5.2 Capacity and Utilization

Aircraft category	Number of aircraft	Departures	Passenger capacity	Passenger load factor	Capacity (tons)	Capacity Load factor	Crew size	Block hours	Daily utilization (hours)	Fuel burn per hour (gallons)
Wide body with more than 300 seats	46	20,038	327	81%	62	62%	9	220,210	13.1	2,451
Wide body 300 seats and below	467	250,735	256	82%	47	59%	8	2,091,230	12.3	1,860
Narrow body with more than 160 seats	980	1,180,930	183	86%	24	67%	6	3,991,243	11.2	911
Narrow body 160 seats and below	2,525	3,920,223	152	84%	19	69%	6	9,267,585	10.1	779
All aircraft	4,018	5,371,926	230	83%	38	64%	7	3,892,567	11.7	1500

Note. Adapted from Bureau of Transportation Statistics (2018).

At airports, there is often only limited competition concerning ground handling services, terminal services, and further transport access. Fuel companies are structured in an oligopoly (Kangis & O’Reilly, 1998), which forces air carriers to develop alternatives inclusive of undertakings such as fuel hedging or refinery operations. In addition to competition from within the industry, air carriers face competition from new entrants that affects the value chain in diverse ways, sometimes forcing carriers to become innovative and more risk taking to be able to succeed. Options such as point to point or hub and spoke systems are all possibilities that are examined.

Another major piece of the industry is the aircraft manufacturing component, which is characterized by two dominant manufacturers: Boeing and Airbus. These two companies represent the largest manufacturers in the market (Newhouse, 2007), particularly regarding large and wide-body aircraft. Both OEMs tend to focus on the technical and operational characteristics that become the core of their marketing campaigns. These aspects, paired with elevated levels of technology, product support, and financial support, tend to be the drivers of customer decisions to purchase one product or the other. We have indeed come a long way from the purchase agreement signed in a wooden mockup of the cabin of an Airbus at the Le Bourget Airshow in May 1969, which was to launch the original A300 program (Brown, 2001) and marked the entrance of Airbus to the marketplace. The first type certificated (TC) A-300 aircraft flying for Air France entered the market in 1974, still giving the advantage of almost 20 additional years of experience to Boeing.

Concentrated markets such as airlines and aviation are considered oligopolistic industries by economic standards. They are identifiable by the high entry barriers and the small concentration of participants that dominate the sectors. High entry barriers usually take the form of substantial capital requirements, the need for technical knowledge, patent rights, and so forth, according to Munson (1981). Hölzel et al. (2012) pointed to the three major commercial stakeholders in the air transportation system—aircraft manufacturers, airlines, and MROs—who have conflicting goals, as each are striving for profit maximization within their segments. Each of the aforementioned organizations seeks to be profitable in their sectors yet finds that impossible without each of the others spending capital in their sectors. One tends to believe the economic benefit then becomes captured by each of the stakeholders for their own inherent needs.

Airlines have realized that all costs, fixed and variable, must constantly be controlled to create lower unit costs overall, which can translate to lower fares for consumers and thereby a greater market share. Current airlines and legacy carriers have made conscious decisions to use outsourcing to help reduce their fixed costs and be able to increase the capacity of the systems in which they operate. Assessing the industry and understanding that the fixed costs, for the most part, are constant and inclusive of items such as leases, rent, and ownership, the choice is to make gains in the productivity or output of the assets, which can be shown by the industry’s move to a percentage of their fleets leased into their systems. One has to look no further than the Delta Air Lines model of the 1990s where they chose to continue to operate while taking on additional older aircraft, reducing fixed costs just as in the Northwest model before the carriers were merged (Gudmundsson et al., 2020).

Decision-Based Asset Assessments

Commercial aircraft owners consistently find themselves in the process of making decisions and assessing their fleets, both current and future, against an economic backdrop. Due to the high level of competitiveness and the marginal profitability of the airlines, they must constantly measure both micro and macro economic decisions. The strategic decisions made can affect the longer-term fleet and planning decisions, causing limitations in market penetration or the inability to react to external adjustments. A lack of understanding of point-to-point flying could be the difference in life vests or life rafts being installed in an aircraft with the added weight to hinder individual performance, now multiply that concept by the added weight and additional fuel costs to a fleet.

This is just one example of how the technical aspects are intertwined with an operational goal and do not stand alone—this industry does not act in silos. The understanding and integration of in-depth performance and operational constraints cross multiple areas and departments, from finance to fuel planning, to ground handling, to scheduling all external operational elements.

Issues surrounding the life cycle management of assets move across the spectrum of operational areas from initial service implementation, residual values, maintenance check cycle, fleet commonality, safety, and retirements. Due to the considerable length of elapsed time from the introduction of an aircraft through its service life and on toward retirement, external forces can act upon the decisions. Transition from what is believed to be correct initially at the time and planned for may change. When reviewed later in the longevity of the aircraft's operational arc, these decisions may be found to be inconsistent 5 to 30 years later compared to what actually has transpired in the marketplace. The following discussion outlines those maintenance concepts and explains the interconnected detail that asset managers must be well versed in and deal with daily.

Age and Life Discussion, and the Dilemma in Application

The life of an asset as well as the remaining useful life (RUL) is an estimated number. It is a subjective assessment of the length of time or time remaining in terms of years an item will continue to have its form, fit, and purpose before replacement.

As one of the largest groups supporting various aspects of the commercial aviation industry and the largest block of functioning aviation appraisal professionals, the

International Society of Transport Aircraft Trading (ISTAT), which was founded in 1983, sets basic standards that are accepted by the industry at large. This too was a result of the Airline De-Regulation Act as with that legislation the FAA guaranteed loan program was disbanded. One of ISTAT's objectives is to develop standards governing certain practices and procedures in connection with the appraising of aircraft for the benefit of the industry. As an organization used by the worldwide financial community and aviation stakeholders, it has established a series of definitions. ISTAT, in its list of technical terms, defines the following:

> Life, Economic Useful, as it pertains to an aircraft or engine, the economic useful life is the period over which it is (or is expected to be) physically and economically feasible to operate it in its intended role. Periodic maintenance and repair will usually be required to preserve safety and efficiency during the economic useful life. (p. 30)

ISTAT then under the term Capital Lease references the term "useful life":

> The lease term is equal to 75% or more of the estimated economic life of the property (with exceptions for the used property that is already near the end of its useful life). (p. 38)

A reader could be left in a quagmire when trying to distinguish among the terms life, economic life, useful life, and economic useful life. What may they be speaking to? Are they all the same, are they interchangeable, or are there multiple concepts being referenced and defined in the same document?

This is followed by the second largest group of professional appraisers, the American Society of Appraisers (2020), which also defines the term economic useful life in a similar but different manner:

> Economic useful life is the estimated period, usually stated in the number of years, that a new property may be profitably used for the purpose for which it was intended. Stated another way, economic life is the period, usually stated in the number of years, that a new property can be used before it would benefit the owner to replace it with the most economical replacement property that could perform an equivalent service. Functional or economic obsolescence factors may limit a property's economic life. An asset's economic life will often be less than its normal useful life. (p. 53)

This formal definition places the entire concept of EUL as a choice between either functional or economic obsolescence and additionally introduces the fact that the actual economic life and normal useful life may be two distinct measurements.

The U.S. government has gone to great lengths and detail in an attempt to codify aspects of business and corporations. In 1926, the Air Commerce Act was established and the federal government under the Department of Commerce took control of the airways and began the process of issuing airworthiness certificates. In 1938, the Civil Aeronautics Act was established, organizing both the Civil Aeronautics Administration (CAA) and the Civil Aeronautics Board (CAB). The Board had control over the certification and the Administration had oversight for air traffic, safety, and development. The Federal Aviation Act of 1958 established the Federal Aviation Agency, now independent of the Commerce Department, and its responsibility was expanded to the full statutory responsibilities of the agency. The Johnson Administration created the Department of Transportation in 1966, which took over the responsibilities of FAA oversight and the name now changed to the Federal Aviation Administration. The Airline Deregulation Act of 1978 virtually broke up the requirements for CAB oversight of airfares, allowing free for market control. The FAA, having been tasked with both safety oversight and organizational responsibilities, found itself in areas that it had not considered at the time.

A review of federal rules known as the Code of Federal Regulations (C.F.R.) reveals various defined terms located within its content. Under 14 C.F.R. Part 241 – Uniform System of Accounts and Reports For Large Certificated Air Carriers (1972), the following is included:

> The estimated economic life of leased property: The estimated remaining period during which the property is expected to be economically usable by one or more users, with normal repairs and maintenance, for the purpose for which it was intended at the inception of the lease, without limitation by the lease term. (p. 96)

When searching the CFR in its entirety, there are again conflicting definitions and descriptions that appear to be contradictory. The below citations point to each specific reference as located in the following sections of the CFR. These sections appear to present various and subsequent differences as follows. In 47 CFR § 32.2681 Finance (2019) leases, it is stated that:

> (a) This account shall include all property acquired under a finance lease. A lease qualifies as a finance lease when one or more of the following criteria is met:
>
> > (1) By the end of the lease term, ownership of the leased property is transferred to the lessee.

> (2) The lease contains a bargain purchase option.
>
> (3) The lease term is substantially (75% or more) equal to the estimated useful life of the leased property. However, if the beginning of the lease term falls within the last 25% of the total estimated economic life of the leased property, including earlier years of use, this criterion shall not be used for purposes of classifying the lease. (para. 1)

In 26 CFR § 1.162-3 Materials and supplies (2023), the term economic useful life is defined as follows:

> The economic useful life of a unit of property is not necessarily the useful life inherent in the property but is the period over which the property may reasonably be expected to be useful to the taxpayer or, if the taxpayer is engaged in a trade or business or an activity for the production of income, the period over which the property may reasonably be expected to be useful to the taxpayer in its trade or business or for the production of income, as applicable. The factors that must be considered in determining this period are provided under § 1.167(a)-1(b). (Section 4)

In 26 CFR § 1.167(a)-1 Depreciation in general (1972), useful life is defined as follows:

> For section 167, the estimated useful life of an asset is not necessarily the useful life inherent in the asset but is the period over which the asset may reasonably be expected to be useful to the taxpayer in his trade or business or the production of his income. This period shall be determined by reference to his experience with similar property taking into account present conditions and probable future developments. Some of the factors to be considered in determining this period are (1) wear and tear

> and decay or decline from natural causes, (2) the normal progress of the art, economic changes, inventions, and current developments within the industry and the taxpayer’s trade or business, (3) the climatic and other local conditions peculiar to the taxpayer’s trade or business, and (4) the taxpayer’s policy as to repairs, renewals, and replacements. Salvage value is not a factor to determine useful life. If the taxpayer’s experience is inadequate, the general experience in the industry may be used until the taxpayer’s own experience forms an adequate basis for making the determination. The estimated remaining useful life may be subject to modification because of known to exist at the end of the taxable year and shall be redetermined when necessary, regardless of the method of computing depreciation. However, the estimated remaining useful life shall be redetermined only when the change in the useful life is significant and there is a clear and convincing basis for the redetermination. For rules covering agreements concerning useful life, see section 167(d) and § 1.167(d)-1. If a taxpayer claims an investment credit with concerning set for a taxable year preceding the taxable year in which the asset is considered as placed in service under § 1.167(a)-10(b) or § 1.167(a)-11(e), the useful life of the asset under this paragraph shall be the same useful life assigned to the asset under § 1.46-3(e). (Section b)

Finally, in 7 CFR § 1740.2 Definitions, (2022) economic life is defined as “the estimated useful service life of an asset as determined by RUS [Rural Utility Service]” (para. 16).

Scope Ratings, in its 2022 *Aviation Financing Methodology, Project Finance* report, identified four phases in the lifecycle of any aircraft model: (a) phase-in, (b) mature, (c) phase-out, and (d) out of production. They were also concerned with the fact that a late model or aircraft produced at the end of a production cycle can be at the end of the model life as it rolls off the production line. Scope Ratings took this concept further analytically by developing a metric and regression analysis as stated:

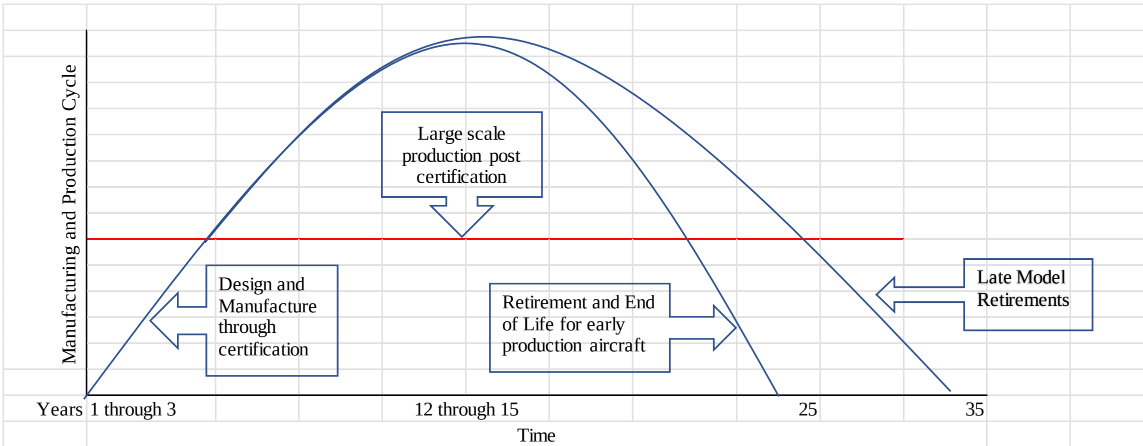
$$\text{Annual depreciation (Age, Body, Phase)} = 4.29\% + \text{Age Factor} \times \text{Age} + \text{Body component (Body)} + \text{Phase Component (Phase)} \quad (1)$$

Where Age is the age of the aircraft in years, and Age factor = 0.23%, Body component depends on the aircraft body type (Regional: 0.77%, Wide body: 1.21%, Narrow body: 0.00%, Freighter: 0.39%), and Phase component is based on the life cycle phase of the aircraft (Phase-in: 1.20%, Phase-out: 1.81%, Phase-mature: 0.00%, Out-of-production: 4.16%; p. 7).

Moody's Investors Service (2020) identified one of the key risks to aircraft investment through securities-backed pools of assets to be the uncertainty in the aircraft's EUL. They stated their understanding of EUL "generally ranges from 16 to 26 years from the date of manufacture" (p. 9). However, there is always the unknown or uncertainty or risk factor due to the long-term nature of most aircraft asset transactions. Thus, over time, the risk factor may change due to changes in the aircraft models' production life or cycle where demand is reduced through the introduction of new technology or replacement model. Based upon the position in the life or age of an aircraft, we may see a shifting as to the retirement age of the asset depending upon the production cycle (see Figure 1) and the placement of such aircraft in the cycle. Retirements come earlier for aircraft delivered during early production years and appear later in life for late models produced during the major manufacturing period.

Figure 1

Aircraft Life Cycle



Age and Life in the Literature

For most, the concept of the "life" of something, whether a product, a tool, or a person, is tied to some understanding of time or usefulness over a period that can be measured. According to the ASA, appraisers speak to age as chronological, effective, and estimated age of the equipment and project a remaining useful life based upon the age of the equipment. They consider aspects such as physical deterioration, loss in value, and the usefulness of a property to affect its useful life. Additionally, aspects such as wear and tear, deterioration, exposure to the environment, and physical stresses are all modeled into an opinion as to the value of an asset.

The age of an aircraft is a fundamental aspect that we take for granted as does the flying public. Yet, the industry may express it as the year of manufacture (YOM) or the date of manufacture (DOM), similar to how people might describe themselves by birth date. Yet aircraft age is fundamentally different in that it is tracked additionally in both a relationship of hours and cycles, much the way in which one tracks miles on cars. In reality, this concept is codified in the regulations as outlined below for Part 121 operators with a similar statement under Part 91 and Part 135 of the CFR:

> § 121.380 Maintenance recording requirements. Each certificate holder shall keep (using the system specified in the manual required in § 121.369) the following records for the periods specified in paragraph (c) of this section: (1) All the records necessary to show that all requirements for the issuance of an airworthiness release under § 121.709 have been met. (2) Records containing the following information: (i) The total time in service of the airframe. (ii) Except as provided in paragraph (b) of this section, the total time in service of each engine and propeller. (iii) The current status of life-limited parts of each airframe, engine, propeller, and appliance. (para. 1)

As more comprehensively explained by Guzhva et al. (2019), flight hours (FHs) refer to the actual number of hours flown by an aircraft over a specific period from the time it lifts its wheels from the ground during takeoff to the time the wheels touch the ground during landing, whereas flight cycle (FC) includes takeoff and landing. MacLean et al. (2018) explained how early evidence that came out of degradation was a precursor for accelerated failure rates in the industry. Additionally, it is said that as aircraft age accumulates there is a long arc of trajectory that the asset exhibits which can be identified as the aircraft life cycle of that particular aircraft. However, in the United States, airline operators are bound by the regulations identified above to account for the hours and cycles although there are multiple other reasons and logic to do so.

Age is a major factor in how aircraft are looked at both by experts and the public. In any consideration of operating condition, the age of a particular aircraft is a major factor. Much attention is focused on planes that are aged; that is, aircraft with chronological age or accumulated hours of use beyond a threshold (MacLean et al., 2018). MacLean et al. (2018) made the distinction that “being aged is a state, and should be distinguished from aging, which is a process of degradation with use” (p. 1). Those in the industry understand that as fleets mature, maintenance will increase and the degradation of these aircraft started on the first flight and continues throughout the time of operation, with the rate being affected by aircraft design, patterns of use, and maintenance procedures accomplished by the operator. The FAA, through Order 8900.1 for Part 121 operators, developed guidance for aviation safety inspectors (ASIs) to ensure the operator they oversee incorporates additional age-related structural inspections into its scheduled inspection program.

Ahmed (1973) stated a given truck (or any other vehicle) reaches its maximum economic life when its repair cost is higher than its replacement cost. The key issue becomes how to determine the economic life of a vehicle such as an aircraft—did Ahmed intend to include planes, boats, and trains when he used the term vehicle? Carreira (2018) stipulated that in the aircraft leasing market aircraft may have shorter lives, although the economic lives of aircraft may be around 20–30 years. Does the ESL establish the point at which the minimum equivalent annual costs occur (Blank & Tarquin, 2018) but is it true that the service life is a manufacturer-defined term? Is remaining useful life not a subjective measurement?

Keyghobadi (1958) stated the total cost of the acquisition of an asset as well as its productivity are usually measured over the whole life of the asset, but in the next sentence noted economic life is unclear. Blank and Tarquin (2018) clearly stated that life cycle cost (LCC) = the total cost of acquisition + the total cost of ownership + disposal. Lawand et al. (2020) used the terms product's life, component's life, lifecycle, and lifespan interchangeably in his research. The expression commonly used in referring to the life of a particular asset is economic life. However, the meaning of economic life is not always clear, according to Ireson and Grant (1955).

The lifespan of aircraft has evolved and continues to change along with the technologies used to design, develop, and build aircraft. Kourousis (2020) mentioned lifespan in his discussion of airworthiness but did not identify any specifics as to its application. He followed the pattern of many, believing life or the lifespan is an "understood" aspect of the industry. Costa Jardo et al. (2011), in their development of a life cycle assessment model, determined there to be three main phases of aircraft lifespan that consist of the system boundaries: aircraft manufacturing, aircraft maintenance, and aircraft operation.

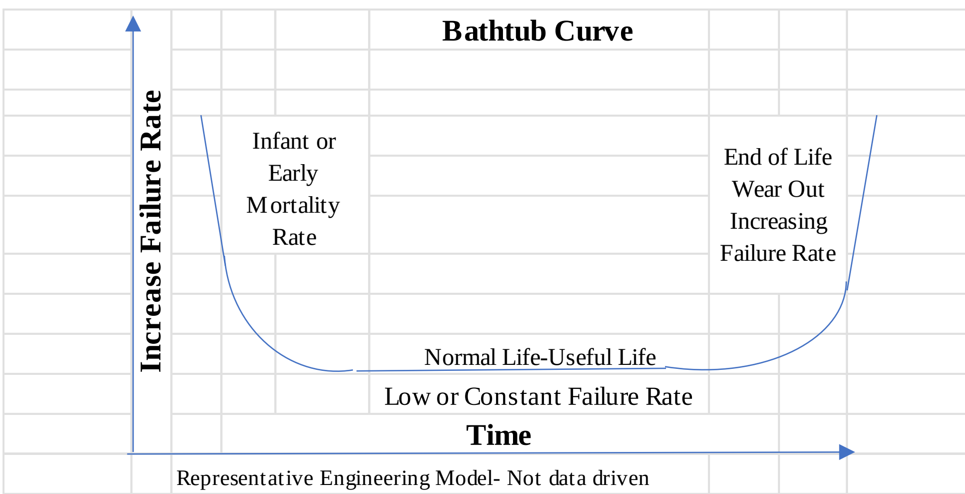
It would appear that, according to Badiru and Omitaomu (2011), there are three distinct divisions of the life of an asset: ownership life, useful life, and economic life. The ownership point is when the asset becomes acquired until the point at which it is disposed of. The useful life by all accounts is the point at which the asset remains in productive service, whereas economic life is shorter than useful life and the measurement used for replacement calculations.

Manufacturers produce aircraft retirement data modeled using a 20-year horizon in their market forecast development documents. Heng et al. (2009) looked at the machine failure aspect to estimate and forecast the survival probabilities of assets by developing survival curves. Previous research conducted by Dhillon (1989) and later by

Blanchard (1991) developed economic curves referred to as "bathtub" or survival curves that presented the average distribution in the percentage of aircraft maintenance cost across facilities in Europe. Their findings were presented as an average total maintenance cost during the lifespan of the aircraft. This was calculated by multiplying the average maintenance cost per block with the service life of the aircraft. However, the question is, what is the service life or the lifespan of an aircraft? They identified both yet defined neither—Are they the same or different, or is it assumed that these are understood? As we seek to visualize and understand life and the life cycle we use a traditional bathtub model as shown in Figure 2.

Figure 2

Bathtub Curve for Failure Rate Analysis



Note. Author's representation using concepts from Zhou et al. (2017).

According to Ireson and Grant (1955), the meaning of EUL is not always clear. They further stated that because the meaning is not clear, its application to the investment of capital may not be specific and absolute. Thus, as applied, economic life is not only dependent upon the asset but inclusive of the environmental circumstances in which that asset operates. Ireson and Grant continued this thought process and included it specifically in the text, *Principles of Engineering Economy*:

> The notion that an asset has an economic life determinable in advance is decidedly misleading. However, if enough elements of the replacement economy situation were immune from change "economic life" could then have a definite and useful meaning. If each new asset could be I counted on to repeat the cost history of its predecessor asset, having the same first cost, the same salvage value of each age, and the same annual receipt and disbursements as its predecessor for each year of life, there would be one particular life that would be economically superior to all the others. If receipts, other than from salvage value, were independent of age, the life would be the one that resulted in minimum equivalent uniform assessed cost in the long run. (p. 96)

Discussions around economic life must consider issues such as the obsolescence of the asset. But how is that measured with any projection for future obsolescence with a reasonable degree of certainty of the asset's continued use? Prienriech (1940) stated the economic life of a machine cannot be determined in isolation. However, as aircraft are developed, we may find that the parts of the whole aircraft may exceed the lifespans of the components from which they are assembled. Management of such obsolescence becomes an important aspect of overall lifespan considerations. In their study, Li et al. (2016) pointed to another aspect that can determine the obsolescence of an aircraft—the sufficient availability of spare parts, which is crucial for the prolonged maintenance of long field-life systems. This concept was further supported by Feng (2007), who stated that over 20 to 30 years, thousands of parts for a single aircraft alone face obsolescence every 1 to 2 years because the system life is approximately 10 times longer than the procurement life of many of the electronic parts (p. 2). As the industry has moved from analog to digital systems, this may be part of the reason the lifespan appears to be getting shorter.

Ahmed (1973), in his study of optimal equipment replacement policy, stated that: “As machinery grows older, the increasing operating and maintenance costs are accompanied by a fall in its value and productivity. The maximum physical life of a capital good ends when its repair is physically impossible” (p. 72). Similarly, the maximum economic life of a machine may be defined at the point in time when its repair costs will exceed the replacement cost of the machine. Then there are those such as Prezas (1994) who described a model that shows optimal investment and optimal asset life are interdependent through operating cash flows and depreciation allowance with no indication as to what type of life or how it is determined. Although this premise is widely accepted, aircraft are considered by some to be outside of the actual model and may continue to survive well past the point of physical life as determined by the industry. As an example, the DC-3 aircraft was built in the 1930s–1940s and some of its commercial and military variants still function as freighters in revenue service as well as a large block at the Israeli Defense Forces (IDF) until recently. Similarly, the Lockheed C-130 aircraft was first delivered to the U.S. military in 1956 and is still in active service some 65 years later, long past what most would consider to be the life of the asset.

Hours and Cycles

According to *Aircraft Value News* (“10 million sale of 20 B737-200ADVs,” 2004), one carrier, due to its operations of short-haul flights, accumulated a higher hour cycle rate, which “places great demands on its aircraft in terms of utilization and they likely have accumulated a considerable number of hours and cycles, making them less attractive to the market” (p. 1). This implies hours and cycles have an impact on the value of the underlying equipment. This was supported by Avitas, when speaking to *Airline Financial News* (“Regional Jet Sector Continues Its Power Surge,” 2000), who stated the “structure of an aircraft and the systems fitted within it may be repaired or upgraded over time, the airframe gradually ages as flying hours and cycles are logged” (p. 1). Mofokeng et al. (2020), in a study related to the life phases of an aircraft (i.e., design, production, operation, and decommissioning), found that the aircraft with the highest maintenance cost had the highest flight hours in the fleet, thereby showing the concept and tracking of times are correlated to maintenance costs.

Recent large-capacity jet data from the FAA-sourced Form 41 data collection show that of the 4,018 aircraft operating in the United States in the year 2018, average daily utilization exceeded 11.7 hours. Some believe in a statistical difference in the ability of low cost carriers (LCCs) to get greater utilization of aircraft than the legacy carriers. That may have been true in the past. However, as LCCs develop basically a similar flight time schedule to the same airports that is no longer true. According to the FAA’s John Petrakis,

> Aircraft lifespan is established by the manufacturer . . . and is usually based on takeoff and landing cycles. The fuselage is most susceptible to fatigue, but the wings are too, especially on short hauls where an aircraft goes through pressurization cycles every day. (Maksel, 2018, para. 3)

The industry may focus on the age of an aircraft, which for most is a measurement cogent aspect, but it does not stand alone. Lifespan should be calculated using numerous factors, such as cyclic utilization, pressure cycles, flight hours, and maintenance and operational inputs, in an attempt to understand how long an aircraft will remain in service. We do not use miles traveled like an automobile to determine both value and lifespan.

Duncan (1991) stated aviation experts agree that chronological age alone is not an effective measure of a plane's condition and that the times (i.e., hours and cycles) must be considered. He went on to discuss the concept of the impact of flight cycles or the pressure cycling of operations on the fuselage. Most could point to the Aloha incident of 1988 as empirical support for that theory about the loss of life, thus showing the short flight segments and the pressure cycling of the aircraft detrimentally affecting the aircraft and placing constant expansion and contraction stresses on the structural members. In theory, an aircraft could be considered to "fly forever," or as some may state fly to failure; however, the question is at what cost, and does that make sound economic sense and policy if an operator's costs are increasing?

Scheduled maintenance occurs using three criteria for measurements: hours, cycles, and calendar times. As aircraft continue to age, they may reach the age and cycle threshold of their "economic design goal" where specific Airworthiness Directives apply.

Maintenance

Per the Federal Aviation Regulations (FARs), the strict definition of maintenance is the inspection, overhaul, repair, preservation, and replacement of parts, but excludes preventive maintenance. Under the definition provided by the airline industry standard *World Airlines Technical Operations Glossary* (WATOG; ATA, 1992), maintenance is "those actions required for restoring an item to serviceable condition [note *serviceable i*s not a defined term] including servicing, repair, modification, overhaul, inspection, and determination of condition" (p. 68). For the executive who may operate in multiple regulatory environments, there appears to be conflicting guidance as to exactly what it is that is being spoken about. The maintenance and management of today's commercial fleet have developed over time into a labor-intensive marketplace where maintenance and repair organizations (MROs) have grown to accommodate the demand. For the most part, the legacy carriers still perform in-house support of their equipment but have grown to rely upon the ability to farm out as needed the aspects that would throw off their standard lines of production. Trade unions, the lifeblood of most established carriers, have complained as work is shifted to outside MROs where labor-intensive work is accomplished at reduced costs. Additionally, the OEMs have offered their product lines such as "Gold Care," which is provided at a fixed cost solution as the payments are directly tied to a cost per flight hour rate. This program is also sold as a residual value enhancer to both leasing companies and operators who own their equipment. This is parallel to the type of product support options that have previously been developed for business jet fleets that are designed to avoid maintenance and support overhead costs. Such support programs have enabled OEMs to become a more integral part of the operations side of the equation, allowing for closer contact with the operators over the life cycle of the product, which gives way to enhancing new product and sales developments as technology warrants.

The overall concept of maintenance is implemented mostly as a form of preventative maintenance or preemptive approaches to the actual maintenance, and therefore outside of the FAA’s defined term. Airlines and operators choose to do such work to avoid the possible service interruption that can occur from actual faults being found, at which time the event becomes a true maintenance task. It is understood from an industry perspective that the essential aspects of the aircraft must be in complete and functioning order, save and except those that may be deferred by use of the operator’s maintenance program or that of the minimum equipment list (MEL). For example, changing a tire before it falls below allowable tread limitations is a preventative action; an additional quantity of landings could be obtained through its replacement but a service interruption at a non-maintenance station could damage a series of scheduled flights, causing increased operational and economic impact to the carrier. Such a decision is made at the actual mechanic level as a function of that individual making both an operational decision and an economic one as the tire still has a level of functional life remaining, but a preventative act is deciding to abandon that life still within the unit. Although rarely thought of as such, the mechanic is determined to act in a preventive function via their decision to replace the tire.

Maintenance Fundamentals and Philosophies

Reliability has increased as changes occurred in maintenance, and such advances have changed the maintenance philosophy. These have evolved since the Second World War as shifts have occurred to the concept of hard time maintenance events (S. J. Wright, 2021). Changes began to develop conceptually as the industry moved to greater numbers of aircraft being produced. Thus, aircraft were able to account for both expansion in sizes and gauge of equipment as well as performance changes in equipment. As such, a philosophical change ensued, moving from labor-intensive overhauls and part disassembles to removal and replacement strategies employed in daily operations. Training to determine fault identification and isolation as opposed to the remove and replace strategy changed the focus of maintenance support. Present-day thought is that regular maintenance activities are optimized for the use and operation of the system (i.e., the aircraft). As an industry, the focus has shifted from tearing down components to minute levels and rebuilding them from the ground up to mathematical and computer-driven data collection systems to view performance data across the fleet and industry.

The efficiency and effectiveness of aircraft maintenance are dependent upon multiple factors. However, the paramount consideration is that of integration within the airline's operating system (i.e., how the airline functions and performs). Take, for example, a carrier that is highly dependent upon summer travel for a customer base. This would dictate that during the summer months, an aircraft should not be down for maintenance. That forces maintenance scheduling to either "extend" the check time or accomplish the scheduled task prematurely, thus losing part of the actual period of a time interval. The maintenance and scheduling philosophy must be capable of dovetailing into the fundamental business of the air carrier. Therefore, it is imperative that the maintenance organization interacts with and influences the marketing and operational needs of the carrier. Maintenance is no longer a standalone entity and the financial implications carry through to the rest of the organization.

Evaluating the engineering capability of the supplier becomes a management decision where the matter of reputation is based on the experiences and satisfaction of others (Leonard, 1984). However, we should consider the analysis and decision aspect as a system analysis philosophy. Such processes begin with the discovery of a fault or defect, whose subsequent analysis determines sometimes through consequence an outcome that determines whether a specific preventive maintenance task should be developed. Most analysis is done for the program and the overall philosophy for a fleet of aircraft as opposed to a single unit. What this process in general omits is that of a specific unit causing an issue. That may be overshadowed by the larger data analysis and therefore details must be reviewed at a granular level to find an airplane issue as opposed to that of a fleet.

