Sustainment Analysis Methodology for Cost Models and Business Cases

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Abstract

Government infrastructure systems often require detailed sustainability analyses – parts failures, procurement, end-of-life, and economic analyses – to (1) forecast the optimum date for an acquisition to replace aging infrastructure with a New Investment, (2) conduct a cost-benefit analysis to justify further F&E investment, and (3) provide a standard sustainment cost estimate (corrective and preventative maintenance) for acquisitions. Using parametrics, research, and software algorithms, the team demonstrates an optimum approach for sustainment analysis.

1 Introduction

Many government agencies maintain large infrastructure systems and programs to meet their operational obligations to the government and the public. With limited capital and operating budgets, these agencies must make critical sustainability decisions, determining the most cost-effective and operationally efficient way to deliver services, continue uninterrupted infrastructure operations, and plan the continued viability of these operations as long as they are required. To help sustain major government infrastructure systems, measure their cost, and estimate when agencies must replace aging infrastructure, program managers, logistics analysts, and cost estimators must conduct reliable sustainability analyses and develop accurate infrastructure sustainment models that are predictive and repeatable. These models require a comprehensive understanding of infrastructure operating performance and a means of collecting the source data that would provide this assessment. They require historical data on parts' failures, inventory, procurement, end-of-life, and economic value in order to:

- Forecast the optimum date for an acquisition to replace an aging infrastructure system
- Conduct a cost-benefit analysis to weigh the best option between continued sustainment and system replacement
- Develop a comprehensive cost estimate of replacement costs and ongoing operational costs

In this study, the team defines sustainment analyses drivers, considerations, and process methodologies to help cost estimators make data-driven recommendations for the continued sustainment of government infrastructure projects and the timing of their replacement. To demonstrate the utility of these processes and methodologies, the team applies sustainment analyses best practices for major government acquisitions and capital investments to a business case for the Federal Aviation Administration (FAA). At the FAA, program offices utilize sustainment data and analyses to justify future investments. Second level engineering uses sustainment analysis to evaluate strategic sustainment options. F&E budget offices evaluate investment urgency based on legacy system, end-of-life cost estimates. In this case study, we define how and why sustainment analysis is conducted for the assessment of ongoing infrastructure evaluation, explain the steps and considerations for conducting parts and system failure analyses, inventory forecasting, and project sustainability, redefine system end-of-life, and prescribe sustainment and cost modeling methodologies, forecasts, and applications to help government agencies make critical informed investment decisions to maintain infrastructure operations.

2 What is Failure Analysis?

2.1 What Is Failure Analysis, and How Is It Used in Government Investments?

In many government agencies, large capital investments in information technology, infrastructure, and existing operations require continued sustainment for many years after the initial investment. Sustainment needs are initially calculated using estimates of (1) system and parts failures, (2) required repairs and frequency of repairs, (3) lifetime buys or continued supply of spare parts, and (4) product and analysts' projections of failures and increases of failures over a lifecycle. In these analyses, cost estimators must establish an investment timeline. The cost estimator must determine and then incorporate into a sustainability cost model the following:

- How long will the projected system last?

- What does a system failure curve of critical parts look like?
- How does an analyst estimate future parts' demand and sustainability?
- Which system parts are unique and difficult to procure on the open market?
- How many spare parts must be procured over the lifecycle?
- At what time and using which measurement criteria does the agency declare a legacy system obsolete or end-of-life?
- In what situations would the government continue to sustain aging infrastructure or determine when it should be completely replaced?
- When does the cost analyst conduct a failure analysis to decide on further system sustainment or replacement with a new procurement or government acquisition?

Failure analyses, also known as demand analyses, are conducted for government infrastructure projects and systems on an ongoing basis to validate these acquisition estimations, assess the risk of continued sustainment, and to estimate the timing of new investments to replace aging infrastructure. For many agencies, the focus on system availability, redundancy, and expansion are major considerations for failure analyses and obsolescence.

Cost estimators conduct failure analyses by:

- Collecting historical data on parts failures
- Analyzing failure trends – increased failure rates and failure rate adjustments
- Revising system obsolescence dates and estimating system end-of-life
- Adjusting estimates for risk
- And, determining when to consider system replacement

Failure analysis is the collection of historical parts' demand data, the analysis of that data to forecast future parts' demand, statistical analyses used to estimate how we anticipate failures to increase over time as older systems fail at increasing rates, and the estimate of how that demand for parts depletes existing inventory, parts sustainment, and system end-of-life.

If agencies, analysts, and program managers are provided with robust, standardized, and consistent historical failure data, failure trend analyses provide a strong basis for estimates of future sustainment and inform decision-makers of (1) which systems need replacement, (2) when replacement is required, (3) and how much continued sustainment of aging infrastructure will cost over a finite period of time.

While historical information is directional and can inform analysts about the likely obsolescence data of a system, how much continued sustainment would cost, and what might fail in the future, hardware and software systems fail at differing rates in the future than the recent past, and trend analyses cannot project the failure acceleration often encountered at the beginning of a "bathtub curve." Therefore, even with accurate historical data, adequate parts supply, and a full account of sustainment costs, failure and sustainment analyses are challenging and subject to change without warning.

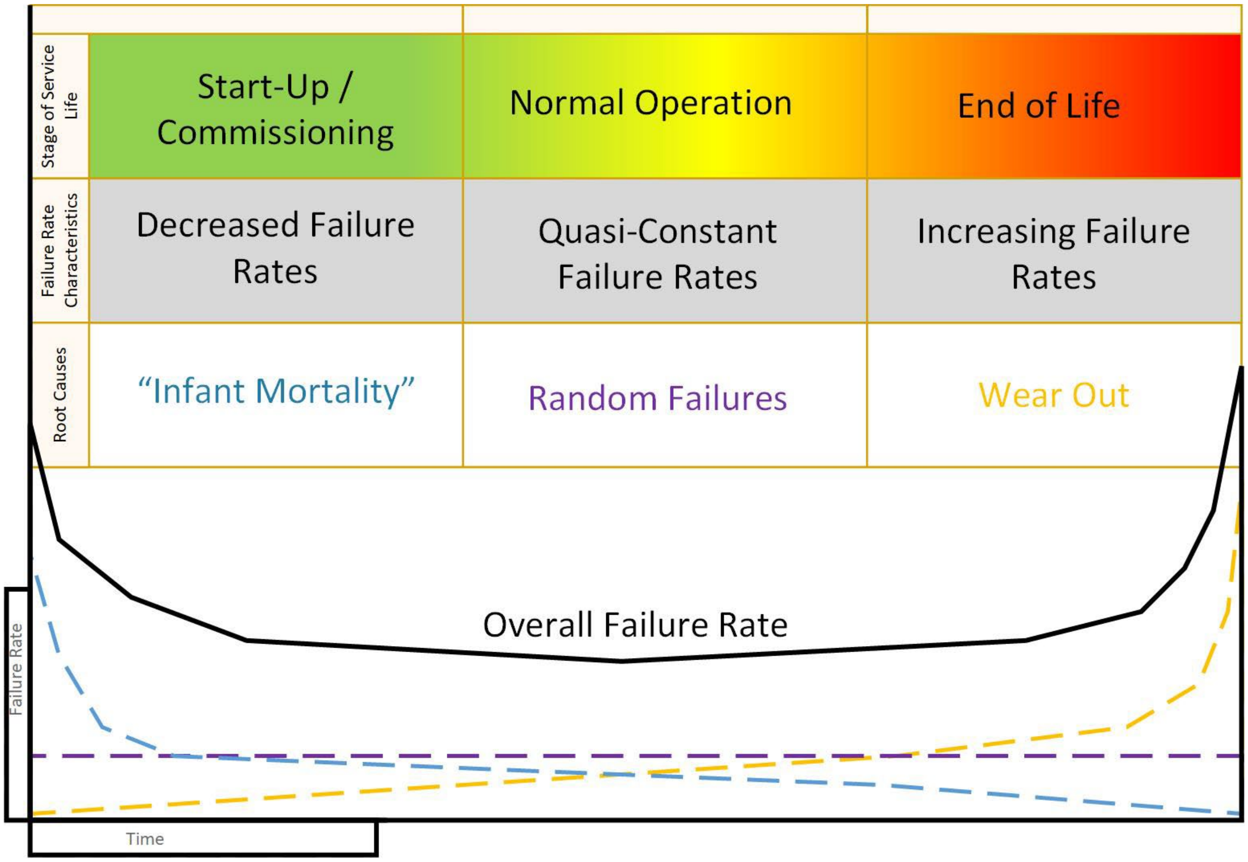


Figure 1: Supply Chain Bathtub Curve

Figure 1 depicts the "Bathtub Curve" where expected parts failure rates are constant during most of the system's intended operational life but not static. At the beginning of deployment, new parts have an abnormally high failure rate referred to as "infant mortality" where parts fail as they are just integrated into systems and are phased in. During the primary and normal operating period, parts failures level out to a more consistent and predictable rate unless some other factors of integration or configuration-specific cause a disproportionate failure rate. Toward the end of a system's intended life, failure rates increase, often exponentially as parts start failing frequently. In sustainment analysis, we try to estimate failure growth rates and the rate of increase of failure rates, especially if systems exhibit rates toward the back end of the bathtub curve.

Understanding how to interpret, process, and project failure data in sustainment analyses is critical for cost estimators, government agencies, and stakeholders to estimate infrastructure risk and make informed investment decisions.

3 Infrastructure Investment Decisions

3.1 Major Government Capital Investments

Government agencies, like the Federal Aviation Administration (FAA), develop business cases to measure the value – cost estimates and benefits quantification – for major capital investments and acquisitions. Each year, government civil agencies allocate billions of dollars to capital investments and Facilities & Equipment (F&E) spending to (1) retain and restore government infrastructure and services, (2) add new services or capabilities for an agency or for the stakeholders they serve (i.e., for the FAA, the flying public, airlines, airports, and transportation infrastructure), and (3) to improve efficiencies for the delivery of services or capabilities of an agency.

For some civil agencies, the development of these business cases for capital spending serves as a benchmark of investment decision-making. While F&E spending is usually in the billions of dollars each year, these capital amortized allocations are finite and must be carefully allocated over portfolios of programs, systems, and agency functions. Too much funding allocation to programs with new capabilities could risk infrastructure neglect or loss of service. Too large of an annual funding allocation to infrastructure programs could delay the deployment of new technologies or efficiencies. Finding that balance requires a means of evaluating business cases, and some civil agencies provide cost-benefit analysis metrics to distinguish between investments and to assign value to them.

To develop and establish robust business cases, cost estimators must develop accurate cost estimates for (1) multiple alternative implementation solutions and (2) a legacy case, which serves as a benchmark legacy system or a base case from which each alternative can be compared. The analyst must also identify, quantify, and monetize program benefits to all stakeholders. In the case of the FAA, those stakeholders would be the FAA, the flying public, airlines, airports, and other aviation companies.

For capital investment analysis and cost estimators, the legacy case development is critical for the following reasons:

(1) It serves as a basis of comparison for each alternative and measures the operational and sustainment costs of the legacy system being improved or replaced.
(2) It helps determine the required timing of the investment decision. If the legacy system cannot be sustained longer than 5 years without significant capital investment or system replacement, a solution must be identified and deployed in advance of that timeline.
(3) It sets a threshold for cost avoidance. The legacy case cost sets a maximum threshold of cost for each investment solution. To provide a more cost-effective or efficient solution, the investment solution must cost less than the legacy system in place now.

To properly estimate the cost and timing of the legacy case cost model, analysts must understand and model legacy system sustainment costs, analyze and project failures of legacy systems, and conduct trend analyses to project system end-of-life. Understanding agency supply chain constraints, failure data sources, and data constraints are critical to provide an accurate assessment of legacy sustainment and to develop accurate cost models.

