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Internal Dynamics of the Short-Term Commercial Aircraft Engine Leasing Market

by

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Abstract

General trends in the commercial aircraft aftermarket indicate an increased reliance of leased engines in operators’ spare engine strategies. A methodology for forecasting short-term engine lease demand is developed using Pratt & Whitney’s existing simulation capability. This method demonstrates the ability to estimate demand mean and variance. This forecast is then used in a single SKU inventory model to set inventory levels. Using historical data this method demonstrates the ability to recommend inventory levels that minimize stock outs. A less computationally intensive system dynamics model is then constructed to replicate the lease demand forecasting model. Sensitivity analysis is performed using the system dynamic model and influential parameters are identified. The results of the sensitivity study are used to propose and test a new sales strategy for short-term engine lessors.

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Glossary of Terms

ADEMTM – Advanced Diagnostic & Engine Management™
AOG – Aircraft on Ground
CSN – Cycles Since New
CSO – Cycles Since Overhaul
EAC – Estimate at Completion
EBIT – Earnings Before Interest and Taxes
ESN – Engine Serial Number
FOD – Foreign Object Damage
GE – General Electric
IAE – International Aero Engines
LLP – Life Limited Part
LTSA – Long-term Service Agreement
MISC – Miscellaneous Shop Visit
NEB – New Engine Business
OEM – Original Equipment Manufacturer
PLI – Post Lease Inspection
P&W – Pratt & Whitney Dependable Engine Company
PWEL – Pratt & Whitney Engine Leasing
SKU – Stock Keeping Unit
TSN – Time Since New
TSO – Time Since Overhaul
WWTAT – Wing to Wing Turnaround Time
1.0 Introduction

1.1 The Commercial Aircraft Engine Business

The engines that power modern airliners are complex turbomachines that have steadily evolved since the first jet powered aircraft flight in 1939. At nearly ten feet in diameter, a single 112-inch PW4000 engine can produce more thrust than a Redstone rocket, the first rocket to carry an American into sub-orbital flight.

Commercial jet airliner service in the United States began in October 1958 when Pan American World Airways began offering service between New York and Paris on a Boeing 707 equipped with four Pratt & Whitney (P&W) JT4 engines. The engines' combined thrust was about 42,000 pounds allowing the new 707 aircraft to takeoff with 45,000 pounds of payload and carry it roughly 2,300 nautical miles. A modern Boeing 747-8i, equipped with four GEnx engines, capable of producing over 60,000 pounds of thrust each, can takeoff with over 160,000 pounds of payload and carry it more than 7,000 nautical miles. Incremental improvements in aircraft engine technology have vastly improved engine performance, but they also have increased the time and cost of engine development.

The cost and risk associated with the development and fielding of a new commercial engine creates a very high barrier to entry. An additional dynamic limiting entry into the market is that when a commercial airliner is designed and certified, it may include two or possibly only one engine option that can be ordered and installed on an aircraft. If an aircraft manufacturer chooses not to work with an engine OEM, that engine OEM may be shut out of a portion of the market for decades. This dynamic is illustrated by Boeing's decision to source engines for the 737 aircraft exclusively from CFM International in 1974. Since then CFMI, a joint venture formed by GE Aviation and SNECMA, has amassed a 70% market share for aircraft engines in the single isle market\(^1\). P&W and Rolls-Royce formed the joint venture International Aero Engines (IAE) in 1983 in response to CFMI, but the fact that the 737 was designed and certified exclusively with the CFM56® engine has shut P&W and Rolls Royce out of the 737 market for decades. A virtuous cycle has formed between Boeing, the airframe designer, and CFMI, the engine designer, where cooperation and trust formed over years of working together lowered the perceived risk of future exclusive arrangements\(^2\). This dynamic requires engine OEMs to be responsive to airframe OEMs and constantly improve their products in the hope of winning the opportunity to be designed into a new or upgraded aircraft model.

\(^1\) Morrison, "The Power of Two."

\(^2\) Ibid.

CFM and CFM56 are trademarks of CFM International
If an engine OEM finds the resources to design, build, and test a new engine and it manages to convince an airframe manufacturer to design the engine onto one of its aircraft, it has one remaining hurdle to clear: in the case of multiple engine options for an aircraft it must convince the aircraft buyers to choose its engine. The competition an OEM faces to get its engine selected can be fierce and most often results in selling installed engines for less than their unit manufacturing cost, resulting in the engine generating negative cash flow for over ten years\(^3\).

The upside to this business occurs once the engine is selected, installed, and flying. OEMs seek to generate a return on their investment in the form of engine overhauls, spare parts, and various other aftermarket services. Once an OEM’s engine is installed and flying, the engine and aircraft may be in service for twenty or as many as thirty years. Since aircraft are rarely converted from their original engine configuration, every engine added to the installed base represents a long-term addition to the OEM’s total market. Growing the installed base thus becomes paramount to the long-term financial success of an engine program.

The hunt for better return on investment has driven engine OEMs to increase their presence in the commercial engine aftermarket business. The OEM’s in depth understanding of an engine’s design and the relationships it has with its suppliers gives them an advantage over other third-party aftermarket service providers. To fully understand the range of aftermarket services OEMs have come to offer, it is useful to first discuss the design and maintenance requirements of modern commercial aircraft engines.

### 1.2 Commercial Aircraft Engine Design Overview

Commercial aircraft engines are nearly exclusively turbofan designs, meaning a configuration where a gas turbine engine core is used to power a large ducted fan. The core of the engine works by using a compressor section to compress inlet air, the compressed air is then injected with fuel and ignited in a combustion section, finally compressed and heated air is exhausted through a turbine section. The turbine section is mechanically linked to the compressor and the ducted fan such that the exhaust gasses turn the turbine, which then powers the compressor and ducted fan. The ducted fan draws and accelerates a mass of air through the engine. A portion of that air enters the engine core to be used for combustion and the remainder is pushed around the core and out of the back of the engine to help cool the core and generate thrust.

Modern turbofan engine are modular designs, the modules of which can generally be broken down into five types: the fan and low pressure compressor, high pressure compressor, combustor, high pressure turbine, and low pressure turbine\(^4\). The typical

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\(^3\) Epstein, “Innovation and Value Creation in a Very Long-Cycle Business.”

engine architecture has the compressor and turbine split into two or three sections. Each section of the compressor is mechanically linked to a corresponding section of the turbine to create a “spool”. A “dual-spool” architecture has a low pressure spool and a high pressure spool. A “triple spool” architecture has low, intermediate, and high pressure spools.

Modern engines use axial compressors, which allow air to flow through the engine with minimal direction changes. The compressor and turbine modules consist of a series of airfoils arrayed around a circular hub. Each row of airfoils attached to the hub constitutes a stage. The low pressure module generally consists of several stages attached to a hub that can be removed as a single unit from the drive shaft. Traditionally, the airfoils can then be removed and replaced individually from the module. Airfoils in each module must endure significant temperatures and stresses. Advances in materials used for these airfoils, their shape, and cooling mechanisms have been critical for improving engine performance.

The combustion module is where compressed air is mixed with fuel and ignited. It is the hottest running section of the engine. Gas temperatures in the combustion section can exceed 2000° F at takeoff power settings, causing tremendous wear on the materials and components within the section. These hot gases are exhausted directly into the high pressure turbine module making these two sections accumulate damage faster than other sections of the engine under normal operating conditions.

The shafts that the modules are attached to ride on bearings, which attach to the structure of the engine. Various types of seals are required to prevent gas from leaking around the fan, compressor, and turbine airfoils, which would degrade engine efficiency. Typically, the shafts and seals are categorized as Life Limited Parts (LLPs) that must be inspected, repaired, or replaced after a set number of hours or engine operations.  

In the majority of turbofan engine designs, the fan is attached to the same shaft as the lowest pressure section of the compressor, and thus, turns at the same speed. Unfortunately, for efficiency the low pressure compressor section needs to rotate faster than what is optimal for the fan and vice versa. The mechanical linkage of the fan and low pressure compressor is a design compromise that degrades each component’s performance.

P&W’s latest engine offering, the PW1000G PurePower® family of engines introduces a revolutionary architectural change where the fan and the low pressure compressor section are separated by a speed reduction gearbox. This allows both the fan and the compressor to turn at more optimal speeds. Slowing the fan improves efficiency and reduces noise as the fan blade tips can be slowed below sonic velocities. While this

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5 Ibid., 8.

6 Coy, "The Little Gear That Could."
type of architecture has been used for years on other gas turbine powered vehicles, such as ships and turboprop aircraft, the PW1000G engine will be the first aircraft turbofan engine to use a reduction gearbox.

The purpose of the fan and the engine core is to induce a change in the overall momentum and pressure of the air that enters the engine to create thrust to propel the aircraft. Thrust can thus be generally expressed in terms of momentum change and pressure:

\[ T = \dot{m}_e u_e - \dot{m}_o u_o + A(p_e - p_o) \]

In reality there are other forces acting on the engine, namely drag, which influence the overall thrust produced, but these have been removed to focus the discussion. The more dominant component in thrust generation is the momentum change created by the acceleration of the air mass.

Over time engine designers have sought to improve the fuel efficiency of engines in order to make them more economical to operate. An engine's efficiency can be expressed as the ratio of propulsive power produced to the total power available in the fuel consumed. The propulsive power is the thrust produced (force) multiplied by the resulting flight velocity. Fuel power can be expressed as the fuel mass flow rate times the fuel energy per unit mass. Thus overall efficiency can be written as:

\[ \eta_{overall} = \frac{T u_o}{\dot{m}_f h} \]

The overall efficiency can be broken into the thermal efficiency and the propulsive efficiency. The thermal efficiency relates the rate of kinetic energy generation to fuel power inputted and is expressed as:

\[ \eta_{thermal} = \frac{\frac{\dot{m}_e u_e^2}{2} - \frac{\dot{m}_o u_o^2}{2}}{\dot{m}_f h} \]

The propulsive efficiency relates the propulsive power actually produced to the rate of kinetic energy generated:

\[ \eta_{propulsive} = \frac{T u_o}{\frac{\dot{m}_e u_e^2}{2} - \frac{\dot{m}_o u_o^2}{2}} \]

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7 "UNIFIED PROPULSION LECTURE #1."

8 Ibid.
Thus thermal and propulsive efficiencies are related to the overall efficiency as such:

\[ \eta_{\text{overall}} = \eta_{\text{thermal}} \times \eta_{\text{propulsive}} \]

The core of turbofan engines operate using the Brayton Cycle. The thermal efficiency of an ideal Brayton cycle is a function of the ratio of the temperature on either side of the compressor. It can be expressed as:

\[ \eta_{\text{Thermal Ideal Brayton Cycle}} = 1 - \frac{T_{\text{atmospheric}}}{T_{\text{compressor exit}}} \]

Making an adiabatic assumption about the work done by the compressor on the atmospheric air, thermal efficiency can be expressed in terms of pressure ratios across the compressor as:

\[ \eta_{\text{Ideal Brayton Cycle}} = 1 - \frac{1}{\left( \frac{P_{\text{compressor exit}}}{P_{\text{atmospheric}}} \right)^{\frac{\gamma-1}{\gamma}}} \]

This relationship is shown graphically in Figure 1 below.

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\[9\text{ Ibid.}\]
As depicted in Figure 1

, increasing the compressor pressure ratios tends to improve the thermal efficiency of the engine. Not surprisingly the designed operating overall pressure ratios (stagnation pressure at the front of the compressor over the pressure at the rear of the compressor) of commercial aircraft engines have increased over time, as seen in Figure 2. Due to the relationship between pressure and temperature, however, higher pressure ratios result in higher temperatures at the compressor exit with a cascade effect that increases the overall operating temperature of the engine.
Looking at thrust and propulsive efficiency, if we assume constant mass flow through the engines, we can assume:

\[
T \approx \dot{m}(u_e - u_o)
\]

\[
\eta_{\text{propulsive}} \approx \frac{T u_o}{\dot{m} (u_e^2 - u_o^2)}
\]

Substituting the thrust equation into the propulsive efficiency equation and simplifying yields: \(^{10}\)

\[
\eta_{\text{propulsive}} = \frac{2}{1 + \frac{u_e}{u_o}}
\]

Several key relationships thus present themselves. As \(\frac{u_e}{u_o}\) approaches 1, the propulsive efficiency of the engine improves. However, this means \(u_e\) and \(u_o\) are also moving closer to parity. From the thrust equation, we can see that this will cause a reduction in

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\(^{10}\) Ibid.
the thrust produced at a given mass flow rate. So long as an engine produces enough thrust for safe operation, commercial aircraft operators are more concerned with fuel consumption than with thrust performance. To create an engine that is both efficient and produces sufficient thrust, the mass flow rate must be increased while bringing $u_e$ and $u_0$ closer together.

In practical terms this means increasing the diameter of the ducted fan attached to the core of the engine. A larger fan increases the cross sectional area of the engine allowing it sustain a higher mass flow rate of air. A larger fan also results in more air passing around the outside of the engine core increasing what is called the bypass ratio: the ratio of the mass flow of air passing around the outside of the engine's core to the mass flow of air entering into the combustion section of the engine. Not surprisingly the general trend in commercial aviation has been for increasing bypass ratios with each succeeding generation of airliner, as shown in Figure 3.

