Innovative Techniques for Analyzing Incomplete Data Sets to Improve Accuracy of Cost Estimates

George O. Bayer, Jr.
Bryan Anderson
Cobec Consulting, Inc.
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Abstract

Cost estimators are often presented with incomplete data sets from which they must develop business case solutions. Understanding, interpreting, and improving the data integrity are critical factors for cost estimate accuracy. In this use case, the cost estimators analyze and interpret incomplete data sets, forecast spares depletion, and estimate obsolescence. Using innovative data mining techniques, topic analysis, and machine learning, the estimators demonstrate how improved data can result in better estimates and business cases.

1 Introduction

For government acquisitions and investments, cost estimators are often presented with incomplete data sets from which they must develop parametric analyses, business case solutions, and projections for legacy system obsolescence and new system implementation. Understanding and interpreting the data and improving data integrity are critical factors for cost estimate accuracy. The FAA Program Management Organization (PMO), Investment Planning & Analysis (IP&A), and the FAA Logistics Center (FAALC) all try to measure the health of systems in the FAA infrastructure to evaluate the best time to replace legacy systems, perform technology tech refreshes, and justify capital investment replacement systems. Data collected to estimate historical parts failures uses supply-based parts’ returns to the Logistics Center as a proxy for parts demand. To improve the fidelity of this demand data, so it can be confidently used to forecast future demand and system obsolescence, the cost estimation team explored the use of a second equally incomplete data set to supplement, compare, and consolidate with the primary data. Unlike the first data set, the supplemental data is collected at the time of system failure, but during maintenance logging, failures and parts are recorded in “free text” fields, which lack necessary data standardization to effectively forecast demand alone. Using innovative data mining techniques and employing topic analysis, the analysts demonstrated how the interpretation and understanding of partial data sets can lead to better forecasts, better cost estimates, and timely business case investments.
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 estimated 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 cost model the following:

- How long will the projected system last?
- What does a system failure curve of critical parts look like?
- 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?
- When does the cost analyst conduct a failure analysis to decide on further system sustainment or replacement with a new procurement?

Failure 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 data for trends in failures – increased failure rates, different failure projections, or changes in estimates,
- Revising system obsolescence dates,
- Adjusting estimates for risk,
- And, determining when to consider system replacement.

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.
Given the challenges of existing failure and sustainment analyses using robust historical data on systems, parts, maintenance, and logistics, what would happen if the data sources for these analyses were non-standardized, unreliable, or collected from multiple incomplete sources? How would cost estimators project future failures and infrastructure sustainment needs if:

- Maintenance records were recorded in free text or not collected at all,
- Parts demand estimates were based on centralized recordings of field parts returns without consistent rules for parts returns,
- Field inventory was not centrally tracked or recorded,
- And, maintenance recording systems did not communicate with supply?

These types of maintenance, supply chain, logistics, database, and unintegrated systems are not uncommon, and cost estimators conducting sustainment analyses, legacy system cost estimates, and investment analyses decisions must have a complete understanding of the strengths and weaknesses of the failure data they analyze. Too much confidence in incomplete data can result in poor decision-making or add significant risk to infrastructure sustainment:

1) If legacy systems are replaced after they reach obsolescence and systems fail, service interruptions can have cascading impacts on agencies, industry, and the public.
2) If legacy systems are replaced sooner than required, the agency might needlessly spend limited capital funds on infrastructure prematurely that could have been spent on more critical infrastructure replacement needs or on new technologies.

Understanding how to interpret, process, and project data in failure analyses is critical for cost estimators, government agencies, and all stakeholders.

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 and services and their components,
- Determine the logistics and spare parts sourcing requirements and availability,
- Conduct an inventory analysis of spare parts’ sustainment,
- Evaluate the supply chain of the infrastructure sustainment operations,
- Compare infrastructure investments to determine which is more urgent,
- And, evaluate each investment and portfolio against a constrained capital budget and determine 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 Investment Decisions – Four Cost Estimation Considerations

For infrastructure investments, government agencies must consider four 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 F&E 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 four 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?

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?

4) **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.).

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. Without accurate data from which cost estimators can extrapolate, calculating accurate
forecasts of infrastructure needs and replacement needs becomes increasingly difficult to manage.

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 according a
technology improvement and integration timeline. 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) using historical data, trend analyses, and forecasting to estimate
a system’s end-of-life and when legacy systems should be replaced. These departments 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.

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 has to 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 procuring 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.

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. The more accurately they can determine the optimum timing of replacement investments, the better they can preserve and allocate limited capital budgets.