Safe-Life, Fail-Safe, and Damage Tolerance

As both the airlines and the industry aged, three different approaches emerged to ensure the safety of aircraft. The approach that began the process is that of a “safe-life.” In this approach, a given component is assumed to be safe, under the prescribed operating loads, for a given number of service or pressure cycles. Should a component’s cyclic count exceed this limitation, it would become scheduled for replacement. This limitation is derived from experimental data. Eastin (2009) took the concept of a “safe-life” approach to a further level. His concept was based on replacing or retiring structure before the probability of cracking is significant and he referred to it as safety-by-retirement (SBR). In the early 1970s, the USAF established the safe-life of the airplane by dividing the number of successfully tested flight hours by a factor called the scatter factor (Lincoln & Melliere, 1999). The USAF believed this factoring would account for any variation in an aircraft-to-aircraft analysis and thus become the baseline statistic. However, the research would only be used to determine by a cost factor as to when an aircraft should be retired. Therefore it measured the economic life of the product according to their conclusion in 1978 this process again was reconsidered to become safety-by-inspection (SBI) at which time it became the preferred methodology employed. This process may produce an economic burden as a component could experience an unnecessary maintenance event, thereby increasing unwarranted costs. The outgrowth of this approach saw the industry embrace the concept of a “fail-safe” design where the requirement was for the complete structure to be capable of sustaining levels of damage without encountering a catastrophic event or loss of the entire aircraft. Inherent in this process are multiple load paths for the distribution of that loading factor. The FAA amended its Fatigue Evaluation in December of 1978 to include a “damage tolerance” in addition to both “fail-safe” and “safe-life” concepts. Before the change, FAR 25.571 contained an option for the manufacturer to design to either concept. Boeing had manufactured aircraft using the fail-safe concept for the most part. However, some components were developed and manufactured using the safe-life concept of fatigue evaluation. Through this concept, redundancy was built into the system to avoid a catastrophic failure that could be attributed to fatigue failures. The inclusion of the damage tolerance concept brought the manufacturers to an evaluation process whereby they had to assure a catastrophic failure due to fatigue, corrosion, or accidental damage would be avoided during the operational life of the aircraft (FAA, 2011). In response to these new requirements, inspection philosophy and techniques were combined with inspection interval scheduling to ensure no cracking of the structure would develop and progress to a level of criticality before detection. This philosophical change that moved the industry to a damage-tolerant concept was supported through analytical assessment, full fuselage testing, and experimental tests. Aircraft experience fatigue throughout their operational life. With such stress, there is a need to determine crack growth in critical areas. Once detected, repairs or modifications/replacement must be accomplished so the cracks do not affect other areas of the aircraft. This philosophy entails the knowledge related to the fatigue life of the structure. The goal is to eliminate a partial failure of a single principal structural element that, if left undetected, could affect the entire aircraft. Since amended in 1978 and over the last 40 years, the FAR changed to include a "damage tolerance evaluation." This process has shown evaluation to ensure damage-tolerant structure based on crack propagation and residual strength analysis has paid off. Concerns exist that cracks, if left unchecked, could progress and reach a critical size.

Boeing developed a maintenance philosophy from the 737-600 forward of commonality of the family type that enabled both maintenance and training efficiencies. In the mid-2000s, Boeing lengthened approximately 33% of its scheduled maintenance task intervals, which equated to savings in both time and costs for all operators. These extensions were able to be accomplished based on the statistical analysis and reliability of the systems as reported to the OEMs by the operators from in-service data.

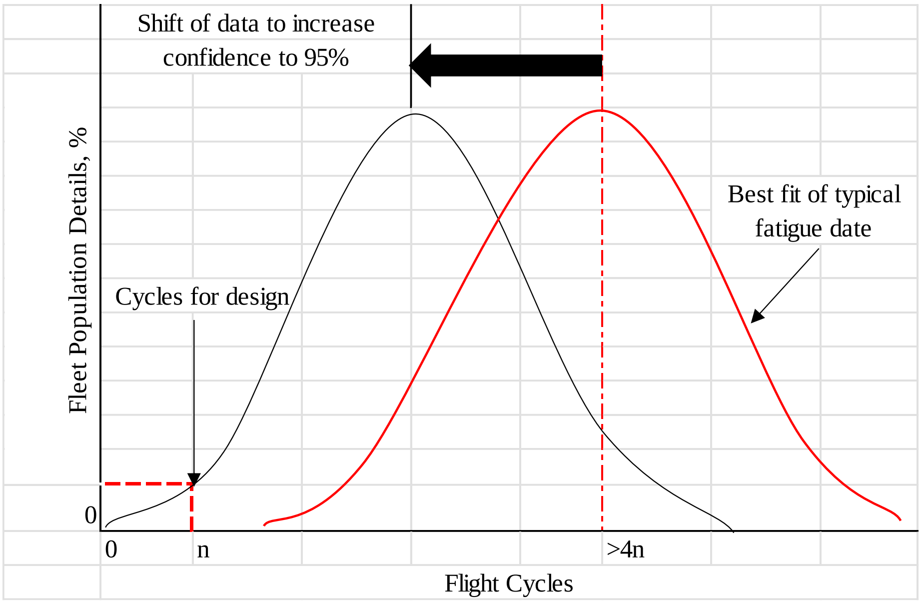
The concept of LOV is established by regulation 14 CFR § 25.571 that outlines the initial period during which aircraft may operate prior to exceeding their total operational life as support from the manufacturer will no longer be available as the milestones are achieved. "The total accumulated flight cycles or flight hours or both, during which it is demonstrated that widespread fatigue damage will not occur in the airplane structure" (FAA, 2010, p. 69781) thereby tying the concept's valid data and hours and cycles together.

To visualize the progression of the development of an aircraft program, the same threads become clear irrespective of the manufacturer. The endeavor to tie the product to a concept of both continuous improvements and a sunset possibility at some point in the future is standard. Typical aircraft programs begin with a conceptualization phase or that of initial design concepts. This process is a high-cost high-risk aspect of the design. Conceptually at this point, there is no launch customer, there are only forecasts as to both the sustainability and long-term production of the product under consideration. Yet we find that the modern design/concept is the replacement of an existing model that may begin its sunset and the modern design or replacement is to be undertaken to improve aspects such as performance and economics.

Airframe maintenance tasks are divided into line maintenance, A checks, and base check maintenance. To be specific, the term A check no longer finds a basis in MSG-3 program guidance though many operators tend to continue to use such a term as a “generic” measurement interval for a small check. Manufacturers develop a document identified as the Maintenance Planning Document (MPD). This document undergoes revisions based on input from the in-service and technical analysis accomplished by the OEMs and operators. Maintenance programs and practices have continued to evolve since the original MSG-1 programs of the 1960s. Programs have transitioned, and philosophical changes have taken place in the movement from safe-life considerations to fail-safe designed initiatives to the current trend of damage-tolerant structures. Figure 3 outlines the data shift experienced between original design data and that required to achieve a 95% confidence level in the structure.

Figure 3

Fatigue Design Criteria and Confidence Levels



Note. Adapted from The Boeing Company (1999b) with permission.

Aircraft Maintenance Programs

In focusing on a single manufacturer and conducting a U.S. concentric investigation, it should be noted that differences exist between the FAA and EASA requirements related to the overall aircraft maintenance program concept as defined by the appropriate regulatory bodies. At a high-level distinction, EASA views the accomplishment and findings of the repetitive maintenance or preventative maintenance accomplished to be considered a reliability program and sets forth procedures for the management of the task accomplishments. Most misunderstand a maintenance program and assume it to be the schedule or maintenance plan (MP) or what is identified in the OEM's maintenance planning document. That is not correct, as the maintenance program consists of multiple independent programs and resources that provide data and information for analysis. On the FAA-centric side, each Continuous Airworthy

Maintenance Program (CAMP; FAA, 2016) must contain 10 unique and specific elements:

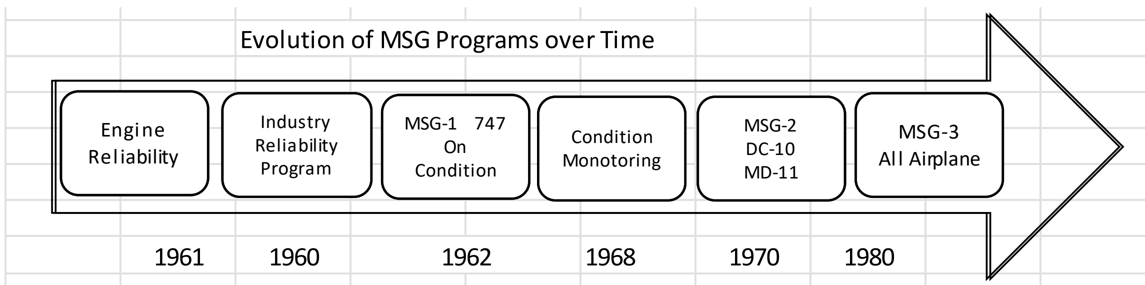
- Airworthiness responsibility
- Air carrier maintenance manual
- Air carrier maintenance organization
- Accomplishment and approval of maintenance and alterations
- Maintenance schedule
- Required inspection items (RIIs)
- Maintenance recordkeeping system
- Contract maintenance
- Personnel training
- Continuing Analysis and Surveillance System (CASS)

Dhillon (2006) discussed an “optimum” maintenance program as a six-step process including the following: (a) identification of issue, (b) definition of periodic maintenance, (c) determination of the frequency of accomplishment, (d) task level approval either by regulatory or program incorporation, (e) schedule activity for accomplishment within the 12-month cycle, and (f) expansion of preventative tasks based upon operational feedback. Aircraft maintenance programs are extracted from the type design certification of the aircraft and the Airworthiness Limitations Section (ALS) and the Certification Maintenance Requirement (CMR). In 1968, the first of the joint efforts of the airline industry, manufacturers, and the FAA took place and outlined the Maintenance Evaluation and Program Development document as part of the undertaking of the MSG. The establishment and guidelines for maintenance programs reside in the

MSG-3 (Air Transport Association of America [ATA], 1970). The concept of a decision-based logic approach was introduced to maintenance professionals, whereby units would become removed from operational service before a fault could occur that would affect the operational reliability of the product. Through the use of the decision logic approach to scheduling maintenance events, the goal was to design a system that would constantly be evolving to meet the needs of the community. Figure 4 displays the evolution of the maintenance program development over time.

Figure 4

Maintenance Program Evolution



Original maintenance programs and concepts relied upon issues predominantly described as hard time. This process involved a component being removed at a specific interval and sent out to be overhauled, refurbished, or bench checked and tested before reinstallation on an aircraft. The early experience came from programs that were developed during the formative years of commercial aviation when items would wear out at a predicted rate, such as in the case of radial engines, which included pistons and rings on internal combustion engines. That experience was carried through to the jet age fleet only to find out through operations that it was not necessary to overhaul all components. At the time most would speak to the “overhaul” as making like new or rebuilding to original specifications (FAA, 2009, p. 844). There were, at the time, some in the industry who believed the life of the hard time component could be fully restored through the appropriate maintenance activities.

Next came the process known in the industry as MSG-1, which contained two processes, that of hard time, or a preventive maintenance process that requires a system or component to be overhauled or removed from service at fixed periods, and on-condition (OC), or a preventive maintenance process that requires a system or component to be inspected for serviceability (i.e., to be removed from service before failure). This required that the item be checked or inspected against some standard of measurement.

The ATA (1970) updated its MSG-1 program to what was referenced by the industry as MSG-2, to which a decision logic matrix was added for newly manufactured aircraft. This also contained failure mode analysis for removed components and analyzed the process-based accomplishment of tasks as well as added a third maintenance process of condition monitoring: maintenance process, no preventive, which allows a system or component to operate until failure without an adverse effect on safety. The MSG-2 process increased the effectiveness of the previous program but also failed to consider specific aspects of maintenance. A major portion of missing information was the fact that there were no economic considerations within the program. This was combined with a large number of components to track, the increasing level of interrelated system aspects due to complexities of systems, and that of an industry still functioning on what was known as a Kardex (cardex) system of paper-based tracking before the broad acceptance of computerization applications. A key aspect to understand is that not all aircraft made the transitions as programs changed. According to R. W. Anderson (1999), the conversion of an existing MSG-2 aircraft maintenance program to an MSG-3 program is a significant effort, but one that results in both safety and economic/operational benefits. It became clear that operators of smaller fleets would not find the benefit and thus continued to operate under their current maintenance programs.

Aircraft maintenance checks are guided by the MSG-3 philosophy (Muchiri, 2002). In 1980, a revised program titled MSG-3 was adopted that revised and changed the entire concept, breaking down failure modes to that of both safety and economic orientated. The original MSG-3 consisted of two basic tasks/checks; the first was a functional check (i.e., on-condition inspection), which aims to detect potential failures, and the second was an operational check-visual inspection (failure finding inspection), which aims to detect hidden failures (Nowlan & Heap, 1978). Those most familiar with the MSG-3 program would describe it as a reliability-centered maintenance program concept. A major change in the MSG-3 concept was a movement away from the term "on-condition inspection" used in the original program to "inspection/functional check." This change removed the ambiguity as some maintenance personnel misunderstood the previous term to indicate nothing was done and neglected the item of equipment until a failure occurred. As the concept of a task-originated process developed, the industry moved away from the three original processes to a program that invoked a structured logic metric inclusive of Corrosion Prevention and Control Program (CPCP), Enhanced Zonal Analysis Procedure (EZAP[1]), and Electrical Wiring Interconnect System (EWIS)

[1] AC No: 120-102A - Enhanced Airworthiness Program for Airplane Systems/Fuel Tank Safety (EAPAS/FTS) Rule includes the electrical wiring interconnection systems (EWIS) and instructions for continued airworthiness (ICA) using an enhanced zonal analysis procedure (EZAP).

as well as Lightning/High-Intensity Radiated Fields (L/HIRF[2]). Although there are sections of this chapter that discuss both corrosion and the CPCP in greater detail within this investigation, to be all-inclusive, a brief discussion of the three sub-programs follows. Each of these subprograms in and of themselves could be an expanded discussion.

EZAP

EZAP consists of four basics for analyzing airplane zones, with an emphasis on wiring systems. If the zone contains both wiring and combustible materials, tasks are assigned to remove or minimize the buildup of combustible materials in the zone, which is now part of the MSG-3 process through a detailed inspection of the condition of the wiring properly (FAA, 2017).

EZAP applies only to zones of the aircraft that contain systems installation with electrical wiring, including the potential for combustible material presence. EZAP is the standalone inspection task focused on the zonal inspection process. Figure 5 shows the EZAP program falls within the decision matrix of the zonal concept of an overall maintenance program.

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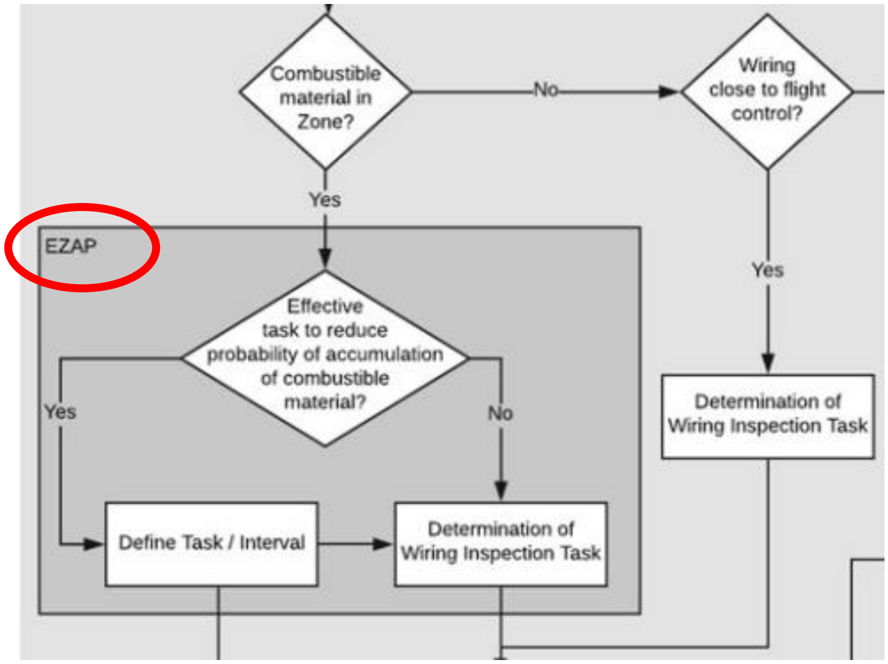
[2] DOT/FAA/AR-99/50 - Recent advances in electronics and the growth of radio communications and other electronic technologies have introduced into the operational environment phenomena known as High-Intensity Radiated Fields (HIRF). The addition of "L" adds the aspect of damage as a result of lightning strikes received by the aircraft and expands the investigation to include such (ref. 14CFR§29.1317).

Figure 5

Enhanced Zonal Analysis Procedure (Required Tasks)



EWIS

Issues were identified and located in aircraft due to the degradation of the electrical wiring systems such as the termination of unused wires and arcing events after the investigation of TWA Flight 800. Degradation is a process that is a function of several variables; aging is only one of these other factors that influence EWIS. Additional causes are degradation due to the environment in which it flies, the physical properties of the EWIS (i.e., type of wire and insulation), and the physical installation of the wiring (e.g., in a fuel tank or a hot area; FAA, 1997).

L/HIRF

Lightning strikes to airplanes can affect structures at the entrance and exit points and may occur without indication to the flight crew. The maintenance and engineering staff look for evidence such as melt-through of the metal, discoloration by heating, pitting on the surface or burn around rivets, and in extreme cases loss of structure at entrance points. This is now included as part of the MSG-3 process. The largest possibility for a lightning strike on an aircraft is when the aircraft in directly in the cloud (see Table 3).

Table 3

Airplane Lightning Strikes by Cloud Orientation

Cloud orientation	Percent of total reported
Above	<1%
Within	96%
Below	3%
Between	<1%
Beside	<1%

Note. Summary data adapted from Plumer et al. (1985).

In its current state of development and continuous revision, the program is viewed as a progressive logical decision. As such, it takes inputs and feedback and adjusts to account for changes within the population. The program's key elements related to the structural component include age exploration, accidental damage, fatigue damage, and environmental deterioration of the aircraft. Additionally, the analysis as to the system level has become the norm, shifting from the component level, and the old process-orientated aspect has been replaced by that of specific task-orientated reviews.

A substantial part of airlines' operational costs is taken up by the accomplishment of maintenance that takes place during the operational phase of an aircraft's life cycle (Stadnicka et al., 2017). As the concepts matured and information was gathered and analyzed from an engineering perspective, both the complexity and interactivity began to develop that subsequently influenced changes in the associated respective aircraft systems. Table 4 presents the three basic maintenance functions and their application. The industry has moved away from hard time to checking and testing the functionality of systems on the aircraft as opposed to the hard time removals and checking the component in a back shop.

Table 4

Maintenance Processes Defined

Maintenance process	Explanation or defined terms
Condition monitoring (C/M)	A maintenance concept that relies on surveillance plus evaluation of the airplane system or component performance as its primary criteria for airworthiness. The program consists of collecting data and the analysis of that data to keep the airplane in a safe condition. The unit is neither hard timed (H/T) or on condition (O/C).
On condition (O/C)	Applicable to components on which a determination of continued airworthiness may be made by visual inspection, measurement, tests, or other means without teardown inspection of an overhaul.
Hard-time (H/T)	A preventative maintenance process that requires a unit to be removed from service and physically restored to its design configuration (zero timed) at a specified time interval (time between overhaul [TBO]) by the unit Component Maintenance Manual (CMM).
Notes for changes	C/M units that have an age-related trend or pattern of malfunction could be changed to either H/T or O/C. O/C components may become changed to H/T if the ability exists through data collection to validate a predictable rate of deterioration.

Design Service Objective/Design Service Goal (DSO/DSG)

Manufacturers in the type certificate application process identify an expected economic life for the airplane, known as a design service goal (DSG). Applicants traditionally defined the DSG early in the development of a new airplane based on economic analyses, past service experience with prior models, and in some cases fatigue testing. Many aircraft today are still being operated and have exceeded their design service objectives (DSOs); as a result, the incidences of fatigue and corrosion may become widespread, according to McGuire and Goranson (1992). Aircraft continue to display safe and reliable performance well past their original design specifications related to total time and total cycles accumulated. The DSO is the flight cycle, flight hours, and calendar time goals used in the design of the airplane. Boeing airplanes are designed to provide corrosion protection throughout their design service life of 20 years (The Boeing Company, 1999a). Boeing also indicates the DSO is a concept that is useful for assessing the economics of airplane structural maintenance: "Continued airworthiness up to, and beyond, the DSO is assured by effective scheduled maintenance and compliance with mandatory actions" (p. 1). As part of the certification process, 14 CFR§ 25.571 requires a full-scale fatigue test demonstrating that widespread fatigue damage is not occurring before the aircraft reaching its DSG expected economic life. This DSO/DSG ties into the issue of the age or life of the aircraft and therefore the discussion comes full circle as to why we track hours and cycles as a defined measurement of the aircraft equipment. This concept should be familiar to all who drive with an oil change interval at every 3,000 or 5,000 miles accumulated on the vehicle. On aircraft, we usually do not do an oil change but do change the filter as an assigned task interval and add oil daily.

The ICAO addresses the term “operational life” throughout its materials, annexes, and guidance, particularly under Annex 8, Airworthiness of Aircraft Chapter 3, yet there is no definition of the term as it is implied to be understood. Boeing (The Boeing Company, 1990), used the term original design life objectives when addressing that both economic and market conditions resulted in the use of aircraft beyond that threshold while forecasting a retirement age upwards of 25 years. Boeing (The Boeing Company, 2003) at the time stated that “as proven by the high time airplanes still in service, the useful economic life of transport category aircraft has proven to be greater than the original design objective” (p. 1-2).

Table 5 identifies the dates of entry into service (EIS) of the aircraft in the study and the specific DSOs applicable to each model as it relates to flight cycle, flight hours, or actual calendar limitations imposed by the manufacturer. It should be noted that the prevailing limitation in all cases is whichever of the three events would occur first as the precedent setting factor.

Table 5

Design Service Objective and LOV Data

Airplane model / Series	Entry into service	Produced	In commercial service December 31, 2021	Interval C=F/Cycles H=F/Hours Y=Years	Minimum design service objectives	Limit of validity
707	1958	856	0<	C	20,000	NO
				H	60,000	LOV
				Y	20	14CFR26.21(g)
720	1960	154	0<	C	30,000	NO
				H	60,000	LOV
				Y	20	14CFR26.21(g)
717	1999	134	92	C	60,000	110,000
				H	60,000	110,000
				Y	20	
727	1964	1831	29	C	60,000	85,000
				H	50,000	95,000
				Y	20	
737-100/200	1968	1144	36	C	75,000	75,000
				H	51,000	100,000

Airplane model / Series	Entry into service	Produced	In commercial service December 31, 2021	Interval C=F/Cycles H=F/Hours Y=Years	Minimum design service objectives	Limit of validity
				Y	20	
737-300/400/500	1984	1988	542	C	75,000	85,000
				H	51,000	100,000
				Y	20	
737 MAX	2017	706	525	C	75,000	100,000
				H	51,000	150,000
				Y	20	
737 NG	1997	7088	5,641	C	75,000	100,000
				H	51,000	125,000
				Y	20	
747-100/200	1970	639	376	C	20,000	35,000
				H	60,000	135,000
				Y	20	
747-300/400	1983	775	535	C	20,000	35,000
				H	60,000	165,000
				Y	20	
747-8	2010	150	136	C	20,000	35,000
				H	60,000	165,000
				Y	20	
757-200/300	1983	1049	531	C	50,000	75,000
				H	50,000	150,000
				Y	20	
767-200/300	1982	1240	676	C	50,000	60,000
				H	50,000	150,000
				Y	20	
777-200/300	1995	1679	1,122	C	40,000	60,000
				H	60,000	160,000
				Y	20	
787-8/9/10	2011	1006	914	C		35,000
				H		165,000
				Y		
DC10	1971	446	11	C-10	42,000	60,000
				C-30/40	30,000	160,000
				H	60,000	
				Y	20	
DC8	1959	556	2	C	25,000	110,000
				H	50,000	150,000
				Y	20	
DC9	1965	976	24	C	40,000	110,000
				H	30,000	110,000
				Y	20	
MD11	1990	200	114	C	20,000	40,000
				H	60,000	150,000
				Y	20	
MD80	1980	1191	95	C	50,000	110,000
				H	50,000	150,000
				Y	20	
MD90	1993	116	0	C	60,000	110,000
				H	90,000	150,000
				Y	20	

Note. Adapted from Boeing data compiled by the author from various documents.

Limit of Validity

The LOV is the threshold beyond which the aircraft maintenance program is no longer considered valid in detecting widespread fatigue damage (WFD) before the strength of the aircraft diminishes below regulatory prescribed levels. It is also defined as the onset of multi-site or multi-element damage, which the FAA now uses to define (limit) the operational life of civil transport aircraft (Eastin & Sippel, 2011). It establishes a bound in the indefinite operational life allowed for by earlier regulations (Tavares & De Castro, 2019). In layman's terms, it becomes the point at which the OEM can no longer statistically predict or substantiate what will happen to the aircraft due to the fatigue of the materials used in the manufacture of the product. LOV is a point in the structural life of an airplane where there are significantly increased uncertainties in structural performance and an increased probability of the development of WFD (Mohaghegh, 2005). It becomes the point at which the maintenance and inspections conducted in the normal process of the MPD may not be of sufficient quantity and quality to detect fatigue damage before strength failures. In practical terms, the establishment of the LOV regulation for commercial aircraft is the point at which operators can no longer fly their aircraft beyond half the number of fatigue cycles that have been accomplished on a full-scale test. Because the LOV is based on the actual full-scale test of the aircraft, this process is an expansive undertaking by the OEM.

Historically, this concept/program took place in 2001 after a proposal by the Aviation Rule Making Advisory Committee (ARAC) that the industry and regulators impose a limitation on the extent to which the maintenance program would remain a valid document with which to maintain an aircraft. The MPD is understood to be the manufacturer’s instructions to the operator and maintenance personnel regarding the continued airworthiness of the product (as delivered). This proposal was further moved ahead by ARAC in 2003 and included a new Part 25 (Airworthiness Standards: Transport Category Aircraft) rule for specification of manufactured aircraft. Jian et al. (2011) stated that ARAC believed the cognitive degree of fatigue failure of aircraft structure was limited by analysis and the number of tests. The inspections conducted by maintenance programs provide feedback about the structural fatigue and should be used to establish a basis for the analysis and tests to be included in the maintenance program.

In 2011, the FAA ruled on the LOV for civil transport aircraft above 75,000 lb. takeoff weight, its requirement for full-scale fatigue tests, and its implications concerning damage tolerant assessments (Jones, 2014). The process and regulatory requirement to implement this program are identified more readily in 14 CFR §26.21 Limit of validity, which outlines the aircraft affected, those exempted, compliance dates, and plans to implement the entire process. The FAA further addressed how OEMs could extend such limitations in § 26.23, which allows OEMs to demonstrate such proposed extensions by an

> evaluation of airplane structural configurations and be supported by test evidence and analysis at a minimum and, if available, service experience, or service experience and teardown inspection results, of high-time airplanes of similar structural design, accounting for differences in operating conditions and procedures. (p. 475)

Table 6 incorporates data from various sources into one location to enable the reader to understand the applications, limitations, and dates as they apply to various maintenance concepts as incorporated into each aircraft by type and model. The references as to hours and flight cycles are the driving aspect of the analysis combined with the actual document. However, as the limitations apply, it is whichever event (i.e., flight hour/flight cycle) occurs first that becomes the controlling limitation. It should also be noted that on earlier model aircraft, there is a variance by serial numbers that is not present in later production aircraft.

Table 6

Boeing Limit of Validity by Aircraft Model and Sub Variant

Model-minor model	FAA approved LOV		Document	Operator compliance date
	Flight cycles	Flight hours		
Group 1 airplanes				
727-100 L/N 1-47	50,000	50,000	D6-8766-AWL	14-Jul-13
727-100/200 L/N 48 and on	85,000	95,000	D6-8766-AWL	14-Jul-13
737-100/200 L/N 1-291	34,000	34,000	D6-38278-CMR	14-Jul-13
737-100/200 L/N 292-1585	75,000	100,000	D6-38278-CMR	14-Jul-13
737-300/400/500 L/N 1001-2565	75,000	100,000	D6-38278-CMR	14-Jul-13
737-300/400/500 L/N 2566-3132	85,000	100,000	D6-38278-CMR	14-Jul-13
747-100/200/300, SP, SR	35,000	135,000	D6-13747-CMR	14-Jul-13
747-400	35,000	165,000	D621U400-9	14-Jul-13
DC-8 ALL	56,000	125,000	MDC 12K9006	14-Jul-13
DC-9 ALL	110,000	110,000	MDC 12K9007	14-Jul-13
MD-80 ALL	110,000	150,000	MDC 12K9008	14-Jul-13
DC-10 ALL	60,000	150,000	MDC 12K1003	14-Jul-13
Group 2 airplanes				
737NG--600/-700/-700C/-800/- 900/-900ER, BBJ/BBJ2/BBJ3 without Lower Cabin Altitude	10,000	150,000	D626A001-CMR	14-Jan-16

Model-minor model	FAA approved LOV Flight cycles	Flight hours	Document	Operator compliance date
737NG- BBJ/BBJ2/BBJ3 with Lower Cabin Altitude	50,000	150,000	D626A001-CMR	14-Jan-16
757 ALL	75,000	150,000	D622N001-9	14-Jan-16
767-200/300	75,000	180,000	D622T001-9	14-Jan-16
767-300F/400ER	60,000	180,000	D622T001-9	14-Jan-16
777-200/300	60,000	180,000	D622W001-9	14-Jan-16
MD-10	60,000	160,000	MDC-99K1082	14-Jan-16
MD-11 ALL	40,000	150,000	MDC-K5225	14-Jan-16
MD-90 ALL	110,000	150,000	MDC-94K9000	14-Jan-16
717 ALL	110,000	110,000	MDC-96K9063	14-Jan-16
Group 3 airplanes				
747-8I/-8F	35,000	165,000	D011U721-02	14-Jan-17
767-300BCF	75,000	180,000	D622T001-9	14-Jan-17
777-200LR/-300ER	60,000	180,000	D622W001-9	14-Jan-17
777F	37,500	180,000	D622W001-9	14-Jan-17
New airplanes				
737MAX-8	100,000	150,000	D626A011-9-01	
87-8/-9/-10	76,000	230,000	D011Z009-03-01	
737MAX-7/-9/-10	100,000	150,000		

Note. Data compiled by the author, extracted from various documents of the Boeing Company aircraft-related data and FAA documents.

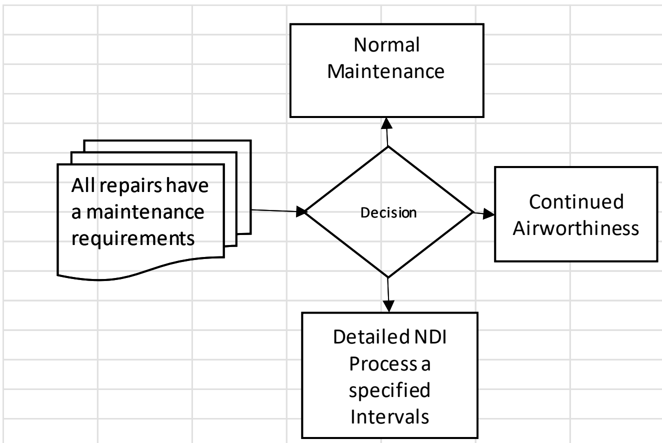
Repair Assessment Program (RAP)

Repair assessments on the fuselage pressure vessel for older aircraft must be conducted as prescribed in by 14 CFR§121.370. The Repair Assessment for Pressurized Fuselages (RAP) is a cycle-based schedule related to the DSG of an airplane. The program was initiated for transport categories in the early 2000s timeframe, establishing damage-tolerance structural inspections to inspect for previously accomplished repairs and to assess any damage as a result of those repairs. The methodology employed is used to determine the effectiveness of repairs and evaluate them to determine the continued airworthiness surrounding the fuselage pressure boundary. In addition to the inspection and review of the repairs, the aspect of the continuous airworthiness and durability of such repairs was examined. This aspect is intended to re-examine every repair accomplished on the aircraft during its lifetime, validate the repair for correctness and its implications for the damage tolerance of the aircraft, and certify that repair or determine whether it should be removed and replaced with a different repair. However, once incorporated into the operator's maintenance, no additional RAP reporting requirement or burden was placed upon the airline.

One of the major technical concerns with repair assessment program is previous repairs and the underlying reason behind the initial of repair. This produces what is referred to as "compounding" or that of repair on top of repair or multiple structural repairs within a specific area location, which changes the structural load transfer aspects of the fuselage structure. The main concern was that the FAA, in its defined terms, also included a structure that, if repaired or altered, could be susceptible to fatigue cracking and contribute to a catastrophic failure. This was a huge unknown as the repairs accomplished previously were for the most part never cataloged or inspected aside from the usual visual inspections they received as normal maintenance. Therefore, no stress or structural analysis was done to understand how a repair that may have caused the "stiffening" of one section was transferring the structural load to the rest of the aircraft. In operational airlines, the RAP resides within the operator's maintenance program as an integral component of the structural maintenance portion of the maintenance program. The MP involves a decision logic approach to each subject repair (see Figure 6).