3.2 Infrastructure Sustainment Decisions

Of the two major types of government capital investments – (1) infrastructure and (2) new capabilities – infrastructure investments are critical to the sustainment of existing operations, of a going concern, and for meeting the obligations of an agency to the public and its constituents. Most government agency operations whether mechanical, service, hardware, or software oriented require product replacement, technology refreshes, or another means of capital investment over time to maintain the service or operations without failure. About half of the FAA's capital investments are dedicated to maintaining, improving, or replacing existing infrastructure, and to assess the infrastructure needs, the timing of those needs, and the best spend of limited capital resources, the agency needs to be able to:

- Evaluate the condition of existing operations, services, and their components
- Determine the logistics and spare parts sourcing requirements and availability
- Conduct an inventory analysis of spare parts' sustainment
- Conduct a spare parts demand analysis to forecast part failures, failure growth, and inventory depletion that drives system end-of-life
- Evaluate the supply chain of the infrastructure sustainment operations
- Compare infrastructure investments to determine which is more urgent
- Evaluate each investment and portfolio against a constrained capital budget and determine the best time to invest in each project to minimize opportunity costs and maximize efficiency

Infrastructure investment decision-making requires a holistic view of existing operations, sustainment options, and project valuation in order to make the best decisions between mutually exclusive investments. Understanding the tradeoffs between investments is critical for agency decision-makers, and the cost estimation community are critical facilitators of these business case sustainment considerations.

3.3 Sustainment Decisions – Major Cost Estimation Considerations

For infrastructure investments, government agencies must consider five main factors to best manage existing operations and services and to prudently manage and time the need to replace existing systems and invest in new capabilities. Most civil agencies are allocated a limited annual Facilities & Equipment (F&E) capital budget from which they can allocate capital funding between infrastructure sustainment initiatives and initiatives supporting new capabilities or services. To make that determination, cost estimators need to understand what is the real need of existing operations, and until when can they be sustained using operations spending? When does it make sense to replace an aging infrastructure, and by what means can estimators make that determination?

The FAA constantly analyzes the tradeoffs between infrastructure sustainment needs and those of new capabilities in the National Airspace (NAS). System availability and redundancy is critical to the FAA to continuously maintain operations without loss of service, and, often, the safety of the flying public depends on that continuous infrastructure sustainment. That doesn't mean that the agency must not weigh tradeoffs between different capital investments. The balance between safety and fiduciary responsibility remains with the FAA decision councils, each organizational department, and the finance organizations that evaluate new business cases.

To evaluate the needs of existing infrastructure and determine the best timing of infrastructure capital investments, the agency must measure sustainment needs and establish a balance between the five factors of infrastructure decision-making:

1) **Cost to Sustain** – What is the cost of sustaining operations with existing operational expenses versus replacing aging infrastructure in the NAS? This is a trade-off between continued and increasing sustainment costs or capital costs of a replacement system.
2) **Ability to Sustain** – At what point will continuing existing operations risk loss of service, or at what point will sustainment without significant investment no longer be feasible?

3) **Timing of Replacement** – When is the best time to invest new capital to replace existing infrastructure? How long can the system be maintained before replacement?
4) **Sustainment Methods to Extend System Useful Life** – This includes analyzing parts failures for cause and replacing problem components, making lifetime buys of high-risk parts, and cannibalizing parts from other systems to extend the useful life of a system and delay system replacement.
5) **Cost/Benefit Analysis** – When do the costs of continued sustainment with an increase in parts failure or loss of service risk outweigh the cost of replacement? How do we justify capital investment in infrastructure?

3.3.1 Cost to Sustain

The first step in analyzing existing agency infrastructure and sustainment as cost estimators is to collect operational data and estimate the cost of existing operations. To calculate the operational cost of existing infrastructure, cost estimators must collect and estimate the costs to operate a service or technology, the labor required to operate the system with current procedures in place, the cost of system failures and repairs to the agency and stakeholders, the supply of parts to maintain the system, and recurring training on the system. To forecast this sustainment cost, estimators must collect all of this historical data, determine and analyze the data for trends, and forecast the continued sustainment needs of the program or service. This forecast includes anticipated and observed continued increases in failures of aging parts, software, and hardware, the cost to procure, supply, or maintain inventory of system spares or replacement parts to maintain the service, and an estimate of at what point the system becomes outdated, parts can no longer be procured, or software systems can no longer continue (loss of 3rd party support, etc.).

Data for Cost Sustainment

These cost analyses require historical data and the ability to forecast failures and sustainment needs in the future, both of which may not be available, depending on the agency's data collection and processes. Historical parts demand data is used to estimate the cost to sustain government infrastructure systems.

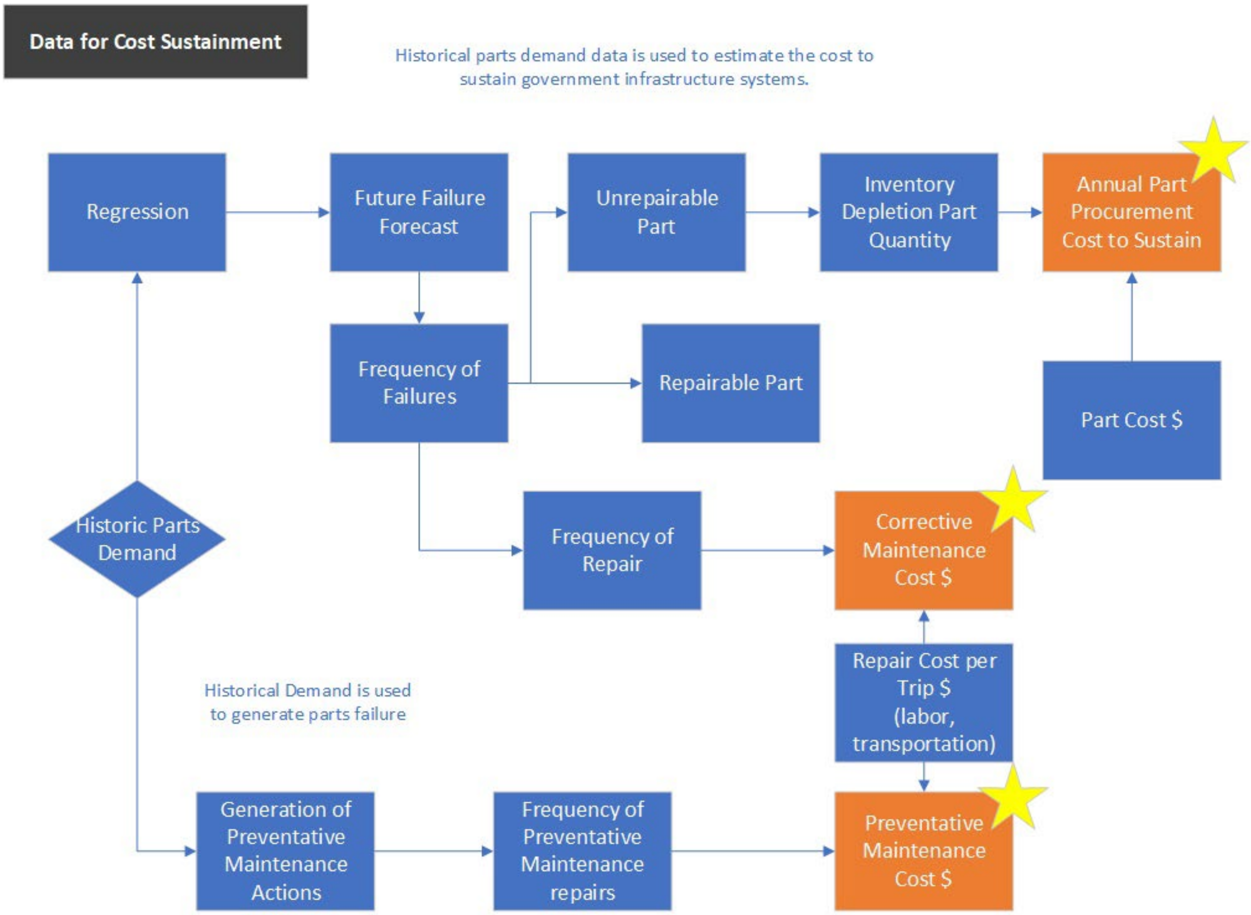


Figure 2: Historical Demand Data Used to Estimate Sustainment Costs

Historical demand is used to generate parts failure forecasts using regression analysis, providing the quality of annual parts failures. Parts failure frequency drives parts procurement costs and the cost of corrective maintenance repairs. Historical demand can also be used to generate preventative maintenance, scheduling parts replacement instead of waiting for them to break.

For safety and flight operations systems at the FAA, corrective maintenance actions cause flight interruptions, often costing millions of dollars to flight operators and passengers. Preventative maintenance repairs, since they can be scheduled when there are fewer flights, have a much smaller cost impact.

Sustainment costs can be complex, but by setting up scalable sustainment models, cost estimators can conduct effective cost-benefit analyses agencies can use to make data-driven decisions.

3.3.2 Ability to Sustain – Obsolescence

The second major factor in infrastructure investment decision making, is determining the ability to sustain an existing system or service. Obsolescence can be defined as simply as when a technology or service can no longer be supported or when a software system needs replacement. For the FAA, the most definitive estimation of obsolescence is the point at which the agency can no-longer sustain the system without risking loss of service.

The FAA has a mix of services, software, and hardware systems with varying baselines, replacement schedules, and customization. Obsolescence for the FAA is more complicated than following a replacement schedule, and the agency uses a cost/benefit analysis to determine and justify F&E investments for both new capabilities and infrastructure investments. In other words, in many cases to justify infrastructure replacement, cost estimators and analysts must justify the need of replacement and estimate system obsolescence.

To estimate obsolescence an analyst will holistically examine the critical parts of the existing system, the historical cost and means of replacing parts, performing corrective and preventative maintenance, and carrying parts' inventory, and an estimated date when the system can no longer be physically maintained by operations expenses alone. At the point of obsolescence, the system will require a significant capital investment to maintain existing operations.

Sometimes, the agency will design custom systems to fit a need, and after the initial procurement, these systems will contain customized parts which can no longer be procured in the market. Once the agency depletes its inventory of customized parts, creative sustainment efforts, like cannibalizing like parts from other decommissioned systems, making lifetime buys of critical parts to keep in inventory, and the remanufacture of customized parts can only sustain systems for so long, and obsolescence would be inevitable. In such a case, obsolescence would be defined as that date at which the system runs out of inventory and risks loss of service or the point at which continuous operations depend on system redundancy or backup systems.

3.3.3 Timing of Replacement

Agency decision-makers, cost estimators, program offices, and finance organizations, like the FAA's Investment Planning & Analysis (IP&A), use historical data, trend analyses, and forecasting to estimate a system's end-of-life and when legacy systems should be replaced. Using forecasts of parts demand, analysts can estimate system end-of-life (EOL) and for how long a legacy infrastructure system can e sustained. In other cases where replacement system investment timelines are established, the sustainment time horizon is extended to align with the new investment plans.

These organizational departments, stakeholders, and analysts might recommend a Technology Refresh capital investment, where a like system that is new with the same functionality replaces the old legacy system. They might also recommend a new capital investment with augmented capabilities. Not only does the replacement system include the same functions and capabilities as the legacy system, but it also includes improved capabilities to make the system more cost efficient, functionally superior, or inclusive of new processes or features not available at the time of the legacy procurement.