![Commercial Engine Bypass Ratios Over Time](image)

Notice that both single aisle and wide body aircraft are presented in Figure 3. The maximum thrust of the engine, which is invariably higher for wide body aircraft, is not necessarily indicative of the bypass ratio. As stated, an efficient design with higher thrust requires a higher mass flow rate. Remember that mass flow rate is a function of density, area, and velocity:

$$\dot{m} = u \cdot \rho \cdot A$$

The density of the air entering the inlet is limited to the ambient air density at the inlet and the velocity change in the air must be minimized to increase propulsive efficiency.
Thus, the area of the fan must be increased to increase thrust. Again, this trend can be seen when comparing the maximum thrust of engine designs and their fan diameters, shown in Figure 4 below:

![Figure 4: Commercial Engine Maximum Thrust vs Fan Diameter](image)

Note here the bifurcation of the single aisle and wide body aircraft. There is no value created by putting more thrust on an aircraft than is required. In the single aisle market, the maximum thrust required has remained relatively constant but the fan diameters have grown. In the wide body market, the trend has been towards two engine aircraft designs vice three or four engine configurations. This has increased the required maximum thrust on a single engine and driven the upward trend in the wide body aircraft engine thrust seen in Figure 4.

Larger fan diameters thus prove themselves to be necessary and desirable, but they are not without their challenges. The fan is driven by the extraction of energy from the high temperature and pressure gasses exhausted from the combustion section. Increasing the power generated in the core is necessary to drive the larger fans. However, this means higher temperatures and pressures experienced by the combustion section and turbine section components. Different sections of the engine rotate at different speeds, but generally rotational velocities on the order of magnitude of 4000 RPM and 10,000

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RPM are common inside turbofan engines. This combination of high temperature, pressure, and rotational velocity presents serious design challenges.

To achieve higher core temperatures, improvements in cooling effectiveness, materials, component efficiencies, and reduction in air leakage has been required. The development of exotic metal alloys have helped engines withstand higher temperatures while driving up engine and spare part costs and development time. Under high centrifugal loads and temperatures, rotating components can experience non-trivial expansion and contraction, which creates challenges in sealing the gaps between stationary and rotating parts in order to prevent air leakage. The increased size and weight of larger fans also increases the structural loads on the engine itself. Increased gyroscopic forces and uneven heating of the engine’s core structural beam have required designers to adapt their designs.

The focus of this paper is not to discuss the various design improvements that have allowed for increasing engine efficiency, rather to provide insight into why an engine with desirable fuel consumption is subject to the maintenance requirements that will be discussed. The temperatures, pressures, gyroscopic forces, and structural loads an engine must generate itself, not to mention the external flight loads it must endure, all increase its cost and create degrees of freedom that complicate its maintainability. This discussion on the design considerations and operating challenges of a modern, fuel efficient turbofan engine informs the following discussion on the typical maintenance requirements of these engines.

1.3 Commercial Aircraft Engine Maintenance Overview

The core of the turbofan engine is the most significant driver of maintenance requirements of the overall engine. The engine core is generally divided into modules that can be removed and replaced individually. These modules are serialized and tracked individually.

The engine itself is also given an engine serial number (ESN) that corresponds to the data plate installed on the engine at the factory. The data plate ESN is used for tracking the service history, flight hours, number of take offs (referred to as cycles), and the LLPs and modules installed. Because of the modular design, an ESN could have high lifetime hours and cycles, but all the modules installed on that ESN could be brand new. Clearly, such an engine would have higher monetary and operational value than an

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12 Ibid.
13 Ibid.
14 Ibid.
engine with identical hours and cycles but its original modules. This is because the value of an engine to an operator is largely a function of how much “life” or “green time” remains on an engine. Estimating the remaining life of an unknown engine, or even understanding its serviceability, is not possible without accurate records. Not surprisingly the records that track the utilization of a particular ESN and the timing of which modules are installed on the engine are statutorily prescribed by the various aviation regulatory bodies around the world. An engine without accurate records holds very little commercial value beyond its scrap value. Such an engine would have to have all its modules and LLPs replaced with known components before it could be returned to service.

Typical maintenance cycles for commercial turbofan engines include a period of time where the engine operates on wing followed by its removal and shipment to an overhaul facility where it undergoes a series of maintenance actions related to the amount of damage in each module. The extent of the repairs required or desired is referred to as the work scope and it cannot be assumed that two engines that have been operating in similar conditions will have identical work scopes, or even remain on wing for the same amount of time. The time beginning when an engine is installed and starts operating to when it completes an off-wing performance restoration overhaul is referred to as an interval. Interval is not purely a function of time, but rather is driven by numerous parameters.

The completion of the on-wing portion of an engine interval is signaled by the engine performing below acceptable limits. Typically engine performance is benchmarked using Exhaust Gas Temperature (EGT) margin. It is not possible to keep all dirt and particulates out of the air entering the engine. When the particles come in contact with the airfoils and seals in the engine moving at high speeds, erosion occurs. Over time this erosion degrades the aerodynamic efficiency of the engine requiring more work, measured as higher EGT, to achieve the same thrust. The delta between the EGT required to generate takeoff thrust and the EGT redline value is the EGT margin.\textsuperscript{17}

The engine must be designed to withstand the stresses of operation at takeoff power, the highest amount of thrust the engine is required to produce during a typical mission profile. Cruise thrust settings, where the engine operates the majority of the time, are significantly less than takeoff settings. Additionally, takeoffs occur near the ground where the concentration of dust, dirt, and aerosolized industrial pollutant particulates in the air tend to be higher. The factors influencing engine performance degradation have been studied including work by Hanumanthan.\textsuperscript{18} Hanumanthan identifies take-off thrust

\textsuperscript{16} Kline, Interview with Greg Kline.

\textsuperscript{17} Ackert, “Engine Maintenance Concepts for Financiers.”

\textsuperscript{18} Hanumanthan et al., “Severity Estimation and Effect of Operational Parameters for Civil Aircraft Jet Engines.”

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setting (commonly referred to as derate) and outside air temperature as influential parameters in engine performance degradation. Because of the high thrust required and the relatively more severe conditions in the takeoff environment, EGT margin tends to deteriorate as the number of cycles on an engine increases. The EGT margin also degrades as the number of operating flight hours increases.

There are no hard and fast rules about how many hours and cycles an engine will endure before it reaches its interval. Interval should instead be thought of as a damage limit. The engine accumulates damage as it operates at some variable rate that is driven by the conditions under which the engine is operating. When the engine accumulates damage up to the damage threshold, it reaches interval. Two identical engines operated under different conditions will accumulate damage at different rates and thus reach interval at different times.

For example, consider an operator who flies a route between Honolulu (PHNL) and Los Angeles (KLAX) using a narrow body aircraft. This is nominally a five-hour flight requiring one takeoff (5:1 hour to cycle ratio). Due to operational and market limitations, the aircraft, and thus the engine, are likely only able to make this trip twice a day, resulting in maximum two cycles a day or 60 cycle/month. Both cities are at sea level, have moderate average temperatures, and average levels of air pollutants.

Contrast this scenario in one with an operator flying a Dubai (OMDB) to Riyadh (OERK) route with the same airframe/engine combination. This is a nominally 1.5-hour flight requiring one takeoff (1.5:1 hour to cycle ratio). If demand was sufficient, this route could be flown six or more times in a day using the same aircraft resulting in upwards of 180 cycles/month. Additionally, the average outside air temperature in both of these cities can be relatively high and the surrounding terrain of both airports is dominated by sand.

The engines in the first scenario would most likely have a lower damage accumulation rate than the second scenario. The engines would encounter fewer takeoffs on average and those takeoffs would be much less severe environments. Roberson’s work sought to refine the impacts of environmental factors on engine degradation.

In practice operators will vary the routes their aircraft are assigned to in order to balance aircraft and engine utilization. However, since operators tend to fly a consistent network of routes, the possible hour to cycle ratios and destinations an engine may experience tends to be determined by the operator’s business strategy. An operator who makes their hub in Honolulu will necessarily have to fly longer routes and will thus

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19 “World Air Quality Index.”

20 Roberson, Application of Multiple Information Sources to Prediction of Engine Time on-Wing.

21 Kline, Interview with Greg Kline.
be unable to accumulate cycles as quickly as a carrier who focuses exclusively on European city pairs, which tend to require no more than two flight hours per cycle.

Thus it is not reasonable for one operator to expect the same maintenance intervals from their engines as another operator. Interval is highly dependent on the manner and environment in which the engine is operated. This is why a high fidelity model that predicts time on wing between full interval shop visits must be done at the operator level or lower, vice some other higher level aggregation such as across the entire engine model fleet.

Another engine removal driver is LLP expiration. When an LLP reaches its designated life limit, it must be replaced. Many of these components cannot be replaced on wing, forcing a shop visit even if the engine has sufficient EGT margin. Typically engines operating shorter haul routes run into LLP limits before running out of EGT margin as LLP lives are typically expressed in terms of cycles.22

“Miscellaneous (MISC) Shop Visits” are generally triggered by three types of events: bird ingestion, foreign object damage (FOD), and other mechanical malfunctions that cannot be repaired on wing. In practice, predicting these types of events is extremely difficult and their occurrence can be approximated as random events occurring at industry accepted per flight hour rates. By volume, they constitute a much smaller proportion of total engine shop visits compared to full interval shop visits. However, a miscellaneous shop visit may turn into a full interval visit. This would occur if upon removal and inspection the scope of damage in the engine is such that a full interval performance restoration work scope is warranted or the green time remaining on the engine is minimal enough that it is more economical to complete performance restoration maintenance while the engine is already in the shop than to repair the engine only to bring it back to the shop a short time later.

In summary, engines may be driven off wing for a variety of reasons: EGT margin degradation, LLP life expiration, bird ingestion, FOD, or other mechanical failures discovered during inspection. When engines are removed and sent to a repair facility, the scope of work performed varies from isolated repair of a specific issue to full EGT margin restoration. The period an engine is on wing between performance restoration overhauls is referred to as engine interval.

1.4 The Commercial Aircraft Engine Aftermarket

The increasing development costs of new engine programs drove OEMs to seek revenue in their engines’ respective aftermarkets. The first major innovation in this regard, beyond selling parts and service, came with Rolls-Royce’s offering of a long-
term service agreement (LTSA) branded as TotalCare in 1997. Since then the other OEMs have introduced their own LTSA products. The structure of these agreements varies, but in general the value proposition of an LTSA is that it shifts risk from the operator to the OEM as the OEM is on the hook to pay for an engine's maintenance with the money they have collected to date. It also provides the operator with a predictable cost structure for their engine maintenance and smoothes out what would be large repair bills over time, which benefits an airlines cash flow.

The OEM can afford to maintain the overhaul facilities and additional maintenance overhead because of the economy of scale gained by offering aftermarket services to a multitude of operators. The OEM also retains the expert knowledge of their product and the manufacturing infrastructure to produce parts. An LTSA provides an incentive for the OEM to design low maintenance engines that remain on wing longer, a feature that is also attractive to operators.

To entice operators to enter into LTSAs, OEMs have steadily refined the coverage options available. Some have included lease engine coverage options that provide a spare engine lease on a short-term basis whenever the covered operator's engine is removed for off wing maintenance.

1.5 Aircraft Engine Leasing

Aircraft operators buy and maintain engines with the sole intent to run the engines in a revenue generating capacity. Thus, the availability of the engine to produce lift is of keen interest to an operator. Operators seek to maintain constant lift capacity by filling every available engine station on their aircraft with a serviceable engine. When an engine must be removed for a shop visit, it will be unavailable for revenue generating service during the time required to prepare and ship the engine to and from the engine center plus the time required to repair the engine.

Table 1 shows the estimated daily revenue, based on median ticket prices from January 16, 2015 to January 16, 2016, of the top three operators by daily flight frequency who provide commercial flights between Boston Logan International (KBOS) to John F. Kennedy International Airport (KJFK).

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23 Baker, "Aftermarket Battle."
### Table 1: Estimated Daily Revenue for KBOS to KJFK Flights

<table>
<thead>
<tr>
<th>Operator</th>
<th>Per Flight Revenue</th>
<th>Average Number of Flights Per Day</th>
<th>Estimated Daily Revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td>JetBlue</td>
<td>$27,922.05</td>
<td>6.95</td>
<td>$194,058.25</td>
</tr>
<tr>
<td>American Airlines</td>
<td>$193,581.37</td>
<td>3.88</td>
<td>$751,095.72</td>
</tr>
<tr>
<td>Delta Airlines</td>
<td>$130,030.58</td>
<td>3.11</td>
<td>$404,395.10</td>
</tr>
</tbody>
</table>

Source: Flightaware.com

The daily revenues presented in Table 1 represent flights in only one direction. If it is assumed that the airline offers an equivalent amount of daily service in the opposite direction, the daily revenue from this city pair could meet or exceed $1 million per day for some operators.

Operators will typically adjust the city pairs an aircraft is assigned to in order to balance utilization hours and cycles across their fleet. Thus, quantifying the loss of an aircraft in terms of lost daily revenue is not straightforward. Estimates have been made ranging from $20,000 USD per day to $150,000 USD per hour depending on the size of the airline. It is clear, however, that if an engine removal is required that aircraft will be out of revenue service (referred to as Aircraft on Ground or AOG) until it receives a replacement engine, even if there is nothing wrong with the rest of the aircraft. With revenue on this order of magnitude at stake, an operator’s desire to keep an aircraft flying is understandable and brings clarity to how much they would be willing to spend to prevent such an occurrence.

Today an operator has the option to purchase, hold, and maintain their own exclusive use spare engines or they may be able to lease a spare engine. Owning spare engines is attractive because it lowers the risk of a disruption in service. When the spare engine is owned, there is very little uncertainty about where the engine is located, if it is serviceable, what configuration it is in, or how long it will take to move it to an engine deficient aircraft. The operator can more easily predict when an aircraft that requires an engine removal will be able to reenter revenue service.