Figure 6

Logic Diagram of Repair Assessment Program Requirements



Corrosion and its Implications

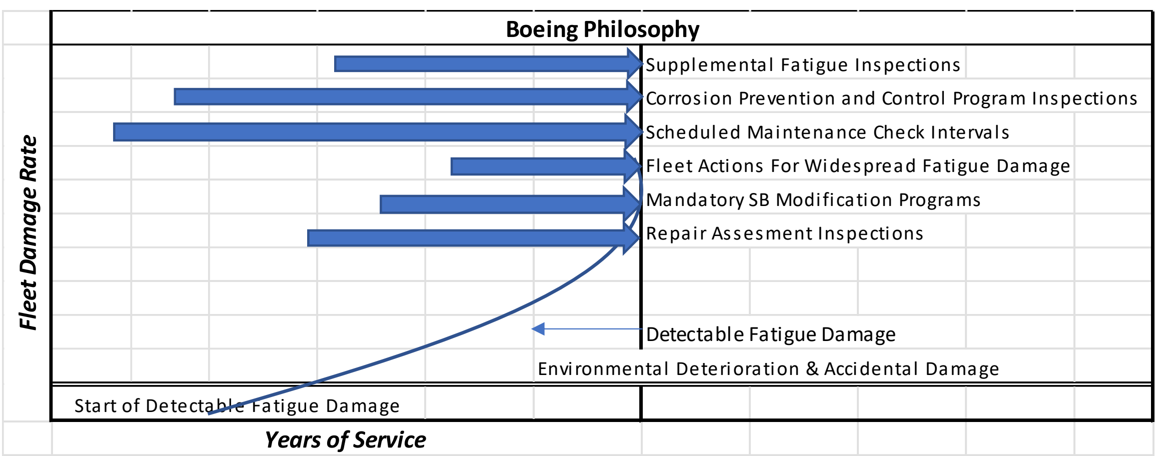
Boeing, through numerous publications, has stated that “as airplanes age, corrosion becomes more widespread and is more likely to occur concurrently with other forms of damage such as fatigue cracking” (The Boeing Company, 1993, p. 2.18). Corrosion degrades the structural integrity of the aircraft, and if left unchecked may lead to the inability of the structure to sustain its fail-safe design and load-carrying capabilities. As Hall (1993) stated:

> At the same time, the continual cycling of the structure means an ever-increasing likelihood of structural fatigue damage. This gives rise to one of the most significant “Aging Airplane” safety concerns, which is the potential for corrosion combined with other forms of damage, such as fatigue. (p. 1)

According to Akdeniz (2002), metals in nature exist as compounds; however, pure metals and alloys are not stable. They tend to want to revert to their natural states, known as a corrosion reaction. Additionally, he claimed that the economic life of an aircraft may be more limited by corrosion rather than fatigue. This aspect would highly correlate corrosion and economic life as opposed to the DSO of an aircraft. There are many instances where aircraft designed on the safe-life principle have developed cracks before their design lifetime has been achieved, or where technical and economic considerations have demanded the extension of their service lives beyond the original design goals (Cole et al., 1997). As aircraft age, various maintenance operations, occur including those mandated by regulatory agencies as summarized in Figure 7.

Figure 7

Aircraft Life Over Time With Maintenance Concepts Added

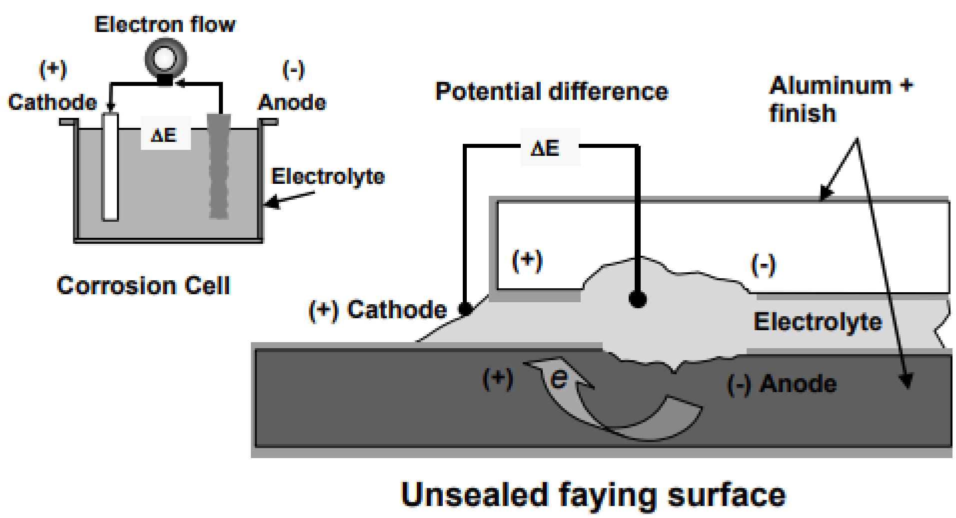


Note. Compiled from The Boeing Company data and author's comments.

Corrosion has been one of the most serious concerns of aircraft manufacturers given their understanding of the metallurgy of the elements used in the construction of their aircraft. The Boeing Corrosion Prevention manual (D6-41910) first appeared in 1974 and saw few revisions in the early years. This document is not to be confused with the Corrosion Prevention and Control Program (CPCP), a regulatory-mandated process applicable to aircraft by the incorporation of an Airworthiness Directive. Findings early on through the use of in-service reporting showed corrosion was at a point of starting to incur major repairs. This combination was resulting in accelerated degradation of the aircraft structure. Additionally, it was found that as the aircraft were aging, corrosion was also associated with fatigue damage. Most in the early years believed the information contained within that manual to be supplemental information that went in conjunction with the normal application of the Aircraft Maintenance Manual (AMM), Structural Repair Manual (SRM), and supporting documentation; however, as findings increased the process was reexamined. Corrosion is ongoing and constant as a simplified electrical reaction such as that between an cathode and anode (see Figure 8).

Figure 8

Corrosion Development Process



Note. Adapted from The Boeing Company (1993).

The intent of any corrosion program is not to eliminate all corrosion, but rather to provide a means to mitigate and control the buildup and development of corrosion. This is accomplished by keeping corrosion below levels that do not jeopardize the airworthiness of the aircraft. It must be understood that should corrosion go unchecked or unmitigated early on, in the long term it will cause structural failures. It was not until the late 1980s and early 1990s that this became a major focal process of the OEMs and corrosion prevention moved to the forefront. The CPCP established a minimum level of requirement that operators lacking a proven-effective program would establish and use to show compliance with the Airworthiness Directives. According to published information, the five aircraft shown in Table 7 have a type-specific CPCP applicable to each model type.

Table 7

Data Related to Aircraft Manufactured Without a CPCP Aspect to the MP

Model	FAA AD No.	Effective date	Boeing document no.
707/720	90-25-07	December 31, 1990	D6-54928
727	90-25-03	December 31, 1990	D6-54929
737	90-25-01	December 31, 1990	D6-38528
747	90-25-05	December 31, 1990	D6-36002

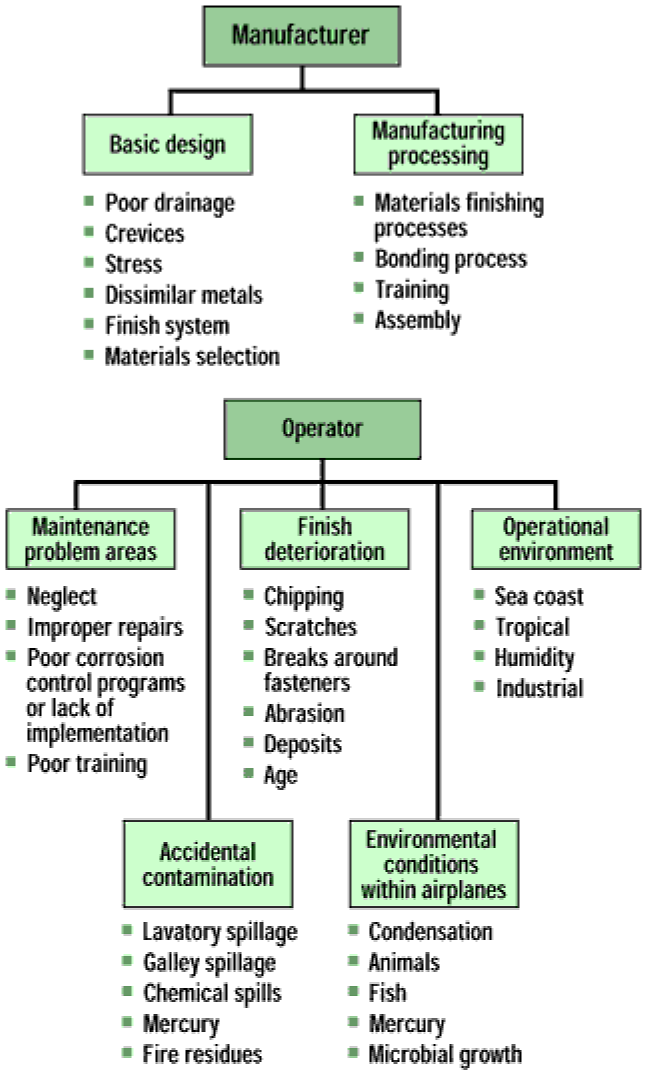
Note. Information obtained from FAA (n.d.).

Corrosion is the deterioration of metals caused by their interaction with environmental conditions, or their tendency to revert to a low-energy state of matter. As this electrochemical process occurs and interacts with environmental and operational conditions, corrosion develops. These causes occur both in the manufacturing and operational aspects of the design and functionality of the aircraft. Ancillary factors that contribute to corrosion are issues such as volcanic ash and increased industrial pollution in the environment. Hence, operational and atmospheric environments play a major determining factor in the impact of corrosion on aircraft. Sand, ash, pollution, rainfall, humidity, and operational temperatures all play a role.

Operationally, issues such as runway conditions, snow and ice, flight altitudes, turbulence, stage lengths, and types of cargo carried contribute to the propagation of corrosion. Since the 1980s with the introduction of CPCP, manufacturers have set out to define requirements for preventing or controlling corrosion on aircraft and that could affect the continuous airworthiness of the products. These programs defined the minimum requirement for preventing or controlling corrosion of Boeing aircraft at a baseline level. As aircraft age, corrosion can become more widespread and is more likely to occur with multiple forms of damage such as fatigue cracking or damage from use (ramp rash). To counteract corrosion, programs have been put in place by manufacturers, regulatory agencies, and operators who have in-service experience. Programs have grown from the original baseline offerings to completely integrated complex methods of tracking all aspects and findings with the understanding that the effectiveness of the program is only valid when applied in total or all primary structures. Yet the key element to any CPCP program is the ability to recognize corrosion in its early stages and take corrective action before its rapid expansion. Both operators and manufacturers have specific functional responsibilities when assessing, reporting, and tracking corrosion as it occurs in products (see Figure 9).

Figure 9

Operator and Manufacturer Delineation in Responsibilities for CPCP Factors



Note. Reprinted from The Boeing Company (1999a).

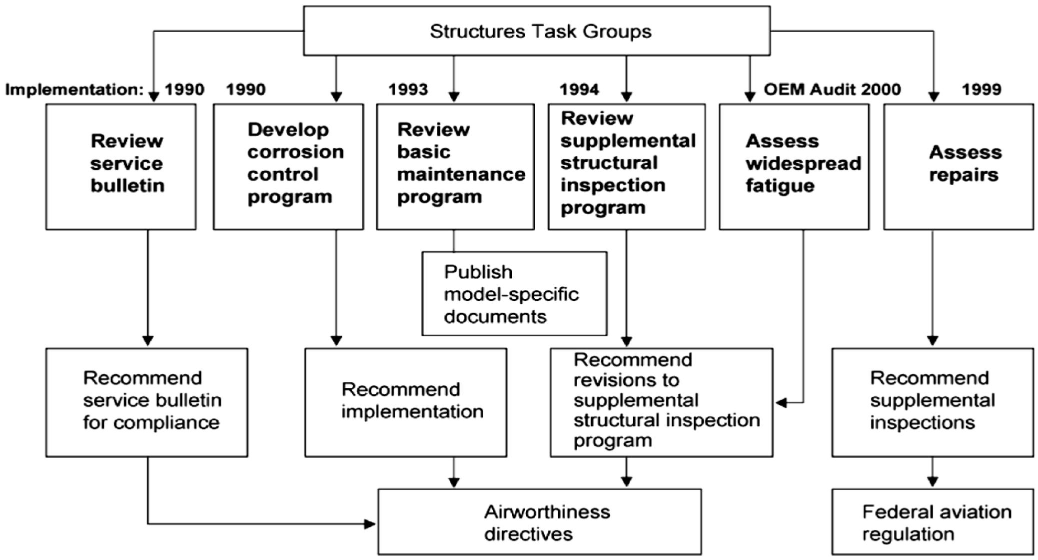
On April 28, 1988, Aloha Airlines flight 243, a Boeing 737-297 manufactured in 1969 and the 152nd of the model, experienced an explosive decompression, losing an 18-foot section of the upper fuselage. At the time of the incident, the aircraft had accumulated 35,496 flight hours and almost 89,680 flight cycles or a 2.5 to 1 cycle to hour ratio, which was well beyond the normal utilization for the fleet type, but the incident led the National Transportation Safety Board (NTSB) to focus on the issues surrounding metal fatigue. This was the corrosion event that both captured and horrified the traveling public, if not the world. Investigations ensued and members of the airline, management, maintenance, and regulatory agencies were interviewed, and processes were examined. In their final report (NTSB/ARR-89/03), some of the NTSB's recommendations to the FAA were that they:

> Develop a model program for a comprehensive corrosion control program to be included in each operator's approved maintenance program. (Class II Priority Action) (A-89-59).
>
> And that the operator Aloha, revise the maintenance program to recognize the high-time high cycle nature of the fleet operations and initiate maintenance inspections and overhaul concepts based on realistic and acceptable calendar and flight cycle intervals. (Class II, Priority Action) (A-89-70)

Such actions became a focal point for the OEMs to assist and revisit their compliance strategy as well as their Instructions for Continued Airworthiness (ICAs). Corrosion became a word that concerned all maintenance staff. Numerous nondestructive inspection techniques were developed and applied inclusive of eddy current, ultrasonic, radiographic, penetrant, and magnetic particles, all of which had been represented in maintenance activities and now became the activity level norms. Phillips (1990) reported that the industry investigation of the Task Force on Aging Aircraft reported that corrosion may be a greater problem than anticipated. It was understood that airlines, through their inspection process, monitored corrosion levels, but as no specific standard existed, some were more diligent in their level of detail than others. Once such inspection actions became mandatory, the United States General Accounting Office (1991) estimated that on a per-plane basis, the costs of airframe-related work alone ranged from about $100,000 for a DC-9 to over $1,000,000 for a 727 for fatigue-related work alone. This cost analysis would make corrosion the single highest line item in the repair budget aside from possibly an engine replacement. The problem of corrosion in airframes is very important because of its crucial economic implications. Czaban (2018) estimated the direct annual cost of corrosion in the U.S. aircraft industry to be $2.2 billion in total, inclusive of aircraft downtime and repair. A previous estimate by Winkleman et al. (2011) placed the amount higher at almost $437 billion annually for maintenance and restoration of corroded structures just in the United States alone. The industry, in conjunction with the OEMs and regulators, developed a plan for the identification, integration into their maintenance plan, and mitigation of the spread of corrosion that is continuously updated and used throughout the industry. As such, and for consistency, a decision logic tree was developed to have all stakeholders report and take action in the identical manner (see Figure 10).

Figure 10

Early Block Diagram/Process Diagram of Industry Actions



In the early period, the CPCP focus shifted from initial identification and categorization and repair to that of mitigation techniques and level assessments, technically the corrosion control process. Various types of corrosion appear throughout the literature. As all corrosion is electrochemical in nature, the researcher only chose to mention the forms of corrosion in summary as surface (filiform), dissimilar metal, intergranular (including exfoliation) stress, and fretting forms (FAA, 2018). According to Banis et al. (n.d.), Boeing has instituted the use of advanced alloys in its 747-8, -8F, and 777 production aircraft that greatly reduce corrosion factors. What we do find through investigation is that no particular maintenance issue resides on a single standalone application of purpose but rather a level of interactivity. MSG-3 methodologies changed to a task-oriented maintenance approach that analyzes system failure modes. Previous programs were based on a top-down philosophy, and the new focus has created improvements in all modes of failure. The Boeing Company (2000), in its risk analysis system of prioritizing in a Pareto chart, gave the corrosion factor a rating of 7–8 (on a scale of 1–9 with 1 being the highest risk). This indicates that through the implementation of a production-wide uniform approach, the OEM can control and mitigate corrosion through an effective and functioning CPCP. Cooper et al. (2019) indicated that the new, more advanced technologies and materials used can reduce overall fatigue and corrosion maintenance tasks by 60% for certain aircraft. Corrosion and its expansion are difficult to predict, and for the most part, are accomplished by the choices in materials that the OEM selects initially. However, it becomes the operator’s ongoing responsibility to assure maintenance, application of CIC, and diligence in the CPCP to keep the manifestation of corrosion in check and at a level 1 as defined by the program.

As operators experience unacceptable levels of corrosion, they must adjust their CPCP to reduce the occurrence of their findings, thereby precluding the recurrence of a repeat type of corrosion finding. Program adjustments could include additional treatments of corrosion inhibiting compounds (CICs), adjustment of reinspection intervals reducing the frequency, and repetitive inspections. It should be understood that by current regulatory policy (FAA, 2018) corrosion through the application of a CPCP is kept to a Level 1, which is defined as “damage occurring between successive inspections that are local and can be reworked/blended out within allowable limits as defined by the manufacturer’s service information, such as structural-repair manuals and service bulletins” (p. 6-19). Such determinations are made in conjunction with the maintenance, inspection, and engineering staff to verify the actual level identified and to be sure it falls within the defined term, the maintenance program, and the operational requirements of the airline all while maintaining the airworthiness of the product.

Costs, Economic, and Financial Fundamentals

The valuation of commercial aircraft is a detailed process dependent upon multiple factors both internal to the system operation and external in a macroeconomic determination. The International Air Transport Association (IATA, 2016) indicates multiple units of measurement for the useful life of an aircraft in terms of its component make up which ranges from 2 years upwards to 15. These IATA accepted country standards, however, are used as a depreciation method for accounting reporting purposes and to comply with either International Financial Reporting Standards Foundation (IFRS) or Generally Accepted Accounting Principles (GAAP) predicated on location. These value points include the acquisition prices of new aircraft paired with the residual value of the asset over the period of depreciation. Yet airlines may make decisions in which the economics do not affect the decision-making process. Occasionally, external factors such as passenger perception, a more modern fleet, and new interiors or other elements can play a substantial role in the process. There is no consistency. Table 8 shows how multiple airline organizations approach the concepts of depreciation, useful life, and residual values.

Table 8

Typical Depreciation Rate Information For Different Aircraft Types

Airline	Aircraft/Fleet type	Useful life (UL)	Residual value (RV)	Depreciation rate (DR=(100%-RV/UL)
Air Astana	Flight equipment	10–20 years	-	5%–10%
	Rotable spare parts	5–10 years	-	10%–20%
Air China	Core parts	15–30 years	5%	3%–6%
	Airframe and cabin – refurbishment	5–12 years	-	8%–20%
	Overhaul of engine	2–15 years	-	7%–50%
	Rotable parts	3–15 years	-	7%–33%
Air France-KLM Group	Not specified	20–25 years	-	4%–5%
Cathay Pacific	Passenger	20 years	10%	5%
	Freighter	20–27 years	10%–20%	3%–5%
	Aircraft product	5–10 years	-	10%–20%
	Freighters converted from passengers	10 years	-	10%
EasyJet	Aircraft	23 years	-	4%
	Aircraft spares	14 years	-	7%
Emirates Group	New	15 years	10%	6%
	Used	5 years	10%–20%	16%–18%
	Engines and parts	5–15 years	0%–10%	6%–20%
Kenya Airways	Boeing 787, 777, 737-300, 737-700	17 years	-	6%
	Boeing 767	3 years	-	33%
	Simulator	20 years	-	5%
Korean Airlines	Aircraft fuselage	6–15 years	-	7%–17%
	Aircraft engines and parts	15 years	-	7%
Lufthansa Group	New commercial	20 years	5%	5%
Qatar Airways	Passenger	12 years	15%	7%
	Executive	10 years	60%	4%
	Freighter	7 years	20%	11%
	Passenger	15 –20 years	5%–10%	5%–6%

Airline	Aircraft/Fleet type	Useful life (UL)	Residual value (RV)	Depreciation rate (DR=(100%-RV/UL)
Singapore Airlines	Freighter	20 years	5%	5%
	Used freighter	20 years less age of aircraft	5%	5%
	Training	5–15 years	10%–20%	5%–18%
	Simulators	5–10 years	-	10%–20%
South African Airways	Aircraft and simulators	5–20 years	-	5%–20%
Turkish Airlines	Aircraft	20 years	10%–30%	4%–5%
	Cargo Aircraft	20 years	10%	5%
	Components	7 years	-	14%

Note. Taken from IATA (2016).

The aviation industry and more specifically airlines have witnessed aircraft pricing changes as the cycle has ebbed and flowed since the onset of the jet age. Cohen (1957) defined “the jet age to be that period in which the bulk of air traffic will move in turbine-powered equipment” (p. 398). Yet Cohen also hypothesized that

> economically, the jet age should operate to increase commerce and quicken the pace of industry growth on a global scale. It should not only contribute to higher standards of living and an expansion of the world’s supplies of food and essential goods, but it should intensify the inter-dependence of nations. (p. 408)

The jet age did in fact expand economic growth on a worldwide basis allowing the ability to not only transport goods but to move people, bringing the inhabitants of the globe to be in closer proximity and have access to each other.

According to Dumville and Quinn (1994), the largest costs airlines incur are the maintenance costs necessary to keep their aircraft flying safely, which was further supported by Ott (1988). The continuous aspects of the inspection, defect identification, and repair are more clearly defined by 14 CFR §1.1, which states maintenance means inspection, overhaul, repair, preservation, and the replacement of parts, but excludes preventive maintenance. There is no disagreement among the OEMs that as aircraft age or get older, their costs increase. This point alone could give airlines a strong determinant factor in whether to own, lease, keep, or return an aircraft. These costs as well as the associated ground time to accomplish maintenance, repair, and modify aircraft become the decision hurdles technical personnel must address.

Depreciation of aircraft as a percentage of original acquisition is usually thought to range between 20 and 25 years. However, aircraft as assets do not change at a constant rate. As financiers and analysts try to develop models to estimate aircraft economic life, most look at the asset in terms of where it is within the production cycle. This concept is included in the variables of the model looking at early, mid, and late-produced aircraft in the analysis. Those who are earlier off the production line more typically will sustain a longer useful life and those toward the end will encounter something lesser in terms of longevity as new production aircraft of new types are added to the production cycle (i.e., contingent new technology). This will usually work with production rates, which start slower, increase in mid-delivery periods, and tend to diminish as the aircraft near the end of their production cycle as competing for newer aircraft is more than likely to be introduced at this point.

Society recently has witnessed what the air transport industry has contributed on a global scale, as travel, with its good and bad aspects, allowed for the unprecedented spread of disease (i.e., COVID-19) to overtake its predecessor (i.e., the Spanish flu, 1981–1920) in record time. Additionally, we have witnessed Russia “seize” approximately 500 plus commercial aircraft leased into the country given the ongoing situation in Ukraine. This singular issue in and of itself violates both the Chicago Convention and the Cape Town Treaty and has created billions of dollars in losses for the global economy. Issues such as these and others such as economic uncertainty or the introduction of modern technology are fundamental aspects of the economic life assumptions that managers consider when trying to decide the economic life of an asset.

Today's maintenance and engineering professionals have had to grow as the industry has expanded. They must now consider aspects in the decision-making of management to not only encompass the technical capabilities of aircraft, their repairs, and production but a much broader base of economic and practical theories that are put into their decision-making matrix. Long gone are the days when the management of maintenance organizations is just a mechanic or engineer who was promoted through the ranks to fill such a position. The individuals who fill these positions currently must be management professionals who know and understand more than just the rivets and sheet metal of an aircraft. Not only are they there to effectuate the regulatory requirements such as safety and protection of the loss of life to the public, but to protect of the investments in equipment and personnel.

Investment Economics

The capital investment of organizations is the method most used for the financing and acquisition of new aircraft. Funds to pay for new aircraft must be supplied either directly or indirectly by capital investments from the financial industry, the airline itself, or in some cases the manufacturer. In the case of an airline, the fleet acquisitions are financed by equity, unsecured debt, or Enhanced Equipment Trust Certificates (EETC), which are the debt instruments secured by the aircraft. A concerning aspect is the high acquisition cost of replacement equipment as aircraft age. The longer an owner can spread that cost over a range of time, the more economically sound the investment will appear. *Aircraft Value News* ("Freighter lease rates remain steady," 2022) suggested extending the life (PTF conversion) of an asset also implies environmental benefits as the manufacturing of a replacement asset will be deferred.

An aircraft replacement decision must reflect overall fleet and scheduling strategy aspects that are not practical to include in the evaluation of one aircraft as a replacement for another. These strategy considerations include such factors as fleet commonality, minimum practical fleet type size, maintaining a certain level of capital reinvestment to avoid peaking in capital needs, scheduling through hub cities versus point-to-point scheduling, and so on (E. B. Anderson, 1978).

Chao et al. (2017) discussed the fact that airlines must make decisions regarding fleet acquisition and retirements using long-term strategic outlooks. Furthermore, they cited the interdependencies of numerous factors upon which airlines make decisions. Their position mirrored that of Belobaba et al. (2019), who explained that factors such as network, available fleet, forecasts of demand growth, the performance characteristics of available aircraft, as well as environmental impact, and even political influences. They developed a model that uses the net present value (NPV) of the asset, fuel prices, and gross domestic product (GDP) and never considers any inputs from aircraft maintenance, age, or condition.

Economics as a Variable

Economics may play an important role in determining when a fleet should be disposed of or parked based on the current situation. To assist in analyzing the impact of economics on fleet age and useful life, the researcher in the current study used GDP for the correlation to the production years. The operation and support costs of aircraft are drivers in assessing the replacement of a fleet in analyzing the possibility of replacement aircraft for the USAF. Greenfield and Persselin (2002) used these costs to determine the optimal replacement period for military aircraft. Ramey and Keating (2009) determined that designs (type/model) serve as long as they are technologically and economically viable, which further supported the use of economic measurement as a variable in this investigation. Dixon (2006) spoke to the overall life cycle in which older equipment requires more funds to maintain, which, in turn, decreases the funds available for new equipment. The Congressional Budget Office (CBO) estimated spending on operation and maintenance for aircraft increases on average by 1% to 3% for every additional year of age after adjusting for inflation (Kiley, 2001).

The retirement of aircraft considers many factors and has changed over the last decades. Schlesinger and Grimme (2021) analyzed the influence of economic data such as oil prices, GDP per capita, and the number of annual passengers on aircraft retirement and found that without the economic data, the ability to predict is uncertain.

Fuel and Emissions

Morrell and Dray (2009) stated global aviation emissions are affected by new aircraft purchases, changes to aircraft in the fleet, and retirements. As the issue of global warming continues to be in the daily vernacular of society, we can see the implications and interactions that aircraft contribute to emissions. There appears to be a conceptual link between the prices of jet fuels and the warming effect of emissions on the planet as global aviation continues to grow. The industry as a whole has committed resources and workforce to increase fuel efficiencies, reducing fuel burn, and overall emissions. The airlines have stated for years their intent to become carbon neutral but there appears to be minimal progress toward such a goal.

Dhara and Muruga Lal (2021), using microanalysis of types of aircraft, identified that wide-body aircraft provide better fuel economy compared to other variants. The dilemma becomes that consumers would have to sacrifice convenience such as frequency of service to have this become economically advantageous to the operators. Recently, Huang and Cheng (2022) delivered research showing how ADS-B data combined with digital DFDR data can be used to produce real-time understanding and more efficiently control fuel flow or consumption through machine learning techniques. Such research enables the use of a multivariable model in a statistical relationship and expects more accurate results as the data-rich ADS-B information gains accuracy through the systems. This is a previously unidentified benefit of the regulatory change to introduce the technology-rich system and its data collection abilities in addition to the primary reason of safety.

Movement from fossil fuels is all the current buzz with discussions focusing on green or solar energy, wind turbines, wave/ocean power generation, renewable alternatives, and new sources. Singh and Sharma (2015) conducted a study exploring the potential of alternative aviation fuels (e.g., conventional jet fuel from petroleum resources, synthetic jet fuels, biodiesel and bio-kerosene, ethanol, and butanol, liquefied natural gas, and hydrogen) and highlighted the technical feasibility parameters (e.g., high energy density, high specific energy, high flash point, low freezing point and vapor pressure, high thermal stability, adequate lubricity, and sufficient aromatic compound content). They concluded that a suitable alternative fuel can be selected based on a variety of criteria, societal priorities, economic viability, and sustainability considerations, which will further reduce aviation fuel consumption. It is obvious that more work needs to be accomplished in these areas and that much more investigation is warranted.

Fuel as a Variable

The fuel burn of an aircraft and its reductions have been both policy and priority over the years. As the cost of jet fuel increases, airlines find that their pricing must follow, thereby increasing consumer costs. Over 10 years from 2009–2019, the number of passengers carried by air transport was around 2.25 billion and increased to 4.56 billion (The World Bank, 2020), an approximately 103% increase before a sharp drop as the world entered the period of COVID. As of April 2022, global air travel is rebounding from the pandemic and is currently at approximately 3.43 billion according to data published by Statista (2023). As individuals, we all can agree that the aviation industry as it relates to commercial operations is a major contributor to the global economy. Research into commercial jet fuel burn by Zheng and Rutherford (2020) indicated that the past decade, from 2010 to 2019, saw a quickening of fuel burn reductions as a result of the introduction of many new fuel-efficient models, including the Airbus A320neo, Boeing 737 MAX, Airbus A350, and Boeing 787 families. However, they indicated fuel burn is measured block to block, therefore considering the taxi out and in as well as any implied gate delays. As technology and airport infrastructure improve, we may find ways to make the ground operations more effective. If this occurs, we could notice even further reductions of ground time delays as well as the use of direct air route traffic flows cutting down air distances.

Fuel is one of the major elements in today's financially savvy airline environment at approximately 1,471.3 million gallons consumed for U.S. carriers and estimated to be approximately 15%–20% of the direct operating costs based (Bureau of Transportation Statistics, 2022). Thus, control of this cost is a fundamental undertaking to increase profitability. Hassan et al. (2018) estimated that approximately 5.8% of the world's fuel use is in the aviation sector.

Airlines today operate in a high-pressure environment and find themselves both connected to the global economy and a victim of globalization. We recently witnessed the shutting down of U.S. airspace to Russian registered aircraft affecting deliveries of materials to the Boeing production facilities by the Antonov An-124 and the world's largest cargo aircraft, the An-225, destroyed beyond economic repair on the outskirts of Kyiv, Ukraine, in the hostilities. Successful operations are tied to issues such as operating costs, both direct and indirect; the technology of the equipment being flown and manufactured; and the ability to provide rapid directional changes to a shifting of patterns in use. Technology has become a key driver in both the consumption of fossil fuels to improve the economic positions of the operators and the development of alternatives for future consumption.

Additional Concepts for Contextual Understanding–Non-Independent Variables

In today's current economy and social constructs, there are large investments of capital focused on moving forward the concepts of the environment, society, or the social aspect and the integration of governments throughout the world. Funds flow toward investments that not only yield high performance but align themselves with businesses that seek to produce value propositions that do not destroy the world in which they reside. As a society, there is a greater focus on sustainability, a company's stewardship, and evolving norms. Companies wish to move toward reductions in their carbon footprints, moving into neutral or net zero goals. Understanding how society makes such transitions varies by both business sector and a particular impact made by certain markets. Aviation and aircraft is a sector that is heavily based on fossil fuels and produces a large footprint through noise, greenhouse gasses, and emissions. These areas have become a focal point for society and activists. Although currently there is no specific set of metrics that can correlate all these sustainability factors, we believe it is worth mention for future considerations as each may affect the longevity of aircraft in unique ways.

Noise

A sound wave is an energy that is transmitted through the air in a longitudinal motion as when an aircraft would break the sound barrier, producing a sonic boom. Yet we see how airports are designed, built, and operated around areas where society has either encroached upon the facility or the facility has led to growth in the surrounding areas. This has caused in some instances the limitations of operations usually in the late night to the early morning period as residents of the surrounding areas are asleep within these hours. In other cases, sonic booms have stopped or curtailed development in such transport categories but may be changing again with recent developments. Beginning in the 1970s, the ICAO has developed and supported standards intended to reduce aircraft noise on a global basis. As we approach a period where the introduction of supersonic flight may once again become a possibility, this also will require a future review.

Environmental and Sustainability Concerns

Although fuel was the only independent variable used in the analysis, currently referenced as environmental, social, and governance (ESG) philosophy warrant future discussion. They were not used in this research, but rather should be considered at a future point in the analysis given governmental, regulatory, and traveling public awareness. Sustainability standards are becoming a focal point as airlines commit to products and safety aspects that are green or environmentally sustainable (Park et al., 2017). This was further highlighted by S. Lee et al. (2013) as they expressed management's openness to attempt to better handle aspects of the ESG concepts in a more open and frank discussion as the airline industry looks to improve its image. As both airlines and manufacturers try to increase the awareness as to how their products are helping make society and the environment better globally, we will see more research in these areas.

Summary

This chapter presented a review of the literature surrounding the various underlying topics that contribute to the analysis of the subject matter. The review was accomplished to determine a specific relationship of the subtopic areas. These reviews and discussions enabled the researcher to address the relationship between concepts and application in the industry. The decision-making matrix of aircraft and longevity related to age and life problems is often overlooked and sometimes omits maintenance, engineering, and technical perspectives in the decision. This examination was undertaken by approaching the problem from a firsthand perspective with years of industry experience to optimize and develop a rational response to the gaps in understanding the technical perspective and decisions made by management. The optimization of any asset is imperative to a financial institution; however, the profitability is always based upon the buy side of the transaction and rarely made on the sale of the asset at a future point in time.