Timing Matters

In both cases, the agency's objective is not to procure a replacement system prior to its need. With a finite annual capital budget and dozens of potential investments that benefit the agency, stakeholders, and the public, civil agencies must decide between the funding of mutually exclusive investments each year, or they might delay one capital investment for a more urgent one. Establishing and accurately and objectively defining that urgency is critical for the agency to make prudent decisions and to maximize the benefit of future investments. Mistiming infrastructure replacement capital investments can have devastating consequences to both an agency's mission and to capital investment portfolios:

- **Investing Too Early** – If an agency procures a replacement system before the end-of-life of the legacy system, the premature investment might come at the expense of investments with new capabilities or may delay new services that improve the lives and way of life of the public. With limited annual capital budgets, the agency must decide in which investments it must invest and which ones can wait. Premature legacy replacement system investments can have major impacts on investment portfolios. In addition, if a legacy system is replaced before it draws down existing spares inventory or is replaced by a new system more costly to maintain, the investment will negatively impact operational budgets as well.
- **Investing Too Late** – If an agency delays procurement of a replacement system that is needed, it risks waiting too long to replace legacy infrastructure. The consequence could be a costly loss of service or a less effective system until eventually replaced.

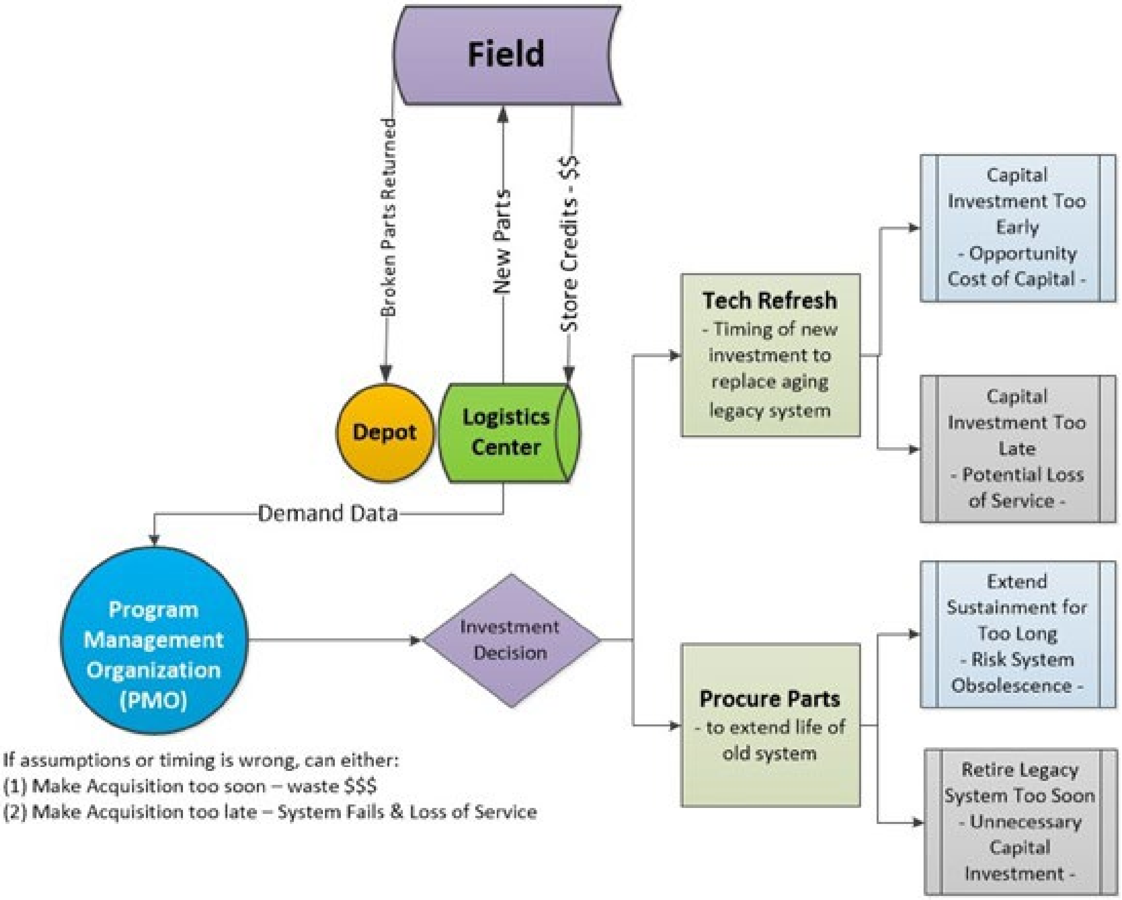


Figure 3: Investment Decision Timing

Program offices, agency decision councils, finance organizations (like IP&A), and cost estimators all play crucial roles in determining the right time to replace legacy infrastructure systems and services. Sustainment analysis and end-of-life forecasting accuracy helps agencies decide when to replace legacy infrastructure, and model accuracy can have large consequences on system operations and F&E budget allocations. The more accurately agencies can determine the optimum timing of replacement investments, the better they can preserve and allocate limited capital budgets.

3.3.4 Other Sustainment Options

In addition to analyzing the cost and ability to sustain infrastructure systems and to measuring the optimum timing of investing in infrastructure replacement systems, agencies also analyze and determine other means by which they can sustain legacy systems longer.

Identifying Causality & Targeted Corrections

By utilizing parts demand data, failure frequency, component risks, and calculating metrics like Mean Time Between Failure (MTBF), agencies and logistics organizations can identify causality of parts failures and address recurring parts issues that might be causing a disproportionate quantity of system failures and adverse outcomes. While many system failures are attributed to system age and normally anticipated failure quantities, certain configurations of systems, environmental conditions, parts manufacturing quality, and other part-specific failures can be diagnosed and corrected. In these cases, addressing the causality of failures could extend the life of a legacy infrastructure system and postpone a full system replacement.

Lifetime Buys

For high-risk parts that drive system obsolescence – (1) abnormally high failure rates, (2) robust failure growth rates (back-end of a bathtub curve), (3) high scrap rates, or (4) any combination of these, if the agency can still procure replacement parts, it could consider making a lifetime buy of these parts by making a capital or operations-funded large quantity purchase of replacement parts to extend the life of the legacy system until it is replaced.

Parts Cannibalization

In addition to replacing problem parts and initiating lifetime buys, agencies can potentially source replacement parts which are no longer manufactured by cannibalizing parts from other similar decommissioned systems. In information technology hardware, the government often decommissions aging hardware systems in large quantities, and instead of expensing these component parts, sometimes the government can reuse these parts in other systems operating on the same hardware systems which are no longer manufactured. By cannibalizing parts from other decommissioned systems, agencies can augment spares inventory and extend the life of legacy infrastructure systems at a low component cost. This strategy does present significant risks, however, as cannibalized parts are usually just as old or older than systems for which they are supplementing scarce inventory. Failure rates of these parts are usually high at end-of-life, and cannibalization alone is not a long-term strategic solution.

3.3.5 Cost/Benefit Analysis of Replacement Versus Sustainment

One means by which civil agencies like the FAA evaluate the need and timing of infrastructure replacement capital investments is by developing a business case for each investment and conducting a cost/benefit analysis, where both costs and benefits in present value (discounted by the agency's cost of capital) are quantified, monetized, and measured by specific finance metrics. Program offices and finance organizations employ cost estimators and operations research analysts to accurately cost capital investments and calculate the benefits to the agency, 3rd party stakeholders, and the public. If the cost savings and altruistic benefits outweigh the capital costs of the new investment or replacement system, the investment is worthwhile.

Similarly, cost estimators can conduct sensitivity analyses centered around the timing of system replacement. What are the trade-offs between project delay and start? The cost analyst must estimate the increasing annual costs associated with corrective maintenance, preventative maintenance, and parts procurement required for legacy system sustainment and compare these costs to the annual sustainment costs and capital investment costs of a new investment. Cost estimators develop a business case lifecycle by which to compare legacy costs to those of a new investment, usually monetizing costs over a 10-20-year lifecycle. By measuring the net present value (NPV) and timing of each alternative investment, estimators can objectively decide the right time to invest and the path for sustainment.

3.4 Data-Driven Business Case Analysis

To conduct objective business case analyses and determine both in which business cases to invest and in which year to invest, cost estimators and analysts must collect historical data, conduct trend analyses based on the data collected, improve the fidelity of that data where possible, and make forecasts for systems’ end-of-life estimates to establish urgency. Infrastructure replacement investments can take precedence over new capabilities if those investments sustain a critical service or capability upon which many stakeholders depend.

Cost estimators and business case analysts must document their assumptions and justify investment recommendations. At the FAA, program offices present business cases to the Joint Resources Council (JRC) for multiple investment decision points, deciding between solution alternatives and requesting F&E funding for specific years of funding. The selected solutions and timing of those investments are completely dependent on the data analysis to support the recommendation.

For FAA infrastructure replacement investments, to estimate legacy system end-of-life and obsolescence, which heavily influence the timing of the replacement system, cost estimators collect historical inventory records, failure records, and spare parts demand for each critical system component. When parts failed, how frequently they fail, the rate of increase by which they fail are all essential factors for consideration and obsolescence forecasts. If any of that data is difficult to collect, is inaccurate, or contains “noise,” it could misinform investment decision-makers and risk the same pitfalls of mistimed infrastructure replacement investments described earlier.

3.5 Non-Standardized Data

To develop accurate business cases and analyses for legacy system sustainment and obsolescence government agencies require the collection of relevant data, the recording of that data at the right times, and the sharing of that data, so it is accessible for analysts and decision-makers. In the case of legacy case sustainment at the FAA, to determine a system’s true end-of-life and obsolescence forecast based on projections from historical inventory and parts failures, the agency must record and establish:

- Spares inventory to establish supply
- Parts failures to estimate demand
- Accessibility of parts procurement and restock
- And trend analyses to forecast future supply and demand

If any of these data sources is compromised or clouded by noise of irrelevant data, forecasts could be compromised, and decision makers would be challenged in their investment planning and the timing of those investments. If analysts do not have the data to make objective decisions, they cannot prioritize or distinguish urgency between investments.

Currently, at the point of data collection, the FAA does not collect standardized failure data at the time of failure, and the Logistics Center estimates demand by parts orders after the failure for field inventory replacement. If broken parts are returned weeks or months after the failure occurs, the Logistics Center cannot accurately measure and forecast parts' demand. Sustainment analyses would be more accurate if the parts data were collected at the time of failure.

Incomplete data sets are a challenge for all cost estimators analyzing and prioritizing capital investments. Without understanding the source and accuracy of data sets, estimators may not even realize the data gaps and may overconfidently make recommendations to decision councils.

4 Sustainment Cost Considerations

Cost estimates for government investments and acquisitions rely upon historical data collected and parametric data from other business cases to forecast cost. This data-driven methodology is applicable to a variety of investments – IT investments for software and hardware components, building construction estimates, major manufacturing, services and capabilities, and in this paper's use case – infrastructure replacement projects.

4.1 Cost Estimates – New Capabilities or Sustainment

For new capabilities, cost estimators develop project cost estimates based on multiple assumptions by a work breakdown structure (WBS) for Facilities & Equipment (F&E) capital funding, and they collect historical data from other business cases, from standard historical assumptions from cost databases, from complex models which retain thousands of historical standard costs, and from research in industry, government, and other bases of estimates. These new capabilities, whether a new service the agency is developing for its own improved operational efficiency or to provide a service to the public, are not necessarily replacing an existing legacy system and providing more robust capabilities. Sometimes, they are designed to simply replace a legacy system, and in those cases, estimators develop a legacy case cost estimate as well as a baseline of comparison.

For projects which are designed as a one-for-one replacement of a government legacy system or service, infrastructure system, or ongoing operational going concern, estimators develop legacy cost estimates and model the end-of-life and sustainment requirements of the legacy system.