The major downside to owning spare engines is that they represent an enormous capital expenditure. They may see very little utilization while sitting as a large entry in

24 “Flightaware.com.”

25 “AOG Situations Cost Airlines an Arm and a Leg.”
asset column of the balance sheet. As such it would seem there is a strong case to utilize operating leases to move these assets off an operator's balance sheet.²⁶

The problem with an operator relying on lease engines instead of owning spares is that there needs to be someone willing to hold and lease the exact engine model that the operator needs when the operator needs it. There are some major risks to engine leasing that lessen its attractiveness to financiers. The need to repossess an engine from a delinquent lessee poses a pernicious threat to lessors. Aircraft engines are internationally mobile when attached to aircraft and become a tremendous logistical challenge to move even a few feet once removed. Additionally, the particular country that the engine is currently located in may or may not have laws conducive to repossession, and there is no guarantee the engines will remain in that country long enough for the requisite legal proceedings to transpire. Even if an asset can be recovered, there is no guarantee that it will be in a valuable condition or that its records will be with it. As previously discussed, the value of an engine can be heavily tied to its maintenance records. The engine will have no sales value and will likely be refused by any potential lessee until its records can also be obtained and validated. Additionally, the modular design of an engine makes it easy for a lessee to swap out higher value modules from a leased engine for one of their own lower value modules. Despite the covenants of the leasing agreement, the lessor has very little control over what actually happens to the engine's components once it is transferred to a lessee.

While careful advance examination of a lessee's creditworthiness, stringent lease return conditions, and remote electronic engine monitoring can all help to estimate and mitigate the risk of a lease, there remains a tremendous amount of capital at risk whenever an engine is leased. The risks were such that the commercial engine leasing business was essentially non-existent until around 1997 when enough of the risk was understood and the market large enough to entice investors to bet engine leasing.²⁷

Since then the trend in the industry has been for operators to purchase fewer spare engines. The observed and predicted spare engine ratios for four of P&W's engine models that entered service after 1997 are presented in Figure 5.

²⁶ Seymour, "Managing Risk in Engine Leasing."
²⁷ Ibid.
While many factors play into an operator’s decision on the number of spare engines to purchase, there is a clear correlation between the availability of spare engines in the lease market and the spare engine ratios operators are choosing to maintain.

Today, the CFM56 and V2500 engines are the two dominant engines in the single aisle market. There have been over 14,693 A320 and B737 series aircraft delivered since 1984, representing over 30,000 installed engines. Previous estimates place the spare engine requirements for an engine market at 10 to 20% of the number of installed engines and the observations made during this study agreed with that estimate. Thus, assuming an average price of around $10 million per spare engine, the single aisle spare engines constitute an over $30 billion market that has developed over the past three decades. Combined with wide body and business jets, spare engines represent a financially significant and operationally necessary segment of commercial aviation.

Figure 5: Operator Owned Spare Engine Ratios by Engine Model Over Time

![Graph showing spare engine ratios by engine model over time.]

28 "Orders & Deliveries | Airbus, a Leading Aircraft Manufacturer."

29 "Boeing."

30 Seymour, "Managing Risk in Engine Leasing."
1.5.1 Typical Engine Leasing Business Arrangements

Several independent, non-OEM engine lessors, including Willis Engine Leasing and Rolls Royce and Partners Finance, as well as engine OEMs like Pratt & Whitney and GE Aviation have been able to start and operate successful engine leasing businesses.\(^{31}\) Long-term leases, upwards of ten years, have been a popular arrangement that allows an operator to avoid the high initial cash outlay of buying a spare engine while maintaining exclusive use, and the operational predictability that provides, of the engine. Lessors engaging in long-term leases will only purchase an engine when they have a long-term lease for it to fill. They then have several years notice to find a follow on lessee or decide to sell the engine. In this way, the lessor avoids accumulating excess engine inventory.

Another common arrangement is a sale-lease back where an operator negotiates to purchase a spare engine from an OEM at a discounted rate. The operator then sells the spare engine to a leasing company at full price, creating an arbitrage from the OEM’s discount. The sale comes with a long-term lease agreement between the operator and the leasing company where the operator maintains exclusive use of the engine. The leasing company receives some level of guaranteed return on their purchase and the operator maintains a spare engine without a large up front expenditure.

Willis Engine Leasing provides a service where they act as facilitators amongst operators who have underutilized spare engines. The operators enter into a pooling agreement and if one is in need of an engine, Willis will help the operator look for an available engine from one of the other pool participants and then handle the administrative and logistical requirements to transfer the engine. This type of arrangement seeks to create efficiency through pooling of otherwise exclusive use assets. It does not, however, guarantee any sort of availability to an operator and thus can only be counted on as a last resort or opportunistic supply of spare engines vice a central element of an operating strategy.

Short-term, on-demand leasing arrangements are the least common and create serious inventory risk for the lessor. Engine OEMs typically are the only vendors to offer this type of service and generally as a part of an LTSA. Engine lease coverage agreements vary in structure, but in general the operator agrees to maintain a certain spare engine ratio (number of ready spares to number of installed engines). The OEM agrees to provide a spare engine to the operator on a short-term lease at discounted rates when the operator experiences certain predetermined circumstances. Again, there are a variety of flavors this type of agreement can take on, but the end result is that the OEM must maintain an inventory of serviceable engines to fulfill its end of the agreement.

\(^{31}\) Rolls Royce and Financial Partners operates as a separate business from Rolls Royce and does not offer LTSA products in coordination with Rolls Royce.
In theory if the OEM locks up lease agreements with enough operators, the OEM may enjoy some pooling efficiencies with their lease fleet. Since these types of engine leases are generally between three and six months in length, a single engine could potentially satisfy several customers’ needs in a year. In order for a lessor to optimally size their lease engine inventory, they must first have a way to estimate the demand for lease engines. This demand estimate must offer an estimate of demand timing and location. The high capital acquisition and holding cost of aircraft engines coupled with the long lead time required to obtain an engine requires a reliable method for forecasting demand in order to profitably run a short-term engine leasing business with a high service level.

1.6 Project Overview

The ultimate goal of this project was to develop a demand forecasting methodology that could be used for inventory planning in the short-term engine leasing business. The project was sponsored by Pratt & Whitney’s Aftermarket division. All work was performed and data collected in conjunction with P&W Engine Leasing (PWEL) and P&W Engine Services, two business units within Aftermarket.

First, a review of existing forecasting methods and general knowledge about the lease engine market was performed. Based on this review, an updated method was proposed and tested using historical data. This proposed method was built upon an existing engine maintenance interval prediction simulation that required non-trivial amounts of setup and simulation run time. Using the knowledge gained from working with this method, a simplified systems dynamics model was created to approximate the behavior of the lease engine market. This model produced results with significantly less run time enabling faster simulation of a variety of scenarios. Using the systems dynamics model, a sensitivity study was performed to identify the critical variables in the lease engine market’s behavior. The results of the simulations and sensitivity study were used to formulate a strategy proposal for an engine lessor (targeted at an OEM lessor) competing in the short-term engine leasing market.

2.0 Engine Lease Demand Forecasting

Forecasting short-term lease engine demand is necessary to plan lease engine inventory levels and locations in a cost effective manner. An OEM can obtain one of their own manufactured engines at cost to place in their lease pool, a significant advantage over third party lessors. However, a single engine, even at cost, represents a capital expenditure of millions of dollars. Carrying a few extra units of safety stock than are necessary, which see little to no utilization adds unnecessary cost very rapidly on a per unit basis. This section contains an overview of forecasting methods that have been used in the past and the method proposed and tested for this study.
2.1 Work In Process Method

This forecasting method is an application of Little’s Law: \( L = \lambda W \).\(^{32}\) It assumes an operator’s engines and the engine shops are a closed system. The historical average number of shop visits to occur during a time period is found and used as the arrival rate (\( \lambda \)) in engines per unit time. A metric called the average wing to wing turnaround time (WWTAT), representing the average total time from when an engine is removed from service until it is returned to the operator, is used as the expected waiting time (\( W \)).

The calculated expected number of units in the system (\( L \)) then represents the number of engines that are expected to be unserviceable at a given time (in manufacturing settings this formula is often used to calculate work in process, hence the name of this method.) It assumes that an unserviceable engine will be replaced by a spare engine, and so \( L \) represents the number of spare engines required at any given time.

This calculation is performed for each operator using operator specific values for \( W \) and \( \lambda \) to generate an operator specific \( L \) value. The \( L \) values for multiple operators are summed and the available spare engines are subtracted to find the total number of lease engines required to keep all operators flying.

The advantage of this method is its simplicity and ease of calculation. There are relatively few data parameters that need to be collected for each operator.

There are several downsides to this method. The first is that it relies entirely on trailing averages. If an operator were to scale back their operations due to an economic downturn, change the nature of its route structure, or add aircraft and engines to its fleet, the WIP method does not offer a straightforward way to incorporate these changes into the forecast. A new shop visit rate would need to be assumed and used generate a forecast.

Another drawback of the WIP method is that it considers each operator in isolation. This makes it impossible to gain insight into how a global system variable impacts lease engine inventory requirements. The primary variable of concern is engine shop capacity. The historical effects of shop capacity are accounted for in the WWTAT. If the shops are at capacity one year and maintaining a queue, this will be captured as a higher WWTAT for all operators. However, if demand the next year is lower and shops are running below capacity, then this model will predict higher lease engine inventory requirements. Conversely, when transitioning from a below capacity year to an over capacity year, lease demand will indicate lower than it should.

A major deficiency in this method is that it is based solely on the movements of the replaced engine and does not account for inefficient movements of the lease engine.

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\(^{32}\)Little, “A Proof for the Queuing Formula.”
The WWTAT parameter is the time from when the owned engine leaves and returns to the wing, which is all time that a lease engine would be expected to cover. However, from the point in time that the owned engine is removed, it is reasonable to assume that a lease engine is designated to fill its spot shortly thereafter. Once a lease engine has been assigned to a lessee, it is no longer available to fill new demand and lease pool loses coverage from the asset. Once the owned engine returns to its operator, which signals the end of the WWTAT, the lease engine is still unavailable to provide pool coverage. It must first be shipped and inspected, processes that may consume upwards of 25% of the entire time the lease engine is unavailable to the lease pool. This method should really use two different WWTATs, the average for owned engines and the average for lease engines.

Finally, this method provides no insight into expected variation in lease demand. The entire calculation is performed deterministically. A lessor can compare this expected demand to their current inventory and get an indication of their position, but without an estimate of demand variation, calculating an appropriate level of safety stock is not feasible.

Given the high cost of adding a single engine to lease pool inventory, the WIP method of forecasting demand does not provide a high degree of confidence while conducting inventory planning. It does not maximize the use of available information to provide a look ahead capability or estimate demand variation.

### 2.2 Engine Shop Visit Correlation

A second method to estimate lease engine demand uses the assumption that any short-term engine lease is triggered by a shop visit. The number of shop visits at a given time is adjusted by a scaling factor to determine the number of lease engines required. The scaling factor accounts for the shop visits being covered by owned spares and engines leased for reasons other than shop visit coverage.

Much like the WIP method, this Shop Visit Correlation method does not provide any look ahead ability or estimate of demand variation. Additionally, looking at historical data the number of leases required does not exactly correlate to shop visits. Figure 6 shows, for a single engine model, a comparison between the number of engines inducted into the shop during each time period versus the number of engines on lease. While there is some correlation between the two parameters, significant and inconsistent deviations appear as well. The deviations seen in Figure 6 are consistent with those observed in other engine models. While correlating shop visits may get the lease engine forecast in the right neighborhood, it has some deficiencies that make it of questionable value for long-term capital acquisition planning.
2.3 Proposed Forecasting Method

The intent of the following proposed forecasting method is to provide PWEL with the ability to forecast demand for both in-service and soon to enter service engines. Significant long-term financial planning is necessary to ensure capital is available to procure lease pool engines when they are required. As such, it is desirable to look out five to ten years and estimate the number engines that will be required. Additionally, it is desirable to estimate where near-term demand is likely to materialize in order to position inventory appropriately.

2.3.1 Objectives

The forecasting method tested during this project sought to achieve several objectives:

1) Maximize the use of existing data sources and tools to forecast expected demand, demand variability, and demand locations.

2) Minimize the additional workload required to generate the forecast.

3) Provide the ability to test inventory strategies and evaluate the impact of market changes on demand.
2.3.2 Method Overview and Assumptions

The proposed method sought to simulate the transactions that occur in the short-term lease engine market. At its core the proposed method used an existing engine interval prediction model, called the Interval and Cost Estimation (ICE) simulation, which had been developed by Pratt & Whitney to perform contract cost estimation functions. For the lease demand predictions, the simulation setup was modified from how the company traditionally ran cost estimation simulations. Tools and techniques to visualize the simulation results in a meaningful way were also developed. The proposed forecasting method will henceforth be referred to as the ICE Method.

Initially, a baseline set of assumptions were made about the lease market. These assumptions are captured in the flow chart depicted in Figure 7.

![Flow Chart](Image)

**Figure 7: ICE Forecasting Method Assumption Flow Chart**
The initial condition of the simulation is that every aircraft has operable engines and every operator is content with their spare engine level. Thus, the first assumption is that any desire for a lease is triggered by an engine removal event. In reality an operator may decide to lease an extra engine to increase their spare engine level. However, this type of lease demand is far less common than the case where an engine removal necessitates a replacement engine. This type of decision would largely be based on the results of an individual operator’s internal risk management strategy and would be challenging to predict without developed business intelligence sources.