CHAPTER III

METHODOLOGY

This chapter provides details of the methodology and research approach undertaken by the researcher. It includes discussions of the procedures, sample data, data sets, and the choices of independent variables detailed in the previous chapter with additional support outlined herein. The economic life of many aircraft resides in issues such as the availability of replacement alternatives and the costs of operation. Aircraft retirements are dependent upon many independent factors, such as deterioration of the useful life, fuel cost increases or decreases, operating environments, design of the aircraft (i.e., cargo or passenger), and the types of maintenance involved in keeping the assets operating within a margin of safety and regulatory requirements. The contribution of this research will allow both practitioners and academics to more completely understand the maintenance and technical operational aspects and variables considered when making aircraft and fleet decisions and the interaction of each.

Airlines, banks, financiers, and leasing companies all face a similar problem. The planning that must be accomplished to keep the entity competitive as well as focused on long-term strategies is part of the measurements that should be considered. As to the position of the airline that may have a mixed fleet (i.e., partially owned and partially leased), it will begin at a minimum making plans to sunset its own fleet or the leased fleet. Based upon economics, airline leaders could choose to keep their aircraft and manage the retirement process, possibly sell off their own fleet and lease it back into the system thus not having to be responsible for the secondary market for its fleet type at the end of the lease or continue to run its owned fleet until the end of their effective economic life. Aircraft value and longevity encompass many determinants. According to Ackert (2011), key among them is their maintenance status. Aircraft are considered in normal market economic times to be a stable and liquid asset that is openly traded.

A 2016 publication related to Delta Airlines included a SWOT analysis showing Delta still maintained a fleet of multiple aircraft types, including MD-88 aircraft. Delta's leaders had told the industry they would stop operating this type of aircraft years earlier. This allowed Delta to take advantage of the economics present in the industry, thereby finding cheaper alternative engine replacements for leasing into the organization as opposed to incurring the expense of overhauling their own engines. This act allowed Delta to not have to reinvest capital into the maintenance and overhaul of its owned engines, effectively sunsetting the aircraft type strategically by its major components. At the actual end of the life of the aircraft, they were sold with the engines having basically little or no value. This accomplished multiple goals: (a) the airline did not have to reinvest in the repair of the engines; (b) the airline effectively eliminated the possibility of selling to a competitor due to the below minimum status of the engines, which would force a purchaser to reinvest capital during a startup period; and (c) the airline was able to keep the assets (i.e., engines) on the books without the reinvestment and continuing depreciation of the asset or to keep the aircraft and its associated engines on their books as a collective matched set. Similar instances of creative planning can be found across the industry, allowing for the economic life of aircraft to be extended due to cash flow techniques. A similar approach was followed by American Airlines based on the Delta Airlines model of keeping assets on the books and leasing engines. Northwest Airlines used a similar approach keeping the DC-9 aircraft flying beyond what by most would have been their EUL. Leaders of NWA believed the ownership cost of the asset was an enhancement when viewed during the Delta merger and acquisition period.

The aviation industry is a service industry providing transport services (Pompl, 2006). In air transportation, parallels exist that can compare to some of the same aspects found in typical service industries. One could compare the product of a seat to that of the food industry where if the food is not consumed, it perishes. The same may be said as to the seat in an aircraft; once the flight has departed, the seat can never be filled. In the food industry, if food is not consumed, it becomes unusable or a spoilage factor, similar to the unused seat that can never be filled. Additionally, the industry places a high level of importance on the customer service factor from the check-in to the baggage delivery as consumers expect service as part of the product purchase. Air carriers provide the physical delivery of the product or the actual transport aspect yet there are ancillary aspects such as airports that provide the ground infrastructure combined with those governmental aspects such as air traffic control that handle the movements to destinations. Therefore, the universe of stakeholders is vast and interwoven in the process within the monopolistic or duopolistic value chain.

Most industry experts would agree that from a conceptual standpoint, the replacement of older aircraft with newer ones would be advantageous due to the increased efficiencies in operational performance. However, there becomes a point where the performance cannot support the economics of the event. The amount of capital expenditure needed for the new asset ties up the currently available dollars, making other investment decisions incapable of being transacted. Airlines face this dilemma and thus have shifted to leasing as a strategy to reserve or save their cash outlays.

Participants in the industry must be aware that purchasing a new aircraft asset requires the outlay of large amounts of capital and a horizon from which to plan. Consideration must be taken as the “book” delays from the time an entity contracts for an aircraft until the actual time of delivery of that contracted aircraft is usually years. Year-to-date (May 2022), Boeing received 213 orders and 56 cancellations, bringing its net orders to 157 units valued at $11.4 billion with deliveries in the future years. According to IATA (2016) in association with KPMG, orders for aircraft are often made several years in advance of delivery at prices that may include complex mechanisms for discounting the list price, including “credits”; thus, there needs to be a comprehensive understanding as to when an asset will be retired from service. To consider and apply a theory to the process, the following issues should be viewed as the logical approach and reasoning behind a decision to retire a fleet:

- To develop an organized structural approach within a horizon time frame for the acquisition of new/replacement assets.
- To manage in an organized structure a sunset of the retirement of a fleet of assets.
- To forecast airline or operator demand, there is a need to select appropriate equipment for purchases or acquisition of additional equipment in support of ongoing operations or expansion.

To develop a model that includes the variables influencing the purchase and acquisition decision and their economic aspects, maintenance, engineering, and technology need to be reviewed and analyzed. How to structure such problems found within the fleets has to deal with the longevity of aircraft type and the available support assets to extend or provide continued support for the remaining life. The data used for this investigation came from public and commercially available sources within the aviation community. Some of these sources are available for a fee; however, the data sets used in this research were provided at no charge to support this researcher's scholarly endeavor. Chapter III examines the data sets used in this analysis and the methodology applied to the sets. The researcher attempted to incorporate the actual status of each aircraft by merging and re-sorting each data set to align them, identifying the outliers, and researching each individual unit to determine the actual status. Furthermore, the researcher explains in detail how the analysis was performed and compared methods and relationships as they emerged.

Research Approach

The analysis involved using various secondary data sets residing both in the public domain and accessible by the general population and those of paid-for data sets available from a fee-based service. These secondary data sources exist and have been collected by various companies to be used in the development of their opinions, computations, and analysis of the aviation market space. Secondary data stored by various repositories may vary in both complexity and formatting. Additionally, it should be noted that the collection of secondary data is appropriate for quantitative research (Debreceny & Farewell, 2010). This researcher believes the data sources complemented each other and enabled the researcher to develop a definitive set of data absent any bias or other erroneous inputs. Prior to independent analysis and experimentation with the data sets, the researcher culled the materials to define a credible group to be used in the investigation and analysis as a pre-assessment process to determine accuracy.

In viewing the historical data, the researcher believed a prediction as to the remaining useful life (RUL) of when the aircraft/asset would be retired or replaced could be developed based on the historical data, economic data, and extraneous information contained in the maintenance and engineering drivers. A similar discussion was found in the study by J. Lee et al. (2014), in which a data-driven approach was applied relating to both cost savings and engineering data to optimize maintenance. In the existing predictive methods, two groups emerged in the research. The first was the data-driven model as discussed by Liu et al. (2012), where the data-driven predictors use pattern recognition and machine learning for forecasting. The second was accomplished by Mosallam et al. (2013) using an algorithm that was developed into a regression model of machinery health and used later as a predictive model for RUL.

Additionally, there is a calculation that can be applied to an aircraft as it ages to calculate the number of non-routine labor hours that increases proportionally with age. The routine portion, which remains fairly constant with age, sees exponential increases in the non-routine. Pyles (1999), in the presentation of his investigation of workload for aging aircraft before Congress, showed that at approximately a 20-year-old interval, the workload ratio increases threefold and at 30 years old to approximately sixfold. End-of-life can be subjectively determined as a function of operational thresholds that can be measured. These thresholds depend on user specifications to determine safe operational limits (Saxena et al., 2008).

This researcher believes that the introduction of the safe-life limits of the LOV as established by the manufacturers and approved and codified under a regulatory authority becomes the ultimate limitation of aircraft life either from an economic or useful perspective. As Yakovleva and Erofeev (2015) pointed out, there are two possible approaches to data analysis for predictive maintenance. These are physically driven models as with the example of an engine and a data-driven model approach which the researcher considered and applied. As is shown later in this chapter, the sets were all data-driven in context and content. However, these concepts used as variables were extensively discussed and vetted in Chapter II. For the most part, the predictability of physical data would have to consider an unmeasurable amount of variable and subjective input such as who was performing maintenance, the current constraints of the economic wherewithal of the operator, and the levels of technicians and materials available to perform such maintenance. This would produce inaccurate results as these metrics are tracked differently by various entities.

Based on the aforementioned paragraphs, the researcher believed the use of a data-driven approach and multiple regression was an appropriate method for this research. According to Mertler and Vannatta (2017), the purpose of the multiple regression model is to predict the dependent variable (DV) while examining the significance of the independent variables (IVs) and their influence to predict the DV.

Apparatus and Materials

The study consisted of a cross-sectional multiple regression model to analyze the data set, estimate the relationship between the independent variables, and develop a predictive direction for the model. The researcher used this statistical technique to test the data for the existence of predictable relationships between the variables examined. As the researcher used raw data collected and verified over time, the goal was to produce an accurate statement as to when the aircraft were removed from operational service or retired, and the age of the aircraft at that time. The equation used for this analysis is stated as:

$$Y_i = \alpha + \sum_{j=1}^{j=n} \beta_j X_{ji} + \epsilon_i$$

Where:

- Yi is the dependent variable – Aircraft age at retirement
- α is constant
- Xji are the jth independent variables that correspond to observation i
- ϵ_i is the error term

The use of cross-sectional multiple regression analysis to predict the dependent variable (i.e., age) involved the relationships between multiple independent variables inclusive of economic, aircraft-specific, and maintenance variables. A multiple linear regression model is a common tool to predict and describe relationships between multiple independent variables, also referred to as predictor variables. The dependent variable, the retirement age of an aircraft, was modeled as a function of the multiple independent variables, described later in this chapter, their corresponding coefficients, and constant term. In this model, the researcher made the following assumptions:

- Only relevant variables were included in the model. These variables were obtained from the aircrafts' TCDSs or ICAs.
- There was a linear relationship between independent and dependent variables
- The independent variables of the model were multivariate normally distributed.
- There was no multicollinearity in the data.

- There was no autocorrelation in the data.
- The variance of the predictive variable, age, was constant, assuring homoscedasticity in the model.

Population, Sample, and Sources of Data

The focus of this investigation was on aircraft manufactured by the Boeing Company, whose longevity is greater than its rival Airbus. Boeing is a U.S.-based manufacturer that has been in business since 1916 and is currently headquartered in Washington, DC. Boeing is a top U.S. exporter of aircraft and employs more than 141,500 people both in the United States and in 70 other countries. It is known for being diversified, pioneering, and innovative, as well as one of the most talented and capable companies in the world. Approximately 50% of the world's existing commercial fleet (over 10,000 aircraft) is composed of Boeing airliners. Boeing also consists of both a defense and space component. Boeing is considered to be one of the original manufacturers of all metal aircraft at the forefront of this type of construction. The researcher in the current study only investigated commercial turbine-powered aircraft; a block of aircraft produced by Boeing (and McDonnell Douglas) was omitted as they do not meet that criterion. Also omitted were any Boeing or McDonnell-Douglas Corporation (MDC) fleets that are currently used as military platforms or special mission aircraft such as the Space Shuttle lifting platform, J-Stars aircraft, military tankers, and the Boeing Dreamlifter. Additionally, aircraft manufactured for a governmental application were removed from the data set as they fall outside the area of commercial application and based upon mission or special application would skew the data, presenting issues that would have to be addressed in the analysis.

Population

The researcher chose to analyze the entire Boeing fleet because, as Kito (2021) explained, it is difficult to model fleet dynamics based on the life cycle analysis of a single type of aircraft. The original Excel data set was provided by Avitas, Inc., of Chantilly, VA, which has produced the Aircraft Blue Book value database for commercial aircraft, turboprop aircraft, and jet engines that is used throughout the world as a source of determining aircrafts' current market values, base values, and future values. A similar data set was obtained from Cirium/Ascend, which also produces data and information related to aircraft, values, analytics, and operational information. They are an additional producer of aviation data and performance metrics. Both use historical data sets of the global aircraft fleet, which allows queries to be made down to the individual aircraft level. Within this study, the dependent variable was aircraft age in terms of retirement or removal from operational service. At this point, it is assumed the aircraft has reached the end of its EUL. The researcher in the current study used two commercial products applicable to only the Boeing fleet and decided to conduct this investigation using a cross-sectional comparison of data detail. The researcher accessed and reviewed both sets of commercial pay-for data and compared them with publicly accessible data from Boeing the original equipment manufacturers (OEM) "Historical Annual Order" database set accessible in +ableau. Each set was merged together to verify the accuracy of data and seek out inconsistencies. The data available commenced in the year 1958 showing all aircraft produced and delivered by the OEM.

The researcher believed the issue of missing or incomplete data to be present. A review and alignment of the data stratified by specific aircraft manufacturers' serial numbers and cross-referenced to the original customer was conducted to verify the commercially available data sets aligned with that of the OEM. The results produced a slight level of inaccurate data where specific aircraft did not match 100% with either the Avitas or Cirium data set. To preclude the inclusion of missing data to generate statistically misleading results, the researcher decided to remove all line items in which anomalies were found. Additional investigation revealed the OEM claimed to have produced some models more than the commercial data sets shown. To correct that anomaly and produce a valid set of data for further functional application and manipulation and analysis, an investigation of the outliers commenced. Investigation of the serial number basis identified aircraft that were started in the production cycle and subsequently never completed for entry into operational service where some were in fact damaged on the production line, abandoned for technical reasons, or stopped due to litigation. This produced more serial numbers than were actually entered into commercial service. Those aircraft were removed from the data sets. The researcher further sorted the data for specific outliers and researched individual discrepancies and thus was left with a valid set for further functional application and manipulation and analysis.

The data set, now validated, consisted of all Boeing-manufactured aircraft by the OEM distributed by individual type and model inclusive of the original Boeing aircraft models of 707, 720, 717, 727, 737, 747, 757, 767, 777, and 787. Additionally, the product line of the former Douglas Aircraft and McDonnell Douglas Corporation (now Boeing) inclusive of DC-8, DC-8, DC-10, MD-11, MD-80, and MD-90 aircraft was added to produce a new inclusive data set. Upon merging the data sets, approximately 132 line items did not align in terms of consistent data. Each of these line numbers represented an individual aircraft serial number (S/N). Each serial number line item was researched to develop an accurate and conclusive outcome as to the authenticity of the data set and once verified was included into the data set in the correct line/CN position. The majority of the anomalies related to late model 727-200 aircraft and the decision basis was if in fact they were actually produced as “AF” advance freighters of straight model “A” advanced aircraft. Similar issues of discrepant data occurred during model changeovers (e.g., a 737-300 switched to a 737-400 aircraft in the production series). Additional discrepant data were found when deliveries were occurring at the end of a calendar year as the change in calendar versus the actual delivery date of the aircraft could in fact show the build or year of manufacture and the delivery date to be off by plus 1 calendar year. This initial combined data set consisted of 28,547 line items and 41 columns of data for a total of 1,170,427 data entry points. The researcher focused on reducing the set to those aircraft that have been removed from service or have been stored for more than 20 years. This reduced the working population for analysis to 9,806 specific aircraft serial numbers.

The combined Avitas/Cirium/Boeing data set was sorted again, removing all 707 and 720 product lines from the data. Initially, the researcher believed that as these models had no specific FAA-mandated LOV, the data could cause a bias if included. After further investigation and consideration, it was determined to keep those lines of equipment. The original thought for this removal was due to 14 CFR §26.21 Limit of Validity, as stated in the regulatory data both aircraft types are (g) Exceptions to the regulation as it does not apply to these specific model types according to the FAA. However, further review and discussion determined this set should remain, so the 622 line items (i.e., aircraft) were left to be analyzed. This assured the starting set would have similar technical aspects to each other for the investigation and that the bias as to only those aircraft with the LOV would not contribute to an error.

Additionally, all data about both orders and deliveries based on the calendar year 2022 were removed to align with the current Avitas and Cirium data sets that were dated December 31, 2021. Also eliminated were any orders that were identified as non-delivered products or unfilled orders; this task was accomplished to keep the analysis of the set with only those aircraft that had at some point in time been functional and operational during their life cycle. After finalizing all the data the set to be investigated totaled 7,887 specific aircraft by serial number.

Sample

With what was believed to be a consistent set of data, further analysis was accomplished on the sample population. Multiple queries were made through the NTSB data inquiry tool Aviation Accident Database and Synopses to develop a list of all Boeing, Douglas, and McDonnell Douglas aircraft that were involved in an accident that would have resulted in a catastrophic loss of the fuselage, thereby disqualifying them from the study. This occurrence would have affected the true economic life of the aircraft and caused an event other than the retirement of the aircraft. The NTSB uses the following terms.

49 CFR §830.2 Definitions

- **Aircraft accident** means an occurrence associated with the operation of an aircraft that takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage. For purposes of this part, the definition of “aircraft accident” includes “unmanned aircraft accident,” as defined herein.

- **Substantial Damage** means damage or failure that adversely affects the structural strength, performance, or flight characteristics of the aircraft, and that would normally require major repair or replacement of the affected component. Engine failure or damage is limited to an engine if only one engine fails or is damaged, bent fairings or cowling, dented skin, small, punctured holes in the skin or fabric, ground damage to rotor or propeller blades, and damage to landing gear, wheels, tires, flaps, engine accessories, brakes, or wingtips are not considered “substantial damage” for this part.

However, the NTSB database did not delineate accidents or incidents in which an aircraft sustained substantial damage as defined, which required the researcher to review the actual reports for content and disposition and remove all of those considered to be substantial or beyond the economic repair of the aircraft. Additional review and sorting were used to identify aircraft that were considered to have been involved in an accident that would meet the intent of the rule but not affect the economic viability of the aircraft to be sure issues such as an aircraft experiencing clear air turbulence and passengers or crew members becoming injured would not be extracted from the data set.

The researcher then turned the focus to those issues that surrounded aircraft such as regulatory issues or technical issues that affected fleets of aircraft. Some of these are identified below and span the various fleets as focal points to ensure an abnormal number of retirements did not result due to external mandates.

- Investigation 1- 747 SB54A2182 Pylon/Engine Strut modification after two hull loss accidents and one near miss incident aircraft were required to undergo extensive re-machining of the strut attach pin holes and supporting brackets. The estimated cost was between 7,700 and 8,892 work hours in the economic impact (labor estimated @$65.00 USD 1990) $500,500 and $577,980 plus the downtime of the aircraft. This was applicable to 897 aircraft. Research confirmed that only 37 aircraft that were inactive or retired were not complete, indicating approximately 95% of the fleet was complied with. The researcher believed this had an insignificant impact on the retirement age of the world fleet and it should not have any of the affected aircraft removed from the study.
- Investigation 2- 757 SB 54-0034,54-0035, 767-54-0080, 0081, 0082, Pylon/Engine strut improvement program designed to increase strength and maintain damage tolerance of the structure. Each aircraft model affected was expected to take on average 956 man-hours (labor estimated @$125 USD 2000) $115,821 plus downtime. The manufacturer provided both a no-charge kit and reimbursement for direct labor-related costs. The retrofit to the rest of the in-production fleet was accomplished on the assembly line. There was no significant impact on the fleet as all affected aircraft were modified and none were removed from the study.

- Investigation 3- 767-SB 53-0069 Fuselage deflection due to thermos contraction. Between line numbers 5 and 707, operators were experiencing cracking on 107 of a fleet of 702 aircraft at the time of issuance and were growing in numbers. Excessive preloading was shearing fasteners on the aircraft floor beams. The inspection, retrofit, and termination action would take approximately 1,133 man-hours (labor estimated @$125 USD 2000) $141,625 plus downtime. The manufacturer provided no-charge kit replacement parts and did not reimburse for labor costs. There was no significant impact on the fleet as all affected aircraft were modified and none were removed from the study. All additional aircraft were modified and future line numbers were accomplished in the manufacturing process.
- Investigation 4- JT9D7R4 engines. The researcher had concerns related to the specific 16-stage turbine engine produced by Pratt & Whitney and used on the 747, 767, and A310 platforms. There were two specific fleets of aircraft where the actual mount system for the engine was a totally different structure that affected two fleets in the world. One was the Qantas (QAL) fleet and the other was Japan Air Lines (JAL) where each had the engine produced with BG900 engine mounts as opposed to the more commonplace BG800 series. This abnormal/different configuration caused the engine to have a load-bearing nacelle and the engines could not be mixed, modified, or transferred to other platform applications, thus leaving the engines to only be used on the former aircraft of those two independent operators. Investigation revealed that as the two operators began to remove their aircraft from operational service [In both

cases the aircraft accumulated approximately 550 cycles per year] the operators had maintained a spare pool of engines to support operations at that level coordinated with the mean time between removal rates (MTBR) based upon the hour to cycle ratio. As the sales of the used equipment transpired, the aircraft were being modified to freighter configuration and both companies were selling off spare engines with the used aircraft equipment. Therefore, the retrofitting of the aircraft to a freighter configuration where the aircraft would fly approximately 50% of its original utilization in terms of cycles per year assured sufficient serviceable engines to continue to operate the fleet as the two operators removed equipment from service. There is no indication that this transaction caused any impact on the premature retirement of an aircraft type.

- Investigation 5- 14 CFR Part 36 - Noise Standards: Aircraft Type and Airworthiness Certification and the Maximum Noise Levels, of the International Civil Aviation Organization (ICAO) Annex 16. The introduction of required effective perceived noise decibels (EPNdB) that aircraft could produce at various stages of operations. Effectively these rules established what became commonly referenced as a Stage 3 noise level in the United States and its associated counterpart under EASA standards as Chapter III or collectively “Hush Kitting” of aircraft. This process was developed to reduce the noise output or silence high bypass turbofan engines. As of January 1, 2000, Stage 2 noise jetliners, those of 75,000 pounds of thrust operating in the United States, must have Stage 3 hush kits installed for noise attenuation.

> Companies such as FedEx developed and installed kits designed to provide full compliance with both FAA Stage 3 and ICAO Chapter 3 noise standards, whereas companies such as UPS decided to re-engine their entire affected fleet. Additional solutions were developed by manufacturers and implemented effectively, showing alternatives were available at reasonable costs to extend the life and utilization of aircraft affected by the regulations. Overall, the perceived impact of mass retirements did not occur. This action had a minimal overall impact on the worldwide fleet. Although some aircraft were retired, they had already reached the end of their effective and economical useful life, and this was not a premature event.

Of the approximately 22 specific instances investigated, none appeared to adversely affect the longevity of the aircraft negatively and therefore no additional aircraft were removed for regulatory changes, specific service bulletins, or airworthiness directives.

In the pre-analysis and data screening process and the review, sorting, and removal of incomplete and erroneous outliers, the data set was at 7,887 aircraft to be included in the analysis. Additionally, as sorted by the aircraft serial number, each row contained a 48-column data input field of data that pertained to dates of operations, engine types, numbers of engines installed, the aircraft configuration, the date of parking or storage, and many other bits of technical and operational issues. This set equated to a sum of 378,576 individual data points.

As this research involved the use of a quantitative method to measure the relationship and strength between the independent variables of CNT, LOV, CPCP, RAP, and MP intervals with that of the dependent variable of EUL or RUL seeking to determine whether there is a correlation between the variables. The independent variables were either manufacturer limitations developed in the airworthiness limitation section (ALS) of their manuals, Type Certificate Data Sheet (TCDS), or limitations imposed by the regulatory authorities by either code or airworthiness directive (AD).

Table 8 shows each variable followed by a description in the factoring set. Each variable is more completely described for clarification.

Table 8

Variables Used in the Study

Variable	Description
AGE	The physical age of the aircraft from the time of delivery in elapsed months until it was identified as removed from operational service, its retirement age. The age of the aircraft does not affect the safety standards nor the reliability so long as the product is maintained in accordance with the manufacturer’s standards, directions, and guidance.
CARG	Those aircraft that perform as a freighter, combi, or cargo-carrying aircraft inclusive of modified by aftermarket Supplemental Type Certificates (STCs) or by Master Changes to the original TC as accomplished by the OEM.
WB	Wide-body aircraft have a double row of aisles within the cabin of the aircraft and are also called a twin aisle aircraft. The cabin contains seven or more rows across the diameter of the fuselage, in some cases up to 11 across. Wide-body aircraft also allow for increased cargo capacity to be carried in the lower hull areas and in some cases are manufactured or converted to freighter/cargo aircraft. In some cases, the term jumbo is used inclusive of 747 and A380 model aircraft.
MD	Those aircraft were originally manufactured by either the Douglas Aircraft Corporation or McDonnell Douglas Corporation, formed by the merger of McDonnell Aircraft and the Douglas Aircraft Company in 1967 headquartered in St. Louis, MO. These entities were acquired and merged into Boeing in 1997 effectively.
F3Y	Those aircraft produced within the first 3 years of production from the OEM by the issuance of both the Production Certificate (PC) and the Type Certificate Data Sheet (TCDS) issued by the regulatory authority of the Member State.

Variable	Description
L3Y	Those aircraft produced within the last 3 years of production run by the OEM as calculated from the date of last delivery backward by calendar time.
CNT	A contingent new technology factor is when the OEM has developed a new replacement aircraft that is available for purchase and delivery to a customer and the model to be replaced remains within the production capabilities of the OEM. This aspect only takes into consideration those aircraft when both variants hold or held a production certificate and a TCDS simultaneously.
INF	Inflation factor for the retirement year of the aircraft obtained from FRED inflation as measured by the consumer price index reflects the annual percentage change in the cost to the average consumer of acquiring a basket of goods and services that may be fixed or changed at specified intervals, such as yearly. The Laspeyres formula is generally used. The Laspeyres Price Index is a consumer price index used to measure the change in the prices of a basket of goods and services relative to a specified base period weighting.
REC	Recession factor for the U.S. economy obtained from FRED. This index measures the probability that the U.S. economy was in a recession during the indicated quarter. It is based on a mathematical description of the way that recessions differ from expansions. The index corresponds to the probability (measured in percent) that the underlying true economic regime is one of recession based on the available data. Whereas the NBER business cycle dates are based on a subjective assessment of a variety of indicators that may not be released until several years after the event, this index is entirely mechanical, is based solely on currently available GDP data, and is reported every quarter. Due to the possibility of data revisions and the challenges in accurately identifying the business cycle phase, the index is calculated for the quarter just preceding the most recently available GDP numbers. Once the index is calculated for that quarter, it is never subsequently revised. The value at every date was inferred using only data that were available one quarter after that date and as those data were reported at the time. If the value of the index rises above 67%, that is a historically reliable indicator that the economy has entered a recession. Once this threshold has been passed, if it falls below 33% that is a reliable indicator that the recession is over.
RGDPG	The real GDP growth obtained from FRED. Real potential GDP is the CBO’s estimate of the output the economy would produce with a high rate of use of its capital and labor resources. The data are adjusted to remove the effects of inflation.

Variable	Description
NOIL	The nominal oil price obtained from FRED is an estimated price that may not reflect the real market price of an asset (it does not adjust for inflation). It is also known as the current dollar price.
E3	Aircraft having three engines installed as per the TCDS also referred to as a trijet aircraft and considered to be a second-generation jet-powered airliner. The reader should understand the economics involved in the operation of multiple engines and its impact on operational and economic performance metrics.
E4	Aircraft having four engines installed as per the TCDS also referred to as quad jets have four identical engines installed for increased thrust and lift capacities. This aspect was found in the early stages of the modern jet age and also found reemergence with the implementation of the Boeing 747 product line and the Airbus A380. As both performance and reliability increased by engine manufacturers, the need for redundancy diminished related to engines. The failure of a single engine on today's current production aircraft presents a less severe malfunction of the aircraft still allowing for the aircraft to continue operations to a safe landing opportunity.
LOV	The onset of multisite or multielement damage. It applies to certificate holders operating any transport category, a turbine-powered airplane with a maximum takeoff gross weight greater than 75,000 pounds and a type certificate issued after January 1, 1958, regardless of whether the maximum takeoff gross weight is a result of an original type certificate or a later design change. The FAA now uses it to define (limit) the operational life of civil transport aircraft.
RAPY	Repair Assessment Program- For pressurized fuselages applicable to the fuselage skin, door skin, and bulkhead webs. It requires operators to incorporate damage-tolerance (DT) data into their maintenance program. The manufacturers' SRMs include DT repair considerations for the fuselage pressure boundary. The SRM contains brief descriptions of DT considerations, categories of repairs, a description of BZI (Baseline Zonal Inspection), and the repair assessment logic diagram.
CPCPADY	Corrosion prevention and control program airworthiness directive (yes) Holders of aircraft type certificates in conjunction with various steering groups consisting of the manufacturer's representatives and regulatory authorities developed these programs in response to airworthiness directives (Ads) issued by the FAA. These programs were established to maintain the aircraft's structure resistance to the onset of corrosion and mitigate it to level 1. The baseline CPCP, developed by the manufacturer for all operators of a particular model of airplane, consists of corrosion

Variable	Description
	prevention and control tasks, definitions of corrosion levels, compliance time, and reporting requirements to the state airworthiness authority.
D80	Dummy variable for aircraft produced between 1980 and 1989.
D90	Dummy variable for aircraft produced between 1990 and 1999.
D20	Dummy variable for aircraft produced after 2000.

Note. FRED = Federal Reserve Economic Data and definitions; FAA = Federal Aviation Administration Data and definitions.

Sources of Data

The researcher obtained panel data from two commercially available databases and a third public access data set available from the manufacturer, Boeing. In selecting the three data sets all with the same basic information, the researcher was able to combine all sets, removing any duplicative data and developing a set of outliers needing specific missing or erroneous data to be verified. Any abnormalities were addressed on a case-by-case basis. This allowed for the development of the most complete econometric model to be researched.

Treatment of the Data

The researcher developed a maintenance decision model looking at various maintenance-independent variables and economic predictors of the impact of the retirement age of aircraft by a historical examination that is unknown. As discussed by Ackert (2011), aging aircraft have a more elastic response to economic cycles than current technologies available. In a quantitative examination of the data, the researcher endeavored to find both the cause and effect of the relationships and interactions existing between the variables.

The data sets were imported to NLOGIT, a commercially available econometric modeling software program used to build models of discrete choice among multiple alternatives using regression. In the research and model, the researcher examined the variables and the role they each played within the model. The sample consisted of data that reflected individual observations in multiple situations. The logit model was augmented through the use of individual effects as found in regression models.

In the model, the researcher applied categorical variables to the specific maintenance tasks/operations such as in the use of CPCPADY, which indicates that either the aircraft has an airworthiness directive mandated Corrosion Prevention and Control Program or not. Similar variables were introduced indicating the number of actual engines installed on a particular aircraft by model types such as E3 and E4 indicating that the respective model aircraft was equipped and type certificated with either three or four engines installed. All the remaining aircraft were considered to have two engines installed in accordance with their TCDS.

Descriptive Statistics

In this section, the researcher summarizes and organizes the characteristics of the model having collected the sample data and analyzed them through the use of NLOGIT. NLOGIT is a suite of software for the estimation of discrete choice models by Econometric Software, Inc. The researcher describes the statistical relationship of the output data set as produced in the software. In applied econometrics, proprietary software packages such as Gauss, MATLAB, Stata, SAS, and NLOGIT remain the most popular and are taught in most graduate programs (Seabold & Perktold, 2010). Bergtold et al.

(2015), in an examination of the software, found that among the packages tested, NLOGIT generated the smallest root mean squared error (RSME).

Reliability Testing

In attempting to determine the reliability of the measurements, the researcher used NLOGIT, which was tested by the National Institute of Standards and Technology and identified some limitations in programs such as SAS and MATHLAB in specific areas. NLOGIT in version 9.0/4.3 showed in its tolerance settings produced a score of 1e-21 for overall parameters (Odeh et al., 2010). In this model, a reliability test using Cronbach's alpha was conducted to examine the appropriateness of items entered into the factor analysis. The reliability was assured for those having a Cronbach alpha value higher than 0.7 (Voon, 2011) showing internal consistency. As the researcher used this to measure reliability, the researcher assumed the data to be normally distributed and linear in nature.

Hypothesis Testing

In the testing of the hypothesis, the researcher wanted to determine whether there were adverse correlations between the IVs and DVs. Data were entered into NLOGIT from the Excel data (converted to CSV) gathered from the three data sources. The program uses the Wald Test for confirmation that the set of IVs is collectively significant for the model or not. The Wald test samples the population to determine the unobserved true value of the parameter.

Nature of the Study

The nature of the study was to examine how technology and maintenance variables such as maintenance program intervals, the LOV, aircraft configuration (i.e., number of engines), economic design objectives (EDOs), corrosion prevention and control programs (CPCPs), and repair assessment programs (RAPs) combined with economic variables such as fuel prices and GDP affected the EUL of the asset. Cross-sectional multiple regression was chosen but may have resulted in low validity as there could have been extraneous factors acting upon the variables that were not included in this research and were unknown to the researcher.