1) **Estimating End-of-Life** – By estimating the system end-of-life, cost estimators can determine how long an existing system can be sustained until it runs out of spare parts or when spare parts can no longer be procured. End-of-life should correlate with a potential loss of service where at least some stakeholders or customers can be impacted. In the case of the FAA, end-of-life can indicate a potential loss of service for the flying public.
2) **Sustainment** – Cost estimators can also measure and estimate the cost to continue to sustain the legacy system over a period of time. Usually this is measured over a project lifecycle, a predetermined time for which the program office compares the legacy case sustainment efforts to the anticipated life of a new procurement replacement system. The cost to sustain the legacy

system over the life of the project is used as a baseline of comparison for the new procurement business case. Sometimes, the legacy system cannot be sustained over the project lifecycle without significant capital investment.

3) **Cost Avoidance** – Estimating the cost of the legacy case allows cost estimators to have a baseline of comparison to the replacement system procurement. When building a business case for this legacy replacement project, the program office and cost estimator can claim that the cost to sustain the legacy system over the same time period would be the “avoided cost” of the new system. This “avoided cost” would be a quantifiable benefit for the capital investment business case. Usually to justify the new procurement, the sustainment cost of the new system over the project lifecycle would be significantly less than the sustainment cost of the legacy system.

For infrastructure replacement projects and business cases, legacy sustainment estimates and lifecycle comparisons between the new capital investment (replacing the old) and the legacy case are critical to demonstrate agency need and often to justify funding for a project. Agencies also try to determine when funding for infrastructure replacement projects is required. If a legacy system can continue to be sustained for another five years without introducing a very significant sustainment cost increase over a system replacement, the agency may wait to fund the replacement project until a timeline that best meets that need.

4.1.1 Hardware Systems

In government capital investments with significant amounts of hardware, analysts develop cost estimates for new procurements replacing existing hardware based on (1) in-house hardware procurements using market rates or the cost associated with customized hardware configurations and (2) hardware procurement estimates and lifetime spares buys estimated by competitive vendor bids during source selection. For the legacy case sustainment, analysts develop hardware cost estimates based on the procurement of replacement spares and for the maintenance costs of systems as they experience failures in the field. These operational costs in the legacy case are then compared to the hardware procurement costs in the replacement capital investment.

All these data points are critical pieces in business case estimates:

- Vendor-provided hardware procurement costs
- Market rates for bulk-buy government hardware procurements
- Contractual cost of procuring or replacing spare parts and spare systems
- Carrying cost of inventory
- Maintenance costs (operational maintenance, government salaries, travel costs, logistics)

4.1.2 Software Systems

In government capital investments with significant amounts of software, analysts develop cost estimates for new procurements by estimating the amount of code required or an estimate of function points based on well-documented system operational requirements. These parameters are often collected in a software estimating tool or system with significant historical references to prior software estimates as a guide for complexity, level of effort, and common parameters, like a two-way interface for data exchange. When considering the replacement of existing legacy software systems, estimators must consider the possibility and the degree for which software code can be reused to offset coding costs.

Future software sustainment costs can be estimated using a historical collection of software expenses, maintenance, and sustainment costs, and any documentation of future anticipated software system integration of capabilities can be documented to estimate these future coding costs.

4.1.3 Historical Failures

To estimate sustainment costs for hardware systems, cost estimators must collect a significant sample size of data regarding historical parts and system failures, the cause of those failures, and the current and projected inventory of the spare parts in stock. By analyzing the failures over time, estimators can develop "demand forecasts" for parts and establish anticipated future failure trends to estimate future demand. By projecting future demand, cost estimators can then estimate the quantity required for the program office or sustainment office to procure over the project's estimated life cycle. Multiplying volume by price for each year of demand, cost estimators can develop a cost projection for each year for the procurement of replacement parts and the associated labor for maintenance.

4.1.4 Cost to Sustain

When estimating the required cost to sustain a legacy system, cost estimators develop a complete forecast of sustainment costs over the business case lifecycle for the following:

- Historical parts failures
- Annual inventory hardware procurement costs
- Hardware re-manufacture for parts unable to procure
- Technology refreshes (F&E Investment)
- Software code development for new interfaces
- Software code development for new requirements
- Software patches and upgrades (Tech Refreshes)

They then extrapolate those costs using trend analyses from historical data, anticipated future changes, patches, and interfaces, and by defining and forecasting any required procurements or sustainment efforts to keep the legacy system operational over the defined business case life cycle.

Legacy sustainment costs over a business case lifecycle are then used as a baseline of comparison to investment alternatives – new system procurement, full system technology refreshes, or in-house redevelopment. The legacy system sustainment costs are used as a basis of financial metrics valuation compared to other alternatives and the basis for legacy system cost avoidance.

4.1.5 Cost Avoidance – New System Vs. Legacy Sustainment Cost

Usually, the operational costs of the new system are less than those of the legacy system. When comparing each alternative to the legacy system, operational cost savings compared to legacy are calculated as "avoided cost benefits" of the new procurement and part of the business case finance metrics. In the economic analysis, analysts calculate the Net Present Value (NPV) of each alternative, which requires calculating the present value of program benefits and comparing them to the present value of costs. While each alternative should have operational benefits from greater efficiencies, productivity, and new capabilities for the government agency, the public, and all stakeholders, the operational cost avoidance versus the legacy system over the full lifecycle is usually the largest single system benefit. Therefore, properly estimating the lifecycle costs of both legacy systems and alternatives (procurements, new development, or technology refreshes) is critical to develop a business case that convinces agency decision makers that the project is valuable and should be funded.

When evaluating capital investment projects replacing legacy systems, accurately assessing the timing of program benefits from procurement or replacement is critical for decision makers as well. With limited agency capital to fund new investments, if a legacy system can be sustained for a few more years without risk of failure, government investment boards might choose to delay a replacement procurement to instead fund more urgent near-term investments.

4.2 Legacy System Cost Driven by Parts/System Failures

While historical data and forecasted projections drive investment decisions for both new investments and infrastructure replacement systems, legacy cost estimates for existing infrastructure systems depend on the accuracy of historical data and failure analyses more than any other type of estimate. The estimate for the sustainment of legacy systems is the most critical deciding factor for:

- Determining the value of a replacement procurement
- Calculating the sustainment cost of legacy operations
- Calculating operational end-of-life and potential loss of service
- Estimating the urgency of the investment and the optimum time for replacement
- Determining the best method for operational sustainment – lowest cost, greatest functionality, and lowest risk of loss of service
- Optimizing the effectiveness and distribution of agency capital budget allocations

Estimating when legacy systems require replacement factors into government investment panels decisions about capital allocation. If infrastructure replacement is critical, capital funds will often be allocated to infrastructure needs at the expense of projects with new capabilities. If these investments are funded prematurely, new agency capabilities will be delayed.

5 Sustainability Analysis for Government Programs and Business Cases

5.1 Objectives

Cost estimators and program analysts conduct sustainment analyses for program managers and stakeholders to make future decisions about agency capabilities, systems, and investments. In agencies which keep infrastructure systems for years and even decades beyond their intended life, sustainability analysis plays an important role informing management and helping them make data-driven decisions:

- **End-of-Life** – How long a program can be sustained until it reaches end-of-life, runs out of parts to continue operations, can only operate on a reduced capacity, suffers loss of service, or must be decommissioned?
- **When to Invest** – Program managers and agency leadership want to optimize the timing of new investments that replace aging legacy systems. If the agency spends capital dollars to replace a system too soon, those limited capital expenditure dollars would be spent unnecessarily on one project and at the expense of another with significant opportunity costs. If the agency replaces a system too late, the outcome could be costly system failures and loss of service. For an agency like the FAA, that could have safety consequences.

- **Investment Trade-offs and Justification** – Many agencies, like the FAA, require cost-benefit analyses to justify that an investment is “worth” the investment capital. Sustainment analysis helps agencies justify new investments that replace aging existing software and hardware systems.
- **Means of Evaluation** – Sustainment models and analyses provide agency councils and decision-makers with a repeatable and objective process by which they can make confident legacy sustainment and capital investment decisions that position the government agency for the best possible outcome. Many agencies have limited investment capital each year, and they must make the best use of that capital as a service to the public and their constituents.

5.1.1 Estimate End-of-Life of System

When the government invests in major infrastructure projects, it defines the intended project lifecycle for which it would sustain the system with operations dollars, conducting routine preventative maintenance, corrective maintenance for unplanned parts failures, and second level engineering design and other activities to sustain the system. The agency procures a lifetime inventory of spares or plans capital dollars for sufficient sparing over the lifecycle of the system.

Agencies sometimes operate legacy systems longer than their intended life. In some cases, they continue operating systems five, 10, or even 20 years beyond their intended life. Logistics teams, program offices, and agency stakeholders find it difficult to sustain the operations of these systems with increasing failures of parts, difficulty sourcing components to repair parts or systems, inability to procure parts which are no longer manufactured, and near full depletion of original spares inventory. In some cases, as old technology combines with newer technology systems, legacy systems experience compatibility issues and become the bottleneck for operations.

Given these sustainment challenges and operability issues with critical legacy systems, government agencies need to be able to forecast actual end-of-life and have a means of deciding by when they must replace a system, how they decide between new builds and sustainment, the consequences of parts failures and issues, and the risks of loss of service. End-of-Life Forecasting is a means of estimating when a system can no longer be sustained, when the risk of loss of service outweighs that of the cost of a new investment, and for how long a system can continue to operate.

Most of an end-of-life forecast focuses on the sustainment and supply of system parts, the need to make repairs, and the ability to make repairs. To estimate end-of-life, government agencies need to collect and analyze data from supply and demand factors. Not all information critical for end-of-life analyses has a data source or might be collected. The primary factors considered in EOL analyses are the following:

- **Failure rates** – How often a part fails and the system as a result requires repair
- **Failure growth rates** – How much more frequently are parts failing than they were previously and how much worse parts failures will continue to get
- **Scrap rate** – Some parts are repairable and are recycled back into the supply. Some percentage of these repairable parts reach “beyond economic repair” (BER), and that percentage represents parts which are scrapped.
- **Inventory** – There is an existing inventory for a starting point of supply and an ongoing inventory which is maintained and represents which parts remain after parts fail and are scrapped.

- **Procurement** – This represents the availability of parts to procure. As systems age, the spare parts to operate those systems may no longer be manufactured and may not be available for procurement to rebuild inventory levels. This accelerates system end-of-life.
- **Substitution** – Some systems can utilize a variety of parts, so when one part can no longer be sourced, another one can be substituted for it instead. However, government agencies often have unique parts or have a high threshold of testing for compatibility and fit before a substitute can be chosen and enter a system architecture.

5.1.2 Make Investment Timing Decision to Replace Aging EOL Legacy Infrastructure System

When conducting end-of-life forecasting, analysts collect these data sources and build a sustainability model to estimate when a system can no longer be sustained – when parts can no longer be repaired, sourced, or supplemented which are needed for continued operations. Backing up from that risk-adjusted date of no longer being able to sustain, the program office will plan a replacement investment or acquisition with enough time for system design, development, and implementation before the legacy system loses service. This is important for agencies like the FAA in which critical surveillance, communications, automation, navigation, and safety systems assure continuous operations for Air Traffic Control and commercial flights across the U.S.

If the analyst forecasting end-of-life and a risk-adjusted timeline for potential loss of service misinterprets data, has an incomplete data set which adversely impacts the predictability of the forecast, or does not properly account for potential failure growth a difficult to predict bathtub curve exponential failure rate, the timing of replacement investments would be impacted, and the agency would suffer inevitable consequences.