When an operator removes an engine, it makes the decision whether or not to replace that engine to keep the airframe from which it was removed operable. Aircraft retirements are controlled separately in the simulation and will be accounted for automatically. Thus it is assumed that a removed engine will be replaced to keep the aircraft flying.

If an engine is to be replaced, the operator must decide from where it will obtain the replacement. It is assumed that if the operator owns a spare engine and that engine is available, the owned spare will be used. If one is not available, then a lease engine will be used. There are instances when an engine is beyond economic repair and may be sold and replaced by a purchased engine. Incorporating an economic decision module into this forecasting method would be a reasonable and worthwhile addition, however, it was deemed out of scope for this study based on time and resource availability. Thus, the assumption was made that any removed engine is replaced by an owned spare engine or a lease engine.

The operator must then decide from where to lease the engine. For this study, Pratt & Whitney was most concerned with providing a high service level to those customers who had entered into an LTSA that included lease engine coverage. For this reason the assumption was made that the lease engines would come from a single provider. The simulations have the flexibility to designate each individual operator’s lessor preference. However, OEMs tend to be the only providers of the on-demand, short-term engine leases this model was designed to predict, so the assumption that lease engines originate from a single source is reasonable.

With this set of assumptions, several of the key requirements for the model to work reveal themselves. First, the ability to predict engine removals. Second, detailed knowledge of the installed and spare engine levels for each operator is required. Third, the ability to track where engines are in time, be it installed on an aircraft, under repair, or waiting as a ready spare.

2.3.3 ICE Method Advantages

Predicting engine interval and shop visits is a key capability for estimating the long-term costs that will be incurred during an LTSA. As such, Pratt & Whitney Aftermarket has invested heavily in the ICE simulation and its infrastructure. The proposed forecasting method capitalizes on the ICE simulation’s capability to predict engine removals.
The proposed method also leveraged the efforts of existing business processes. New Engine Business (NEB) sales campaigns use the ICE simulation to help set prices for new engines sales and LTSAs. Before a customer takes delivery, these simulations represent the best information available about their likely usage behavior and delivery schedule. Once engines are in service, new simulations are run with updated actual data to continuously monitor the status of various contracts. The proposed method sought to consolidate the relevant information contained in these simulations to provide a look-ahead capability.

P&W maintains a network of customer representatives who work at their customers’ facilities and overhaul shops. One of their functions is to track the activity of each P&W engine including engine installations, removals, shop inductions, and major events associated with the engine. This data is populated in a database and is used in their existing LTSA cost Estimate at Completion (EAC) process. The EAC simulations are similar to the NEB simulations, but include updates regarding actual engine utilization, delivery dates, and shop visits. The EAC simulations represent the best available information about the composition of and interval predictions for a customer’s fleet. Utilizing the existing cost estimation model and the NEB and EAC simulation creation processes ensured that minimal additional business processes would be required. Additionally, tapping into an existing model prevented devoting resources to maintain a new simulation product at the completion of the project.

2.3.4 ICE Method Testing Overview

Testing of the ICE Method involved running inputs derived from historical data through the simulation and comparing the results to the actual leases executed by PWEL. The underlying dynamics driving lease demand were assumed to be the same across engine models because the states in which engines exist do not change across models. These states include: installed and flying on an aircraft, uninstalled but serviceable and available (ready spare), and uninstalled and unserviceable. The rates at which engines flow between these states varies between models, but the variable influencing the rates are the same. These include engine utilization, mission profiles, delivery history, and spare engine ratio, among others.

So, for example, a V2500 engine installed on an A320 and a PW4000 engine installed on an A330 will both spend the majority of their lives either installed and flying, sitting as a ready spare, in an engine overhaul shop, or in transit to one of those three locations. The expense of the assets precludes their use for much anything else other than revenue generation or insurance. While V2500 and PW4000 engines may see very different hour to cycle ratios, operating environments, and shop visit times, these parameters only drive the timing of when an engine switches between states.

The ICE simulation was built to model individual engines and track which of the three states they are in. The inputs to the simulation include those parameters that influence timing of state changes. So, in the ways that engine lives are similar, the simulation
treats all simulated engines the same. The user defined inputs to the simulation capture the ways the engine lives differ.

P&W's ICE simulation incorporates a significant amount of engineering and organizational learnings regarding their products and is proprietary. Thus, it will not be discussed in great detail. A general overview is all that will be required to facilitate understanding of this study. Upon initialization, the simulation assigns every engine a randomly assigned defect threshold. Defect thresholds are determined using physics based models and historical observations of an engine model's performance over time (this makes simulating new, not yet in service models less certain). As the simulation runs in time, each discrete engine accumulates defects at a rate that is determined by a model unique to each engine type. When an engine reaches its defect threshold, the simulation changes its state from installed and flying to in the shop. Shipping time and shop turnaround time are applied before returning the engine to service. Each change of state is recorded as a record in an output database.

The first step in testing the proposed method involved selecting an engine model to use for the test. Due to the complexity of creating the inputs, general quality of the available data, and time available, an engine model with a smaller installed base and number of operators was selected. This model will henceforward be referred to as Engine Model A.

### 2.3.4.1 ICE Simulation Inputs

#### 2.3.4.1.1 Engine and Aircraft Deliveries

The ICE simulation models each engine discretely and thus, a unique key is required to identify each engine. The ESN was used most consistently across various data sources to identify engines uniquely and thus, ESN was selected for this test. The one exception to this came when determining the ESNs that were delivered with new aircraft deliveries. A key input to the simulation is the date when an aircraft enters service with installed engines. In one database P&W had fairly complete records of the production of each ESN up to its delivery date. Another database, populated by the customer representatives, had mostly complete records of the first time an ESN was installed on an aircraft with a particular tail number. A third database, owned by an external vendor who provided marketing data to P&W, contained complete records of aircraft deliveries and included fields for engine type installed at delivery and registration number.

Using reports from these three databases, a complete historical record of aircraft, installed engine and spare engine deliveries was pieced together. This input to the simulation included aircraft and engine entry into service dates and operator.

#### 2.3.4.1.2 Mission Profiles

The next input to the simulation is the mission profile parameters. These parameters include takeoff ambient temperature, takeoff derate, hour to cycle ratio, mean monthly flight hours, and monthly flight hour variation.
The ICE simulation provides a great deal of flexibility in assigning mission profiles to engines. For the ICE Method study, the same mission profile was assigned to all the engines assigned to an operator. Some operators pay for real-time engine monitoring services, known as Advanced Diagnostic & Engine Management (ADEM™). Five years of ADEM™ data were available for seven of the fourteen operators. ADEM™ data was used where it was available to determine the mission profile parameters and other methods used where it was not, as described below.

The first parameter in the mission profile, takeoff ambient temperature, is reported directly to P&W via ADEM™. The average takeoff ambient temperature by year for ADEM™-equipped operators is presented in Figure 8. As seen in Figure 8, average temperature shows very little variability year over year. This is unsurprising as the majority of the operators fly consistent routes from one year to the next year that often depart from and return to a hub city.

![Average Ambient Temperature During Takeoff](image)

**Figure 8: Average Takeoff Ambient Temperature by Operator**

The average annual temperature at the operator's primary hub was used for operators that had no ADEM™ temperature data. Temperature data was obtained from the National Aeronautics and Space Administration's Goddard Institute for Space Studies.
Surface Temperature analysis (GISTEMP)\textsuperscript{33,34}. A comparison of the ADEMTM reported temperatures averaged over all available years and the GISTEMP reported surface temperature at the station closest to the operator's hub is presented in Figure 9. There was general agreement between the ADEMTM average and the GISTEMP average for five of the seven operators' temperature data. Operator D had less than a year worth of ADEMTM data available, which may account for some of the difference. Operator E serviced numerous destinations in the Middle East where average surface temperature tend to be routinely higher than the operator's hub location. This may account for the ADEMTM average reporting higher than the GISTEMP average. Overall, the average ambient temperature at an operator's hub was found to be a suitable substitute for actual ADEMTM temperature data.

![Image: Average Temperature Data]

**Figure 9: Average ADEM vs GISTEMP Data**

\textsuperscript{33} Hansen et al., "GLOBAL SURFACE TEMPERATURE CHANGE."

\textsuperscript{34} "NASA GISS: NASA Goddard Institute for Space Studies."
ADEMTM also reports flight duration. It is assumed that each flight will have only one takeoff, so flight duration is assumed to be the hour to cycle ratio.\[^{35}\] Flight durations were aggregated by month to find monthly utilization mean and variance. For those months and operators with no ADEMTM flight duration data, another P&W database was used to obtain monthly hours flown and cycles for each engine. The database includes all months the engine is in service, which includes months where the engine is unserviceable. The records where the engine was tagged as unserviceable were filtered out. The remaining records tagged as serviceable were filtered such that only months with at least 100 hours of flight time were reported. It was assumed that months with less than 100 hours flight time were months where the engine was unserviceable for a portion of the month. This most likely resulted in little lost information as the end goal was to divide flight hours by cycles to get the hour to cycle ratio in a full month of service. Only those rare months where an engine was serviceable the entire month but flew very few hours would be lost.

The monthly flight hours were divided by the monthly cycles to determine the hour to cycle ratio for a given month. The monthly hour to cycle ratios were averaged across all available months to reduce the available data to a single hour to cycle ratio for each operator.

The final mission parameter needed for the simulation is takeoff derate. This is a percentage that represents takeoff power setting relative to maximum allowable engine power:

\[
Derate = \left(1 - \frac{Actual \ Takeoff \ Power \ Setting}{Maximum \ Allowable \ Takeoff \ Power \ Setting}\right) \times 100
\]

Thus, a derate value of 10.0 means the takeoff occurs at a power setting that is 90% of the maximum allowable. Derate is most directly influenced by the weight of the aircraft, length of available runway, and atmospheric conditions (air density, wind speed, and wind direction). These variables will determine the minimum thrust required to accelerate the aircraft to rotation speed within the available runway length. Using the minimum required takeoff power is desirable because it results in the least amount of damage to the engine. This results in longer time on wing for the engine and lower maintenance costs.

This does not mean, however, that the minimum required power setting is always used. The way that the aircraft is operated can be highly dependent on the procedures, pilot experience, and culture within a particular operator. Additionally, if the operator tends to carry full loads and fly in and out of high altitude, short runway airports, on average it would be unable to use a lower derate than an operator that flew out of low elevation

\[^{35}\] While rare, an aborted landing or missed approach would be an instance where more than one takeoff and climb out was required in a flight.
airports with lighter loads. Thus an operator's typical route structure, safety culture, and managerial oversight of engine assets are also influential to derate.

For these reasons, an average derate value for each operator was used in the simulations. Historical derate data could only be obtained from the ADEMTM database. These values are presented in Figure 10, which shows the relative year over year consistency in derate by operator. The derate value used during all takeoffs recorded in the database for an operator were averaged together to find the single derate value used in the simulation. Having no other way to obtain historical derate data for the other operators, the average of all the available operator averages was taken and used for the remaining operators.

![Average Derate During Takeoff By Operator](image)

**Figure 10: Yearly Average Derate by Operator**

### 2.3.4.1.3 Damage Grids

The damage grids are the models that use many of the simulation inputs to determine how much damage to assign to the engine during each time period. They are developed and used for specific engine models. The damage grids are proprietary to P&W and are regularly updated using actual utilization data.

### 2.3.4.1.4 Miscellaneous Shop Visit Rate
While the ICE simulation uses regression and physics based models to estimate engine interval, miscellaneous shop (MISC) visits are estimated using a historical miscellaneous shop visit rate. The factors influencing MISC rate can generally be localized to the operator, such as the quality of engine maintenance performed, bird activity at airports in a route structure, and the FOD prevention procedures in place at airports in an operators' route structure. Thus, for this study a single miscellaneous rate was calculated using records of historical MISC visits for each operator and applied to each simulation.

The individual operator MISC rate was found using P&W shop visit data and engine utilization data. P&W maintains data on when engines are inducted into overhaul shops and the work scope for the induction. Using this data set, the number of MISC visits each year for each operator was determined. Using engine utilization, the number of flight hours flown each year was also calculated. The two parameters were divided to find mean hours between MISC visits:

\[
\text{MISC Rate} = \frac{\text{Cumulative Flight Hours}}{\text{Cumulative MISC Visits}}
\]

Because a few early MISC visits tended to skew the MISC rate higher, all available shop visit and utilization data was used to find a MISC rate for each operator.

2.3.4.1.5 Full Interval Shop Visits and Time/Cycles Since Overhaul
When an engine had entered service and accumulated hours and cycles before a simulation's start date, the engine's initial conditions had to be entered into the simulation. The simulation used the number of prior full interval shop visits, flight hours (time) since overhaul (TSO), and cycles since overhaul (CSO) as input parameters to pre-age the engine. The pre-aging process used these inputs as well as the specified mission profile to assign a starting damage level to the engine.

A P&W shop visit history dataset was used to determine the cumulative number of full interval shop visits on each shop visit date. The time since new (TSN) and cycles since new (CSN) reported for each engine at the shop visit were subtracted from the TSN and CSN at the simulation start date to find TSO and CSO.

2.3.4.1.6 Shop Visit Time and Shipping Time
Shop visit time is the number of days from induction of an engine into a shop until it is shipped from the shop. Shipping time is the number of days the engine remains in transit. A prior P&W study had determined the average WWTAT for this model of engine. This value was used to determine the initial Shop Visit Time and Shipping Time.