Support for the Approach

Aircraft engineering analysis comprises the basic linear equation such as that of momentum, mass x acceleration. Proctor and Duncan (1954) developed a linear regression model in their examination of airline costs. Recently, the economic theories presented by Marx et al. (1995) represent a life cycle cost analysis related to aircraft from their conceptual design through the production cycle and are modeled using a linear approach. As established by J. J. Lee et al. (2001) in their work entitled, "Historical and Future Trends in Aircraft Performance, Cost, and Emissions," a log-linear regression model is used to qualify the relationship between aircraft price and fuel as part of the direct operating costs and revenue passenger kilometers (RPKs). The use of linear modeling by Li et al. (2016) in the predictability of aircraft failure rates explains how the commonly used statistical prediction methods are inclusive of mainly univariate linear regression analysis prediction methods, multiple regression analysis prediction methods, and nonlinear regression analysis prediction methods. The analysis for this investigation was based predominantly on the individual type/model aircraft produced by one manufacturer across various fleet types. A regression analysis model was chosen by Vasigh and Helmkay (2000) based on the analysis of individual aircraft and accident rates dependent upon the age of the aircraft. A similar model was undertaken in this research.

Support for Use of Economic Variables

Gross Domestic Product (GDP)

In this analysis, the researcher determined that economics play an important role in determining when a fleet should be disposed of or parked based on current situations. To assist in analyzing the impact of economics on fleet age and useful life, the researcher chose GDP for the correlation to the production years. The cost of operation and the ongoing support of aircraft are drivers in assessing the replacement of a fleet. This analysis and the possibility of a replacement aircraft for the United States Air Force (USAF) are considerations, according to Pyles (2003). Greenfield and Persselin (2002) used these costs as a driver to determine the optimal replacement period for military aircraft. Ramey and Keating (2009) determined that designs (type/model) serve as long as they are technologically and economically viable, which further supported the use of economic measurement as a variable in the current investigation. Dixon (2006) spoke to the overall life cycle in which older equipment requires more funds to maintain, which, in turn, decreases the funds available for new equipment. The CBO estimated spending on operation and maintenance for aircraft increases on average by 1% to 3% for every additional year of age after adjusting for inflation (Kiley, 2001).

The retirement of aircraft considers many factors and the age has changed over the last decades. Schlesinger and Grimme (2021) analyzed the influence of economic data such as oil prices, GDP per capita, and the number of annual passengers on aircraft to determine a retirement age.

As an economic variable, the researcher chose to use GDP. As discussed by Gnap et al. (2021), a lack of investment in transport development deters international investors, affecting GDP. Thus, both infrastructure and demand for transport are driven by economic growth. Lo Storto (2016) stated there is empirical evidence that supports a strong statistical positive correlation between the air cargo industry growth and the economic growth of a country measured both by GDP and GDP per capita, again showing a strong relationship. Vasigh et al. (2018) addressed growth factors related to aviation, which include the GDP or gross national product (GNP) as drivers in air travel demand and therefore growth and asset need to fulfill the demand of the prosperous population. Demand in the aviation industry is influenced by numerous factors such as macroeconomics, fuel price, globalization, and competitiveness (Zhang et al., 2017), and GDP is one of the macroeconomic indicators.

Fuel

The fuel burn of an aircraft and its reductions have been both policy and priority over the years. As the cost of jet fuel increases, airlines find that their pricing must follow, thereby increasing consumer costs. Over 10 years from 2009–2019, the number of passengers carried by air transport was around 2.25 billion and increased to 4.56 billion (The World Bank, 2020), an approximately 103% increase before a sharp drop as the world entered the period of COVID. As of April 2022, global air travel is rebounding from the pandemic and is currently at approximately 3.43 billion according to data published by Statista (2023). As individuals, we all can agree that the aviation industry as it relates to commercial operations is a major contributor to the global economy. Research into commercial jet fuel burn by Zheng and Rutherford (2020) indicated that the past decade, from 2010 to 2019, saw a quickening of fuel burn reductions as a result of the introduction of many new fuel-efficient models, including the Airbus A320neo, Boeing 737 MAX, Airbus A350, and Boeing 787 families. However, they indicated fuel burn is measured block to block, therefore considering the taxi out and in as well as any implied gate delays. Should we find ways to make the ground operations more effective, we could notice even further reductions in costs. Additionally, as we institute the use of direct route traffic (i.e., point to point direct as opposed to waypoint flying), we will cut down distances within the navigation patterns and decrease fuel burn.

Marks (1981) stated reducing fuel consumption is only one of many parameters affecting the overall design of an engine, though in the prevailing world economic situation it must be of the first importance in powerplant development. Additionally, there is a balance between the economics of fuel savings and the direct reduction in fuel utilization that affects fuel burn as the engine degrades. Thus, fuel plays a dual role in utilization and economics combined with maintenance efficiencies. Fuel correlation has been used in previous studies in terms of cost, consumption, and maintenance dollars expended.

Although as a society we try to focus on both the production and application of biofuels to help to reduce greenhouse gas emissions, within the aviation sector we are not yet at that point. Airlines use Jet A fuel, a kerosene-based product. It has been shown that a strong correlation exists between fuel prices and its relationship to air transport. Currently, Jet A is the primary fuel source for the power generation of aircraft. In this analysis, the researcher looked at past fuel prices and their impact, if any, on the longevity of aircraft life. Fuel falls into the basic category of issues inclusive of efficiencies, management, and overall weight of an aircraft. The analysis is ultimately always simplistic—How much does it cost to move one passenger or one pound of cargo one mile? The answers may vary greatly, yet we must consider fuel to be an integral part of the analysis. According to the IATA (2020), for the pre-pandemic year 2019, the global airline fleet consumed over 360 billion liters of fossil fuels and pumped more than 910 million tons of carbon emissions into the atmosphere.

Support for Use of Maintenance Variables

Proper maintenance of an aircraft should allow the operation of that asset to function and operate hypothetically forever. The performance of both maintenance and preventative maintenance establishes a safe, reliable asset that is airworthy (understand that under the U.S. FAA system, this means that the aircraft is safe for flight and the aircraft complies with its TCDS). However, there comes a point where the structure, due to extended periods of pressure cycle operation, becomes subject to failure at a greater rate. Structural-related issues increase exponentially with time. Maintenance programs are put in place to identify and correct such occurrences before a catastrophic failure of any primary structural component becomes a living part of maintenance. The stagnation of a program may lead to results that may affect the safety of an aircraft as it ages. The issues of widespread fatigue damage of an aircraft have led to the establishment of an LOV supported by engineering data analysis and a robust structural inspection and maintenance program. The FAA under 14CFR§ 25-132, 26-5, 121-351, and 129-48 has developed rules to address the structural integrity of airplanes as they age that must be adhered to by operators and manufacturers. LOV is a defined measurement in terms of cycle, hours, or a combination that the OEM has proven that widespread damage will not be encountered by an operator due to the inherent design characteristics of the structure. The LOV is thus an ultimate limitation of the life of an aircraft that it may not operate beyond without regulatory approvals.

Maintenance programs (MPs) are part of an operator’s FAA Operations Specification or “Ops-Spec” that dictates how they will provide for the continuous airworthiness of the aircraft. In some cases, this is referenced as a Continuous Aircraft Maintenance Program (CAMP), which combines both the function of inspection with that of maintenance and preventative maintenance. Aircraft have experienced improvements from the first onset as a mode of transportation. Changes to components, materials, and processes have increased reliability. Details of maintenance programs were discussed more completely in Chapter II with explanations as to the regulatory mandates and underlying concepts involved. However, the development of maintenance concepts over time has evolved. Early manufactured aircraft that became operational were delivered under the maintenance concept of hard time where replacements of components or inspections of items had either a cycle count, an hour component, or a calendar component as the controlling factor. According to the Air Transport Association (now A4A) report, 51-93-01, effective maintenance programs are continuously reviewed and updated. This, combined with the continuing airworthiness of aging airplanes, is directly dependent on both the effectiveness and quality of the maintenance program through the interaction and feedback of the status and information.

CHAPTER IV

RESULTS

Chapter 4 presents the results of the analysis used in this investigation into the EUL of commercial aircraft, namely the overall Boeing fleet of commercial jet aircraft produced between 1956 and 2021. There was an average age of 28.63 years from the DOM until the actual cataloged date of retirement for the entire population investigated. It must be understood, however, that the actual physical retirement date (i.e., the point at which the owner of the asset parked or placed the aircraft into storage) from a practical standpoint may have happened earlier than the actual reported date. Some circumstances and underlying reasons that can affect the operator's decision to remove an aircraft include a major maintenance check coming due or the decision to not invest additional funds. There may also have been issues related to an investment strategy where the owner elects to continue depreciating the asset until such time that they actually retire the asset. Multiple other constraints, such the ownership of the airframe or its engines, safety and integrity of aircraft, climate risk factors, environmental concerns, tax issues, depreciation issues, and lease terms, all are part of the decision matrix. These remain hidden to the public and cannot be investigated.

The research questions and corresponding hypotheses investigated in this study were as follows:

R1: Do aircraft cycles, hours, regulatory inputs, and macroeconomic variables influence the EUL of an aircraft asset?

$H1_0$: There are no statistically significant maintenance or technical variables that influence the EUL of the asset.

H1$_a$: There is a statistically significant relationship between the independent variables and the EUL of the asset.

R2: Does the age of the aircraft (DV) exceed the required LOV?

R3: Is there a predominant group of IVs that has the largest effect on the EUL outcome?

R4: Is there a specific model Boeing aircraft that is more susceptible to earlier retirement due to shorter EUL?

R5: Based upon Maintenance Steering Group (MSG) program development, has there been an impact on retirements and a shorter EUL?

Analytical Approach

The technique applied in this investigation was a standard multivariate regression analysis focused on determining the statistically significant IVs that are associated with an increase or decrease in the EUL of Boeing commercial aircraft. This technique is applied to estimate a model with multiple predictors to determine a singular outcome, which in the case of this research was retirement age. As a quantitative analysis is considered to be one of the frameworks suitable for an economic study, the researcher determined that this approach would be the best fit based on the large number of accessible data points from multiple sources in the sample population. Babbie (2010) described quantitative methods as an approach where emphasis is placed on objective measurements and the statistical, mathematical, or numerical analysis of data collected through preexisting statistical data using computational techniques. Such research focuses on gathering numerical data and generalizing them across groups to explain a particular phenomenon. In this study, the researcher endeavored to determine the relationships between various IVs, both maintenance and economic, and the DV of the age of the aircraft asset at retirement from operation. As the researcher views aircraft as a commodity such as a car or a machine, a model that involved a level of macroeconomic scrutiny was applicable in this analysis. In NLOGIT, the statistical tool used, the product of the analysis is the output of z-scores. In their basic form, z-scores equate to standard scores with their mean set to 0 and their standard deviation set to 1 (Dodge, 2016).

The z-scores are used in an analysis to normalize data and make it easier to compare different variables. They are calculated by subtracting the mean from the score and then dividing by the standard deviation. The measurement produced is an indication of how many standard deviations the score is from the mean. This makes for an easier comparison between the different distributions. By application, the z-scores are then all in the same unit regardless of the original units of the data.

Additionally, dummy variables are introduced to represent categorical data as they are an effective way to represent data that cannot be measured numerically. Dummy variables are especially useful when comparing groups or performing regression analysis. Through the use of dummy variables, relationships can be identified among various groups, and possibly among different variables, that might not be immediately obvious when looking at the raw data. The use of dummy variables is quite common in regression models to set artificial variables that represent an attribute with two distinctive possibilities (Skrivanek, 2009). In the current study, the variables were assigned a value of a 0 or a 1 to indicate the presence of a condition as related to production, maintenance, and physical attributes.

To comply with regression assumptions (e.g., linearity, normal distribution, and homoscedasticity), the DV (i.e., aircraft age at retirement) was transformed using natural logarithm function. The log transformation is used to linearize the data set and to produce results that are symmetrically distributed or normalized. A dummy variable representing years of manufacture in 10-year blocks was coded into the data set. Transformation of the actual year of manufacture transitioned the date to a binary variable either falling within the 10 years or outside the 10-year window. The time dummy variable was used to control for the time trend to ensure the statistically significant coefficient of the other IVs captured the relationships between them and the DV without the influence of overall time trend. Though introducing the dummy variable, a determination could be made regarding where the aircraft type and model resided within the production cycle, thus enabling the researcher to determine by comparison one group against another group of aircraft and whether any were affected by external constraints during such a time frame. Refer to Chapter III for detailed description of the IVs included in the model.

Concerns Raised About the Process

Concern emerged over the possible correlation identified in some of the economic IVs considered for the study. West and Cao (2022) investigated this aspect and found positive correlations exist between the long-run, or low-frequency, components of inflation on the one hand and of money growth or long- or short-run nominal interest rates on the other. Additionally, Baghestani (2010) used the 10-year Treasury rate to develop a model to forecast and predict expected inflation with accuracy using a random walk and augmented-autoregressive model, thus showing a correlation. To address this issue, the researcher performed a correlation analysis of the variables and noted there could be a correlation between some of the economic variables, most notably inflation and the 10-year Treasury notes and recession and real GDP. The analysis is shown in Table 9 and highlights the points of concern that needed to be addressed.

Table 9

Correlation Analysis of the Economic Variables

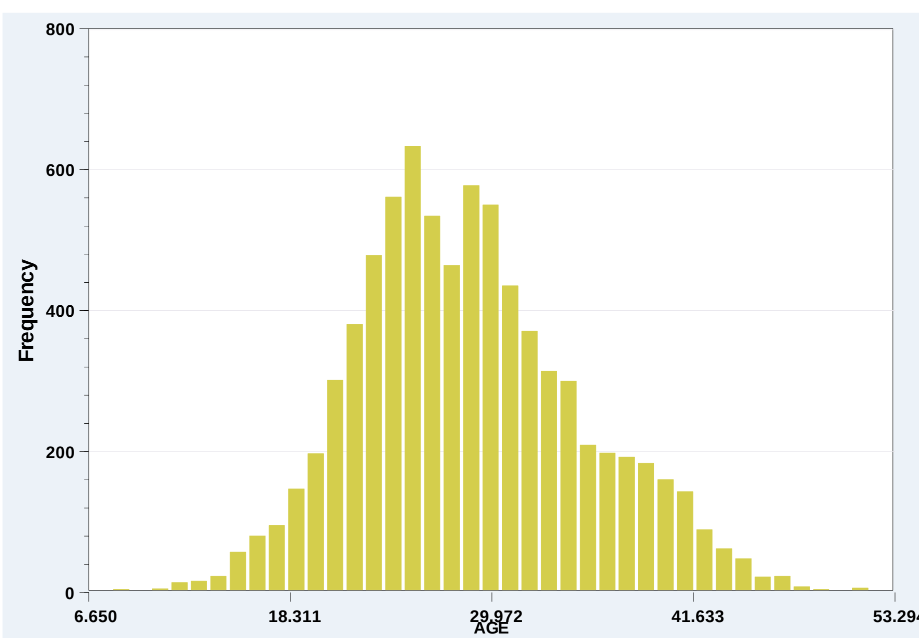
	AGE	LAGE	CARG	WB	MD	F3Y	L3Y	CNT	INF	10YT	REC
AGE	1										
LAGE	0.983024	1									
CARG	0.464148	0.426166	1								
WB	-0.10737	-0.09398	0.054385	1							
MD	0.178431	0.160022	0.026537	-0.10715	1						
F3Y	0.062038	0.048701	-0.06367	-0.00796	0.141332	1					
L3Y	-0.02872	-0.04011	0.069993	-0.05325	0.058108	-0.23214	1				
CNT	-0.02698	-0.02134	-0.05276	-0.05607	-0.00248	-0.1021	0.309509	1			
INF	-0.15633	-0.17634	-0.05547	-0.1193	-0.01619	0.136818	-0.05974	-0.04917	1		
10YT	-0.15409	-0.14963	-0.0317	-0.15586	-0.00431	0.234048	-0.09603	-0.0641	0.595358	1	
REC	0.075324	0.070952	-0.00322	-0.03261	-0.00709	-0.00593	-0.01856	-0.01167	0.131848	0.1134	1
RGDPG	-0.13662	-0.12956	-0.03	-0.01117	-0.0183	0.098961	-0.04437	-0.0324	0.021079	0.242256	-0.6851
NOIL	0.177983	0.15422	0.070231	-0.00704	-0.0018	-0.20269	0.093427	0.064157	-0.07841	-0.46398	0.211485
3E	0.23622	0.243648	0.233212	-0.03364	-0.15982	-0.08108	0.078391	-0.05988	0.03617	0.144849	0.049216
4E	-0.04942	-0.06418	0.252109	0.42076	-0.06746	0.036485	0.009167	-0.05959	0.233987	0.343798	0.007827
MSG1	0.028865	0.045345	0.116056	0.527084	-0.17721	-0.04998	-0.03926	-0.02955	-0.03327	0.026381	0.005339
MSG2	0.090442	0.093543	0.075362	0.39641	0.297707	0.03832	-0.03666	-0.02223	-0.03611	-0.00877	0.020949
MSG3	-0.50429	-0.49492	-0.29761	0.101556	0.001623	0.040135	-0.06513	-0.05325	-0.25573	-0.50031	-0.11831
LOV	0.101581	0.12268	-0.06839	0.11691	0.15567	-0.01551	0.05421	0.025962	-0.3675	-0.47904	-0.04485
RAPY	0.195708	0.201306	0.1085	-0.23364	0.102044	0.011502	-0.03398	0.034634	0.113938	0.218221	0.067665
CPCPADY	0.202591	0.207539	0.084936	-0.26125	0.075858	0.012926	-0.03495	0.035379	0.120209	0.224908	0.070571
D50	-0.06885	-0.07091	-0.02075	-0.04789	0.00884	0.104167	-0.02418	-0.01064	0.240745	0.275222	0.024657
D60	0.341102	0.294013	0.23273	-0.28925	0.116347	0.377215	-0.10876	-0.06504	0.28876	0.517621	0.054214
D70	0.226968	0.244413	0.081513	0.155091	-0.01573	-0.21069	-0.06663	-0.06315	0.002679	0.068987	0.057988
D80	-0.11742	-0.06815	-0.13559	0.013426	-0.03774	-0.10331	0.161147	0.133367	-0.17969	-0.27948	0.013573
D90	-0.40366	-0.40704	-0.16742	0.137752	-0.04587	-0.08137	0.000417	-0.00727	-0.18957	-0.36115	-0.13465
D00	-0.23765	-0.30034	-0.06169	0.037912	-0.0766	-0.03999	0.03324	-0.01456	0.042753	-0.1109	-0.04123

	RGDPG	NOIL	3E	4E	MSG1	MSG2	MSG3	LOV	RAPY	CPCPADY	D50	D60	D70	D80	D90	D00
RGDPG	1															
NOIL	-0.47419	1														
3E	0.010186	-0.1184	1													
4E	0.128993	-0.18398	-0.29947	1												
MSG1	0.021225	-0.04568	-0.14853	0.495987	1											
MSG2	-0.03293	-0.01983	0.355195	-0.10637	-0.05276	1										
MSG3	-0.09027	0.220045	-0.42493	-0.18068	-0.21049	-0.1583	1									
LOV	-0.12195	0.205546	0.130476	-0.43569	0.061621	0.046344	0.184897	1								
RAPY	0.013739	-0.01092	0.174057	0.165738	0.082204	0.061824	-0.39055	-0.07221	1							
CPCPADY	0.013478	-0.01298	0.142719	0.169329	0.083976	0.063156	-0.39927	-0.07377	0.97376	1						
D50	0.081515	-0.10244	-0.05345	0.178483	-0.02524	-0.01899	-0.07574	-0.2576	0.029581	0.030218	1					
D60	0.16282	-0.32231	0.121245	0.195146	-0.14849	-0.1161	-0.46321	-0.30937	0.180905	0.184829	-0.05555	1				
D70	-0.02017	-0.03272	0.326093	-0.00816	0.254102	0.256283	-0.43817	0.102171	0.175633	0.179442	-0.05393	-0.32983	1			
D80	-0.15174	0.287966	-0.19108	-0.16226	0.01757	-0.04026	0.328683	0.151754	-0.09118	-0.08202	-0.06217	-0.38018	-0.3691	1		
D90	-0.02185	0.079548	-0.23613	-0.04563	-0.11861	-0.09322	0.586162	0.108881	-0.2584	-0.28769	-0.0446	-0.27277	-0.26482	-0.30525	1	
D00	0.061864	0.01261	-0.07317	-0.05064	-0.03455	-0.02599	0.164167	0.030354	-0.1236	-0.09804	-0.01243	-0.07604	-0.07383	-0.0851	-0.06106	1

Additional concerns were raised as to the possibility of nonlinearity in the model as to the DV of age of the aircraft. To address this, the researcher decided to transform age into a logarithmic variable. Benoit (2011) indicated "logarithmically transforming variables in a regression model is a very common way to handle situations where a nonlinear relationship exists between the independent and dependent variables" (p. 2). The natural logarithm transformation of DVs has a long history in empirical economics (Mullahy & Norton, 2022). The log transformation normalizes the data set, making it more homoscedastic, which reduces extreme values and stabilizes any variances. Additionally, it helps to make any skewed data more symmetrical. The DV of age was log-transformed to LAGE, and all the IVs remained in their organic state. Figures 11 and 12 show the histograms of age and the log of the age. By application of the LAGE, the researcher was able to produce a more normalized curve.

Figure 11

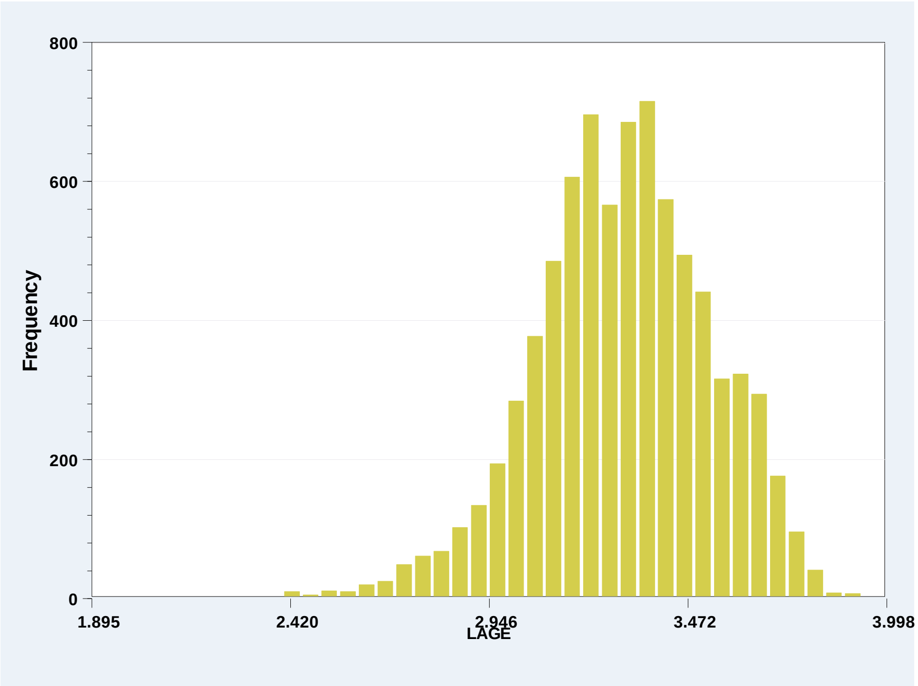
Histogram of Age Versus Frequency



As the comparison of the second histogram (see Figure 12) shows, when the log of age was applied to the data set, the result was a more uniformly produced curve.

Figure 12

Histogram of Log of Age (LAGE) Versus Frequency



Sample Size

The sample size was determined by the identification of those aircraft produced and manufactured by a particular manufacturer, The Boeing Company, between the years of 1956 and 2021. The data sets were discussed extensively in Chapter III for reference. The initial population was 21,839 aircraft produced and was brought down to the 7,887 aircraft confirmed as retired or approximately 36% of the total aircraft population produced. From that universal set of aircraft, the researcher confirmed those to be actually retired and added those aircraft that had been parked and stored, and those having reached an age of 20 years were also included as they were determined to be retired. This was supported in relationship to the COVID-19 pandemic and the ability for aircraft to be returned to service once they reach the 20-year threshold. The economics to restore those aircraft to operational service increase in relationship to both man-hours required (Adrienne et al., 2020) and the consideration of an additional term or lease. Additionally, those aircraft that did not fly as commercial aircraft were removed from the study. The researcher also removed the group of aircraft considered to be special mission or single purpose aircraft. These aircraft included Boeing Business Jets (BBJ), Joint Surveillance and Target Attack Radar System (JSTARS), Shuttle Carrier Aircraft (SCA; extensively modified aircraft for a single mission use and application), Dreamlifter aircraft (a specifically modified 767 aircraft designed to transport Boeing production parts and materials to assembly locations), and those designated aircraft for Heads of State that are not used in the commercial transportation of persons or goods.

Selection of the Variables

The categorical IVs selected as maintenance concepts were identified and coded based on their relationship to aircraft structural design or program identification. These IVs were arranged by either a yes (1) or no (0) answer to the construct to which they were applied, such as in the question, Does the aircraft have an assigned LOV as mandated by the manufacturer and regulators? The considerations and rationale for selecting them were based on various programs instituted by the regulatory authorities and additional programs instituted by the aircraft manufacturers. These data were coded into binary functions, indicating the concept/program was either present on the particular model aircraft or it was absent.

The variables can be further defined by broad ranges as identified in Table 10 which represents, a general discussion of the variables, followed by the reasoning and logic as to their inclusion in the study by variable category.

Table 10

Independent Variables Used in the Analysis

Variable type					
Categorical variables					
Aircraft configuration	PAX	CARG	NB	WB	
Production cycle	F3Y	MAT	L3Y	CNT	
Maintenance - regulatory	LOV		RAPY		CPCPADY
Maintenance - program	HT	MSG-1	MSG-2	MSG-3	
Dummy variables					
Production period	D50, D60	D70	D80	D90	D00
Numeric variables					
Independent economic	INF	10YT	REC	RGDPG	NOIL

Aircraft Configuration

To begin the study, the researcher identified all commercial jet transport aircraft manufactured by Boeing that are broadly classified as transport category aircraft under 14 CFR Part §21.75. This category is further defined by two distinct types of operations as to either a passenger aircraft (PAX) or a freighter aircraft (CARG). This research did not distinguish the classification of combination aircraft as that is not applicable under the FAA system. The secondary distinction is that the aircraft is either classified as narrow body (i.e., single aisle; NB) or wide body (i.e., multiple aisles; WB). The International Civil Aviation Organization (ICAO, 2016) defines the categories and types specifically as follows:

a passenger aircraft is an aircraft primarily designed and configured for the transport of persons and their accompanying baggage;

an all-cargo aircraft or freighter is an aircraft configured for the carriage of freight only (although persons who accompany certain kinds of cargo, such as livestock or oil rig machinery, may also be carried);

a wide-body aircraft is a large transport aircraft with internal cabin width sufficient for normal passenger seating to be divided into three axial groups by two aisles (in practice this means not less than 4.72 metres (15.6 feet));

a narrow-body aircraft is an aircraft having only one aisle in the cabin with passenger seating divided into two axial groups. (pp. 188–189)

The above categorical variables allowed the term aircraft to be more clearly defined as to both size and specific applications. It should be understood that some aircraft may commence their life as passenger aircraft only at a later date to be modified by either master change (MC) or STC and become converted to a freighter or cargo aircraft. As this process is only a one-way conversion, once changed to a freighter these aircraft do not revert to passenger aircraft, so they are counted as freighter aircraft. This conversion process is referenced in the industry as a passenger to freighter (PTF) conversion. Additionally, this research made no distinction between freighter aircraft used in the movement of heavy or large freight and that of freight integrator service or overnight package delivery companies such as DHL, FedEx, or Euro Post.

Production Cycle

In general terms, aircraft conceptually begin life as an idea, and from that point they go through a design and simulation phase. Most of the design time is heavily loaded with trying to “define” the actual aircraft. As the aircraft moves ahead to the development and certification phase, most early aircraft have already undergone changes to the airframe or engines. By the time the first aircraft is ready for test flight, there are others already in the production line following close behind. In other words, the assembly line process has begun, or the industrial ramp up is in process with parts from suppliers coming into the assembly line. The manufacturer does not complete a one-off test aircraft and wait until that is approved. They have customers already in place and are not building on speculation. This is a point at which everyone, from the manufacturer to the government and the potential end user, is concerned with the aircraft’s weight and performance as the outcome has a large financial impact. All wish to have an aircraft that is delivered as advertised in the introduction literature and marketing campaigns and that is compliant with the contractual obligations among the stakeholders. For the analysis, a choice was made to define the aircraft within its production cycle by using the following categorical variables: F3Y to represent aircraft within the first 3 years of production, MAT to represent the mature production and delivery of the aircraft, L3Y to represent the last 3 years of the cycle, and CNT to represent when the manufacturer is offering a competing product within the last 3 years of the production cycle.

Maintenance - Regulatory

Maintenance regulatory items that have a fundamental construct as being implemented by governmental organizations or a regulatory process were introduced to analyze their impact on the industry. Although the researcher did not identify every AD, focus was placed on those that have significance in terms of instituting a fundamental change on the performance of maintenance and may have forced the premature retirement of aircraft by make or model type.

Items such as the LOV represent a period of time or cycles at which the manufacturer can no longer support the aircraft as they have not concluded or completed any testing, evidence, or analysis of an aircraft's ability to fly beyond those circumstances. LOV is further clarified as the point in the structural life of an aircraft at which there is a significantly increased risk of uncertainties in its structural capabilities.

The FAA (2003), in Order 8300.13, instituted a point based upon the specific age of an aircraft where each repair made to the primary pressure vessel of that aircraft must have been reviewed with assurances that the implemented repair conformed to the then current applicable regulations. Also, repairs classified as temporary in nature could be made permanent at a later date. In other words, the temporary repair needs to be made permanent within a prescribed length of time or maintenance period. Both temporary and permanent repairs are to have supplemental inspections to ensure there are not any underlying faults or damage that could become detrimental to the airworthiness of an aircraft.

Unrecognized and unrepaired damage may produce devastating consequences in the safety of the aviation system. Left unchecked, these results could decrease the load carrying capacity of the fuselage structure, cause localized stresses that the manufacturer had not intended, or increase the rate of crack propagation.

As a general concept of a damage tolerance philosophy, both inspection and early detection are key elements. These concepts go hand in hand with a comprehensive maintenance plan determined by the operators, manufacturers, and regulators. At some point, the maintenance of aircraft eventually requires operators to complete repairs. As the level and restoration to meet original design specifications may vary by the capabilities of each operator, a system of standardization was established by regulators to ensure a safe operational fleet. Additional considerations are now required to ensure repairs allow for a method to guarantee a re-inspect-ability factor, meaning the repairs are not buried to where they cannot be accessed and inspected again at a later date. Repair data must now be available and must conform to the original certification basis of the aircraft. Although this could be considered problematic as early production aircraft were certificated to a different standard, those have been practically all removed from the active fleet, so no bias was implied or introduced into the analysis.

Corrosion prevention programs were part of the original documentation for aircraft and not specifically singled out until the 1990 period after corrosion damage to the Aloha 737 went unchecked for a considerable period. Prior to 1988, the industry lacked focus on preventing and controlling corrosion, and the FAA lacked compelling evidence that the existing maintenance and inspection programs were not controlling corrosion at a safe level (U.S. Department of Transportation [DOT], 2016). This was rectified by regulators through the introduction of the Corrosion Prevention and Control Program and the Supplemental Structural Inspection Program.

To analyze this aspect, the research included the categorical variables of LOV to represent the limit of validity, RAPY to represent aircraft that have included by statute the requirement for a repair assessment program, and CPCPY to represent a mandated corrosion prevention and control program by regulatory requirement.

Maintenance - Program

Hard time (HT) maintenance programs were originally specific and developed under each operator's maintenance concept. An HT program is driven by hours, cycles, or calendar time of any combination of each period such as not to exceed Y time or accomplish before the accumulation of X cycles. These programs are accomplished regardless of the actual condition of a component. The component could have just been replaced but if it is scheduled to be included in a check, it could once again be replaced. There is no consideration for economic controls or outcomes and such a concept makes asset management difficult as the tasks are blocked or grouped together, and an event is scheduled in totality.

MSG-1 was the first program developed in conjunction with industry regulators and the manufacturer of the aircraft. This concept only applies to the early model 747-type aircraft and was established to assure both the safety and reliability of the aircraft. This was the first concept that moved away from the HT limitations and the overhaul and replacement time limitations.

MSG-2 also covered only a limited aircraft type as its application was only for the two then current tri-jet aircraft, the L-1011 and the DC-10. This analysis only covered the DC-10 aircraft as it did not include Lockheed manufactured aircraft. One of the major criticisms of the MSG-2 program related to its lack of viewing any economic circumstances related to maintenance or components. This concept was rectified with the next program and has remained part of the MSG processes for all future developed standards.