Using its current supply chain infrastructure, the FAA does not have a direct source for spare parts demand, and it substitutes this data that is not directly collected at the time of failure with parts orders, which approximate parts failures. Over time, this demand profile reconciles, but the timing of parts failures and parts orders can be significantly different if a field location chooses to wait to order replacement parts until a larger quantity of spares inventory is depleted. The sustainment analyst must realize challenges in the data to account for data discrepancies and to interpret historical data correctly. Demand accuracy can impact the timing of end-of-life forecasts and subsequent investment decisions.

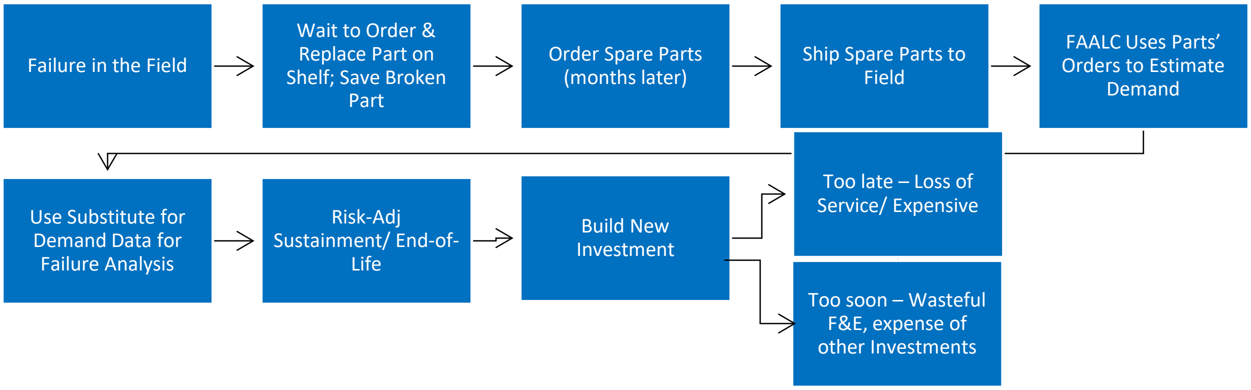


Figure 4: Investment Decision Accuracy & Consequences

The accuracy of end-of-life and sustainability forecasting matters and has a huge impact on agency capital deployed, continued operations of existing infrastructure, and the funding allocation for mutually exclusive capital expenditures that agencies must select for project funding in any given year.

Too Soon – If an analyst forecasts the need for capital funding to replace a legacy infrastructure system too soon, the project may be funded with F&E capital dollars at the expense of other competing capital programs which may be delayed because they did not receive requested project funding. If the EOL forecast were more precise, the project could have potentially waited another fiscal year or more for capital funding to replace the aging system, and the system could have continued to operate without an acquisition.

Too Late – On the opposite end of decision accuracy, if an analyst's EOL forecast recommends replacing a legacy system too late, the current infrastructure system could fail to operate or lose service prior to its replacement. At the FAA, this scenario could result in flight safety hazards or significant decreases in airport and air traffic capacity, causing more flight delays, cancellations, and diversions until the radar system, navigation system (like a glide slope), or communications system is replaced or restored. In these scenarios, the agency might reprioritize system availability by the level of air traffic a facility manages to reduce the impact.

Developing an accurate sustainability model that can forecast end-of-life, alert stakeholders and management of critical risks while there is time for risk mitigation or correction, and accounts for different levels of quality of data or data gaps is important for capital decision-making and the sustainment of government system operations.

5.1.3 Justify and Estimate Cost of Investment Decision to Replace Legacy Infrastructure

Using historical failure data to project both failure rates, failure growth rates, and future parts demand, cost estimators and sustainment analysts can forecast inventory depletion and complete inventory exhaustion of spare parts. For parts which cannot be replaced, substituted, or procured, this often defines system end-of-life (EOL).

Investment Decisions – For federal government agencies, like the FAA, which require a cost-benefit analysis and business case justification to secure F&E funding, sustainment analysis and a projection of EOL can help justify business case urgency and a capital investment to replace an aging and obsolete infrastructure system. If sustainment forecasts estimate potential loss of service that supports the business case timeline for an acquisition, this can help justify the investment and secure F&E funding allocations.

Obsolescence Options – EOL estimates also provide sustainment options for program offices by estimating how long systems can be sustained and providing windows of time for program offices to mitigate operational risk. Program offices can search for legacy parts from other operational systems that share components and might be decommissioning their systems. In this case, agencies can cannibalize the parts from the decommissioned system to extend the life of EOL systems that have or will soon exhaust their inventory supply. Program offices can also develop business cases that replace part of the legacy system at a lower cost. These "Technology Refreshes" provide no further capabilities than the current system, but they have more modern and accessible parts, which can be sustained for an additional lifecycle. By analyzing the parts demand, failure growth, scrap rate, and supply accessibility of legacy system components, the cost estimator can isolate the parts which drive EOL and develop a limited scope business case that replaces these critical parts and their associated components at a much smaller capital cost than a full system replacement.

Comparative Analysis – Sustainability analysis can also be used as a basis of cost comparison for cost estimators, measuring the cost to sustain the legacy infrastructure system with preventative maintenance, corrective maintenance (increasing as parts fail more frequently), spare parts procurement, and engineering solutions versus the capital cost and much lower sustainment costs of a new investment, which replaces the old system. If the cost of sustaining the old system over a 10-20-year lifecycle exceeds that of the capital investment/acquisition, the cost-benefit analysis can be used to justify the new investment.

5.1.4 Repeatable Sustainability Model to Forecast Parts Demand, Inventory Depletion, Procurement Needs, and System Viability

Sustainability analysis is used by multiple stakeholders to make decisions and to ensure continued operational viability for infrastructure systems. Each stakeholder uses sustainability analysis and historical demand and inventory data as a means of predicting parts demand, end-of-life, and system replacement need and timing.

For the FAA, the following primary decision-makers utilize sustainability analyses generated by the Logistics Center and cost estimators and analysts from the Program Management Office (PMO) to make data-driven investment decisions.

- The **FAA Logistics Center (FAALC)** uses historical demand data collected from the maintenance system and by parts orders in the Logistics system. The PMO or FAALC analysts and cost estimators interpret that demand data and forecast future parts demand. The FAALC then uses that forecasted demand to predict which parts will fail the subsequent year and subsequently what volume of parts by NSN they need to repair to meet that field demand for parts. Then, when the field requests replacement parts, the FAALC has the inventory needed to meet the demand. If the sustainment/parts demand forecast is not accurate, the FAALC may not have the volume of spare parts available to meet demand and either has to increase labor to make parts repairs or has to procure additional parts in the market to meet this demand at a higher sustainment cost.
- The **Program Management Organization (PMO)** collects demand data from the same sources – maintenance system at time of failure and parts orders from the Logistics system. Then, the PMO cost estimators and analysts create a sustainability model to forecast future parts demand, model end-of-life based on high risk parts and when they run out of parts supply, provide a risk-adjusted timeline for a new replacement investment, and help the program manager justify a business case for a new capital investment or acquisiton that replaces the legacy system prior to loss of service. The cost estimators in the PMO using a sustainability model help justify the new investment and the timing of that new investment.
- The **Capital Investment Team (CIT)** at the FAA decides what allocation of limited F&E dollars is allocated to which programs and how that fixed allocation is distributed based on capital program needs. Each program office will make a case for a level of funding consistent with their program needs and must justify those funding levels. Since some of these investments are mutually exclusive, not every program gets required funding, and some programs are delayed or not approved. To make the best allocation of finite F&E dollar allocations, the CIT collects

sustainability analyses data and forecasts to estimate the urgency of program funding requests by year and to understand the consequences of not funding one program over another. In this way, they can make informed decisions about the distribution of capital dollars and align near term capital dollars with the greatest impact programs and sustainment urgency.

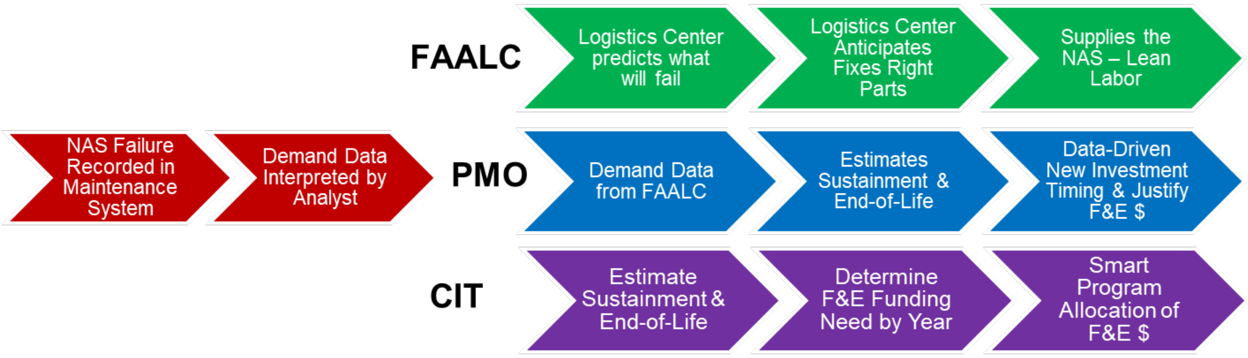


Figure 5: Sustainability Modeling Used by Government Organizations to Make Data-Driven Decisions

As good fiduciaries of government spending, understanding when legacy systems should be replaced by expensive capital investments and how long the agency can wait before spending that capital is important, especially considering limited annual capital budgets. If a replacement investment is funded prior to the need, that system is funded at the expense of a new capability or of other just as important capital investments. If a legacy system is not replaced soon enough by a new capital investment or acquisition, more costly sustainment efforts, including limited technology refreshes or limited procurements, must be initiated, unnecessarily wasting agency capital. Or, in a worst-case scenario, a legacy system might no longer be able to maintain operation, and the system could lose service (See Figures 4 and 5). For an agency like the FAA, this could represent a reduction in flight operations or a safety risk.

6 Sustainability Analysis Models & Methodology

6.1 Challenge: How Do Cost Estimators Conduct Sustainment and Investment Analyses?

For FAA business cases, the team developed a repeatable failure analysis approach with the intention of achieving the following goals:

1. Use one primary data source to collect historical annual demand.
2. Forecast annual demand based on observed historical failures and on trend analyses of failure growth rates from historical data.
3. Refine growth rates based on statistical analyses.
4. Set parameters for failure growth that are reasonable and predictive for entire program lifecycle.
5. Collect inventory numbers from a single source that is consistent and repeatable.
6. Classify parts as either Expendable or Exchange & Repair (E&R) to define which parts are discarded upon failure and which are repaired, respectively.
7. Define procurement and sourcing practices and sustainability for each part.

8. Forecast annual sourcing needs for each part to sustain legacy system through lifecycle.

By collecting and forecasting annual demand for the full 20-year lifecycle, the team developed a full demand profile for the legacy system. By understanding and estimating sourcing needs for each part (inventory minus demand (x scrap rate) plus procurement to meet demand), the cost team estimated the full cost to sustain spare parts' supply.

6.1.1 Failure Analysis & System Sustainment Methodology

The cost team established a standard methodology for estimating legacy system sustainment, including in-depth failure analyses by part (NSN) and part type (E&R vs. Expendable). The team examined procurement practices of the Logistics Center to maintain the legacy system. The agency would do one of the following or some combination:

1) Procure replacement parts annually to sustain the legacy system for the full lifecycle,
2) Estimate and procure a lifetime buy of spare parts for those parts that may no-longer be able to be procured in the future, and
3) Alternative sustainment requirements (F&E capital investment of As-Is functionality, often referred to as a Tech Refresh).

The team determined "authoritative sources" or a consistent single source of data to estimate annual failures by system and part and inventory records and procurement practices. Finally, the cost team developed a robust and repeatable failure analysis and sustainment financial model to estimate sourcing and cost requirements for a legacy case FAA infrastructure system over its entire business case lifecycle of another 20 years.