### 3.3.4 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? By measuring the net present value (NPV) or Internal Rate of Return (IRR) of each alternative investment and timing of those investments, estimators can objectively decide the right time to invest and the path for optimum 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/system 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 the return of parts 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 impaired and less accurate than 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, especially those trying to forecast the optimum time for infrastructure replacement. Even more challenging, without understanding the source and accuracy of data sets and databases,
estimators may not even realize the data gaps and may overconfidently make recommendations to
decision councils.

4  Data-Driven Cost Estimates & Analysis
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
Finance metrics like NPV and IRR can be calculated with the cost avoidance benefit included in these value equations.

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, of replacement hardware procured smaller quantities with existing vendors, and for the maintenance costs (contractually or at a government rate) 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 of 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 actions, government salaries, travel costs, logistics and supply costs)

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.

For software systems, estimating quantity of failures or demand is a little more complicated. Software demand in legacy operations usually relates to one of the following:

- Required software upgrades
- Software patches
- New interfaces to connect to new or updated external systems
- Custom software development related to new requirements or new data customers

Historical expenses related to each of these categories can be captured just as parts demand is recorded for hardware parts’ failures. Cost estimators can develop a forecast and associated projected cost for future software upgrades, software patches, new interfaces, and custom software.

Data for historical failures is usually collected from a maintenance organization at the time of failure, and an existing maintenance logging system or ERP system would record these failures at the system or part level, so these failures and associated estimates of demand could be collected real-time. This data would be collected in a database in which the logistics team could query or generate reports of historical parts’ demand. Cost estimators would retrieve these reports, extrapolate historical failures using trend analyses and a calculated failure growth rate to estimate future demand and cost.

### 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 remanufacture 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 Refreses)

They then extrapolate those costs using trend analyses from historical data, anticipated future changes, patches, and interfaces, and by defining and forecasting any required procurments 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 to Procure
When developing a business case for a new capital investment that replaces an government legacy system, cost estimators must collect data to build up each WBS element for software, hardware, equipment procurement, and all prime costs based on historical data, parametrics, and competitively bid source selection estimates. They must collect and estimate the level of effort for nonprime costs to develop the full independent government cost estimate (IGCE). Adding an estimate for operational costs over the full business case lifecycle, including sustainment costs to maintain the newly procured system for 5-20 years provides a comprehensive lifecycle cost estimate (LCCE). The basis for each procurement alternative is compared to that of the legacy system.

Sustainment data for the new system – operational requirements, spare parts procurement, and forecasted failure rates – is based on estimates the cost estimator collects from historical procurements and parts failure guidelines from the manufacturer or system integrator. Adjustments to the forecasted sustainment costs can be made in updates with a Post Implementation Review (PIR), where actual procurement and sustainment costs of the newly procured system are evaluated sometime after implementation.

4.1.6 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) and Internal Rate of Return (IRR) 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.

Similarly, the accuracy of data in these estimates plays a critical role into the timing and funding needs for infrastructure replacement projects.

4.2.1 Cost per Maintenance Action
To estimate the cost of legacy sustainment, the program office should estimate the cost of the logistics center or field maintenance to address a system outage, failure, or maintenance event (planned or unplanned), assess what needs to be repaired and how to make the repair, to repair the system in the field and replace parts, and replace spare parts inventory. Each cost element is a point in a process of overall maintenance action and should be included in the cost estimate. How an agency addresses maintenance actions and sources parts plays a large role into the level of effort and total legacy cost estimate.

For this paper and use case, we will focus primarily on parts and system sustainment and the related supply chain data.

4.2.2 Labor
As defined in 4.2.1, part of the overall sustainment cost of the legacy system is the labor required to address system outages or planned maintenance events and make repairs in the field. It is also the labor associated with sourcing, storing, and distributing spare parts (logistics). The FAA identifies and tracks outages at OCCs and SOCs where analysts are electronically notified of an outage, notify stakeholders, log the events, assign maintenance actions to the appropriate analysts in the field, and track the repairs and system restoration. After restoration, the OCC or SOC analyst will coordinate the reopening of airspace and make proper notifications. The cost of legacy system sustainment labor would encompass all of these parties who sustain legacy systems, and as failures increase for an aging infrastructure system, these corrective and preventative maintenance costs will correspondingly increase.

4.2.3 Analysis
Legacy system sustainment data is critical for strategic investment decision making. At the FAA, the budget office and Investment Planning & Analysis (IP&A) review and independently evaluate business cases to determine the need and timing of these business cases and if or when to fund them. Legacy sustainment plays a large role in determining the timing and need for infrastructure replacement.

The data for projecting failures and tracking inventory is critical for estimating system end-of-life and assessing risk of when a critical infrastructure system might risk loss of service. Planning back from that date and risk adjusting for potential schedule slips, program offices and IP&A try to determine when
best to fund replacement systems and not to fund a system too late (loss of service) or too early (at the expense of other critical projects with a constrained budget).