MSG-3, as discussed by industry maintenance personnel, is the point that a framework was established to shift from time-based (either calendar hours or cycles) to a program that fundamentally looked at data and the condition of the aircraft and its component make up. This condition-based maintenance concept continues today as both an effective and efficient philosophy for task-orientated maintenance to be performed. These tasks are grouped together or packaged to effectively schedule the accomplishment of maintenance in the most opportune time to ensure there is not a major impact on an aircraft that must remain out of operational service for an extended ground time. During the development phase of both the 757 and 767 aircraft programs, Boeing focused on the development of the reporting/feedback documentation to allow for the integration and changeover to the new condition-based program (Bradbury, 1984). The researcher looked at the production of these two models of aircraft and all subsequent manufactured aircraft as the actual point that a shift to a reliability-based maintenance program occurred, bringing economics into the decision matrix. MSG-3 implicitly incorporates the principles of reliability centered maintenance (RCM) to justify task development. It involves a top-down, system-level, and consequence-driven approach in which maintenance task justification should be based on applicability and effectiveness criteria (Ahmadi et al., 2010).

Data Cleaning

It was determined by the researcher that due to the extensive pre-analysis data screening, the model data returned few, if any, anomalies. Therefore, the data collected for the multivariate analysis had no outliers. The review indicated that, for the most part, any outliers were dealt with during the extensive pre-analysis or review stages discussed in Chapter III. Any aircraft that showed a premature retirement date were investigated individually by serial number. For the most part, those aircraft indicating something outside of the norm, such as having been in an accident or some other loss, were disqualified from the study in the initial data review. As there was an effort to ensure the initial data set was complete, the pre-analysis investigation that produced missing data fields had been researched to determine what aspects of the data may have been missing or had been input erroneously and such instances were corrected at that time. The equation used for the analysis was stated as follows:

$$Y_i = \alpha + \sum_{j=1}^{j=n} \beta_j X_{ji} + \epsilon_i$$

Where:

- *Yi* is the dependent variable – Log of aircraft retirement age
- α is the intercept
- *Xji* are the 22 IVs described above
- ϵ_i is a normal i.i.d. disturbance

There was concern related to both the interpretation and reporting of the results, as Hoetker (2007) stated complexities arise when an interaction between the variables occurs that may be unintuitive. In the discussion section related to the results, this is covered by an interpretation of both present and underlying economic conditions at the time and the exacting maintenance variables being discussed. The researcher understood that there may have been both direct and indirect effects applied against the model based upon external interpretation of the data that may have occurred with differences between the coefficients.

Through the use of the z-score or standard score, the researcher was able to take from multiple populations that contained different means and standard deviations and use a common scale to compare them against each other. The z-score indicates how far a data point is from the mean using the standard deviation. As explained by Thakkar and Chaoui (2022), the process of converting raw data to a standard scale and normalizing is known as normalization. The probability value of z is understood to be a two-tailed test of the hypothesis that the coefficient equals 0 (W. Greene, 2016). "When a sample has more than 30 observations, the normal distribution *can* be used in place of the t distribution" (Meier et al., 2014, p. 191). A z-score is calculated by subtracting the population mean from the raw score and then dividing the result by the population standard deviation.

Descriptive Statistics

The sample population investigated was made up of 7,887 Boeing commercial aircraft or approximately 36% of the total fleet manufactured by the company since the first 707 aircraft came off the line. The sample included the models and quantities presented in Table 11. The following section describes the data, samples, and levels of measurements. This section serves as the building block for the presentation of the results that follows.

Table 11

Statistical Sample by Type/Model

Model	Quantity
707/720	414
727	1553
737-1/2	868
737-3/4/5	950
737-6/7/8	182
747	906
757	226
767	239
777	110
DC-10	301
DC-8	439
DC-9	752
MD-11	34
MD-80	804
MD-90	109

At the time of data transfer from the various database sets to the beginning of the research, a cut off period of December 31, 2021, was established. Boeing had produced and delivered 21,838 aircraft at that point. To determine the minimum size of the sample population, a calculation was performed for a confidence level of 95%. The investigation of the data showed an output of R-bar Sq. indicating over 62% of the data could be explained by the analysis accomplished by NLOGIT output located in Table 12.

Table 12

NLOGIT Output

Ordinary least squares regression			....			
LHS=LAGE	Mean		=	3.32414		
	Standard deviation		=	0.25163		
	No. of observations		=	7887	Deg. Freedom	Mean square
Regression	Sum of Squares		=	312.016	22	14.182540
Residual	Sum of Squares		=	187.308	7864	0.023820
Total	Sum of Squares		=	499.323	7886	0.063320
	Standard error		=	0.15433	Root MSE	0.154110
Fit Model Test	R-squared		=	0.62488	R-bar Sq.	0.623830
	F [22, 7864]		=	595.44581	Prob F>f*	0.000000
LAGE	Coefficient	Standard Error	z	Prob. |z|>Z*	95% Confidence Interval	
Constant	3.46629***	0.01452	238.68	0.0000000	3.43783	3.49476
CARG	.15159***	0.00547	27.72	0.0000000	0.14087	0.1623
WB	.07321***	0.00871	8.41	0.0000000	0.05614	0.09027
MD	.04085***	0.00499	8.19	0.0000000	0.03107	0.05063
F3Y	.01489***	0.00436	3.41	0.0006000	0.00634	0.02344
L3Y	-.05230***	0.00862	-6.07	0.0000000	-0.06919	-0.03542
CNT	-.05068***	0.01713	-2.96	0.0031000	-0.08425	-0.0171
INF	-.04413***	0.00131	-33.6	0.0000000	-0.0467	-0.04156
REC	-.10477***	0.00841	-12.45	0.0000000	-0.12126	-0.08828
RGDPG	-.02052***	0.00163	-12.59	0.0000000	-0.02372	-0.01733
NOIL	.00195***	.7271D-04	26.86	0.0000000	0.00181	0.0021
E3	-.03913***	0.00644	-6.08	0.0000000	-0.05174	-0.02652
E4	-.09701***	0.00835	-11.62	0.0000000	-0.11337	-0.08065
MSG1	-.05375***	0.01094	-4.91	0.0000000	-0.07519	-0.03231
MSG2	-.10615***	0.01479	-7.18	0.0000000	-0.13513	-0.07717
MSG3	-.14321***	0.00822	-17.42	0.0000000	-0.15932	-0.1271
LOV	.08812***	0.01121	7.86	0.0000000	0.06615	0.11009

LAGE	Coefficient	Standard Error	z	Prob. |z|>Z*	95% Confidence Interval	
RAPY	Not Significant					
CPCPADY	Not Significant					
D70	-.08549***	0.00663	-12.89	0.0000000	-0.09849	-0.07248
D80	-.19740***	0.00909	-21.71	0.0000000	-0.21522	-0.17958
D90	-.34012***	0.01122	-30.31	0.0000000	-0.36211	-0.31813
D00	-.61978***	0.01788	-34.67	0.0000000	-0.65482	-0.58475

nnnnn.D-xx or D+xx => multiply by 10 to -xx or +xx.

***, **, * ==> Significance at 1%, 5%, 10% level.

Model was estimated on Feb 05, 2023 at 11:42:49 AM

To comprehend the magnitude and volume being discussed and to grasp what the future may determine, Table 13 and Figure 13 were developed to show in total the aircraft included in this research.

Table 13

Boeing's Active Fleet as of Year-End 2021

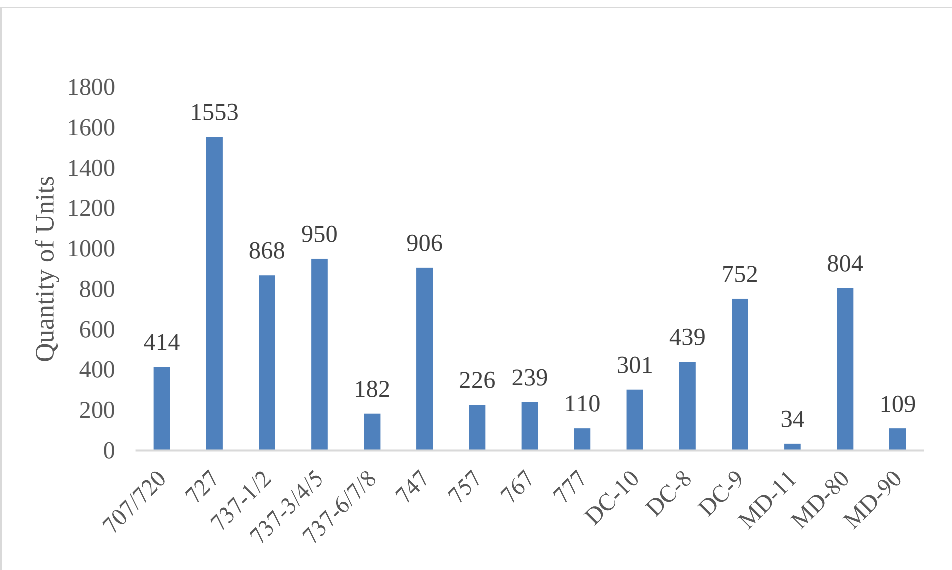
Airplane Model/ Series	Entry into service	Number produced	In service	% of fleet in service	In storage	Removed from service	Grand total
707	1958	856	0<				
720	1960	154	0<				
717	1999	155	75	48%	42	38	117
727	1964	1831	29	2%	13	1789	42
737-300/400/500	1984	1988	542	27%	355	1091	897
737-100/200	1968	1144	36	3%	29	1079	65
737 MAX	2017	706	525	74%	181	0	706
737 NG	1997	7088	5,641	80%	909	538	6550
747-100/200	1970	639	376	59%	82	181	458
747-300/400	1983	775	535	69%	235	5	770
747-800	2010	150	136	91%	14	0	150

Airplane Model/ Series	Entry into service	Number produced	In service	% of fleet in service	In storage	Removed from service	Grand total
757-200/300	1983	1049	531	51%	110	408	641
767-200/300	1982	1240	676	55%	95	469	771
777-200/300	1995	1679	1,122	67%	333	224	1455
787-8/9/10	2011	1006	914	91%	56	36	970
DC10	1971	446	11	2%	16	419	27
DC8	1959	556	2	0%	5	549	7
DC9	1965	976	24	2%	8	944	32
MD11	1990	200	114	57%	10	76	124
MD80	1980	1191	95	8%	114	982	209
MD90	1993	116	0	0%	2	114	2

Note. Taken from Cirium Aviation Analytics (2022), Boeing data, and the researcher's calculations.

Figure 13

Sample Fleet Examined by Model Type



The scatter plot of the data output from NLOGIT demonstrated a continuous drop in the age of aircraft over time as presented in Figure 14. What is demonstrated by the scatter plot is the corresponding decrease in the age of the aircraft as time moves from the

YOM. In the 1970 period, the drop equated to approximately 2.5 years of age and ended in the 2000 time frame with a drop of 14.3 years, both demonstrated by the minus (-) sign in the outputs. This is a factual representation of the data as calculated and produced by NLOGIT.

Figure 14

Plots of Fleet Data Set Related to Retirement Ages

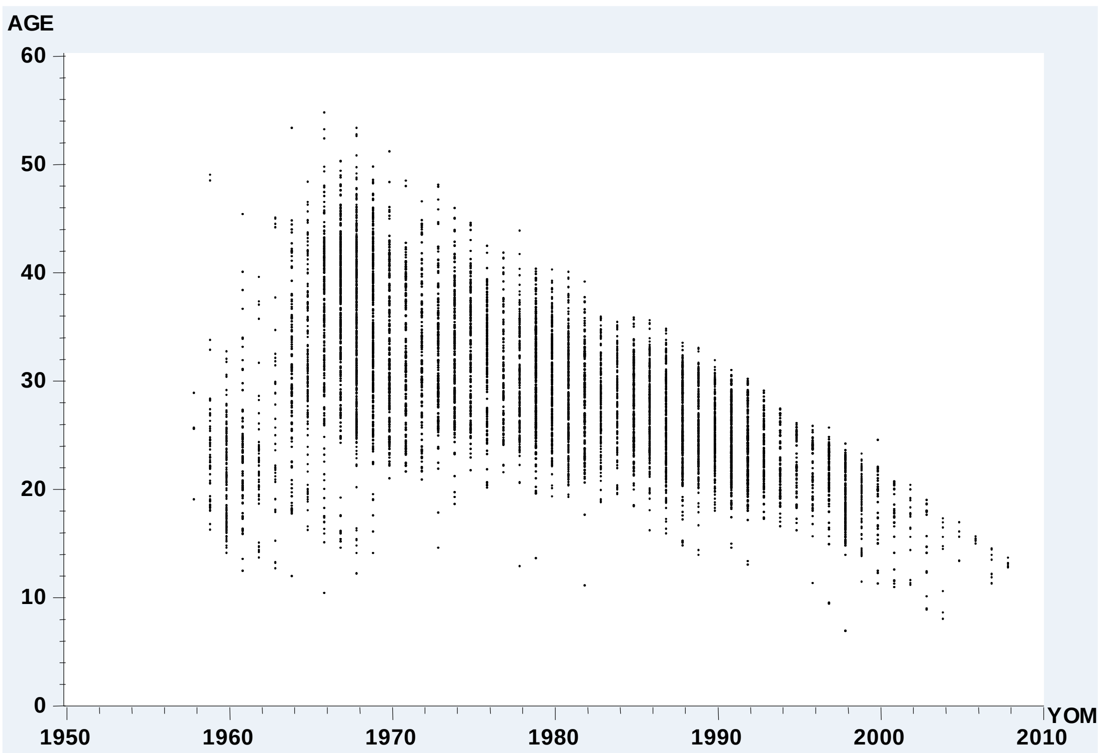


Figure 15 represents the types of aircraft investigated and their application in commercial use. As reference variables in the analysis, PAX, indicating a passenger aircraft, and NB or narrow-body aircraft were used as the most representative segments of the market and produced and delivered models of aircraft.

Figure 15

Aircraft Investigated by Type and Application

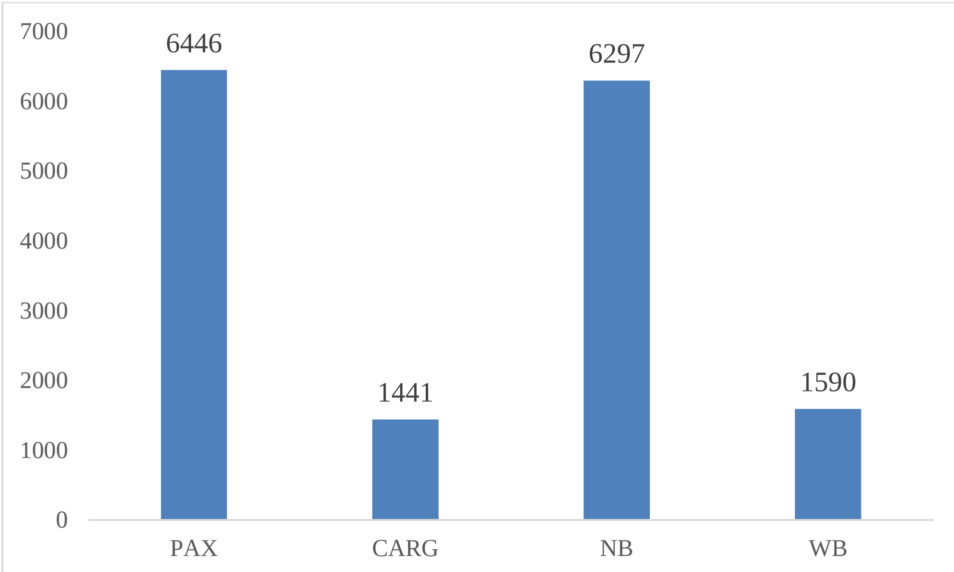
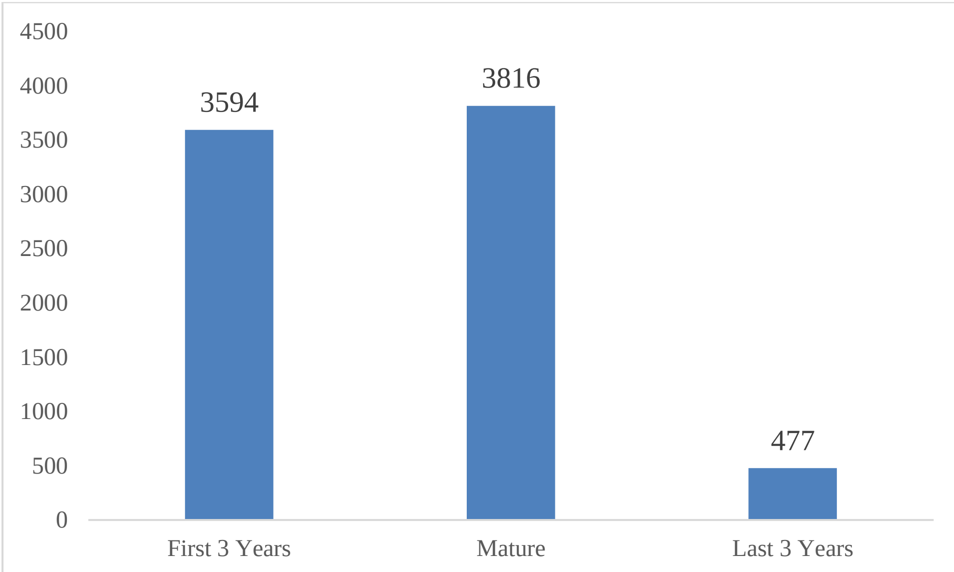


Figure 16 identifies where in the production cycle the investigated aircraft resided: early, mature, or within the last 3 years of the program's completion and shutdown. In this grouping, the mature aircraft (MAT) within the production cycle was used as the reference variable, where the first 3 years (F3Y) were considered more of a ramp up period and the last 3 years (L3Y) were the winding down and termination of the production cycle.

Figure 16

Investigation Within Production Cycle



The concept of contingent new technology (CNT) shows the number of aircraft produced during the periods that the manufacturer had available for sale an aircraft with newer or updated capabilities as well as an older model that is less capable. Given the total population, purchasers elected this option only approximately 1.2% of the time (see Figure 17).

Figure 17

Contingent New Technology

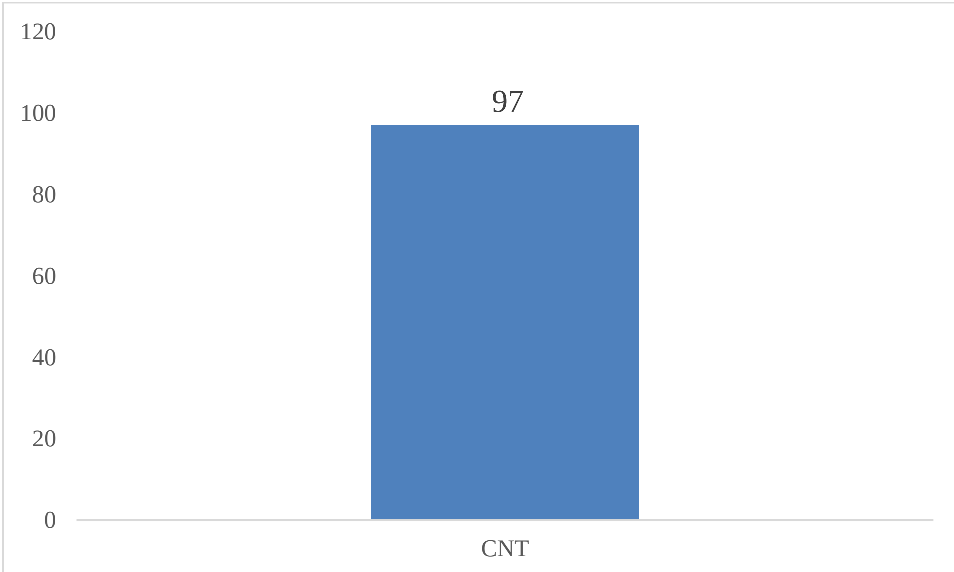


Figure 18 represents the quantity of the aircraft investigated against the quantity of engines installed. The reference variable was the data for two-engine aircraft as this was interpreted as the most common configuration of aircraft currently flying and produced.

Figure 18

Quantity of Aircraft Versus Engine Configuration

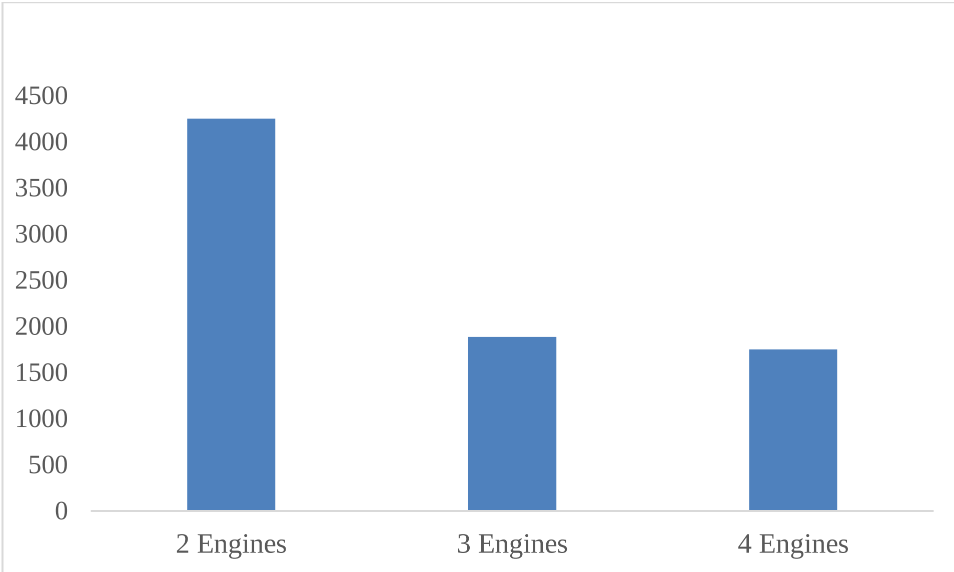


Figure 19 shows the average age of aircraft as applied against the type of maintenance concepts used. Figure 20 shows the actual maintenance program concept and the number of aircraft included by type.

Figure 19

Aircraft Age (in Years) as Calculated by Maintenance Concept Applied

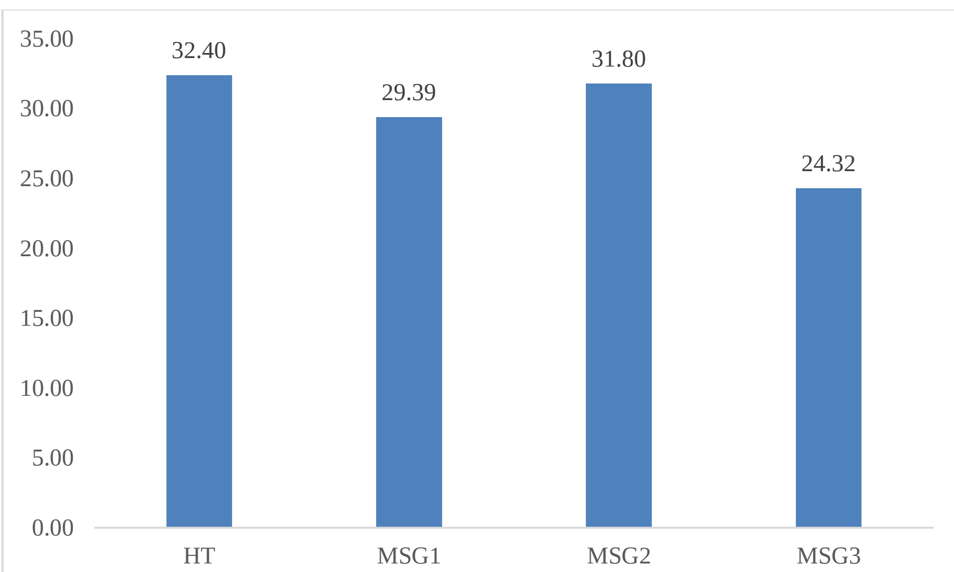
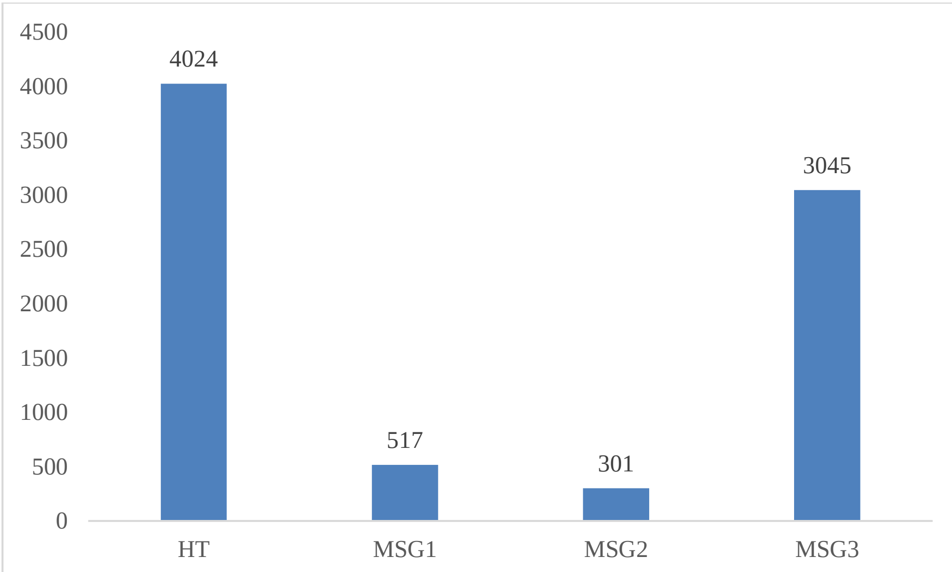


Figure 20

Aircraft Quantity by Maintenance Program Type



The statistics investigated were described above. These descriptives were included to give the reader a better understanding as to the outcome of the research and the subsequent results produced as discussed in the following sections.

Presentation of the Results

Table 14 shows the numerical value of the results expressed as a YEAR quantity. Each item within the results is addressed and described by group indicated on the left-hand side of the table by Roman numeral. The discussions of the results and interpretations of the data correspond to the number appearing in the item column. Additionally, the reference variables are included in the discussion to present a more well-rounded understanding of the analysis.

Table 14

Analysis Summary Converted to Years or Other Appropriate Measurements

Group	Item	Constant	3.43395	30.99885	Years
I	1	CARG	0.15159	16.3683	5.074
	2	WB	0.07321	7.595646	2.355
	3	MD	0.04085	4.169584	1.293
II	4	F3Y	0.01489	1.500141	0.465
	5	L3Y	-0.0523	-5.09559	-1.580
	6	CNT	-0.05068	-4.94172	-1.532
III	7	INF	-0.04413	-4.31704	-1.338
	8	REC	-0.10477	-9.94684	-3.083
	9	RGDPG	-0.02052	-2.03109	-0.630
	10	NOIL	0.00195	0.19519	0.061
IV	11	E3	-0.03913	-3.83743	-1.190
	12	E4	-0.09701	-9.24531	-2.866
V	13	MSG1	-0.05375	-5.2331	-1.622
	14	MSG2	-0.10615	-10.071	-3.122
	15	MSG3	-0.14321	-13.3428	-4.136
	16	LOV	0.08812	9.211917	2.856
	17	RAPY	Not statistically significant		
	18	CPCPADY	Not statistically significant		
VI	19	D70	-0.08549	-8.19377	-2.540
	20	D80	-0.1974	-17.9138	-5.553
	21	D90	-0.34012	-28.8315	-8.937
	22	D00	-0.61978	-46.1937	-14.320

An explanation of each of the IVs and an analysis summary to identify the output of the coefficient and the interpretation follow.

Group I

Group I variables (see Table 15) included the physical attributes of the aircraft as produced and in some cases modified later in life as it related to possible cargo aircraft conversions. As for changes determined by the categorical aircraft configuration variables aside from the PTF, which may have included additional minimal maintenance actions, there was nothing else that was different in scope. It could be argued that the installation of a cargo door may present a possible increase in the maintenance planning, though the offset by the removal of a passenger interior, galleys, and lavatories more than equals that additional workscope.

Table 15

Aircraft Configuration Variables

Categorical variables	PAX	CARG	NB	WB
Sum	6446	1441	6297	1590
Count	7887	7887	7887	7887

PAX–Passenger Aircraft. Reference variable used against the option of cargo aircraft. The researcher examined aspects of the production, manufacturing, and reliability of this group. The researcher researched the configuration overall and determined life based upon the categorical variables.

CARG–Cargo Aircraft (Group I, Item 1). The investigation identified that by the application of either a cargo door conversion or an aircraft produced as a freighter, the cargo carrying aircraft had its useful life extended by 5.074 years as compared to a passenger aircraft. The concept of cargo aircraft is not a new phenomenon. In fact, the airline industry is based upon what was once the original air mail system routes developed in the early 1900s. Bender and Wells (2004) expressed that “the average age of the worldwide passenger carrier fleets is approximately 7 years while their cargo counterparts have an average age of approximately 28 years 4 times as old" (p. 1). They also suggested the conversion process does not take place until the aircraft is 15 to 20 years of age. Morrell and Dray (2009) discussed the freighter conversion occurring at a later point in the aircraft's life cycle, usually when the actual production of the model has ceased. They additionally concluded that the proportion of freighters increases as the aircraft reaches the 25-year mark and that aircraft 30–35 years of age operating as freighters remain in operation as freighters. These data are consistent with the findings of the investigation showing a valid collection and application of the modeling assumptions with results indicating a 5-year increase in longevity.

NB–Narrow Body (Reference Variable). The most produced aircraft by type are those considered to be narrow body or single aisle aircraft used as the backbone in air travel from point-to-point operations.

WB–Wide Body (Group I, Item 2). Research and analysis show the wide body's EUL is increased by 2.35 years as compared to narrow body types. Those aircraft considered to be wide bodies, such as the 747, 767, DC-10, and MD-11 aircraft, cover larger distances in relation to travel miles. The use and cost involved in placing such aircraft on short legs make them uneconomically favorable to the operator. Also, the consideration as to the reduced cyclic count on the airframe, landing gear, and engines increases the economic usefulness and reduces the overall cost associated with a high cyclic count aircraft, such as Southwest with a short point-to-point high cycle daily utilization. Additionally, the investigation showed these aircraft from their maintenance programs (MSG-1, 2, and 3) would have prognostic health monitoring systems tracking and forecasting their maintenance demands (Freeman et al., 2021). As fuel prices would remain low, the use of high-density assets such as wide-body aircraft produces better DOC and performance metrics (Oguntona et al., 2016). Bolat (2019) indicated wide-body aircraft are usually leased for 12 years or longer, which would place them into a renewal period that would occur at 12-, 24-, or 36-month intervals. This appears to also track parallel with the data analysis showing longer life in operation, though it was not substantially above the average.

Boeing (Reference Variable). Although the analysis was developed using all Boeing aircraft, the researcher segregated out those aircraft that were produced before the merger of Boeing and McDonnell Douglas just to see if in fact any differences existed when the two operational sets of aircraft were analyzed. One of the main reasons for this break out was that, in application, Boeing aircraft were normally considered to have flight control systems that were predominantly hydraulic actuated and the MDC product line was mostly cable-driven, having divergent technologies. Secondary, Boeing produced the majority of the heavy bomber aircraft during WWII and was known for lighter aircraft whereby the payload could be increased. The counter of that was the MDC fighter where the aircraft structure was more robust and able to handle higher loads and was designed for speed and efficiencies. These design factors carried into the commercial application of early production aircraft.

MD–McDonnell Douglas (Group I, Item 3). The analysis showed a small increase in the life of an MD aircraft over that of the original Boeing fleet of aircraft at approximately a 1.2-year interval. However, there is no clear date of delineation as to when Boeing and McDonnel actually merged in terms of data. From a corporate standpoint, the announcement of the proposed merger was in December 1996, in July 1997 the U.S. Federal Trade Commission approved the merger, that same month the European Commission approved the merger, and the merger occurred in August 1997. But when the technology, manufacturing techniques, production, design, and various other hardware and software integration occurred is not evident. During that time, each identity did not change nor did the original identity of the aircraft TCDS change the ownership from one entity to the other. It should be understood that the current TC under the European Aviation Safety Agency (2010) reads as follows: “This data sheet incorporates and supersedes previously issued MD-90/ 717 JAA TYPE CERTIFICATE DATA SHEET (Boeing report No. MDC-96K9114, Revision “NEW”, dated August 30, 1996)” (p. 3) and still shows the holder of the TC as McDonnell Douglas Corporation. The data apply to both the MD-90-30 and B 717-200 and make no distinction between MD and Boeing. Additionally, McDonnell Douglas Corporation merged with the Boeing Company in 1997. They retained ownership of the TC A6WE and on January 30, 1998, granted The Boeing Company a license to manufacture these aircraft under the production certificate. MDC is a subsidiary of The Boeing Company (FAA, 1998). Finally, when looking at the increased longevity that Northwest Airlines created in their life extension program for the DC-9 aircraft and the continued use of the MD-80 fleet by Delta and American Airlines up to the pandemic and their parking of the aircraft at that point, one can easily explain that the data in their raw sense provide no clarity to support this aspect of increased longevity either way.

Group II

The next set of variables (see Table 16) reflect where in the production sequence an aircraft falls by its model and production schedule.

Table 16

Production Cycle Variables

Categorical variables	F3Y	MAT	L3Y	CNT
Sum	3594	3816	477	97
Count	7887	7887	7887	7887

MAT–Mature. Indicates the period during which the aircraft model was in mass production and was being both manufactured and delivered. It begins after the 3-year initial production and ends 3 years prior to the last of a model type being delivered and the shutdown of the assembly line and was the reference set for this segment.