STEPS: Cost Estimating Process & Failure Analysis Methodology

In developing this methodology, the cost team defined the following steps in its failure analysis:

Inventory Assessment

1. **Inventory – Comprehensive Inventory of System and Parts**
    - Conduct audit of full list of system parts and the associated Lowest Replaceable Units (LRU) numbers
    - Get initial inventory of parts in storage
2. **Parts Categorization** – break parts supply into Functional categories of parts (COTS, easy to procure, hard to procure, aging, custom for the FAA)
    - **Low Risk** – No procurement risk
    - **Medium Risk** – Supplier risk
    - **High Risk** – No supplier available

Demand Analysis

3. **Historical Demand** – Use Logistics demand data from parts orders and returns to the Logistics Center to estimate historical demand.
4. **Trend Analysis** – Analyze historical demand data by part number (NSN) and check for failure trends.
5. **Failure Growth Rate** – Estimate failure growth rate for each NSN based on trend analyses.

- **Growth Rate Regression –** Develop growth curves to refine growth rates to realistic sustainable levels using regression analysis – define three primary categories of growth for each NSN – zero growth, moderate growth, and high growth.
- **Inventory Turnover** – Forecast growth rates for entire lifecycle with annual failure rate caps of full inventory turnover every three years for high failure rate parts.

Sustainment Analysis

6. **Beginning Inventory** – Collect centralized inventory counts from the Logistics Center for Exchange & Repair (E&R) parts and a starting point for Expendable parts.
7. **Time Horizon** – Analyze by NSN the ability to sustain procurement of each E&R and Expendable part over the system lifecycle of 20 years.
    - For parts the Logistics Center can continue to source, estimate annual procurement needs based on annual demand (minus starting inventory).
    - For parts which cannot be sourced, estimate the year until which the Logistics Center can still source replacement parts, and then institute a lifetime buy estimate to procure parts for the remainder of the estimated lifecycle.
    - For E&R parts which cannot be sustained after all repairable inventory is classified as Beyond Economic Repair (BER), devise an alternative procurement, remanufacture, or capital investment (tech refresh) to sustain the system until the end of its 20-year business case lifecycle.
8. **Forecast Procurement** – Forecast the annual inventory procurement of NSNs for each year using the demand forecast and appropriate failure growth rates.
9. Set limits on annual procurements, so growth rates cannot exceed a specific annual procurement level.
    - For this FAA project, we estimated that even with an aging infrastructure system, annual procurements and demand could not exceed total inventory turnover in a three-year period.
    - After total inventory turnover, failure growth rates would be reset to gradually escalate since old aging parts inventory were replaced.
10. **Lifecycle Analysis** – Finalize inventory procurement and sustainability forecast for entire business case lifecycle.
    - Assess current inventory levels deployed and at the Logistics Center.
    - Compare this inventory versus standard demand levels.
    - Compare these levels to full inventory needed to get to system end of life or next Tech Refresh.
11. **Cost Estimation**
    - **Procurement/ Sustainment Cost** – Multiply annual inventory procurements by the cost of each spare part. Price X Volume
    - Forecast annual cost requirements to procure spares in legacy cost estimate.
    - **Corrective Maintenance** – Measure frequency of maintenance events by quantity of parts repaired by year and multiply by labor cost

6.2 Demand Analysis

Data science and machine learning tools have quickly become prominent throughout many industries. This popularity stems from the remarkably accurate forecasts and predictions that result from models trained on data. Due to the predictive power of models, many industries have begun to increase both the quantity and quality of data to achieve accurate and accessible results for potentially complex problems. Sustainment analyses in the FAA have yet to adopt these emerging technologies, thus providing a unique environment to showcase the predictive power of data driven models to address sustainment and logistics concerns within the FAA.

Demand analysis uses historical parts demand (based on parts failures or replacement) to forecast future parts demand. This understanding of future parts needs is critical to organizations for:

- **Inventory Readiness & Parts Repairs** – Have sufficient inventory on-hand to meet future needs
- **Procurement Strategy** – To estimate how many parts must be purchased to stock inventory based on parts demand
- **Risk Assessment** – Identify anomalies and high-risk parts that could drive end-of-life to the system
- **Sustainment** – Strategic alignment with program office goals to sustain systems until replaced

6.2.1 Historical Failures Used to Forecast Future Failures

To forecast annual failure rates for replaceable units in a system during sustainment analysis, the cost estimator will utilize historical failure data to forecast future parts demand. By observed failure growth trends in historical demand data, analysts can forecast failure growth rates using regression analysis to try to forecast how future parts demand will change over time and, in some cases, replicate the “bathtub curve.”

At the FAA, the primary source of failure data originates from the FAA Depot where failures are recorded based on orders in the logistics system or based on recording of parts that are returned after they fail in the field. This failure data approximates parts failures (based on orders for replenishment), if parts were repaired, and if they were repaired and sent back out to the field as replacement spares. With this information, historical annual failures are constructed by using the time of arrival as a proxy for the time the part failed. This assumption is necessary as the actual time of failure is not recorded by the FAA currently. After collecting historical failures from the depot data, the analyst can try to forecast how part failures behave over time.

Metrics such as failure rate and failure growth rate can be estimated using regression techniques on historical annual failure data. These metrics can be utilized to predict how failures will evolve over time and what impact these failures will have on future inventory levels.

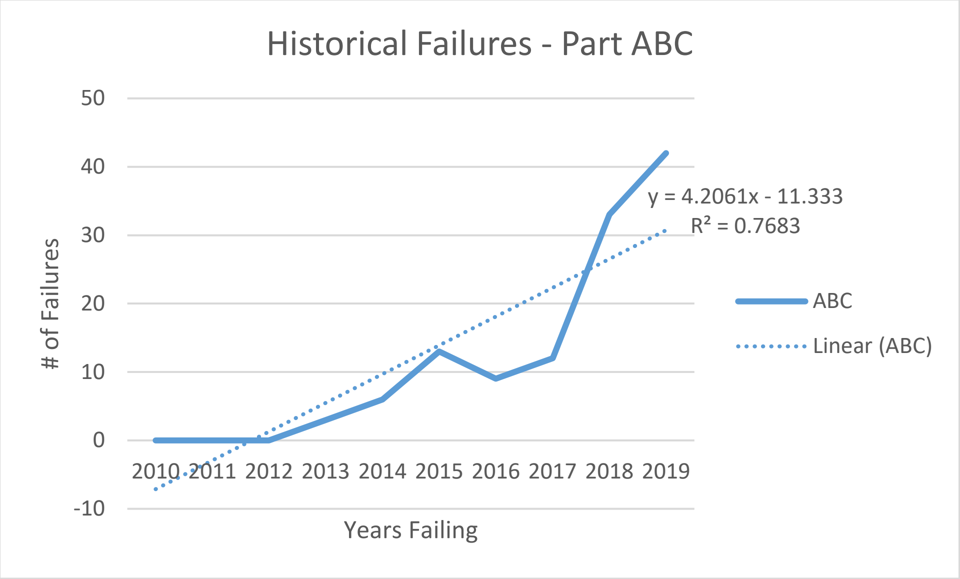


Figure 6: Example of Historical Parts Failures and Regression Analysis Used to Forecast Failure Growth and Future Failure Quantities

6.2.1.1 Failure Rate – Current Observed

The failure rate is broken down on a yearly basis and is defined as the number of annual failures over the number operating in service. The number of parts currently in-service can change on an annual basis which affects the number of failures that may occur. Thus, it is imperative to look at the number of failures with the context of the failure rate to differentiate between an increase in failures due to an increase in operational quantity versus innate properties of the part itself. Parts that experience an overall increase in failure rates are said to have failure growth, and this precise growth rate is estimated from regression.

6.2.1.2 Failure Growth Rate

Using historical failures as a basis to forecast rate of failure and failure growth, regression analysis generates future year-over-year failures which can be used to estimate failure growth rate. We define the failure growth rate as the slope of the regression line fitted to the historical failure data. This number tells the rate at which failures increase year-to-year.

Each part has unique observable trends in its historical failure data from which the analyst must interpret repeatable trends. This historical failure data on a part-level basis is like a part “personality” related to its quality, durability, and operability within a system, estimating how long it will last in operation – a Mean Time Between Failure (MTBF). Understanding how a part behaves allows a model to predict how it will behave in the future. However, some data may convolute predictability based on misrepresentations of demand (parts ordered not due to failure or delayed failure data collection). This misrepresentation comes in the form of outliers that hinder quality analyses.

To overcome this obstacle, the analyst uses statistical methods and data validation to identify noise in the data. The analyst observes data trends and scrutinizes data anomalies. The analyst, based on additional context or within context of the full demand data sample, decides whether to keep, modify, or throw away the data point. The end goal is to choose the historical data that best represents the behavior of the part failure and is likely to predict the future demand outcome.

Once the data selection is complete and the noise is removed, it is time to begin regression analysis to forecast future demand which then can be used to estimate the failure growth rate. The regression line is fitted on the conditional data sets and the slope of this regression line is taken as the failure growth rate of the part.

Completing this work manually in excel is feasible for a small number of parts, but issues of scalability quickly become present once the goal is to efficiently analyze thousands of parts. Fortunately, analysts can develop and apply Python algorithms to replicate this manual analysis. The utilization of Python algorithms from scenario-based demand observations and "conditional rules" allows the analyst to replace hours of manual analyses and interpretations with minutes of repeatable calculations.

6.2.2 Part Type

There exist two types of parts in the FAA cataloguing system:

1) Expendable Parts
    a. These parts cannot be repaired and are thrown away upon failing.
    b. Each failure depletes one unit of inventory.
2) Exchange & Repair (E&R) Parts
    a. **Repair** – These parts are intended to be repaired to original state.
    b. **Exchange –** Broken parts are returned to the Depot for repair and exchanged for repaired parts (or new parts) to restore field inventory.
    c. An Exchange & Repair part (E&R) failure only depletes inventory if it cannot be repaired any further.
        i. A part may be repaired too many times to point where it becomes expendable.
        ii. Sourcing of component parts to make repairs may become difficult over time. This will adversely impact the repairability of E&R parts as systems age.
    d. The proportion of parts that cannot be repaired is known as the "Beyond Economic Repair" (BER) or "scrap" rate.
        i. This rate represents what percentage of failed parts will, on average, not be able to be repaired.

Identifying a part classification as E&R or Expendable is critical for simulating inventory depletions and end-of-life. If a part is E&R, the next step is to estimate this proportion of parts that cannot be repaired. This estimation process is challenging and warrants additional analyses to achieve accurate estimates.

6.2.3 E&R Part – Scrap Rate – Beyond Economic Repair (BER)

The BER rate for an E&R part is critical to determine the percentage of failures that will deplete inventory. Therefore, it is imperative to acquire the most accurate estimates for the BER rate, as different BER rates can result in wildly different parts depletion forecasts.

6.2.3.1 Estimate Annual Scrap Rate

Since the depot at the FAA does not immediately repair a failed part as soon as it arrives, and in some cases does not repair at all, the naïve approach towards scrap rate, that is the total number scrapped divided by the total number failed, for parts is skewed to be artificially lower than the true scrap rate.

To illustrate this notion, suppose 100 failed units of part ABC arrived at the depot in 2020. The depot only attempted to repair 50 of these failed units and had to throw 25 parts away. With the naïve scrap rate estimation, we observe an estimated scrap rate of 25 / 100 = 25%. However, only half of these parts were tested, leaving the other 50 parts as potential additions to the scrap count. After testing these additional failures, the scrap rate could increase to as much as 50%, which could drastically change the outcome of the sustainment analyses.