36 Mishra et al., "Impact of Foreign Object Damage on an Aero Gas Turbine Engine."
These values were then varied to calibrate the simulation outputs to the actual lease data.

### 2.3.4.1.7 Actual Lease Demand

Sufficient data did not exist to determine actual lease demand at every time period in the ICE Method study. PWEL maintained records of the engines that were leased out and the name of the lessee, however, it did not have any data on lease requests that could not be filled. Thus, actual lease activity was used as a proxy for lease demand. A combination of engine leasing invoice records and compiled PWEL utilization records were used to determine the number of engines PWEL had on lease during each month through the study period.

PWEL estimated the number of Engine Model Alpha engines owned by third party lessors was less than 2% of the entire installed base. Thus, the PWEL lease activity was assumed to constitute the entirety of lease demand for Engine Model Alpha. The actual lease demand utilized for the ICE Method study is presented in Figure 11. The number of engines on lease has been normalized to the maximum number of engines on lease during any month of the entire study period.

![Figure 11: ICE Method Study Lease Demand for Engine Model Alpha – Two Month Moving Average](image)

#### 2.3.4.2 ICE Simulation Setup

The ICE simulations used to forecast lease demand were set up to include a fleet of PWEL engines that all operators could utilize. An operator’s aircraft were set to use the operators owned engines first. If a situation arose where an owned engine was unavailable, a PWEL engine would but used. If a PWEL engine was unavailable, the simulation automatically created an engine called a spot lease. A spot lease engine
appears when required and does not accumulate damage. It then is removed from the simulation when it is no longer needed.

The first simulation was run with a start date of January 1, Year A. Six additional simulations were then run with start dates on January 1 in Year B through Year G. The outputs of these simulations were collated and analyzed.

2.3.4.3 ICE Simulation Outputs and Analysis

ICE simulation outputs were written to a database and extracted for analysis and visualization. The number PWEL engines and spot lease engines flying in a given month were summed for each iteration the simulation ran. This resulted in a matrix of lists containing number of PWEL and spot lease engines flying defined by month and iteration.

For each date across all iterations, the mean, variance, median, mode, and 80th percentile of the number of PWEL engines, spot leases, and total leases flying was calculated. This condensed the output to single time series.

The output for each of the runs from Year A to Year G are presented in Figure 12 through 18. The 80th percentile demand is presented in these figures. This was found to most closely match the actual lease demand peaks.

![Figure 12: ICE Simulation Output – Year A Start](image-url)
Figure 13: ICE Simulation Output – Year B Start

Figure 14: ICE Simulation Output – Year C Start
Figure 15: ICE Simulation Output – Year D Start

Figure 16: ICE Simulation Output – Year E Start
It could not be confirmed if the 80th percentile would be optimal for all engine models or just this one. Ultimately, the mean and standard deviation were used for inventory planning, though viewing the 80th percentile demand facilitated visualizing and analyzing the data.

Of the seven simulations, Year B provided the most anomalous result, but also provided a key insight into how the simulation was behaving. As seen in Figure 13, demand is
shown to spike rapidly at the beginning of the simulation. During the pre-aging process, a number of ESNs were determined to require full interval shop visits before the simulation started. In reality these engines came in for visits in the months after the simulation started. Thus when the simulation began, a large number of engines were immediately sent to the shop resulting in a spike in the demand for lease engines. As this group of engines aged in the simulation, they tended to arrive at subsequent intervals around the same time, causing the recurring demand spikes throughout the simulation.

The simulation could have been updated with the actual shop visit dates that were after the simulation start date. However, the intent of this study was to develop the forecast using the information that would have been available to PWEL on the actual date that matched the start date of the simulation. On January 1 of Year B, there would be no way to know when shop visits would occur later in Year B, thus this information was not included in the simulation.

The Year A simulation contains the least amount of information about actual interval dates. Only 5% of the engines had reached their first interval on Jan 1 of Year A. The simulation output shows two distinct spikes in demand around day 3450 and 4950. Engine Model Alpha had several very large customers relative to the entire installed base. The top five operators by engines owned constituted 84% of the installed base. The largest operator owned roughly one third of all the engines delivered, yet maintained the lowest spare engine ratio of the top five operators.

In reality, an individual ESN may experience significant variation in utilization and mission profile relative to its contemporaries. In the simulation however, all engines assigned to an operator are subject to relatively homogenous inputs. Thus, it is not surprising that in the simulation a single operator’s engines that entered service around the same time also reach their intervals around the same time. This would happen in reality if it were not extremely unappealing to operators. Operators want to ensure a continuous supply of lift for their aircraft and so they actively manage their engine fleets to level load the shop visit requirements.

The operator works to minimize the number of engines in the shop at a given point in time by inducting engines early, shifting missions an engine flies, and even swapping ready spares and installed engines to spread utilization across all owned engines. This would tend to dampen the peaks in demand, spreading shop visits out over time. This behavior is reflected as the simulation’s progress and the actual shop visit dates are updated. That said, an engine will only remain on wing for so long and it is financially detrimental to remove it too early. These constraints limit the amount of balancing an operator can achieve.

The simulations make apparent that the number of exclusive use spare engines available to an operator (colloquially an operator’s spare engine ratio), can have a significant impact on demand. While an obvious statement, what is less obvious is that a single operator can drive up the lessor’s safety stock requirement based on their size
and relative under sparing. Since large operators tend to extract concessions, lease engine coverage being an option, one influential customer could cause a dramatic increase in inventory costs. Short-term lessors should keep a close eye on large, poorly spared customers entering their lease pool.

Beyond the oscillatory nature of the demand, it is evident that the simulations do not reliably predict the timing of demand. This result is not overly surprising as such predictions would require the ICE model to consistently predict specific engine removals down to the month, a feat the version used in this study was not designed to accomplish. Although by the Year G simulation, shown in Figure 18, the timing of the demand drop and recovery appears to be captured. Insufficient data was available to determine the reason for the higher sustained actual demand from day 3634 to 4730 than the simulation predicted. Information on why an engine was being leased had not been collected. It was hypothesized that the closure of an engine overhaul shop during this time may have reduced global shop capacity, necessitating more leases. It is possible that such a disturbance had cleared by day 4730 resulting in lease demand behavior to become more predictable, but further study is required to know with certainty.

The most encouraging aspect of this finding of the study was that the simulation appeared to predict peak (maximum) demand before it materialized, as shown in Figure 12, Figure 13, and Figure 14. Additionally, the magnitude of the predicted peak was in some cases very close to the actual. Reliably anticipating a peak is useful because it can discourage the reduction of lease engine inventory at a disadvantageous time. Disposing of lease engine assets could be economically wise, but it must be a well-considered decision. The expected lead time to purchase a new engine could be up to two years and there is little guarantee a suitable engine will be available for purchase in the aftermarket when needed. Thus, obtaining lease engine inventory with short notice can be unpredictable and expensive if sellers catch wind of desperation. Generally, lease coverage guarantees in LTSAs have some sort of Aircraft On Ground (AOG) protection along with them where the lessor financially compensates the covered operator for lost revenue should an AOG event exceed a certain time limit. AOG fees, sales markups, and maintenance costs to refurbish a suboptimal purchase can all quickly exceed any savings gleaned from selling an engine to reduce inventory.

### 2.3.4.4 Developing and Testing an Inventory Policy

Three factors influence the type of inventory policy that the ICE forecast supports and a lessor could reasonably implement. First, the ICE Method forecast’s demand timing prediction deficiencies and peak demand prediction consistency make the forecast a better long-term forecasting tool than near term, tactical decision enabler. Second, operators want very short lead times and high service levels from lessors; they expect it if they are under an LTSA with lease engine coverage. Third, the lead time associated with obtaining engines makes a pull strategy for the lessor untenable if the lessor is to provide a high service level. The lessor must at a minimum maintain the push-pull boundary between the lessor’s engine inventory and the operator’s demand.
The lead times involved with acquiring an engine make a pure inventory pull strategy unsuitable for short-term engine leasing.37 That is to say, an engine could not be manufactured and shipped in the 24 hours an operator generally has the patience to endure an AOG.

A push strategy, where long-term forecasting sets the size of the pool of available lease engines, is a more executable strategy given the goal of high customer satisfaction. The expense of a spare engine makes swallowing any underutilization of those assets unpleasant. However, there is a strategic tradeoff between utilization and availability. Given the deficiencies in predicting demand timing, attempting to contour inventory levels to the expected demand leaves little room to absorb a spike in demand caused by an unforeseen event. For an OEM this can have broader, negative implications regarding brand reputation and in progress sales campaigns that should most likely be avoided.

To determine the appropriate size of the lease pool, the problem was viewed from a single period, single SKU perspective using the Newsvendor Model. This model represents a situation where a single bet, in this case how many engines to have in the lease pool at the start of a given month, is placed before the time period occurs.38 In order to support a strategy that maximizes service in the face of a two year lead time to obtain a new engine and an unpredictable lead time to acquire a used one, it was assumed that orders for new engines would be placed in advance in order to have the desired number of engines, as determined by the forecast, in the lease pool by the month in question. This assumption is made all the more realistic when considering the cost of purchasing an engine. Few firms would be nonchalant about a capital expenditure request for tens of millions of dollars the month before it was required. Capital budgeting for expenditures of the magnitude required to purchase a quantity of aircraft engines would most likely need to be planned out well in advance.

The single SKU assumption was made because there is no benefit to placing multiple engine models in a single forecast. The lease demand of one model is independent of the lease demand of another model within the scope of the simulation. There may be global factors that influence two different models, such as the health of the global economy, that influences demand for one model and retirement of another, but none of the parameters modeled have this sort of interaction.

The critical fractile was calculated using the following costs: depreciation, storage fees, and AOG fees. In the case of overage, one or more engines sits idle for a time period incurring storage fees and depreciation. For underage, in the worst case the lessor will

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37 "Inventory Optimization: The Last Frontier - Inbound Logistics."

38 Cachon and Terwiesch, Matching Supply with Demand: An Introduction to Operations Management.
incur an AOG fee. Using approximate values that PWEL encounters, a critical fractile of 0.95 was calculated and applied to the inventory policy.

For each time period the mean and standard deviation of expected demand and critical fractile were used to determine the optimal inventory level. The resulting time series was then revised such that the inventory level never went down. This was performed for each simulations' outputs resulting in the curves shown in Figure 19.

The inventory policy curves are generally consistent with the exception of Year B, whose anomalous outputs were previously discussed. It was assumed that a Year B like result would prompt the end user of the forecast to investigate why the forecast was so high. The issue would be decipherable with the available information upon comparing predicted and actual shop visits. Thus, it was assumed that the Year B forecast would be ignored and a new simulation run with updated inputs or the prior forecast would continue to be used until a new forecast was run. For this study, Year B was thrown out and Year A was used in its place.

The final step was to combine the seven inventory policy curves into a single policy. This was done using the same rule that the inventory level could not go down. So for...
every time step, the maximum value across each simulation was computed. The final inventory policy plot along with the actual demand are presented in Figure 20.

![Figure 20: Recommended Inventory vs Actual Leases](image)

As expected, given the selected inventory strategy, Figure 20 shows significantly more underutilization of lease pool assets than stock outs. However, at peak demand on day 4212, there were only 15% more engines in the pool than were actually required. Given that this demand would have to be satisfied, it was inevitable that the lease pool would grow to at least 1.0, and given the shipping, inspection, and maintenance requirements for lease engines, most likely higher.

### 2.3.4.5 Conclusions from ICE Method Test Results

The ICE Method forecast proved itself capable of generating expected demand and standard deviation to such a degree that inventory planning with an annual review period could be accomplished in a manner consistent with strategic objectives. Neither the WIP method nor Shop Visit Correlation provide an estimate of variance in demand. Thus the ICE Method can more readily be used with existing inventory models to account for variation.

Forecasting by modeling the underlying dynamics of the lease market encourages a learning organizational culture. When the forecast is wrong, the model provides a way to compare the organization's assumptions to reality. When a discrepancy is found, the model can be updated to capture new learnings. Due to the number of assumptions that had to be made in creating the inputs for ICE and the variability in the airline industry itself, it is not surprising that the ICE Method did not identically reproduce reality.
Unfortunately, the necessary data to ascertain the reason for the deviations in the lease market had not been collected. However, running this test identified those missing data elements, which include: reason an engine is leased and number and date of lease requests turned down.

It is important to remember that each of these simulations were provided inputs regarding the actual numbers of aircraft and installed, spare, and lease engines owned by each operator and PWEL, to include the dates of their deliveries and retirements. There would be no way for a PWEL manager sitting in Year A to know in advance the life story of each engine, many of which had not been built yet. This is an artificiality of the study that was accepted in order to eliminate those degrees of freedom. It is vital, however, that the user of this forecasting method understand the necessity of gathering this type of data. Any information about aircraft and engine deliveries, transfers, and retirements is extremely valuable.

Data availability and integrity is crucial to making forecasting at this level of detail possible. Assembling the necessary information to create these simulations absorbed a large fraction of the time spent on the project. A streamlined data infrastructure that allows analysts to do actual analysis instead of tracking down and synthesizing data sets would increase the learning duty cycle.

The ADEM™ data that was used in this study was extremely valuable. It was unfortunate that it was not available for all the engines in the installed base. Due consideration should be given to a strategy that would enable ADEM™ to be collected from all engines in service.

3.0 Lease Engine Market Dynamics

In the process of conducting the ICE Method study, considerable insight was gained regarding the internal dynamics of the short-term engine leasing market. However, it did not answer a key question about how to plan capital expenditures to acquire lease engines for a yet to be released engine model. In order to answer this question a system dynamics (SD) model was constructed in Vensim. Due to reduced modeling complexity, the Vensim model ran much faster than the ICE Model allowing for faster cycles of learning. Appendix contains complete diagrams of the model and equations for each variable.