F3Y–First Three Years (Group II, Item 4). This indicates aircraft that were manufactured within the first 3 years of the production phase after obtaining a Production Certificate and TC. The data indicate these aircraft experience about .5 years longer life than the average. Aircraft are not produced as automobiles, aircraft are manufactured for an end user, the customer. As such, they each can be unique to fit specific operational roles. Aircraft produced earlier in the supply chain are mostly considered to be heavier, have less range, and have more manufacturing defects as production issues are worked through. This translates to a higher empty weight of the aircraft; therefore, the delta between the maximum weight of the aircraft minus the higher empty weight shows a loss of payload capacity. The aircraft has a reduced capability to make as much as an identical aircraft produced later with the benefit of a decreased operating weight. However, they usually are sold for introductory pricing to those willing to take a greater risk on the new equipment. Buergin et al. (2018) discussed the high customization of aircraft and the changes that occur in the initial manufacturing process. They suggested aircraft manufacturers could offer new free services to their customers, giving them the ability to select or modify some predefined product features at different points in time. What Buergin et al.'s discussion appears to be lacking the actual understanding that this is in fact what actually transpires in the early delivery process. Thus, early-produced aircraft present the operator with less economic risk due to the introductory price point of acquisition, which may not be true. Additionally, the early entrant operator becomes the "expert" on the aircraft due to the increased training offered during the manufacturing process, the access to additional data, and the close working relationship developed with the aircraft manufacturer, all giving them an economic advantage.

L3Y–Last 3 Years of Production (Group II, Item 5). This metric produces negative results of 1.58 years less than the mature production cycle, indicating those aircraft being produced as the aircraft manufacturer is winding down the production line experience a slight 1.5-year reduction in longevity. This aspect can be substantiated in the case of Boeing announcing the cessation of 757 production in 2004. As cited by Hearn (2005), "Avitas suggests that the values of the newest aircraft have been most affected by Boeing's decision to cease production" (p. 3), although the market had to some extent anticipated this situation. The issue again becomes one of economics: Why pay the price for an aircraft that, once delivered, will decrease in value quicker than other aircraft?

CNT–Contingent New Technology (Group II, Item 6). Although only affecting 97 aircraft built during such periods, there was a decrease of approximately 1.58 years in the useful life. This is the time period when the manufacturer or a competing manufacturer introduces and is producing a piece of equipment that is more technologically advanced than the then-current production model. One must also consider that this is usually within the last 3 years of the production matrix. D. L. Greene (1990) made mention of the aircraft fuel technology issue the aviation industry was experiencing during the 1990s. Using the rating of seat miles per gallon (SMPG), through the use of aircraft advances and SMPG improvements the industry could reduce fuel consumption by 5.1 billion gallons by the year 2010. In the 1990 time period, a potential purchaser could buy a 737-300, -400, or -500 or a product manufactured by the competition. Mavris and Kirby (1999) discussed how identifying and implementing new technologies can aid designers and decision makers in identifying the technologies that most influence performance and economic metrics. This aspect of being able to purchase an aircraft that is more technologically advanced could reduce the average age of a piece of equipment by 1.5 years. As new technologies are emerging, the intensifying of competition, incremental increases in development costs, and associated risks all require substantial financial resources and investment from manufacturers. As this industry is based on razor sharp margins and intense marketing campaigns for successful outcomes, there are deals to be made by purchasing entities. The newer aircraft or those perceived as better, more efficient, and more technologically advanced were winning the market share. As investigated, the CNT factor is that period of time during which the manufacturer is already in a reduced production phase for the older aircraft and demand for that model is being diminished and is offering a newer version or a replacement type model/aircraft.

Group III

Economic Variables. The use of economic variables in any study of age appears throughout the literature. Morrell and Dray (2009) discussed GDP, oil, recession, and inflationary factors as they investigated retirements and life cycles of aircraft. Forsberg (2015) discussed oil pricing as it related to both retirement and storage trends and Jiang (2013) discussed recessions. Chao et al. (2017) used inflation, GDP, and fuel costs in their net present value decision matrix to determine both retirements and acquisition of aircraft. The underlying evidence of these variables made them acceptable to be included in the analysis (see Table 17). The researcher also determined that the data related to inflation were highly skewed and the 10 year Treasury showed a moderate skewness. Additionally, the variables of RGDPG and NOIL appeared to be more symmetrical in their skewness as values were between -0.5 and 0.5. The data produced a leptokurtic as the kurtosis was > 3, indicating a distribution where the peakedness was higher.

Table 17

Independent Economic Variables

Variables	INF	10YT	REC	RGDPG	NOIL
Mean	2.335496	3.832223	Categorical	2.236224	60.72058
Standard Error	0.017633	0.025531	Variable	0.019236	0.345112
Median	2.1301	3.2		2.6	59.26
Mode	1.4648	2.3		2.6	133.93
Standard Deviation	1.565962	2.267356		1.708312	30.64896
Sample Variance	2.452239	5.140904		2.918329	939.3587
Kurtosis	13.24885	4.836474		1.93163	-0.73899
Skewness	2.383591	1.859594		-0.57963	0.309891
Range	13.9048	14.7		10.4	129.62
Minimum	-0.3556	0.62		-2.5	4.31

Variables	INF	10YT	REC	RGDPG	NOIL
Maximum	13.5492	15.32		7.9	133.93
Sum	18420.06	30224.74		17637.1	478903.2
Count	7887	7887		7887	7887
Largest(1)	13.5492	15.32		7.9	133.93
Smallest(1)	-0.3556	0.62		-2.5	4.31
Confidence Level (95.0%)	0.034565	0.050047		0.037707	0.676511

INF–Inflation (Group III, Item 7). Inflation is considered a period in which there are broad price increases in multiple parts of the economy and consumer purchasing abilities are in a decline. The investigation showed that during inflationary periods, aircraft experience approximately a 1.338 year reduction in EUL. At first, one may think the reduction indicated is that of the age of the aircraft; however, it is the inflation factor that must not be confused. Therefore, as inflation decreases, economically the country could see more disposable income accompanied by stronger consumer confidence. Additionally, a decrease in the U.S. inflation rate could make U.S. manufactured aircraft more competitive, adding a trade balance. In the United States one would also find the possibility of a higher growth cycle and an increase in investment due to the predictability of wages, prices, and costs.

REC–Recession (Group III, Item 8; Categorical Variable). According to the U.S. Bureau of Economic Analysis (BEA, 2023a), a recession is two consecutive quarters of negative GDP growth. During the analysis period, the U.S. economy was experiencing a recession at the correlated point. This is based upon a quarter-by-quarter summary and not indicative of a specific date. In a general application, it is when the U.S. economy is slipping in terms of economic activities. As used in this application, either there was evidence in the United States of a recession or not as identified by a 1 or 0. Analysis indicated during the time periods of recession, the EUL of aircraft is decreased by approximately 3.083 years. As markets contract, the demand for air travel reduces and excess capacity is either placed into storage or retirement. As a decrease is occurring in the public due to the loss of disposable income and leisure travel, demand is decreasing. Murphy (2021) explained a recession in practical terms as a point where compromises and concessions will often be granted as part of negotiations and, in particular, during periods of economic turmoil or recession when airlines and lessees may come under additional operational and financial pressure. However, it should be understood that a potential purchaser cannot just show up and secure the next aircraft off the production line. The backlog is in most cases approximately a 5-year wait for delivery of an aircraft, so the purchaser is using today's dollars for delivery at a later date.

RGDPG–Real Gross Domestic Product Growth (Group III, Item 9). The unit of measure obtained from FRED. This index is computed on a year-over-year basis to show percentage changes in RGDP and measures economic growth. Real GDP is the inflation adjusted value of goods and services produced by labor and property located in the United States (BEA, 2023a). The analysis showed an increase in RGDP by 1% equated to a 0.640 year reduction in the longevity of an aircraft.

NOIL–Nominal Oil Pricing (Group III, Item 10). The price of oil and inflation are often seen as being connected within a cause-and-effect framework (Anandan et al., 2013). To understand the impact of oil, and thus fuel prices, and its direct economic effect on the ability to travel requires looking no further than an increase in the purchase price of a ticket. As consumers, individuals try to understand the implications realized by increases in the price of oil and usually see that in terms of a fuel surcharge on their ticket price. However, in this case only a marginal impact was realized in terms of the actual longevity of the aircraft. Airline fuel or Jet A is a petroleum-based derivative of oil and tracks parallel with the price per barrel of actual crude heating fuel. The researcher believes that because this is also a condition of inflationary issues, much of the actual impact of NOIL increases is absorbed in the context of the inflation calculation and cannot actually be separated out. Horobet et al. (2022) found a long-term equilibrium relationship among other variables but inclusive of both oil price and inflation. Current technology initiatives are intended to investigate ultra-high bypass ratio (UHBR) engine designs to produce better fuel economics. The logic behind this concept is that by development of the process it will reduce specific fuel consumption (SFC), which is one driver for lowering the DOC of an aircraft. This measurement shows a $1.00 increase in a barrel of oil would produce an approximate increase in the life of an aircraft by 22 days per dollar (0.061 x 365=22.27 days).

Group IV

Group IV is the categorical variable section analyzing aircraft engine configuration. In the early days of aviation, the concept of being capable of making an alternate airport should the aircraft experience an engine loss was the predominant reason for multiple engines. Further to that was the reliability of the product in early testing. Now with the advent of ETOPS, aircraft are capable of flying increased distances from alternate airports with increased reliability. Now engines approved for ETOPS must have an in-flight shutdown (IFSD) rate better than 1 per 20,000 hours for ETOPS-120; 1 per 50,000 hours for ETOPS-180; and 1 per 100,000 hours for beyond ETOPS-180 (ICAO, 2014). These increases in reliability opened the door for more efficient, reliable engines flying further distances.

E2 (Categorical Variable; Reference Variable). Aircraft equipped with two engines installed. This applies to the majority of single aisle aircraft such as the 737 in multiple variants from the -100 to current production -8, -9, and -10. Older aircraft such as the DC-9 and MD-80 series also had a two-engine configuration. It also includes current wide-body aircraft such as the 757, 767, 777, and 787.

E3 (Group IV, Item 11; Categorical Variable). Aircraft equipped with three engines. This relates only to the Boeing 727 aircraft, which was the only original product line with three engines installed as a tri-jet model aircraft. The MD product line of DC-10 and MD-11 was the Douglas line that fit this category of three engines installed. This relationship is directly correlated when given the alternative possibility of flying a comparable aircraft that has fewer engines installed and thus less fuel consumption and associated costs, and the choice is obvious. Therefore, a reduction of almost 1.2 years aligns with the conventional understanding of an aircraft's DOC increasing with more engines. Additionally, one must look no further than the implementation of Chapter III/Stage-3 requirements by regulatory agencies combined with what Graham et al. (2014) described as increased reductions in fuel burn, NOx generation, and noise. Through the ability to reduce the number of engines, companies can reduce economically affected issues such as DOC and environmental issues such as specific fuel consumption (SFC) or fuel burn.

E34 (Group IV, Item 12; Categorical Variable). Aircraft equipped with four engines display the same economic and technical tendencies as those with three engines installed. Specifically, it should be noted that only the 707, 720, and 747 aircraft were equipped with four engines from Boeing and the DC-8 was the only equipment that fit this parameter on the MD side. As this construct applies to the EUL of the aircraft, there was a reduction of 2.866 years and the reasons would be similar to the three-engine construct of more fuel efficient options and lower DOC such as maintenance and engine repair and overhaul.

Group V

Maintenance Program Variables. Examining the output variables of the maintenance programs (i.e., HT, MSG-1, MSG-2, and MSG-3) combined with that of the age periods produced the following results. The analysis of the data coincides with the factual changes happening in a real-time scenario with the aircraft manufacturing industry, the operational airlines, and the regulatory bodies.

Analysis of the NLOGIT output variables showed an alignment of the coefficient of the LAGE of the aircraft and that of the life of the aircraft, the point of retirement being diminished over time as indicated by the negative sign. The first application of the MSG concept was the Boeing 747 aircraft developed and delivered under the concept of MSG-1, which became the first application of a maintenance process other than hard time (HT). The McDonnell Douglas DC-10 aircraft first entered into service in 1971 as an MSG-2 aircraft (MSG-2 was developed and implemented only for the DC-10 and L-1011 aircraft). In the 1970s, the other Boeing models being produced were the 727 and 737 aircraft along with the Douglas DC-9 and DC-8 aircraft, all of which were HT maintenance programs. As aircraft development moved ahead, the concept of check optimization became part of the scheduling function. The optimization of the checks included recalculations of the damage tolerance requirements (DTR) to functionally align the check task with the inspection task card by optimizing the specific type of inspection requirement. The use of visual inspection techniques over that of either high/low-frequency eddy current produced different DTR times within which to conduct the inspection and the elapsed time intervals changed. As for most planning aspects, base maintenance or letter checks can optimally be performed at a frequency of 24 months. This allows for a good fit within all CPCP requirements as a timed event and all scheduled maintenance events that now can coincide with the CPCP allowing for better efficiencies and labor distribution.

Maintenance program development and the initial formulation of the tasks as that of the 787 are some of the key aspects of maintenance planning and document development. The 787 MRBR includes more than 33,000 pages of supporting analysis and eight regulatory agencies were involved (Lefeber, 2009). Kinnison and Siddiqui (2013) defined maintenance as a dynamic process and pointed to how the adaptation of tasks may be different for various operators. However, changes within the process are not implemented in a vacuum. Any interval change must be supported by documented evidence that the change is warranted. If one were to investigate the start of this concept, they would find it originated from Aeronautical Bulletin 7E, dated May 15, 1930, where each carrier developed its own independent program. Today’s collaborative program takes experience and data from industry, manufacturing, and regulatory agencies to produce a product beneficial to all and comprehensive in nature. Table 18 outlines the basic documents used and relied upon to establish a maintenance program with details, not to exceed times and the collective information from industry. These documents were the basis for the current and previous maintenance programs used and reviewed in this analysis.

Table 18

MSG-3 Maintenance Program Incorporation by Type/Model

Aircraft model	Entry into service (EIS)	Maintenance program	MPD document number
737-300/4/5	1984	MSG-2	D6-38278
737-6/7/8/9	1995	MSG-3	D626A011
757	1982	MSG-3	D622N001
767	1982	MSG-3	D622T001
777-200/300	1995	MSG-3	D622W001
787	2011	MSG-3	D611Z009
717	1999	MSG-3	MDC-96K9063

Ahmadi et al. (2007) investigated and discussed the evolution of the various maintenance programs from the 1950s forward and noted the shifts in concepts. Additionally, Tsang (1995) focused on how the program benefits aided in higher margins of safety, better operating performance for the airlines, reductions in maintenance costs and direct operating expenses, and a better understanding of system failure mode. Although the concept of a maintenance program does not appear precisely in the regulations, the aspect of the operator having a mandate to maintain an aircraft and keep it airworthy can be found in 14 CFR §121.363 Responsibility for airworthiness (1964), which places the burden on the certificate holder (i.e., airline) as the primarily responsible entity (p. 155). The use of the maintenance program is imperative both from a practical standpoint as to how the aircraft is maintained as well as from a regulatory standpoint as a requirement. Maintenance programs were used to calculate impact and produced the data shown in Table 19.

Table 19

Maintenance Program Variables

Categorical variables	HT	MSG1	MSG2	MSG3
Sum	4016	517	301	3053
Count	7887	7887	7887	7887

MSG1 (Group V, Item 13; Categorical Variable). MSG1 is the initial program developed specifically for the Boeing 747 aircraft. The correlation again produced a negative output, indicating these aircraft tended to retire earlier than the norm by approximately 1.622 years. However, this number cannot be viewed independently as the 747-model aircraft has four engines installed, it is a wide-body aircraft and for the most part could be or is converted to a freighter. It also needs to be understood that this aircraft is the only model to which MSG-1 could apply. The possibility exists that if viewing all the variables in combination, the 747 aircraft could still fly longer. MSG-1 was the first application that employed a decision tree matrix for all preventative maintenance tasks. This initial program made it clear that using the concept of an RCM approach to conducting preventative maintenance tasks made the process both viable and economically sound (Smith, 1993).

MSG2 (Group V, Item 14; Categorical Variable). MSG2 was only developed and applied to two specific aircraft, the tri-jet families of the Lockheed L-1011 and the Douglas DC-10 aircraft. As this investigation included only the DC-10 family specifically, this variable in isolation produced an earlier retirement by 3.122 years but combined with the E3 or three-engine analysis could be showing earlier retirement. As all the DC-10 aircraft were effectively converted to freighter aircraft, the analysis should be based on the actual longevity, although a negative result was determined independently.

We would also have to look at the 5.074 yar increase for the cargo aircraft and 2.355 year increase for a wide body to gather a better understanding as to the actual condition in this case. Therefore, it should be understood that there is an interrelationship of the variables that must be considered when assessing the outputs and they may not be viewed individually but rather collectively.

MSG3 (Group V, Item 15; Categorical Variable). MSG3 or what is recognized as the current maintenance program development documentation that is now used on current production aircraft was first applied in the 757/767 program development. What the research showed is that aircraft of this maintenance program utilization have a reduction of 4.136 years in longevity. When viewed individually it may be counterintuitive to what most think should be happening. How can a shorter life be better? The MSG-3 application was the first program with an economic element designed to stop or make a conscious decision to reinvest or add additional investment into aircraft that will not produce an economic benefit. Analysis of this information indicates that compared to an HT model, which continued to invest time, money, and resources, MSG-3 aircraft are removed from service earlier. This program focuses on the inherent reliability of the equipment or components of the system. The emphasis is on the establishment of a cost-effective preventive maintenance program based on reliability information derived from Failure Mode Effect and Criticality Analysis (FMECA; i.e., analysis of the modes, effects, frequency, and criticality of failure, and compensation through preventive maintenance; Blanchard, 2008). Operators seek out the task accomplishment at the optimum time in the aircraft’s life cycle and consider the economic implications of the accomplishment of tasks within the continuum of the cycle.

This may force a decision-based assessment to park, store, or retire the aircraft earlier as the task accomplishment becomes cost ineffective. What this program, MSG-3, produces is the ability to preemptively identify issues prior to major costs being incurred.

Maintenance Regulatory Variables. The investigation also included specific issues imposed by governmental organizations in terms of rule changes and airworthiness directives (see Table 20). This portion of the research was shown to have no fundamental impact on either extending or decreasing the EUL of commercial aircraft.

Table 20

Maintenance Regulatory Variables

Variables	LOV	RAPY	CPCPADY
Sum	7482	7194	7160
Count	7887	7887	7879

LOV–Limit of Validity (Group V, Item 16; Categorical Variable). Indicated whether the aircraft had or did not have an LOV. The LOV is a point in the structural life of an airplane at which there are significantly increased uncertainties in structural performance and an increased probability of the development of WFD (Mohaghegh, 2005). As the LOV has not actually been achieved for most aircraft currently flying, they will continue until they reach this limitation or as some call it the ultimate life beyond which no support is available for the integrity of the structure. The analysis revealed the aircraft with an actual LOV had an increase in life of 2.856 years. This is due to the validity found by the LOV to determine structural life by either direct testing or modeling to show the aircraft retains its reliability and may continue to operate. This study did not measure the actual hours and cycles of an individual aircraft as these data are not available to the public. However, it did measure the application of the regulation and the program. As the regulatory requirement changed, most thought it would force the grounding of aircraft, yet to the contrary this actually extended the time that operators and financiers would keep the asset in operational production as they have increased validity of the aircraft both in terms of safety and robustness of the design service objective.

RAPY–Repair Assessment Program (Group V, Item 17; Categorical Variable). The repair assessment program has been developed by each manufacturer to address the continued viability of the pressure vessel structure of each aircraft. Fundamentally, the program assesses existing repairs that have been accomplished on the fuselage and applies a damage tolerance calculation methodology to each. This looks for the compounding of repairs that may stress the structure in ways in which the manufacturer had never intended (FAA, 2003). The statistical analysis resulted in a nonsignificant coefficient of RAPY, indicating this program has no impact on the age of an aircraft as it is regulatory in nature and is considered part of the ongoing maintenance and preventative maintenance process.

CPCPADY–Corrosion Prevention and Control Program (Group V, Item 18; Categorical Variable). The concept of a corrosion program was introduced to the industry over 30 years ago. It became a prevalent concept after the Aloha accident where issues of damage went undetected until a catastrophic event occurred. Corrosion concepts were included in maintenance programs from the onset of jet transports but had not received focus until the accident. Regulators and operators have focused on maintaining aircraft to a level 1 of corrosion and address those identified issues immediately to mitigate the progression to detrimental levels. One would expect and the research showed these programs have a positive impact on aircraft life; however, the analysis could not identify a statistically significant relationship between the CPCPADY and the LAGE. Current production aircraft have these programs included as part of the maintenance concept under which they were developed.

Group VI

Dummy Variables–Production. To qualify the time period in which an aircraft was produced or identify a time frame in the production cycle of an aircraft, dummy variables were introduced into the analysis (see Table 21). Similar to Park (2005), the researcher introduced the dummy to identify blocks of years in which the aircraft under investigation were manufactured.

Table 21

Production Years Variables

Categorical variables	D50	D60	D70	D80	D90	D00
Sum	71	2000	1913	2354	1417	132
Count	7887	7887	7887	7887	7887	7887

- D70–Dummy variable 1970 (Categorical variable). Time of aircraft production between 1970–1979.
- D80–Dummy variable 1980 (Categorical variable). Time of aircraft production between 1980–1989.
- D90–Dummy variable 1990 (Categorical variable). Time of aircraft production between 1990–1999.
- D00–Dummy variable 2000 (Categorical variable). Time of aircraft production after the year 2000.

The inclusion of the four dummy variables into the model captured the overall historical trend in aircraft retirement age. Aircraft manufactured before the 1970s were used as a reference. The dummy variables are summarized in Table 22 and explained in in context of the year periods. This analysis produced one of the key findings of the analysis.

Table 22

Regression Output of Dummy Variables Related to Year Periods

Dummy variable	Reduction in years
D70	-2.540
D80	-5.553
D90	-8.937
D00	-14.320

What was determined through the regression model was that the outputs showed aircraft are in fact retiring earlier and the model was consistently decreasing retirement over time. Starting in the 1970–1979 period, the researcher found aircraft manufacturing was beginning to decrease. Many of the older aircraft have encountered, or can be expected to encounter, aging problems such as fatigue cracking, stress corrosion cracking, corrosion, and wear (Bucci et al., 2000). Additionally, it should be noted that the FAA under P.L. 85-307 provided loan guarantees for up to 90% of the purchase price of equipment for local, short-haul, and feeder air carriers (Fischer & Kirk, 1999). The loan guarantee program was dissolved as part of the Airline De-Regulation Act of 1978 (P.L. 95-504). Historically, the Air Mail Act of 1934 (P.L. 73-308) provided subsidiaries to the airlines as fares and market entry were under the control of the federal government. Minimal impact was found and only the possibility of a 2.540-year longevity decrease was found in the analysis.

During this time period, the Boeing 727-100 and -200 series aircraft were in production from 1960–1982 and the aircraft model was averaging 27 years longevity (Sperry, 2000). Until this model was superseded by the 737, which encountered large technical changes over the production cycle to include a new engine type being installed, the 727 was the most produced aircraft worldwide with 1,832 production units. Currently, the 737 model has far surpassed this number with over 7,000 units but the model variants that have been produced are not the same as the original 737-100 aircraft.

Additionally, the argument can be made that countries that were neither aligned with NATO nor Warsaw Pact nations had experienced more difficulties in obtaining financing. Today, these developing countries have almost equal access to lenders and financial structures as related to aircraft sales and leasing. Although the Chicago Convention (IACO, 1994) was in place, the ability to finance and secure aircraft as they were mobile assets did not come until later on.

As the airlines progressed into the 1980 period, the analysis showed a decrease of approximately 5.5 years in aircraft longevity. During this period of a post deregulated industry, competition was fierce in the market. Bankruptcies, mergers, and acquisitions were prevalent throughout the markets. Deregulation had taken hold for the U.S. consumer for a short period and was embraced by the public, the age of operating leases emerged, and aircraft were plentiful but fuel costs were rising. forcing retirements for a more efficient product. Also, during the 1980s and 1990s, not only was the price of a plane, let alone a whole fleet of aircraft, nearly prohibitive, but the fact that aircraft are mobile and move throughout many jurisdictions made it very difficult to determine the rights of debtors and creditors at any one time, presenting extra risks to potential lenders (Downs, 2013).

The 1990 period entered with the concept of deregulation in Europe taking hold in the markets after having been agreed to by the EU member states in 1986 but not fully implemented until the Treaty on European Union in 1993. However, as liberalization increased, the EU experienced similar results to the United States with bankruptcies and mergers or code sharing and as the prices of tickets dropped, more aircraft were parked. The converse side was that aircraft production was ramping up with more fuel-efficient aircraft and Stage3/Chapter III compliant aircraft filling the void and bringing newer equipment into the operational control. Yet, the longevity of operational use was being diminished by almost 9 years. During this time period, there was a move by aviation equipment financiers and an industry aviation working group to improve legal leasing rights for lenders. It was estimated at the time by the major aircraft manufacturers that the aggregate acquisition cost of aircraft and engine deliveries over the next 20 years would be in the range of US$900 million–$1 billion (Wool, 1995). As organizational lenders were wishing to have better control, security, and rights over their assets, they also wanted to place new equipment into those markets. Hence, more retirements so more new aircraft could be placed. The ability to finance newer aircraft was less burdensome than financing older aircraft, which inherently had higher maintenance risks associated with the placements.

Although the researcher expected to find a constant decrease in the longevity of aircraft through the period of investigation, the 2000 time frame showed a considerable decrease. BEA (2023b) data indicated air transportation was increasing in terms of value added to the GDP output aside from a slight drop in the 2001 time period. This coincides with increases in aircraft production by Boeing with the introduction of the 737-900 as early production models of 757 and 767 aircraft hit the 20-year mark and ended production. At the same time, the 777 was hitting its 10-year production cycle while its competitor Airbus made large market segment gains. Boeing launched the 747-8 midway through the decade. However, toward the end of the decade (i.e., 2008–2009), the industry faced global challenges related to a recession, increased fuel prices, slow economic growth, fluctuating exchange rates, and high financing costs. The Boeing Company’s (2009) 10-K filing categorized the year 2009 as the “worst ever declines” (p. 21) in both passenger and cargo traffic ever experienced by the industry. Additionally, Boeing stated the global airline industry reported losses in 7 out of the last 10 years, and over 30 airlines had entered bankruptcy since the beginning of 2008. It is clearly an alignment with the data of the investigation that more aircraft were being parked/stored or retired at a increased rate, reducing the longevity of the aircraft. The *Boeing Commercial Market Outlook for 2008* (The Boeing Company, 2008) projected that of the world’s fleet of 35,800 airplanes in 2027, only 18% will be made up of airplanes that exist today. The remaining 82% will include airplanes that have yet to be built, thus signifying accelerated retirements. Although growth based upon GDP was increasing, the fleet age was diminishing. Table 23 represents information taken from the BEA (2023b). The data indicate in billions of dollars and percentage of GDP aligned with Boeing production.

Table 23

United States Value Added by Air Transportation Segment to GDP

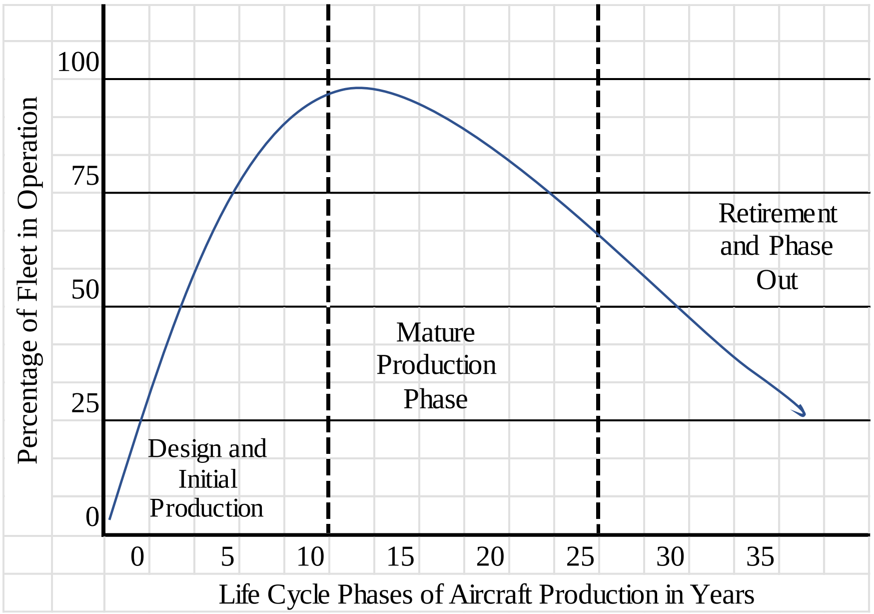
Year	Billions USD	Percentage of RGDP	Boeing A/C production	Retired	% of production
2000	58.1	-8.9	492	105	21%
2001	49.2	2.8	572	122	21%
2002	52	2.6	381	140	37%
2003	54.6	6.2	281	148	53%
2004	60.8	0.9	285	127	45%
2005	61.7	6.3	290	202	70%
2006	68	5.2	398	207	52%
2007	73.2	-4.5	441	211	48%
2008	68.7	2.9	378	312	83%
2009	71.6	12.7	481	256	53%
2010	84.3	8.3	462	249	54%

Note. Taken from BEA (2023b), The Boeing Company, and data set.

In the standard production cycle (see Figure 21), during the mature phase of deliveries the manufacturer is already considering how to end their production to move ahead to the next aircraft model. It is important to not forget that the manufacturers are in the business of selling aircraft and therefore only want to manufacture for a period of time.

Figure 21

Model Representation of Lifecycle of Production of Aircraft



CHAPTER V

CONCLUSION

In this study, results demonstrated the interconnectivity of the IVs and the retirement age of various model types of Boeing aircraft. Through the use of a regression analysis, the investigation showed multiple aircraft specific maintenance and economic variables are associated with changes in the EUL of commercial aircraft. The assessment did not specifically measure for relationships between the maintenance, technical, and regulatory IVs but rather produced an output showing the impact of the variables at a statistically significant level. Although multiple variables clearly were statistically significant, the variables with a slightly greater impact on retirement age were economic indicators. However, it must be made clear that correlation does not indicate causation (Schield, 2004). Each variable, aside from the repair assessment program and the corrosion prevention and control program, produced a result that categorized them independently as statistically significant.

A review of assets that have been retired showed they functioned for a specific time period within a specific operation. All operations are not equal or identical and therefore are subjected to varying parameters. What this research cannot estimate are the forces that Porter (1979) interpreted as competitive ones used to shape the strategies undertaken by various businesses. However, there is a constant risk of retiring an asset too soon, usually based upon a residual value assigned by the owner. Such value imperatives may change from time to time and therefore should be adjusted as markets and economic indicators change. Any review and analysis of the retirement age of aircraft must be dynamic just as the macro-economic factors that affect the decision are dynamic.

Economic variables when applied to a maintenance concept are important as they can affect the cost of the maintenance. Furthermore, the number of resources available to an operator become decision variables as to how they must apply and use resources such as manpower, materials, logistics, and hangar space. The performance of the aircraft could become influenced by the overall maintenance and ability of the operator. The inference as to performance is not just to imply the flying capability of the asset but the ability of the asset to maintain a schedule and perform within such constraints providing reliability for the operator and thus the consumer. It could also affect the safety of the aircraft as maintenance costs and resources may be limited. Economic variables are also important in aircraft maintenance because they can determine the size and scope of maintenance projects, as well as the timing of maintenance activities. Finally, viewing the economic variables as a measurement of performance and efficiency of either the MRO or the in-house maintenance organization helps to identify areas for possible improvement.

Discussion

The researcher identified in Chapter I that a problem exists in the commercial aviation industry as to the consistent identification of an EUL pertaining to modern jet commercial aircraft. The investigation showed there is a direct correlation between maintenance and economic variables and the actual retirement age of the aircraft. As the variables were all statistically significant, the null hypothesis was rejected. The investigation showed there are statistically significant maintenance and economic variables that affect the EUL of the commercial aircraft assets analyzed in this project as stated in R1. Additionally, H1 was proven as both the maintenance and economic variables statistically contributed to EUL. As asserted by R2, the application of the LOV as related to Boeing aircraft was statistically significant and affected EUL. Those IVs directly related to global economic indicators affected EUL as hypothesized in R3. As the data related to R4, there was no one specific model or subvariant that appeared to have a shorter EUL. Analysis of the various MSG maintenance program derivatives showed they affected EUL by causing it to become shorter as hypothesized by R5 and did not adversely affect retirement age over time but rather contributed to a diminishing trend. Table 24 was developed to assist the reader in comprehending the initial questions and the product of this investigation. The two items that had no statistical significance on the model were RAPY and CPCPADY. The fundamental reason for this is that after the institution by regulation of the CPCP by FAA AD (various by model type but applicable to all aircraft), the program is instituted into normal maintenance activities and is no longer a standalone requirement. As of current production, this program has become part of the manufacturer's instructions for the continued airworthiness of the product (i.e., aircraft) and is incorporated into the manual structure via the Airworthiness Limitation Section.