To avoid this underestimate, the total number of units tested rather than units failed is used as the baseline to compare scrap. The outcome of testing a part is: (1) It is repaired, or (2) it is scrapped. Thus, the new baseline to compare scrap to becomes the number of units repaired plus the number of units scrapped. In the above example, rather than a scrap rate of 25/100 = 25%, the new estimated scrap rate becomes 25 / (25 + 25) = 25 / 50 = 50%.

Although not perfect, this new estimation provides a more accurate depiction of how many units of a part should be expected to be scrapped. Still, estimates can vary greatly depending on how many units are scrapped from the untested batch. To capture these scenarios, the analyst performs a sensitivity analysis on the scrap rate/BER rate to observe changes and its impact on sustainment.

6.2.3.2 Current Scrap Rate

The scrap rate is a point estimate of the proportion of parts that will be thrown away when attempting to repair a failure. Cumulative scrap numbers are used to derive this point estimate. These cumulative scrap numbers represent the total amount of units that have been scrapped for a given part since the data has been recorded. There are issues with using only a point estimate scrap rate. Most notably, scrap rates can change as time progresses, and a point estimate of scrap would not capture this evolution. Thus, additional steps are taken to measure potential changes in scrap rate over time.

6.2.3.3 Scrap Growth Rate

Estimating the growth rate of scrap numbers on a yearly basis is a challenging endeavor since failures are repaired in batches and not immediately tested upon arrival at the depot. Due to this, the total scrap number experiences little movement followed by large increases in scrap quantity. This choppy nature makes estimates of scrap growth rate from a data driven perspective extremely challenging. To help remedy this data noise, sensitivity analysis is performed on a heuristic choice of scrap growth based on the cumulative historical data.

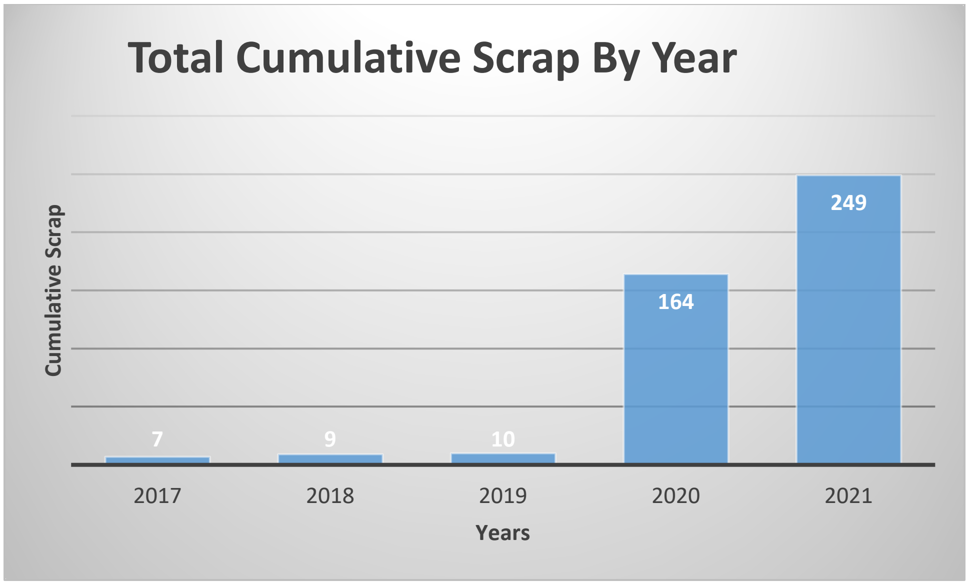


Figure 7: Example of Cumulative Scrap Rates and Impact of Data Collection on Inventory Forecasts

6.2.3.4 Forecast of part Depletion

Forecasts of future failures are developed from the historical annual failures of E&R parts in service. First, the historical failures are compared with the in-service numbers to deduce an overall increase in failure rates over time. If failure growth is detected, the analyst conducts a regression analysis of the historical failures.

The regression analysis tells us how many failures will occur on an annual basis up to the projected end year. Alongside the forecasted failures is the estimated scrap rate of the part. Over time as parts get older, the ability to repair the parts may decrease, causing an increase in the scrap rate. Therefore, an estimated scrap rate is forecasted from the historical scrap growth rate point estimate.

Analysts forecast inventory needs and required parts procurements by estimates of forecasted demand and scrap. Parts that cannot be repaired are the proportion of forecasted failures that are beyond economic repair. This number is simply the estimated scrap rate multiplied by the forecasted failures.

Unrepairable parts = Future parts demand X scrap rate

This calculation is conducted each forecasted year, and the total amount of part needs is actualized. This analysis allows for the identification of how many parts will need to be acquired to sustain an operation until the specified year. Rather than procuring an excess number of parts and hoping things go well, the forecasts tell how many parts will be needed and by what date.

6.2.4 Demand Forecasting Basis for Sustainability Modeling

Demand forecasting methods provide the ability to estimate procurement needs of critical parts. By combining the predictive power of regression models on time series failure data with the evolving scrap rate over time, it becomes possible to identify when a specific part will need to be procured to sustain key systems. This is effectively identifying problems that have yet to occur and having the opportunity to remedy the situation years before it happens. This precise date when the part will need additional procurement is based on the inventory levels of the part and is another key feature of the sustainment analyses.

6.3 Inventory Analysis

Inventory is the final key component of the sustainment analyses efforts. To identify when a specific system will become critical, that is, the parts that compose the system can no longer be efficiently replaced when a failure occurs, inventory levels are simulated based on the forecasted demand and scrap rate. A system enters a critical state when the inventory has been fully depleted from scrapped parts or the predicted incoming number of scrapped failures exceeds current inventory levels. This can signal potential system loss of service. Identifying when this date will occur is at the core of inventory analysis.

6.3.1 Initial Inventory

For FAA inventory analyses, analysts assess inventory at the depot. This is a challenge exclusive to the FAA as field inventory is not tracked as precisely as centralized inventory at the depot. The inventory is composed of:

- **Serviceable parts –** Parts readily available on the shelf to be shipped to the field
- **Repairable parts (internal to agency) –** Parts that can be repaired or is currently in a repair state
- **Repairable parts (external to agency) –** Parts in repair at the vendor

This initial inventory provides the baseline for the simulated inventory depletion.

6.3.2 Inventory Depletion

Starting from the current year, the number of failures from the regression analysis is actualized and the number of units scrapped is calculated from the scrap rate. This amount scrapped is then used to deplete the current inventory for that year. Going into the next year, the newly depleted inventory becomes the starting inventory and the process repeats. This process allows for the identification of the exact year where inventory levels will fall below a critical threshold. This is the time when a decision must be made to address the inventory issue. Figure 8 depicts the date at which all inventory is exhausted and when a part can be a single source of failure and system loss of service.

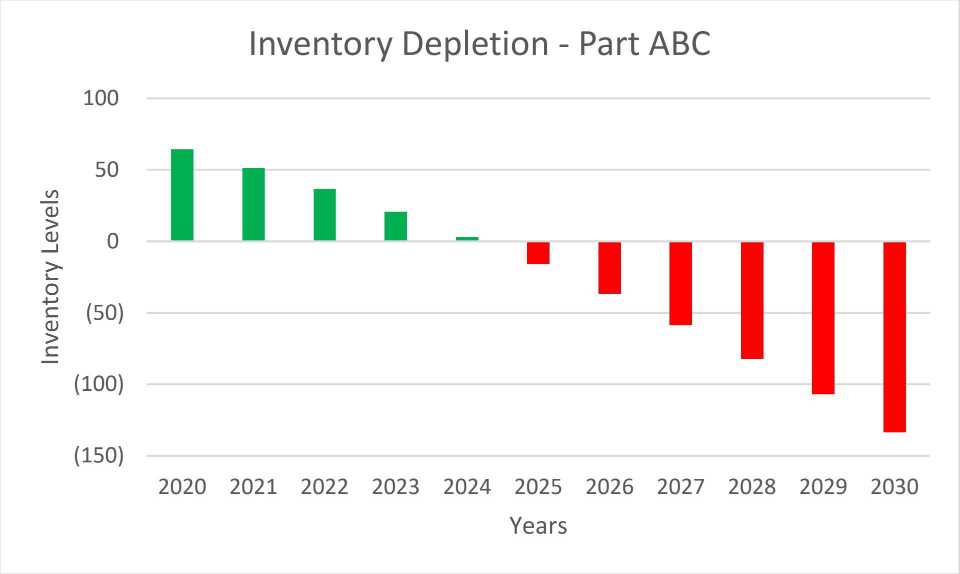


Figure 8: Example of Forecasted Inventory Depletion/Exhaustion

6.3.3 Ability to Source Parts

Once a critical year is identified, the challenge becomes how the agency will address the issue. The most straightforward approach is to simply purchase more parts. However, for systems operating beyond their intended life, component parts may no longer be available for procurement. Some parts have been operating for decades and are no longer manufactured. In this scenario, the agency can either:

- Procure a like-for-like part and test for system compatibility
- Cannibalize parts from a similarly old system which recently has been decommissioned.

These methods can help extend the life of a system until an acquisition can replace the legacy system. If a part can still be sourced from a vendor, the cost analyst can estimate a “lifetime buy” using the required lifecycle end date, projected parts failure rate, and unit cost of the parts to procure.

6.3.4 Ability to Repair Parts (E&R)

The ability to repair E&R parts may change over time. If a specific serial number is repaired too many times, it may become infeasible to repair it when it fails again. The scrap growth rate is intended to capture this behavior. Depending on how many times a part is repaired, the scrap rate for an E&R can increase quickly or slowly which affects the time frame for when inventory levels will be fully depleted. Scenario analysis can be performed to observe how the ability to repair E&R parts fluctuates over time and what quantity of inventory will change based on these different scenarios.

6.4 Putting It All Together

The conjunction of historical failures, failure growth, estimated scrap rates, inventory levels, and procurement availability allows for detailed sustainment analyses to identify high-risk parts that drive obsolescence of key systems. Historical failures provide the framework for forecasted future failures, and the estimated scrap rate is the dial the defines what impact these forecasts have on inventory levels. The procurement capabilities of each part detail what actions can be taken to further extend the sustainment period of a critical part. These tools are utilized in several different types of models with a key similarity in sustainment analyses.

7 Sustainment Models

Uniting the core concepts discussed in section 6, the sustainment models are designed to identify high-risk parts and present solutions to mitigate sustainment issues. Each model plays a separate but equally important role in achieving this goal. The large-scale sustainment model is used to identify high-risk parts in an intelligent and efficient manner among the thousands of parts operating. The deep dive model will take a closer look at high-risk parts to incorporate any latent factors or unique situations that may affect the forecasted date of full inventory depletion. The sustainment procurement models (lifetime buy models) answer the question of how the sustainment period can be achieved given the forecasted inventory depletion.

Using these tools comprehensively allows analysts to perform detailed sustainment analyses in an efficient manner by partitioning the problem (sustainment) into three separate risk classifications (high-risk identification, high-risk justification, and high-risk mitigation).

7.1 Scalable Sustainment Model

The scalable sustainment model applies the concepts in section 6 to thousands of parts operating in the FAA. Rather than conducting painstaking analysis in Excel, the analysis is calculated in Python, a computer programming language, that conducts demand analysis across all parts in a matter of minutes. More precisely, the Python program achieves the following:

1) **Data Engineering** – Constructs historical annual failures, in-service, current inventory levels, and estimated scrap rate from the FAA depot data
2) **Regression Analysis** – Conducts regression analysis (estimating failure growth from fitted trend line and forecasting failures) on failures time series data selected by selection algorithm
3) **Inventory Simulation** – Utilizes estimated scrap rate and forecasted annual failures to simulate impacts on current inventory levels and to estimate date of full inventory depletion

This model's primary goal is to identify the small subset of critical parts among the thousands of parts operating in the FAA. These critical parts can then be further scrutinized by the development of a deep dive sustainment model to include potential latent factors that may accelerate the depletion of inventory.