3.1 Key Stock and Flow Relationships in the Model

The SD model has two major stock networks that form the basis for the model. The first keeps account of the installed engines in the market. These are engines that were originally delivered to the market as engines installed on aircraft. The installed engine stock network is depicted in Figure 21. The number of engines in this stock network is limited to the number of available engine stations on aircraft in the market. The model assumes that an engine will always be in one of these stations.
The Flying stock represents the number of engine stations filled by one of the original installed engines. Engines arrive to this stock as the rate aircraft are delivered to the market and leave in proportion to the aircraft retirement rate. As these engines become unserviceable, they are replaced by either a spare engine or a lease engine. The number of engine stations being filled by each of these two options is accounted for by the Out of Service Installed Engines Replaced by an Owned Spare and Out of Service Installed Engines Replaced by Lease Pool Engine stocks.

Figure 21: Installed Engine Stock Network

The second key stock and flow network represents the lease pool. The Lease Pool stock network is depicted in Figure 22. It represents the states in which short-term lease engines exist. The Lease Pool stock represents engines that are ready and available for lease. The Leases Requested stock represents engines that will be required to fill incoming demand. The Designated for Lease stock represents lease pool engines that have been assigned to a lease customer and are waiting to ship. Collectively these three stocks represent engines still sitting in the warehouse or in transit to the lessee.
The On Lease stock represents engines that are in the lessee's possession and are being used to replace an installed engine. Once an operator’s original engine is returned, however, the lease engine cannot immediately return to the lease pool. There is a period of overlap where two engines, the installed engine and the lease engine, are collocated with an operator and both filling the need of one engine slot. This creates an inefficiency that persists until the engine is returned to the lease pool.

The Prepping to Ship stock represents those lease engines that are no longer needed by the lessee, but are still in the lessee's possession. These engines are still generating lease revenue, but are not available to fill new demand. Once the engines have been shipped, they move to the Off Lease rate where they are no longer generating revenue.

A key assumption in this stock network is that the lease engines will receive their required interval maintenance on a not to interfere basis with lease operations. It was assumed that the number of lease pool engines unavailable for maintenance would be small relative to the size of the lease pool and have a negligible impact, however, follow-on investigation of this assumption would be prudent.

The Installed Engine stock network and Lease Pool stock network are connected via two key rates: the Replaced by Lease Rate and the Replaced by Lease Return Rate. The rate at which engines in the lease pool are designated for lease and thus unavailable to fill other demand is identical to the rate that flying engines become unserviceable and replaced by lease engines. The rate at which unserviceable installed engines are repaired and return to their homes is identical to the rate at which lease engines are removed from service and begin preparing to ship.

3.1.1 Automatic Lease Pool Sizing

In order to eliminate the need to manually set the size of the lease pool, an automatic proportional controller was incorporated in the model to set the lease pool size. The initial condition of the Lease Pool stock is set by a constant in the model named Initial Lease Pool Size. The number of engines to add to the lease pool each time period is controlled by a rate called Lease Pool Growth that is modeled as a Poisson process. The average value for Lease Pool Growth is calculated using the shortage of engines in
the market as an input signal. Two additional constants are used to condition the shortage signal. The first is the Shortage Threshold. This sets the value that the shortage signal must achieve before more engines will be ordered. This value models the point at which the lessor gets nervous enough about their inventory level to buy more assets. The second constant is the Lease Engine Order Gain. This constant is used to scale the shortage signal and determine the average order size. This arrangement assumes that the lessor would have access to some portion of the monthly engine production, up to the Maximum Monthly Lease Pool Additions, which if not planned out ahead of time would likely incur some additional cost. This model then represents the lowest cost lease pool growth schedule a lessor could hope to realistically implement.

3.2 Vensim Model Operation

3.2.1 Model Stochasticity

The model is set to run stochastically by calculating various rates and values within the model using Poisson distributions. For example, the number of engine removals each month is calculated in this manner. The minimum is set to zero and the maximum set to the total number installed engine stations in service (represented by the Flying stock). The rate is the MISC rate in engines per month plus the number of flying engines divided by the average time on wing between intervals. This results in an integer number of engines to be removed each month. Some scaling is done to account for the time step at which the simulation is run, but the end result is a stochastic model that operates using whole numbers of engines without performing a discrete event simulation. This cuts down the processing time required to run each iteration. Details on how each parameter is calculated is presented in Appendix.

3.2.2 Model Calibration

After constructing the Vensim model, the various input parameters were calibrated using the outputs of an ICE Model. The intent was to verify if the simplified Vensim model captures the same dynamics as the ICE Model. The ICE outputs used for calibration were from an ICE simulation constructed for a newer engine model, henceforward referred to as engine model Bravo, which was more relevant to PWEL’s interests for this study.

The inputs and outputs for the ICE Model run for engine Model Bravo were analyzed to extract the average interval in cycles, engine deliveries in time, the average cycles per engine per month, the MISC rate, and average shop time. Shop capacity was unconstrained in the ICE Model and thus set higher than the final installed base value in the Vensim reproduction.

The spare engine ratio is not a global variable in the ICE Model. Looking at the total spares to the total engines in the ICE model is not an analog to the Vensim spare engine ratio because most spares in the ICE model are for the exclusive use of a single
operator. Thus, spare engine ratio for the Vensim model was approximated and then adjusted to calibrate the Vensim results to the ICE model results.

A comparison of the calibrated Vensim output to the ICE Model output is presented in Figure 23: Comparison of ICE Model and Vensim Model Outputs for Engine Model Bravo. The Vensim model exhibits a more rapid initial rise in demand. This is unsurprising due to the continuous functions which underpin its calculations. As soon as engines enter service in the Vensim model, they begin entering the shop. While this has some basis in reality, the ICE simulation's delayed demand response is more realistic.

Over time, the two models begin converge once growth of the installed base stops. However, without further additions to the Vensim model that captures the dynamics of the entry into service period. The ICE model takes a bottom-up approach, modeling at the engine level and aggregating lease requirements. The Vensim model takes a more global, top-down approach to estimating lease demand. In the long-term, both models converge on a similar solution. The Vensim model is not sufficiently granular to predict what will happen tomorrow in the lease market, it is however, a useful tool for understanding the long-term effects of various parameters on the overall market and how the business could be financially impacted by them. This makes it a useful tool for
understanding the short-term engine leasing business and formulating and testing strategies.

3.3 Embedded Financial Metrics

The fiscal viability of the short-term engine leasing services is of chief concern and so financial metrics are embedded in the model to provide an understanding of the profitability of the business over time and the impact of various market changes on the business. A number of relevant fiscal metrics are calculated in the model and the equations and model for each are presented in detail in Appendix.

Several metrics relevant to the operation of a short-term engine leasing business have been derived and incorporated and warrant discussion.

Utilization, in this model, refers to the ratio of lease pool engines generating revenues to the total number of engines in the lease pool. This parameter provides some insight into how much of the lease pool is being used to generate revenue. It does not indicate, however, any specific financial malady but is rather a high level look at the lease pool. One key driver of utilization is how efficiently the lease pool is employed or how much non-value added time is involved in each lease transaction. Another driver of utilization is the overall size of the lease pool. If it is larger than necessary, there will be unused engines sitting in inventory decreasing utilization.

Lease Engine Coverage Ratio is one metric that provides insight into the efficiency of the lease pool. This is equal to the total number of engines in the installed base divided by the total number of engines in the Lease Pool. It represents the number of installed engines each lease pool engine is able to provide coverage for. The higher the coverage ratio, the more efficiently the lease pool is at keeping the fleet flying. This metric penalizes a larger than necessary lease pool, but may provide a false sense of efficiency for one that is too small.

If the lease pool is too small there will be an increase in unmet demand. In reality this would mean unhappy customers, potentially lost sales, contract concessions, and in some cases where lease coverage is assured in an LTSA, fees incurred by the lessor. To account for the costs of shortages, an AOG fee has been included and is charged for each Engine × Day that one of the original installed engines has no replacement.

Finally, the time value of money should be considered when considering the timing of the very large capital expenditures required to build the lease pool. Asset Value in this model is the total cost of the engines procured for the lease pool minus depreciation. It is calculated in Day 0 dollars. Dividing the total value of assets by the number of engines in the installed base yields Asset Cost per Installed Engine. The lower this value, the more financially efficient the lease pool is at providing coverage for the installed base. Total asset value is reduced by either buying fewer assets, buying them later, or using older assets longer. All of these activities are financially efficient. Covering a larger installed base with the same value of assets is also preferable. Thus,
a shrinking numerator and growing denominator are the preferred states and correspond to low Asset Cost per Installed Engine.

3.4 System Dynamics Model Deficiencies

Both the ICE Method and the Vensim model represent a first attempt to understand a complicated engine leasing market. While they both capture some significant drivers to short-term lease demand, some known factors have been deliberately omitted in order to complete and test a first iteration of the model in a timely manner.

The economics of commercial engines are not modeled by either method. When an operator is faced with a multi-million dollar full interval shop visit bill, they begin to examine all their options carefully. The models discussed made the assumption that if an engine is required and an owned spare is unavailable, a lease engine will be used (see Figure 7). In reality, an operator could sell their depleted asset and buy a new engine. They could also buy a used engine that has a sufficient green time on a particular module that the operator needs for their unserviceable engine. The modularity of commercial aircraft engines and the high cost of each module makes using ESNs the most feasible way to model the leasing market, but does not exactly replicate reality. Early in an engine program these effects will not be as pronounced. However, as the installed base grows and the modules in different engines begin to vary greatly in remaining life, there will be more used engine and used part buying and module swapping to make serviceable engines. This will have an as yet unpredictable effect on short-term lease demand.

The version of the ICE model available for this study did not account for shop capacity. As will be shown in the sensitivity study section, shop capacity is a very influential parameter and should be watched closely.

The Vensim model places no restrictions on the use of spare engines. In reality an operator’s spare engines are for that operator’s exclusive use. Generally, operators buy some number of spare engines to support their operations, but this number can vary greatly from operator to operator. Exclusive use engines can only replace a certain subset of the installed engine population, unlike the Vensim model where spare engines are treated as interchangeable and independent of which engine enters the shop.

The Vensim model does impose the interval maintenance periods on lease pool engines. In reality these engines must also undergo shop visits. However, the utilization of lease engines has historically been difficult to forecast. If lease engine shop visits were included in the model, this would likely drive the required size of the lease pool up for all combinations of input parameters. Due to the relatively small fraction of the total number of engines the lease pool represents and the difficulty with forecasting lease pool intervals, this causal loop has been omitted. It would, however, be a valuable addition to a follow-on iteration of the model.
4.0 Sensitivity Study

A study of the various input parameters to the Vensim model was conducted to generate insight into the dynamics of the short-term engine leasing market. A set of explanatory variables were independently varied above and below baseline values to observe any changes in the response variables. The explanatory variables included: WWVTAT, Interval, Average Cycles per Engine per Month, Spare Engine Ratio, Processing Time, Ship to Lessee Time, Operator Return Delay Time, Ship From Lessee Time, and PLI Time. The response variables were Total Lease Pool Engines, Utilization, Lease Pool Coverage Ratio, Asset Cost per Installed Engine, and Total Net Income.

The baseline simulation was the engine model Bravo simulation calibrated to the ICE model outputs, discussed in 3.2.2. The simulation was run for two thousand iterations varying the Noise Seed for each iteration. Prior to running the sensitivities, three constants were derived using Vensim’s optimization routine: Initial Lease Pool Size, Shortage Threshold, and Lease Engine Order Gain.

4.1 Global Market Parameters

Four parameters exhibited a similar pattern of influence on all the response variables. These included WWVTAT, spare engine ratio, interval, and average cycles per engine per month. These parameters comprised the global explanatory variables in that they affected all engines and drove much of the dynamics related to demand.

The sensitivity of Engine Asset Value per Installed Engine is presented in Figure 24, Lease Pool Coverage Ratio in Figure 25, Utilization in Figure 26, Total Net Income in Figure 27, and Total Lease Pool Engines in Figure 28.

In general, when a global parameter changes in such a way that demand for lease engines decreases, the response variables behave as would be expected. Thus when interval increases and engines take longer to come in for overhauls, demand for lease engines declines and size of the lease pool contracts. This results in fewer assets required to supply the market, which increases the coverage ratio. Reduced demand results in decreased utilization and overall net income decreases as well.
**Figure 24: Engine Asset Value per Installed Engine Sensitivity**

**Figure 25: Lease Pool Coverage Ratio Sensitivity**
Figure 26: Utilization Sensitivity

Figure 27: Total Net Income Sensitivity
4.2 Lease Pool Operation

The remaining five explanatory variables have more localized impacts on the lease pool itself rather than global demand. The response variables were less sensitive to Processing Time, Ship to Lessee Time, Operator Return Delay, Ship From Lessee Time, and PLI Time. These variables were influential in determining how quickly a lease engine could complete the loop around the lease pool stock network.