The second set of data points that had no statistical impact on the model related to the Repair Assessment Program (RAP; FAA, 2003). This portion of the program or the fifth element has been implemented in totality over the last 20 years. The repairs mandated by order are those of the external pressure boundary of the aircraft. These structures include the fuselage, doors, and bulkheads. When picturing an aircraft, these are the prevalent portions that are subject to contact with ground equipment or servicing materials. This program has become highly successful due to a feedback mechanism established by the regulators and manufacturer whereby survey forms are used to report and record key repair designs. Each repair now incorporates an investigation into the DTR of the structure undergoing the repair to ensure the strength as designed by the manufacturer does not become degraded. This requirement was adopted as an amendment to 4 CFR part 25, § 25.571 by Amendment 25-45 (43 FR 46242).

Table 24

Summary of Findings Related to the Research Questions

Research question	Finding or outcome
R1: Do aircraft cycles, hours, regulatory inputs, and macroeconomic variables influence the EUL of an aircraft asset?	Yes, maintenance variables and global economic variables influence the EUL of the aircraft.
H_0: There are no statistically significant maintenance or technical variables that influence the EUL of the asset.	The null hypothesis was rejected. Thus, there are specific maintenance, technical, and economic IVs that influence EUL.
H1: There is a statistically significant relationship between the independent variables and the EUL of the asset.	The maintenance, technical, and economic variables were significant and all influenced the EUL except for the RAP and the CPCP.
R2: Does the age of the aircraft (DV) exceed the required LOV?	The inclusion of the LOV as an IV was statistically significant and had an influence on the LOV.
R3: Is there a predominant group of IVs that has the largest effect on the EUL outcome?	Those IVs that are related to global economic conditions at the time of retirement seemed to jointly affect the aircraft retirement age more significantly than the maintenance variables.
R4: Is there a specific model Boeing aircraft that is more susceptible to earlier retirement due to shorter EUL?	No specific model or subvariant showed signs of earlier retirement.
R5: Based upon Maintenance Steering Group (MSG) program development, has there been an impact on retirements and a shorter EUL?	There is evidence that the various changes to the MSG have lowered the EUL of commercial Boeing aircraft over time.

The outcome of the analysis accomplished in this study showed a direct correlation between the maintenance variables examined and the actual retirement age of the aircraft assets. Early on in the Airline Quality Ratings, Bowen and Headley (2008) used the average age of the fleet as one of their rating factors, assigning a weighted average of 5.85 and a negative impact by the consumer. This metric and the financial stability metric (6.52 weighted average with a negative impact) were later dropped from the rating system. This is a clear indication that the traveling public has little or vague understanding of the actual age of the flight equipment or the financial wherewithal of the carrier on which they travel. Clearly, the consumer could use the physical aspects of an aircraft such as a three-engine versus a four-engine aircraft in visually assessing age but, for the most part, could not determine a 737-300 from a 737-800 aircraft. Most individuals cannot distinguish age or determine it visually. What the public understands and equates is the abstract concept discussed by Peters and Austin (1989), who stated "coffee stains on the airline tray table equated to bad engine maintenance" (p. 102) in the mind of a customer. It is really about the condition and care of the asset, a clean interior, a good paint job, and windows one can see out of.

One of the drivers of age reduction is the concept of aircraft development and the processes manufacturers currently employ in moving from concept to production. In 1952, William Allen and his executives and board of directors at Boeing decided to invest 25% of the firm's net worth to design and construct the prototype of the Model 707 (Serling, 1992). The industry was skeptical about this process, but the 707 emerged to be sold as the 717 to the USAF as a tanker. It was not until 1955 when Juan Tripp of Pan Am placed an order for 59 units of the 707 aircraft that Boeing emerged as a successful commercial provider of aircraft. According to Mowery (1988), the development of aircraft is a design-intensive process, and the design phase is lengthy. In some cases, this process, from conceptual idea to drawing board to actual production and certification, can be in excess of 10 years. In today's development constructs, initial design concepts are undertaken with a family concept or stretch concept developed during the initial phases of development. Take, for example, the 787 families, which included the -8, -9, and -10X that were considered and studied in co-development with each other and in a combined process inclusive of freighter conversions. A summary showing a decrease in elapsed time from initial concept to the aircraft's actual entry into commercial service is presented in Table 25.

Table 25

Summary of Aircraft Model From Design to EIS

Aircraft model	Initial concept	Launch	Entry into service	Elapsed time
707	1950	1954	1958	8
DC-8	1950	1958	1959	9
727	1956	1960	1963	7
DC-9	1961	1963	1967	6
737 Original	1963	1967	1968	5
DC-10	1965	1970	1971	6
737 Classic	1979	1981	1984	5
737 NG	1991	1993	1994	3
737 4 Gen.	2011	2011	2016	5
747	1965	1968	1970	5
757	1978	1982	1982	4
767	1978	1982	1982	4
777	1990	1994	1995	5
787	2004	2009	2011	7*

Note. Information compiled from Nayler (1978).

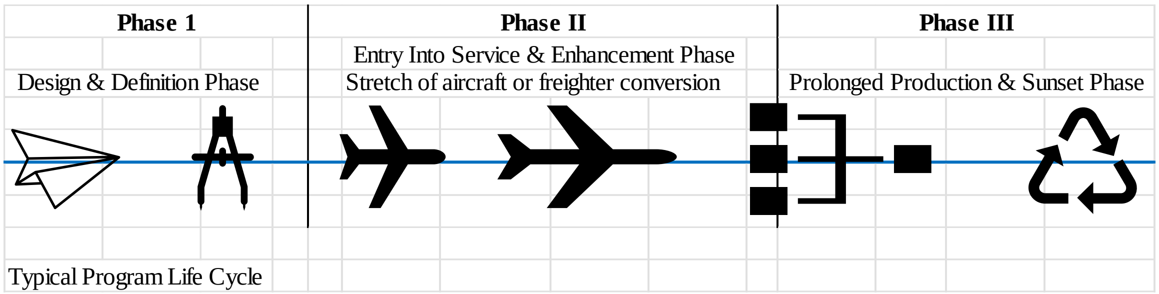
First, it should be noted that there were some issues discovered in the initial production and flight test of the prototype of the 787 aircraft and the roll out of the aircraft in 2007 occurred without all major systems functioning. The initial flight did not happen until almost 2 years later and the TC was not issued until August 2011 with an EIS of the actual aircraft in October of that year. This was the first attempt to bring in fuselage barrel structures from outside producers and join them together in the final assembly stage at the Seattle plant, rather than building from the ground up as Boeing had done in the past. Additional concerns were that the Charleston facility, which was new, was not completely capable of the tasks at hand. Technical issues with lithium-ion batteries added to the confusion with fires breaking out on board, a never experienced before component issue. Also, the first production aircraft were weighing in at over 5,000 pounds above the stated weight, which would decrease the fuel efficiencies Boeing claimed as being 20% less than the 767 aircraft. Overall, the aircraft was a huge problem for the manufacturer.

Table 25 shows a constant decline over time for the elapsed time from the initial concept to the aircraft's entry into service. For the most part, this decline can be demonstrated through the introduction of digital design concepts such as computer-aided drafting (CAD) and electronic information sharing combined with coordinating and sharing information in a digital format. Such collaborative processes have reduced elapsed time by integrating processes in the design phases. Grebenikov et al. (2021) explained how the use of such systems led to methods for ensuring regulated durability in the design of a structure in the early design stages of aircraft. According to Castro (1990), computer-aided engineering (CAE) workstations in the 1980s expanded upon the CAD process by enabling engineers to conceive, design, simulate, modify, layout, and test components using computer simulations and finite element modeling (FEM) in aircraft structures. The first aircraft to be completely computer designed and developed was the 777 model in 1990. Clough (1990) traced the root of FEM back to the 1950 and argued that although computerization of design processes has developed, the model cannot be viewed in a vacuum but still must rely upon the underlying engineering skills. He did, however, agree that its use and implementation have shortened design timelines from concept to production. Vankan et al. (2014) actually discussed the FEM use in carbon fiber products and demonstrated how the fast development of materials can be associated with a highly optimized delivery strategy in the aircraft manufacturing process. This is an additional concept that diminishes the time lag from concept to production capabilities.

The design and implementation, as explained by Pardessus (2004), contains the following five major phases of feasibility, concept, definition, development, and series or production. As the production ramp up begins in the definition stage, subassembly parts are being offered and deliveries throughout the supply chain are occurring. Logistically, as this process is condensed the ability for a major financial loss could occur should the definition of the aircraft be correct. This was the focus of his conclusion in that the ambitious and compressed schedule tests management's ability to stay within the definition and make no subsequent changes. This compression allows for more and newer aircraft or replacement aircraft to be developed in shorter time frames than previously. Therefore, if new acquisitions are occurring, then retirements are also occurring at a similar rate. Figure 22 represents a normal production cycle in an aircraft's life. What happened was that the Phase I segment was compressing and taking less time from drawing board to production implementation.

Figure 22

Representative Aircraft Production Cycle



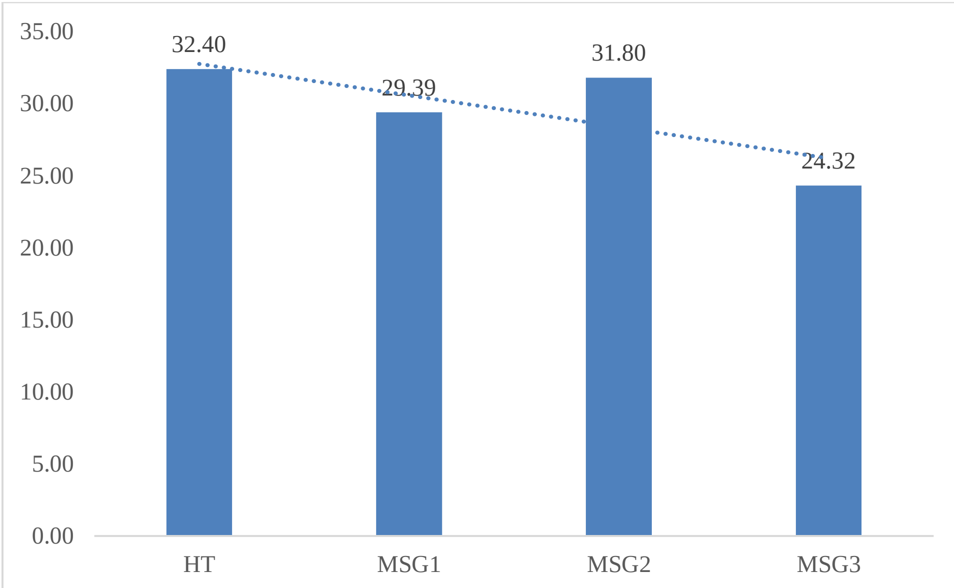
According to Maclean et al. (2018), aircraft age plays a major role in the contribution of maintenance cost drivers. As the aircraft and its systems age, they degenerate to a point where they are no longer able to fulfill all intended functions. Mofokeng et al. (2020) stated the average age for a 737-300 aircraft is 26 years and the age for a 737-800 is 18 years. That appears reasonable considering the product's first delivery occurred in 1998 to Hapag-Lloyd Flug. Also, this coincides the results of the current investigation, as they were consistent with industry norms. According to *Aircraft Value News* ("Financing of middle age aircraft," 2014), new aircraft have a slimmer margin than older aircraft and although there may be more risk involved in the transaction, there is more opportunity for greater margins found in older equipment. Age should also be understood as Dixon (2006) suggested maintenance costs may stop growing at a certain age, and if correct this would also produce an opportunity for greater return on investment. Feir (1996) pointed out that the premise that age was a factor in terms of safety was perpetuating a myth that older aircraft are unsafe. He claimed that factually, aircraft age has been one of the least relevant factors in virtually every aviation disaster.

The industry has conducted previous research into the topic of EUL with various outcomes. Aircraft age has long been considered by most to be a major factor in the determination of retirements of aircraft from operational service. “The average retirement age for all commercial jet aircraft is 25.7 years in 2015 (compared to 25.9 years in 2012), with 60% (unchanged) of delivered aircraft still in service at 25 years of age” (Forsberg, 2015, p. 2). Jiang’s (2013) study revealed that whichever surrogate (i.e., the average age of airplanes when they are permanently withdrawn from service or the time interval for a cohort of airplanes to be reduced by half) one chooses to use to measure airplane EUL, there is evidence to support that the measure has remained stable for more than 15 years.

The investigation provided no evidence to dispute either of the aforementioned researchers’ work, but rather the new evidence included herein supports that the decision is driven by maintenance, regulatory, economic, and program applications. The research showed the EUL has diminished over time. Additionally, this research proved statistically that as the maintenance programs have matured to the current MSG-3 concept, the retirement age of aircraft has decreased from that of early manufactured aircraft with HT maintenance programs by approximately 8 years (see Figure 23).

Figure 23

Average Age by Maintenance Program Type

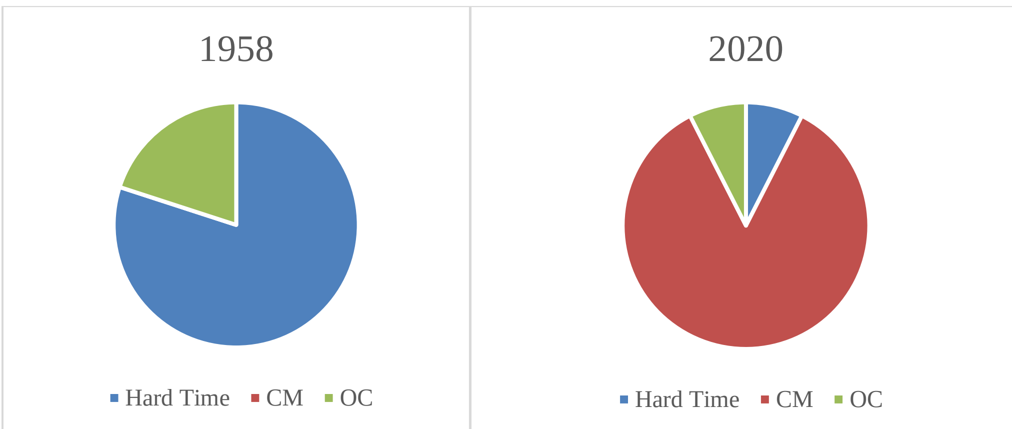


Current maintenance programs employ an RCM concept, which was discussed by Nowlan and Heap (1978) who concluded that about 89% of items cannot benefit in terms of reliability from a limit on operating age (HT overhaul). This would appear to be one of the first times the concept of operational consequences was discussed and tied to indirect economic losses for an operator. They contended that “the consequences of failure are economic, and maintenance tasks directed at preventing such failures must be justified on economic grounds” (p. xvii). Furthermore, they defined a significant item as one whose failure could affect operating safety or have major economic consequences (p. 80).

During the late 1990s, Boeing was conducting training seminars with the intent of teaching engineering and maintenance planners how to incorporate CPCPs, structural maintenance programs, and ADs into a comprehensive program. Such consolidation was intended to develop an integrated MPD and maintenance program. As the CPCP was a standalone issue due to the fact that it was tracked as an accomplishment of an AD, caution had to be exercised to ensure 100% accomplishment. Current maintenance programs have changed dramatically since the time of early commercial jet production. The standards and concepts employed have shifted away from the HT maintenance approach to one dealing with statistical reliability or RCM as demonstrated in Figure 24.

Figure 24

Shift in Maintenance Philosophy Over Time



Current aircraft have been developed and produced using the MSG-3 concept, which applied an RCM approach to the maintenance programs; thus, an economic component is present in all maintenance currently conducted. This internationally recognized standard has developed guidance for the most effective and efficient performance standards for the completion of maintenance tasks. Originally, the researcher viewed these as parallel constructs but has concluded that they are in fact one and the same—maintenance is an economic variable and economic variables include maintenance. One of the factors used to determine whether a task should be accomplished, according to Coetzee (2002), is if it is “both technically and economically feasible to the correct degree” (p. 17). Kołodziejski and Matuszak (2017) stated the only time a task should be implemented is if it reduces the probability of multiple failure to a tolerable level and is justified on economic grounds.

MSG-3 has been assessed to have increased safety within the maintenance realm of applications. It has also been credited with providing a statistical way to determine and support task intervals, thus accomplishing the unique task at the correct time within the process, which both reduces costs and adds to predictability of both the task assessment and outcome. Table 26 shows the main program differences and the main points and constructs within the programs.

Table 26

Maintenance Steering Group Summary Information

Methodology	Characteristic
MSG-1 (1968)	Bottom-up approach
	Component level
	Maintenance process oriented
	Aircraft type-related (Boeing-747)
	Using On-Condition and Condition Based Maintenance
MSG-2 (1970)	Same as MSG-1
	Generic document, non-aircraft type related
MSG-3 (1980)	Generic document
	Top-down approach
	System level
	Maintenance task oriented
	Emphasis on structural inspection programs
	More rigorous decision logic diagram
	Distinction between safety and economy
	Hidden functional failure treatment

Spitler (1990) stated the economic cost of performing maintenance should be less than the return derived from the results and that data should be used to analyze the economic efficiency of life limits versus operation to failure.

Recommendations, Education

Airline applicants who are applying to the DOT to fly in operational service must obtain economic authority issued by the Air Carrier Fitness Division (ACFD). The standard phrase used by the DOT to issue an economic authority is that the applicant is "fit, willing, and able" to conduct operations, and evidence of insurance coverage has been presented as prescribed by 49 USC.[3] This process represents half of the requirements to become an airline operator. Figure 25 shows the two distinctions the government has between the FAA and the DOT and each of their primary roles.

Figure 25

Two-Channel Process for Certification

Federal Aviation Administration (FAA)	Office of the Secretary of Transportation,
Air Carrier Certificate and Operations Specifications	DOT Economic Authority
SAFETY	ECONOMIC

As part of their mandate, the ACFD of the DOT performs an initial analysis to determine that the applicant meets the stringent requirements from a financial perspective and that the applicant is "fit, willing, and able" to engage in the business of airline operations. Once the economic authority has been issued, the ACFD continuously will

[3] General Requirements for Certification, https://www.faa.gov/licenses_certificates/airline_certification/135_certification/general_req

review on a regular basis the operations and financial conditions of the carrier. Additionally, in times of financial distress such as bankruptcy filings, the ACFD takes a more active role in oversight.

For the DOT to issue a certificate, a three-part test is applied

- Managerial competency–key individuals have experience and background.
- Operating financial plan–understanding of the costs involved, third-party verifiable capital/cash on hand, or plan to raise capital.
- Compliance record–owners and managers' history of safety violations or fraudulent activities, compliance with the law.

Additionally, The Boeing Company (2002) indicated the cost of maintenance is between 10%–20% of the DOC for an airline. This is slightly higher than the fuel and flight and cabin crew salaries as a percentage of total DOC. Although this cost varies by both aircraft type and mission allocation, it is a substantial component of the airplane's DOC, yet is somewhat passed over or briefly mentioned in academics. When mentioned it is only done so as it relates to major maintenance activities such as HMV and D checks.

A paradox is present in the way in which economics are stressed at the university level with basic macro/microeconomic theory and concepts. There should be an obligation to educate and develop the next generation of leadership to be well-rounded across the broad spectrum of aviation. Rarely in educational settings is the focus of the students on areas that, if managed correctly and learned, may have the greatest effect on the operator's DOC. Educators spend time addressing subject matter such as fuel hedging, fuel cost, and correlation to stage lengths along with price per barrel. Along with this thought, focus is placed on aspects of the air transport industry, the economic principles of making money, and issues related to revenue generation. Education sometimes omits the fundamental aspect of an operator's fitness and ability to perform as stressed by the ACFD. Should educators consider the aspect of maintenance and the cost to accomplish it to be truly an economic aspect? Academics teach maintenance accounting and maintenance management, but are they missing the concept of maintenance economics? Do the current individuals produced from university settings need a more in-depth and robust understanding of how economics influence their decisions?

Giniesis et al. (2012) performed an analysis of academic journal literature on air transport. The journals examined between 1997 and 2009 are summarized in Table 27. They categorized maintenance as part of management, which they further described as: "including articles on various subjects, such as (1) air transport management, (2) the services provided, (3) air traffic, (4) airline crews, (5) industrial policies, (6) maintenance, (7) programs, (8) engineering, and (9) flight scheduling" (p. 34).The topic of management covers 29.7% of the total articles written for the time period as broken down in Table 28. If one were to assume that each of the above terms received equal coverage, that would allow for 3.3% of the published articles as maintenance-related academic articles investigating all aspects of maintenance. From a global viewpoint it would appear that maintenance received only minimal coverage during the period investigated. Discussion of maintenance in economic journals appears relatively rare. Although there are some articles, the subject matter does not appear to be commonplace within the economic literature, yet most would agree that depending on how an airline expresses it, maintenance would be approximately 10%–25% of DOC.

Table 27

Number of Articles Whose Title Includes the Keyword "Air Transportation" in ISI Web of Knowledge Category Transportation

Journal	Total
Journal of Air Transport Management	521
Transportation Research E: Logistics and Transportation Review	111
Transportation Science	75
Journal of Transport Geography	68
Transportation Research A: Policy and Practice	57
Journal of Transport Economics and Policy	42
International Journal of Transport Economics	40
Transportation Research D: Transport and Environment	29
Transport Policy	28
Transportation Research B: Methodological	25
Transport Reviews	18
Accident Analysis and Prevention	16
Journal of Safety Research	9
Transportation	8
Transportation Research F: Traffic Psychology and Behaviour	4
Transportmetrica	4
Road and Transport Research	3
International Journal of Sustainable Transportation	1
Total	1059

Table 28

Breakdown of Selected Studies According to Main Theme

Main theme	%
Management	29.7
Airports	21.6
Passengers	11.9
Regulation	8.5
Environment	5.4
Networks	5.4
Alliances	5.2
Costs	4.6
Finance	3.5
Safety	2.6
Models	1.6
Total	100

Vasigh et al. (2018) appeared to argue that there is a relationship between economics and safety as a macro-level aspect. If true, then would the majority of maintenance actually be a function of economics as it relates to safety? Thus, institutions of higher learning may end in a circular argument whereby maintenance could be an economic function and thus no different than GDP or nominal oil price. If that is accepted, then one could conceivably agree that all of the IVs used are macroeconomic in nature.

Is aircraft maintenance economics a part of how airlines manage their operations? Aside from always focusing on revenue passenger kilometers (RPK) or revenue passenger miles (RPM), are not both micro and macro theories and concepts where the larger focus could be maintenance from both a cost and savings perspective? Leaders of colleges and universities with a focus on both aviation and airlines should pay strict attention to aircraft maintenance as it affects the age of the asset. The performance of preventative maintenance and servicing and repairing aircraft, including the costs associated with these functions and the benefits that are derived from accomplishing these tasks to keep the asset safe, efficient, airworthy, and in operational service, are key to the success of the global aviation organization. If it is true that both performance and cost of the maintenance function are ways to maximize efficiency and reduce costs, then is not maintenance economic?

Recommendations, Industry

Construct, What is Economics?

Maintenance in a global sense was a statistically significant component within the analysis. However, the economic variables influenced the model at a greater propensity. Blaug (2022) indicated economists seek to analyze the forces determining prices—not only the prices of goods and services but the prices of the resources used to produce them. Taken a step further, he discussed the microeconomic aspect of the consumers, companies, farmers, and traders and the macroeconomics aspect of the larger economy overall and issues such as investments. Taken individually, each can have various and different outcomes. However, if the industry combines those concepts, could they be speaking of aircraft? The reasoning may be as to how maintenance is viewed in part if it is in fact a necessity or the demand to maintain. Most would agree that is the case, but what does maintenance do to value? Sahay (2012) stated one of the objectives of MSG-3 was accomplishment of the maintenance tasks at a minimum total cost, including maintenance costs and the costs of resulting failures (p. 8). Schlesinger and Grimme (2021), while developing their retirement probabilities study, discussed the retirement curves and their relationship to both the economic and technical life spans of aircraft. Additionally, Gorjidooz and Vasigh (2010) indicated “macroeconomic factors are also extremely important because they indicate the aviation industry cycle, and this can have the greatest impact on aircraft values” (p. 3). Abbate et al. (2020) called maintenance costs an economic issue. Why then does the industry sometimes refrain from including maintenance as an economic issue?

Wacker et al. (2016) identified the concept of transaction cost economics (TCE) as it relates to contractual obligations between the parties and how the process is governed. Yet would not an aircraft’s maintenance be TCE? Williamson (2010) also discussed the same issue as it related to conducting a transaction, but is the industry limiting the term? Is not the purchase of the aircraft and its subsequent maintenance, preventative maintenance, and repair exactly that, costs related to the transaction or ownership? If there are economic factors as to how goods are priced for sale, does not the cost of aircraft maintenance factor into the cost per seat mile and thus is an economics factor?

The U.S. military (U.S. Department of Defense, 1996) defines economic life in a detailed description that takes up about 30% of a page. Some of the key points are identified below:

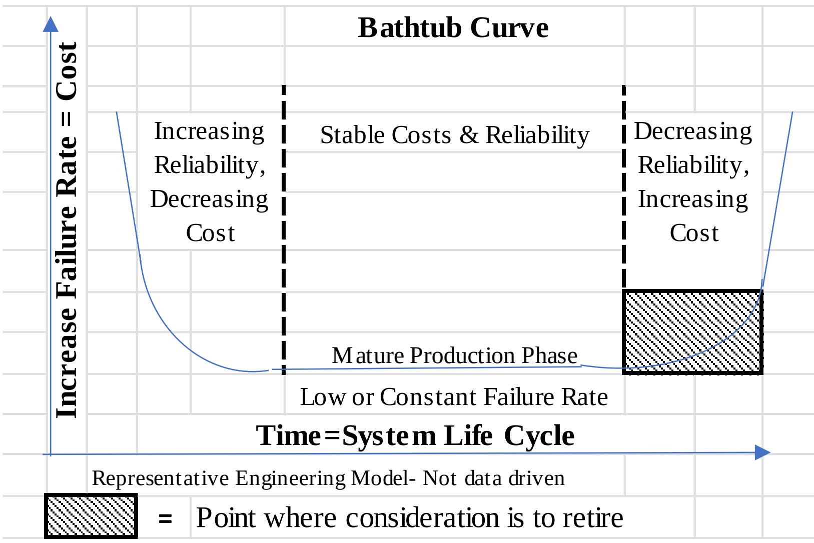
- no significant departure from the cost burden (i.e., of original production)
- occurrence of fatigue cracking which could be uneconomical to repair.
- increase in the number of damage locations or repair costs as a function of cyclic test time. (p. 3)

It would appear that the salient points as defined by the government are either cost or economics related, basically showing how maintenance costs are the driver in decisions surrounding economic life.

Using the identical bathtub curve presented in Chapter II, the researcher has added some points and details that have a specific interest as applied to age. There is a point where the sale of an aircraft would appear to be the best technical decision (i.e., the shaded area) in Figure 26 based on the increase in cost paired with the decrease in reliability. This process was identified by Guzhva et al. (2019) where they discussed decision modeling with cash flows and identification of the key driver, which assuredly is the increase in cost. Pulvino (1998) explained the rationale as to when an airline may choose to reduce maintenance expenses by selling aircraft that have little time remaining until the next maintenance overhaul if the company finds itself in financially constrained circumstances. This creates multiple issues, such as (a) it reduces their need to accomplish the maintenance and thus the expense; and (b) it reduces their capacity, also reducing both its footprint and expense.

Figure 26

Bathtub Curve Model Showing Life Cycle Phases of an Aircraft



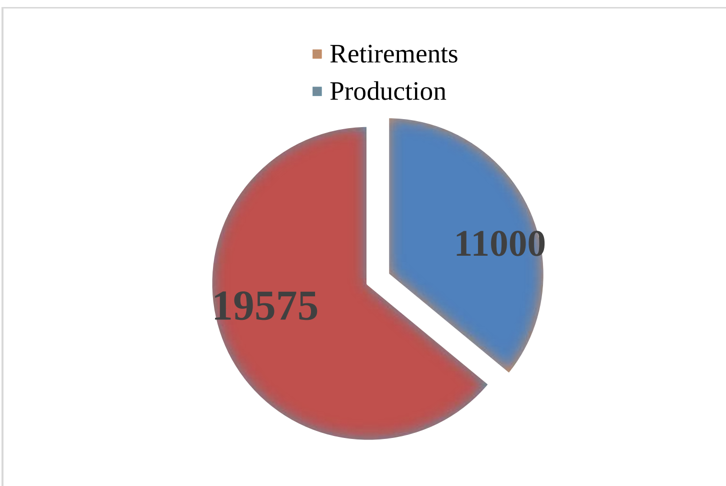
Dempsey (2017) explained how new aircraft must be ordered years ahead of delivery; aircraft are ordered in good times and delivered in bad. Lincoln and Melliere (2012) explained how the USAF, when adopting a damage tolerance approach, found that it made sense to implement the concept of economic life. Do the purchasers of aircraft at airlines not consider the aircraft to be an economic benefit to their business? Are not the costs discussed by Vasigh and Azadian (2022) as DOCs all economic? Clearly the fuel efficiency of the aircraft, its airport fees range, and maintenance expenditures are in fact all economic costs. If one was to agree that part of the foundation of aircraft valuation could be aircraft economics and maintenance is part of that assessment, then one could agree that maintenance is an economic variable that contributes to the value of an aircraft.

Future Retirements

As airlines attempt to transition to more efficient aircraft such as the Boeing 787 and 737 MAX, older models such as the Boeing 737-800 and 757 are likely to be retired sooner. According to the Aircraft Fleet Recycling Association (n.d.), a trade organization, an estimated 12,000 aircraft will be retiring in the next 2 decades. Boeing data (The Boeing Company, 2022) indicate the demand over the next 10 years will be 19,575 aircraft to be delivered. Assuming both estimates are accurate, that would indicate 36% retirement, increasing the number of aircraft being removed from the system and more than likely decreasing the number of years in service. Figure 27 shows the forecasted deliveries against the forecasted number of aircraft that would be retired or recycled.

Figure 27

Retirement Versus Production Over 10-Year Forecast



Note. Taken from the Boeing Company (2022) and Aircraft Fleet Recycling Association (n.d.).

The Boeing Company (2022) stated the decision to replace an airplane is driven by considerations such as its age, the number of flight hours and pressurization cycles it has undergone, and maintenance requirements. In some instances, retiring even a relatively new airplane and re-selling its parts ("parting-out") can yield the best economic return (p. 13). The aerospace industry should consider maintenance to be an economic variable. As an industry, there is a need to plan and address the upcoming decreases in longevity and increases in retiring aircraft.

Future Research and Investigation

As the retirement age of a particular aircraft or fleet model is measured, consideration must also be given to the need for the development of replacement alternatives. During the early period of the modern jet age, manufacturers were adding alternatives at a pace driven by the mechanics of engineering solutions. What experience has shown is the ability to bring a new variant to market has become somewhat easier due to both the design and manufacturing technologies involved in the process. What industry leaders sometimes fail to see is the current longevity of a product line that extends over decades from the original variant as developed. One could not compare the original 737-100 with its Pratt and Whitney JT-8 engines and its currently produced 737-10 MAX with CFM LEAP engines, yet they fall under the same TCDS. Future research should account for such fundamental differences and seek to segregate out on a nuanced level with model development using actual costs. Although the gathering of cost data is problematic, the investigation would be worthwhile.

In future research, this analysis technique could be applied to investigate other manufacturers. The model could be applied to the turbo-prop market and other manufacturers such as Embraer. With limited modification, this could possibly see application in the business jet market segment, although some of the indicators may not apply. This model may be applied to selected later model aircraft from both of the major manufacturers (i.e., Boeing and Airbus). This investigation has left the researcher with many questions that can drive future study and are summarized in Table 29.

Table 29

Possible Future Research Topics

Future research	Investigators
Predictability of deterioration of future structure types such as composites and graphite.	Engineering function
What role would or would the use of artificial intelligence have on the useful life	Engineering and operational
New technology such as sensor installation in the aircraft and maintenance feedback.	Engineering and operational
Unforeseen regulatory issues	Economics and engineering
Can scheduling impact life of an aircraft	Economics and operational
Can design changes such as supersonic flight impact the EUL of aircraft	Engineering and operational

Conclusion

Commercial aviation has evolved substantially over the history of the modern jet era as it has grown and expanded throughout the world, providing air services to those areas that did not receive them in the past. This industry has sustained and induced economic growth and technological changes on a worldwide level. As changes in the financing and trading of aircraft become a more commonplace occurrence, leaders in the industry are looking to find some metric, some standard they can apply to make decisions and validate the expected or economically useful life of the aircraft being used. Management wishes to be able to point to an absolute number or value that has no variance, making their decisions ironclad.

The age at which aircraft are traditionally moved into retirement has not fundamentally changed yet the investigation has shown the driver is economics and the subsequent technological advances move with those trends. The researcher has shown how older aircraft may lack the fuel efficiencies of their newer series, that costs related to maintenance tend to increase as aircraft age, and that the newer version is quieter and more environmentally friendly.

The use of maintenance and economic data has proven successful in developing a predictable solution for the retirement of commercial aircraft. Yet, the validity of the model can only be maintained should the users update it based upon current economic conditions as opposed to taking a snapshot at a point in time and filing it away after the transaction's closing. The extent of this model's success currently is not yet determined; however, working with the data sets and updating the model based on global economic changes in real time should prove its reliability and predictability.

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