7.1.1 Selection Algorithm

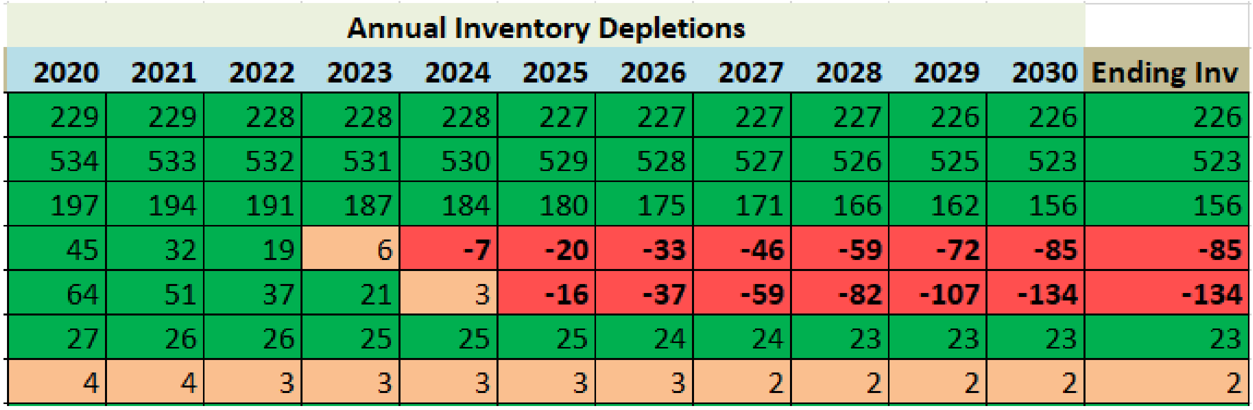
The selection algorithm is a tool that reduces the amount of noise from the historical annual failures time series data. Using statistical tools for outlier detection, the selection algorithm chooses the most accurate and relevant data to form the basis of the regression analysis. It achieves this goal by selecting the longest span (or most recent span) of time where no outliers occurred. The assumption is that this time period best represents the behavior of the time series data, allowing for accurate analyses to be performed.

The algorithm will march through each data point in the time series and check if an outlier is present. The end goal is to select the longest (and most recent) sequence of time without observing outliers. To keep track of sequence sizes, bins are created. Each bin represents a sequence of data. Each bin is initiated to zero. To increment the value of the bins, the algorithm marches along the time series data, starting from the initial data point, and checks the relative difference between the current and subsequent data point. If this difference is reasonable (defined by the standard deviation rule for outliers), then the value of the current bin is incremented by one. If the difference is considered an outlier, then the algorithm moves to the next bin and repeats the same process. The result returns the bin with the highest value which defines the sequence of data to form the baseline for regression analysis.

Figure 9: Example of Historical Annual Failures Time Series Data

7.2 Deep Dive Sustainment Model

The deep dive model utilizes the sustainment analysis methods detailed in section 6.2 in addition to problem specific factors. Some parts may have unique situations that accelerate the depletion of inventory, and the deep dive model's objective is to capture these additional factors into the demand analysis. Since the deep dive model is not easily scalable, the large-scale sustainment model is used to identify potential high-risk parts. These high-risk parts are further scrutinized by the deep dive model to validate the results found from the large-scale sustainment model.



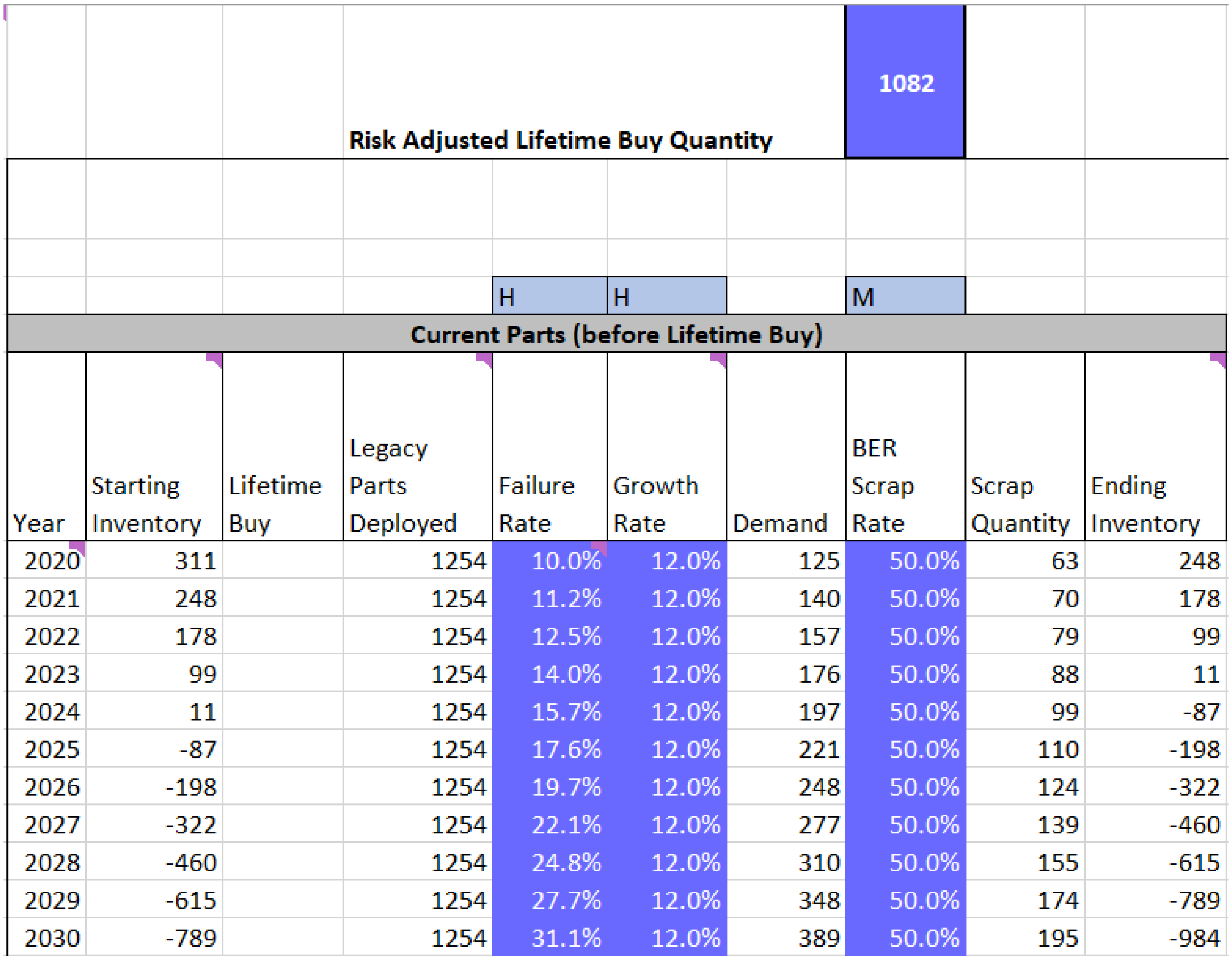
Annual Inventory Depletions											
2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Ending Inv**
229	229	228	228	228	227	227	227	227	226	226	226
534	533	532	531	530	529	528	527	526	525	523	523
197	194	191	187	184	180	175	171	166	162	156	156
45	32	19	6	**-7**	**-20**	**-33**	**-46**	**-59**	**-72**	**-85**	**-85**
64	51	37	21	3	**-16**	**-37**	**-59**	**-82**	**-107**	**-134**	**-134**
27	26	26	25	25	25	24	24	23	23	23	23
4	4	3	3	3	3	3	2	2	2	2	2

Figure 10: Example Output of Deep Dive Model – Forecasted Inventory Depletion

7.3 Sustainment Procurement Models

Once high-risk parts have been identified by the large-scale sustainment model and validated by the deep dive model, the next step is to identify the quantity needed for continued sustainment of the critical system. The sustainment procurement model, also known as "lifetime buy model," is developed for each high-risk part for this precise purpose.

The lifetime buy model uses demand analysis from the deep dive model in conjunction with sensitivity/scenario analysis on key metrics that drive inventory depletion to provide options for procurement of critical parts. This model allows decision makers to accurately assess what quantity should be procured to meet the desired timeframe, the dollar amount needed to fund the lifetime buy, and the risks associated with potential fluctuations in demand or scrap rate.



			Risk Adjusted Lifetime Buy Quantity				**1082**		
				H	H		M		
Current Parts (before Lifetime Buy)									
Year	Starting Inventory	Lifetime Buy	Legacy Parts Deployed	Failure Rate	Growth Rate	Demand	BER Scrap Rate	Scrap Quantity	Ending Inventory
2020	311		1254	10.0%	12.0%	125	50.0%	63	248
2021	248		1254	11.2%	12.0%	140	50.0%	70	178
2022	178		1254	12.5%	12.0%	157	50.0%	79	99
2023	99		1254	14.0%	12.0%	176	50.0%	88	11
2024	11		1254	15.7%	12.0%	197	50.0%	99	-87
2025	-87		1254	17.6%	12.0%	221	50.0%	110	-198
2026	-198		1254	19.7%	12.0%	248	50.0%	124	-322
2027	-322		1254	22.1%	12.0%	277	50.0%	139	-460
2028	-460		1254	24.8%	12.0%	310	50.0%	155	-615
2029	-615		1254	27.7%	12.0%	348	50.0%	174	-789
2030	-789		1254	31.1%	12.0%	389	50.0%	195	-984

Figure 11: Example of sustainment procurement model with input from demand analysis in blue

7.4 Summary

The core demand analysis principles form the backbone of the three primary sustainment models. Each sustainment model works in conjunction with the other to perform the most accurate sustainment analysis in the most efficient manner. This is achieved by delegating different models for different tasks: the large-scale sustainment model for high-risk part identification, the deep dive sustainment model for high-risk validation, and the sustainment procurement model for high-risk mitigation. The sustainment analysis adheres to the following pipeline:

1) **Large-Scale Sustainment –** FAA depot data is inputted to the large-scale sustainment model. The large-scale sustainment model performs demand analysis to all parts in-service and outputs a list of potentially high-risk parts to further analyze.

2) **Deep Dive Sustainment –** The list of high-risk parts is further scrutinized by a deep dive sustainment model. Further research and detective work is conducted on each high-risk part to identify any latent factors that may affect failure volume or inventory depletion. The results of the deep dive model on potentially high-risk parts are a finalized list of validated high-risk parts with estimated dates of full inventory depletion
3) **Sustainment Procurement –** The results from the deep dive sustainment model are further scrutinized to identify precisely what quantity should be procured (if procurement capabilities are available) to reach the desired sustainment period of the system. These results can be used to quantify cost and other factors such as loss of functionality so that an effective business decision can be made

This approach to sustainment allows for fast and robust analysis of large systems. It combines the quick and elegant approach of modern data science with the careful, delicate analysis of traditional methods to provide accurate sustainment analyses for programs of any scale.

Our sustainability modeling for FAA systems was utilized and applied to help maintain existing operational infrastructure systems in the National Airspace (NAS), to estimate system end-of-life, to plan risk-mitigation strategies to sustain systems until they were replaced with a new investment or acquisition, and as a repeatable and objective means of managing parts demand, inventory readiness, procurement, and inventory strategies. The methodologies and modeling can be applied to other agency sustainment analyses, adjusting to their unique supply chain infrastructure (data sources, practices, and management).