One key tension present is the desire to make the lease pool operate efficiently and the desire to generate revenue. Figure 29 shows the response of Net Income, Utilization, and Coverage Ratio to Operator Return Delays. This is the time it takes an operator to get a leased engine shipped after their own engine has returned. During this time the lessee continues to pay to lease the engine. As the figure shows, increasing return delays result in more net income and higher utilization. However, the coverage ratio also declines indicating that a larger lease pool is required to serve the same installed base. This introduces some inventor risk in the system and inefficiencies like these should in principal be eliminated.
Looking at Figure 30, however, the system reacts differently to variations in the post lease inspection time. During this time the engine has returned to the lessor’s possession and is no longer generating revenue. This added time tends to decrease the coverage ratio in much the same way the operator return delay did. However, total net income is much more negatively affected. This is because new engines had to be purchased to cover the shortage created by the increasing delay and no additional revenue was generated during the delay.
The delays inherent in the cycle of a lease engine moving from ready spare to under lease and back to ready spare cannot be thought of in the same way. Each delay should be evaluated on two basic characteristics: whether or not the delay generates revenue and if it satisfies demand. A delay satisfies demand when it is designated to replace an out of service engine, but is not yet in operation doing so. Table 2 summarizes each delay. In general delays that either generate revenue or satisfy demand can be thought of as less financially detrimental though not desirable.

<table>
<thead>
<tr>
<th>Delay Type</th>
<th>Generate Revenue</th>
<th>Satisfy Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing Time</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Ship to Lessee Time</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Operator Return Delay</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Ship to Lessor Time</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>PLI Time</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 2: Lease Pool Delay Characterization

### 4.3 Minimum Shop Capacity

Hidden in the above sensitivities was the assumption that there would always be sufficient shop capacity to repair engines in the assumed WWVTAT. Adequate Shop Capacity is critical to the financial viability of a short-term engine leasing pool. If flow
becomes constrained through the shop, demand for lease engines will begin to rise precipitously. Shop capacity is a discontinuity in the market that should be watched closely regardless of the forecasting method.

4.4 Sensitivity Study Summary

A summary of the explanatory variables tested and their relative effect on the response variables is presented in Table 3.

<table>
<thead>
<tr>
<th>Interval</th>
<th>Cycles</th>
<th>WWAT</th>
<th>Spare Engine Ratio</th>
<th>Processing Time</th>
<th>Ship to Time</th>
<th>Operator Return Delay</th>
<th>Ship from Time</th>
<th>PLI Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asset Cost per Installed Engine</td>
<td>Strong</td>
<td>Negative</td>
<td>Strong</td>
<td>Positive</td>
<td>Strong</td>
<td>Negative</td>
<td>Neutral</td>
<td>Neutral</td>
</tr>
<tr>
<td>Utilization</td>
<td>Strong</td>
<td>Negative</td>
<td>Strong</td>
<td>Positive</td>
<td>Strong</td>
<td>Negative</td>
<td>Weak</td>
<td>Negative</td>
</tr>
<tr>
<td>Lease Pool Coverage Ratio</td>
<td>Strong</td>
<td>Positive</td>
<td>Strong</td>
<td>Negative</td>
<td>Strong</td>
<td>Positive</td>
<td>Neutral</td>
<td>Neutral</td>
</tr>
<tr>
<td>Total Net Income</td>
<td>Strong</td>
<td>Negative</td>
<td>Strong</td>
<td>Positive</td>
<td>Strong</td>
<td>Negative</td>
<td>Negative</td>
<td>Positive</td>
</tr>
<tr>
<td>Total Lease Pool Engines</td>
<td>Strong</td>
<td>Negative</td>
<td>Strong</td>
<td>Positive</td>
<td>Strong</td>
<td>Negative</td>
<td>Neutral</td>
<td>Neutral</td>
</tr>
</tbody>
</table>

Table 3: Summary of Study Explanatory Variable Effects on Study Response Variables

5.0 Lessor Strategy Proposal

So what is an engine OEM to do? They want sell engines and engine services to pay off their massive product development costs. Their customers want to keep their aircraft in the air at as small a cost as possible. In light of what has been learned here, what sort of strategy should an OEM leasing company pursue? Let us revisit the interests of the operator, the OEM lessor, the market trends, forecasting capabilities, and the internal dynamics of the lease market.

5.1 Review of Findings

Operator interests as follows:

a) Operators see value in having exclusive access to spare engines.

b) Operators want lift capability for little upfront cost and predictable recurring costs as possible.

The OEM's interests as follows:
a) The OEM needs to produce enough engines so that the market is sufficiently spared, preventing the product from developing a bad reputation and impacting sales.

b) Over producing engines is expensive and creates sales competition for the OEM.

c) The OEM wants to sell LTSAs in order to maintain revenue and repay development costs. Offering engine lease coverage is a competitive LTSA sales advantage.

General trends in the market as follows:

a) Operators have increasingly shown a willingness to enter into LTSAs.

b) Spare engine ratios for owned spare engines have been steadily declining with subsequent engine releases.

c) In general, operators have displayed increasing unwillingness to expend large amounts of capital up front for spare engines and services in favor of smaller payments over time.

Key learnings from the forecasting study include:

a) Even with a sophisticated interval estimation simulation and near perfect knowledge of engine operators, prediction accuracy of actual lease demand does not facilitate “right sizing” an engine lease pool. Right sizing meaning buying and selling engines in order to conform the lease pool to demand fluctuations, thus minimizing underutilization.

Relevant insights provided by the study of the sensitivity study include:

a) While interval, monthly cycles flown, and WWTAT are very influential in the lease market, a lessor has very little control over these factors.

b) Spare Engine Ratio demonstrates some interesting effects on the market. Increasing the spare ratio tends to increase total net income by reducing the required size of the lease pool.

c) Four of the five operational delays that lease engines experience have negative impacts on net income.

5.2 Proposed Leasing Strategy

Given these findings, the following leasing strategy is proposed. Satisfy the operator’s desire for the certainty and responsiveness that owned spare engines provide and lower capital expenditures to obtain spare engines by offering a long-term, pay by the month
lease pool product. Much like an LTSA, the operator would enter into a long-term agreement with the OEM. The operator would pay by the month for access to an exclusive use spare engine or engines. The spare engines would be stored at the operator’s facility. The lessor would retain the right to exchange the ESN that is assigned to an operator while always maintaining availability of the agreed upon number of engines. Operators would pay maintenance reserves at an agreed upon rate for the hours and cycles used. Instead of leasing engines, the lessor would effectively be leasing lift capability. This Lift Lease concept has several advantages and its own set of challenges.

5.3 Proposal Advantages

The Lift Lease concept has the advantage of meeting many interests of the involved parties. The operators get exclusive access to spare engines without large capital expenditures. The OEM lessor ensures the market is sufficiently spared while lowering inventory risk.

This strategy effectively increases the spare engine ratio by providing more exclusive use spare engines. The OEM would, however, have the advantage of flexibility to move spare engines around to extend intervals. The lessor could move engines between heavy use operators and low use operators to extend the interval of the entire lift lease pool. This would create a maintenance cost savings that operators would not be able to take advantage of if they owned their spares.

Putting more exclusive use spare engines into the market would move the lessor’s push-pull boundary closer to the customer, which would cut down on the numerous transactions, inspections, and shipments that would otherwise occur. Shipping and inspection time was shown to have negative impact on net income, so cutting transactions would provide a bottom line benefit.

This strategy would help to cut down on uncertainty by allowing operators, who have the most information, make their own decisions about how much safety stock to hold vice the lessor attempting to forecast safety stock requirements for the entire market. The amount of demand for leases would be greatly reduced once the effective spare engine ratio was increased in the market resulting in the need for a smaller lease pool.

Providing storage for unused lease engines is cost to the lessor, but operators likely have room to store a few extra engines. Operators would most likely be glad to trade room and board for immediate access to a spare engine. Recently, operators have been asking to store lease engines at their facilities as a part of their LTSA as a concession from the OEM. The lessor could greatly reduce its holding costs by distributing its inventory more broadly and closer to the customer, effectively rent free.

If the OEM lessor maintains the flexibility to move engine assets between operators, it also gives the lessor the flexibility required to ensure the promise of continuously available lift can be met.
5.4 Potential Lease Lift Challenges

Storing a lease engine at an operator’s base is a potential risk. A serviceable engine is an attractive target for aircraft mechanics in search of spare parts. A key component of the Lift Lease concept is that the engine remains serviceable at all times. The security of the lease engine asset would need to be studied in detail before this concept could be implemented.

5.5 Lease Lift Strategy Testing

The proposed Lease Lift strategy was incorporated into the Systems Dynamics model to evaluate the financial viability of such a concept. The installed engine stock network was modified to include a fourth stock: Out of Service Installed Engines Replaced by a Lease Lift Engine, shown in Figure 31. The Lease Lift engines are treated in much the same manner as spare engines, but count towards the financial performance of the lease pool.

![Figure 31: Installed Engine Stock Network with Lease Lift Concept Implemented](image)

Diagrams of the complete model with Lease Lift incorporated along with equations for each parameter are presented in Appendix.
5.5.1 Lease Lift Test Results

The Monte Carlo runs of the Vensim model were executed using various Lease Lift Ratios. The mean effects of Lease Lift Ratio on Total Net Income are presented in Figure 32.

The baseline scenario with no lease lift engines shows the lease pool project operating at a net loss initially and reaching a breakeven point around month 180. As the lease lift ratio increases, this breakeven point moves earlier. This is the result of more revenue coming in and the requirement to buy fewer engines for the on demand lease pool. As show in Figure 33, the size of the on demand lease pool is decreased by adding lease lift engines to the market. This model, however, does not make an accurate prediction of the size of the lease pool when lease lift engines are present. Some portion of the lease pool would need to be dedicated to replacing lease lift engines that require repair with the remainder of the pool covering lease demand. Regardless of the exact magnitude, the same trend would follow where fewer non-exclusive lease engines are required when lease lift engines are introduced to the market.
Figure 33: Lease Lift Ratio Effect on Total Lease Pool Engines
6.0 References

http://www.giss.nasa.gov/.


7.0 Appendix: Lease Engine Demand Model with Lease Lift

Figure 34: Lease Engine Demand Model
Figure 35: Lease Engine Demand Model Financial Metrics
Figure 36: Lease Engine Demand Model Financial Metrics Continued
Lease Engine Demand Model Equations

aNOISE SEED =
Constant
Units: Dmnl

Available for Lease Not Generating Revenue =
Lease Pool
Units: Engines

Average Cycles Per Engine Per Month =
Constant
Units: Cycles/Engine/Month

Average Monthly Deliveries =
Constant
Units: Engines

Average Monthly Lease Pool Additions =
IF THEN ELSE (Shortage Signal < Shortage Threshold, Lease Engine Order Gain * (Shortage Threshold - Shortage Signal), 0)
Units: Engines/Month

Delivery Rate =
IF THEN ELSE (Installed Base < Total Production, 1, 0) * (RANDOM POISSON (0, Max Number of Monthly Deliveries, Average Monthly Deliveries * TIME STEP, 0, 1, aNOISE SEED) / TIME STEP)
Units: Engines/Month

Designated for Lease = INTEG (Identify Engine Rate - Shipping Rate, 0)
Units: Engines

Engines Reaching Interval Rate =
Flying / Months Till Interval
Units: Engines/Month

Engines Removals =
RANDOM POISSON (0, Flying, (Engines Reaching Interval Rate + MISC Rate) * TIME STEP, 0, 1, aNOISE SEED) / TIME STEP)
Units: Engines

Engines Required =
On Lease + Pipeline Stock + Prepping to Ship
Units: Engines

Flying = INTEG (Delivery Rate + Replaced by Lease Return Rate + Replaced by Lease Lift Return Rate + Replaced by Spare Return Rate - Replaced by Lease Rate - Replaced by Lease Lift Rate - Replaced by Spares Rate, 0)
Units: Engines

Identify Engine Rate =
RANDOM POISSON (0, Leases Requested, (Leases Requested / Processing Time) * TIME STEP, 0, 1, aNOISE SEED) / TIME STEP
Units: Engines/Month

Initial Lease Pool Engines =
Constant
Units: Engines

Installed Base =
Flying + Out of Service Installed Engines Replaced by a Lease Pool Engine + Out of Service Installed Engines Replaced by an Owned Spare + Out of Service Installed Engines Replaced by a Lease Lift Engine
Units: Engines

Interval =
Constant
Units: Cycles/Engine

**Lease Engine Coverage Ratio**
IF THEN ELSE(Total Lease Pool Engines=0, 0, Installed Base/Total Lease Pool Engines)
Units: Dmnl

**Lease Engine Order Gain**
Constant
Units: DMNL

**Lease Engines Generating Revenue**
On Lease+Prepping to Ship
Units: Engines

**Lease Engines to Be Used**
min(Other Than Lease Lift Engines to Be Used, Lease Pool)
Units: Engines

**Lease Lift Engines**
INTEGER(Lease Lift Ratio*Installed Base)
Units: Engines

**Lease Lift Engines Available**
max(0, Lease Lift Engines-Out of Service Installed Engines Replaced by a Lease Lift Engine)
Units: Engines

**Lease Lift Engines to Be Used**
min(Lease Lift Engines Available, Other Than Spare Engines Required)
Units: Engines

**Lease Lift Ratio**
Constant
Units: Dmnl

**Lease Pool**
INTEG {
Lease Pool Growth+Return Rate-Replaced by Lease Rate, Initial Lease Pool Engines)
Units: Engines

**Lease Pool Growth**
RANDOM POISSON(0, Max Monthly Lease Pool Deliveries, Average Monthly Lease Pool Additions*TIME STEP, 0, 1, aNOISE SEED)/TIME STEP
Units: Engines/Month

**Lease Pool Utilization**
Lease Engines Generating Revenue/Total Lease Pool Engines
Units: Dmnl

**Leases Requested**
INTEG {
Replaced by Lease Rate-Identify Engine Rate,0)
Units: Engines

**Max Monthly Lease Pool Deliveries**
Constant
Units: Engines/Month

**Max Number of Monthly Deliveries**
Constant
Units: Engines

**MISC Rate**
Constant
Units: Engines/Month

**Months Till Interval**
Interval/Average Cycles Per Engine Per Month
Off Lease = INTEG
  Operator Prep Rate - Return Rate, 0
Units: Engines

Off Lease Rate =
  Replaced by Lease Return Rate
Units: Engines/Month

On Lease = INTEG
  Shipping Rate - Off Lease Rate, 0
Units: Engines

Operator Prep Rate =
  RANDOM POISSON(0, Prepping to Ship, (Prepping to Ship/Operator Return Delay) * TIME STEP, 0, 1, aNOISE SEED)/TIME STEP
Units: Engines/Month

Operator Return Delay =
  Constant
Units: Month

Other Than Lease Lift Engines to Be Used =
  max(0, Other Than Spare Engines Required - Lease Lift Engines Available)
Units: Engines

Other Than Spare Engines Required =
  max(0, Engines Removals - Spare Engines Available)
Units: Engines

Out of Service Installed Engines Replaced by a Lease Lift Engine = INTEG
  Replaced by Lease Lift Rate - Replaced by Lease Lift Return Rate, 0
Units: Engines

Out of Service Installed Engines Replaced by a Lease Pool Engine = INTEG
  Replaced by Lease Rate - Replaced by Lease Return Rate, 0
Units: Engines

Out of Service Installed Engines Replaced by an Owned Spare = INTEG
  Replaced by Spares Rate - Replaced by Spare Return Rate, 0
Units: Engines

Pipeline Stock =
  Designated for Lease + Leases Requested + Off Lease
Units: Engines

PLI Time =
  Constant
Units: Month

Prepping to Ship = INTEG
  Off Lease Rate - Operator Prep Rate, 0
Units: Engines

Processing Time =
  Constant
Units: Month

Ready to Lease Ratio =
  Available for Lease Not Generating Revenue / Total Lease Pool Engines
Units: Diml
Replaced by Lease Engines Returning Home =
\[ \min(\text{Shop Capacity} \times \text{TIME STEP}, \text{RANDOM POISSON}(0, \text{On Lease}, (\text{Out of Service Installed Engines Replaced by a Lease Pool Engine/WWTAT}) \times \text{TIME STEP}, 0, 1, a\text{NOISE SEED})) \]
Units: Engines

Replaced by Lease Lift Rate =
\[ \text{Lease Lift Engines to Be Used/TIME STEP} \]
Units: Engines/Month

Replaced by Lease Lift Return Rate =
\[ \text{Replaced by Lease Lift Returning Home/TIME STEP} \]
Units: Engines/Month

Replaced by Lease Lift Returning Home =
\[ \text{RANDOM POISSON}(0, \text{Out of Service Installed Engines Replaced by a Lease Lift Engine}, \min(\text{Shop Capacity}, \text{Out of Service Installed Engines Replaced by a Lease Lift Engine/WWTAT}) \times \text{TIME STEP}, 0, 1, a\text{NOISE SEED}) \]
Units: Engines

Replaced by Lease Rate =
\[ \text{Lease Engines to Be Used/TIME STEP} \]
Units: Engines/Month

Replaced by Lease Return Rate =
\[ \text{Replaced by Lease Engines Returning Home/TIME STEP} \]
Units: Engines/Month

Replaced by Spare Return Rate =
\[ \text{Replaced Spare Engines Returning Home/TIME STEP} \]
Units: Engines/Month

Replaced by Spares Rate =
\[ \text{Spare Engines to Be Used/TIME STEP} \]
Units: Engines/Month

Replaced Spare Engines Returning Home =
\[ \text{RANDOM POISSON}(0, \text{Out of Service Installed Engines Replaced by an Owned Spare}, \min(\text{Shop Capacity}, \text{Out of Service Installed Engines Replaced by an Owned Spare}/\text{WWTAT}) \times \text{TIME STEP}, 0, 1, a\text{NOISE SEED}) \]
Units: Engines

Return Rate =
\[ \text{RANDOM POISSON}(0, \text{Off Lease}, (\text{Off Lease}/(\text{PLI Time+Ship from Lessee Time})) \times \text{TIME STEP}, 0, 1, a\text{NOISE SEED})/\text{TIME STEP} \]
Units: Engines/Month

Ship from Lessee Time =
Constant
Units: Month

Ship to Lessee Time =
Constant
Units: Month

Shipping Rate =
\[ \text{RANDOM POISSON}(0, \text{Designated for Lease}, (\text{Designated for Lease}/\text{Ship to Lessee Time}) \times \text{TIME STEP}, 0, 1, a\text{NOISE SEED})/\text{TIME STEP} \]
Units: Engines/Month

Shop Capacity =
Constant
Units: Engines/Month

Shop Capacity Required =
\[ \frac{\text{(Replaced by Lease Engines Returning Home+Replaced by Lease Lift Returning Home+Replaced Spare Engines Returning Home)}}{\text{TIME STEP}} \]
Units: **undefined**
Shortage =
max(0, Other Than Lease Lift Engines to Be Used - Lease Engines to Be Used)
Units: Engines

Shortage Signal =
SMOOTH(Lease Pool - Other Than Lease Lift Engines to Be Used, 0.25)
Units: Engines

Shortage Threshold =
Constant
Units: Dmnl

Spare Engine Ratio =
Constant
Units: Dmnl

Spare Engines Available =
max(0, Total Spare Engines - Out of Service Installed Engines Replaced by an Owned Spare)
Units: Engines

Spare Engines to Be Used =
min(Engines Removals, Spare Engines Available)
Units: Engines

TIME STEP =
Constant
Units: Month

Total Lease Pool Engines =
Available for Lease Not Generating Revenue + Unavailable for Lease Replacing an Engine + Unavailable Lease Engines Not Replacing An Engine
Units: Engines

Total Production =
Constant
Units: Engines

Total Spare Engines =
INTEGER(Spare Engine Ratio * Installed Base)
Units: Engines

Unavailable for Lease Replacing an Engine =
Designated for Lease + On Lease + Leases Requested
Units: Engines

Unavailable Lease Engines Not Replacing An Engine =
Off Lease + Prepping to Ship
Units: Engines

WTAT =
Constant
Units: Month
Lease Engine Demand Model Financial Metrics Equations

AOG Cost = Constant
Units: Dollars/Month

Asset Cost Per Installed Engine =
IF THEN ELSE (Installed Base = 0, 0, Total Engine Asset Value / Installed Base)
Units: Dollars/Engines

Asset Growth Rate =
Time Step Engine Asset Change / TIME STEP
Units: Dollars/Month

Asset Turnover =
IF THEN ELSE (Total Engine Asset Value = 0, 0, Total Revenue / Total Engine Asset Value)
Units: Dmnl

Average Shipment Cost =
Constant
Units: Dollars/Engines

Change in EBIT =
Monthly Revenue Change - Change in Shipping Costs - Change in Storage Costs - Depreciation Change - Rate of Shortage Cost Accumulation - Monthly Engine Costs
Units: Dollars/Month

Change in Shipments =
Total Time Step Shipments / TIME STEP
Units: Engines/Month

Change in Shipping Costs =
Time Step Shipping Costs / TIME STEP
Units: Dollars/Month

Change in Storage Costs =
Time Step Storage Costs / TIME STEP
Units: Dollars/Month

Depreciation Change =
Time Step Depreciation Charges / TIME STEP
Units: Dollars/Month

Depreciation Time =
Constant
Units: Month

Discount Rate =
Constant
Units: Dmnl

Engines Stored =
Designated for Lease + Lease Pool + Leases Requested
Units: Engines

Financial Leverage =
IF THEN ELSE (Total Equity = 0, 0, Total Engine Asset Value / Total Equity)
Units: Dmnl

Gross Margin =
IF THEN ELSE (Total Revenue = 0, 0, Gross Profit / Total Revenue)
Units: Dmnl
Gross Profit=
Total Revenue - Total Shipping Costs - Total Storage Costs
Units: Dollars

Lease Lift Monthly Rate=
Constant
Units: Dollars/(Engines*Month)

Monthly Depreciation=
Unit Cost Per Lease Engine/Depreciation Time
Units: Dollars/(Engines*Month)

Monthly Engine Costs=
Time Step Engine Costs/TIME STEP
Units: Dollars/Engines

Monthly Lease Lift Revenue=
Time Step Lease Lift Revenue/TIME STEP
Units: Dollars/Engines

Monthly Lease Rate=
Constant
Units: Dollars/Engines

Monthly Revenue Change=
(Time Step Lease Lift Revenue + Time Step Lease Pool Revenue)/TIME STEP
Units: Dollars/Month

Monthly Storage Rate=
Constant
Units: Dollars/(Engines*Month)

Net Income Change=
Time Step Net Income
Units: Dollars/Month

On Lease = INTEG (Shipping Rate - Off Lease Rate, 0)
Units: Engines

Profit Margin=
IF THEN ELSE (Total Revenue = 0, 0, Total Net Income/Total Revenue)
Units: Dollars

Rate of Shortage Cost Accumulation=
Time Step AOG Costs/TIME STEP
Units: Dollars/Month

ROE=
Profit Margin * Asset Turnover * Financial Leverage
Units: Dollars

Tax Rate=
Constant
Units: Dollars

Time Step AOG Costs=
((AOG Cost * Shortage * TIME STEP) / (Discount Rate^Time))
Units: Dollars

Time Step Depreciation Charges=
((Total Lease Pool Engines + Lease Lift Engines) * TIME STEP * Monthly Depreciation) / (Discount Rate^Time)
Units: Dollars/Month
Time Step Engine Asset Change=
\((\text{INTEGER}(\text{Delivery Rate} \times \text{Lease Lift Ratio} \times \text{TIME STEP}) + (\text{Lease Pool Growth} \times \text{TIME STEP})) \times \text{Unit Cost Per Lease Engine}) / (\text{Discount Rate} \times \text{TIME STEP})\)
Units: Dollars/Month

Time Step Engine Costs=
\((\text{INTEGER}(\text{Delivery Rate} \times \text{Lease Lift Ratio} \times \text{TIME STEP}) + (\text{Lease Pool Growth} \times \text{TIME STEP})) \times \text{Unit Cost Per Lease Engine}) / (\text{Discount Rate} \times \text{TIME STEP})\)
Units: **undefined**

Time Step Lease Lift Revenue=
\((\text{Lease Lift Monthly Rate} \times \text{TIME STEP} \times \text{Lease Lift Engines}) / (\text{Discount Rate} \times \text{TIME STEP})\)
Units: Dollars

Time Step Lease Pool Revenue=
\((\text{On Lease} + \text{Prepping to Ship}) \times (\text{TIME STEP} \times \text{Monthly Lease Rate}) / (\text{Discount Rate} \times \text{TIME STEP})\)
Units: Dollars

Time Step Net Income=
\(\text{IF \ THEN \ ELSE}(\text{Change in EBIT} < 0, \text{Change in EBIT}, \text{Change in EBIT} \times (1 - \text{Tax Rate}))\)
Units: Dollars/Month

Time Step Shipping Costs=
\((\text{Average Shipment Cost} \times \text{Total Time Step Shipments}) / (\text{Discount Rate} \times \text{TIME STEP})\)
Units: Dollars/Month

Time Step Storage Costs=
\((\text{Monthly Storage Rate} \times \text{TIME STEP} \times \text{Engines Stored}) / (\text{Discount Rate} \times \text{TIME STEP})\)
Units: Dollars/Month

Total Depreciation = \(\text{INTEGER} (\text{Depreciation Change}, 0)\)
Units: Dollars

Total EBIT = \(\text{INTEGER} (\text{Change in EBIT}, 0)\)
Units: Dollars

Total Engines =
\(\text{Total Lease Pool Engines} + \text{Lease Lift Engines}\)
Units: Engines

Total Engine Acquisition Costs = \(\text{INTEGER} (\text{Monthly Engine Costs}, 0)\)
Units: Dollars

Total Engine Asset Value = \(\text{INTEGER} (\text{Asset Growth Rate, Initial Lease Pool Engines} \times \text{Unit Cost Per Lease Engine})\)
Units: Dollars

Total Equity =
\(\text{Total Engine Asset Value} + \text{Total Net Income}\)
Units: Dollars

Total Lease Pool Engines =
\(\text{Available for Lease Not Generating Revenue} + \text{Unavailable for Lease Replacing an Engine} + \text{Unavailable Lease Engines Not Replacing An Engine}\)
Units: Engines

Total Lease Lift Revenue = \(\text{INTEGER} (\text{Monthly Lease Lift Revenue}, 0)\)
Units: Dollars

Total Net Income = \(\text{INTEGER} (\text{Net Income Change}, 0)\)
Units: Dollars
Total Return on Assets = IF THEN ELSE(Total Engine Asset Value=0, 0, Total Net Income/Total Engine Asset Value)
Units: Dmnl

Total Revenue = INTEG (  
Monthly Revenue Change,0)  
Units: Dollars

Total Shipments = INTEG (  
Change in Shipments,0)  
Units: Engines

Total Shipping Costs = INTEG (  
Change in Shipping Costs,0)  
Units: Dollars

Total Storage Costs = INTEG (  
Change in Storage Costs,0)  
Units: Dollars

Total Time Step Shipments =  
(Return Rate+Shipping Rate)*TIME STEP  
Units: Engines/Month

Unit Cost Per Lease Engine =  
Constant  
Units: Dollars/Engines