If the data source used for estimating failures or inventory is compromised or inaccurate, IP&A and other deciding organizations will not have confidence in the end-of-life estimates provided and will likely fund infrastructure programs earlier than needed rather than risk a system losing service. If the data provided clouds the interpretation of urgency, organizations deciding in which investments to fund may not realize they could be risking infrastructure integrity. This might result in an unintended loss of service or a costly accelerated plan to continue legacy sustainment.

4.2.4 Parts Procurement, Storage, and Distribution
Most of the data used to estimate infrastructure sustainment is collected at the time of system failure or maintenance actions. Field analysts record the systems and parts on which they worked to make repairs, and this data is stored in a database and shared with the Logistics Center and with the maintenance community. IP&A and program offices would access this data to conduct sustainment analyses, assess failure trends, and address parts and systems of need. Program offices would use these analyses to plan replacement procurements and business cases, and review organizations, like the FAA’s IP&A, would validate the recommended replacement dates to optimize F&E budget spending.

At the FAA, the Logistics Center is responsible for sustaining much of the FAA’s parts inventory, providing spare parts for systems in the National Airspace (NAS), backfilling local field inventory, optimizing field inventory to meet parts demand, and distributing the right parts when systems are repaired or parts proactively replaced.

Data for inventory is stored and managed by the FAA at the Logistics Center and then distributed to field locations in the number estimated based on local demand forecasts. When system parts inventory is depleted or forecast to be depleted, the Logistics Centers procures additional exchange and repair (E&R) and single use parts. If in some aging systems, these parts could become scarce, larger single procurements or other arrangements are made to increase the carrying inventory of parts to meet the intended system lifecycle.

Analyzing changes in inventory and demand, the Logistics Center and program offices can conduct sustainment analysis and assess the need or urgency in procuring an infrastructure replacement system. Again, the data collected and used as a basis for demand and current and future inventory is critical making accurate assessments of need.

In addition, demand data is the primary source for the Logistics Center supply. The Logistics Center uses demand forecasts to determine which E&R parts on the shelf should be repaired to anticipate future demand and be prepared to distribute the right amount of parts to meet that demand. The FAA does not staff the Logistics Center to repair every part returned at the time of return and focuses its efforts on repairing those parts that are required to meet demand. If the forecasts are inaccurate, the Logistics Center must take extra measures to repair parts it did not plan to repair in the same timeframe, so demand data is a basis of efficient spare parts inventory repair as well.

4.2.5 Time to Repair – Outage Impact
Demand date based on actual system failures or repairs in the NAS are used to determine “time to repair” or to estimate the Mean Time Between Failures (MTBF). These calculations use real historical
data to calculate parts demand, how often specific parts and specific configurations of parts are failing in
the NAS, if the failures are increasing in frequency and by how much, and, correspondingly, how many
parts will need to be procured annually to meet this demand. For aging infrastructure projects and
systems, understanding and estimating the parts demand is critical to sustain a system over its intended
lifecycle. For investment decisions where program offices try to estimate how long a system can be
maintained before end-of-life or loss of service, estimates of time to repair or MTBF are critical factors in
sustainment models.

4.2.6 Ability to Source Parts & Managing Risk
Using demand models based on actual failure data is also a means for the Logistics Center to estimate
how it can sustain supply, how long it takes to make repairs to parts at the Logistics Depot, and how
parts can be sourced to maintain existing operations.

As the Logistics Center estimates parts demand, they assess current parts inventories and procurement
needs at least three years into the future. For parts which can no longer be procured or which may no
longer be procured in that three-year window, Logistics might need to make other preparations to
sustain procurement in the future. That includes lifetime parts buys, the remanufacture of critical parts
which are customized for the agency or which can no longer be procured on the market, and technical
refreshes, which involve an F&E investment – a competitive bid or sole source procurement.

4.2.7 Do We Have Adequate Data to Make Assessments?
Using historical data to forecast demand, compare to inventory, assess procurement, optimize field
inventory, and estimate end-of-life is an effective way to project system obsolescence, time
infrastructure replacement capital investments, and make wise capital investment decisions. However,
how do we know if the data we are using to estimate end-of-life and project when to replace
infrastructure is accurate? How can we be assured that future projections of demand are reasonable
based on collections of historical demand data?

Analyzing the source of data and determining what might compromise our assumptions and its
application to analyses is just as important as the analysis itself. If the data used to estimate demand is
inaccurate and cannot be trusted, how do we improve that data set to make useful assumptions about
future demand? This is where the analysis of this paper demonstrates methodologies by which we can
assess data validity, use multiple sources of data to improve our assumptions, and make more accurate
forecasts of demand and sustainability.

5 Government Supply Chain Does Not Replicate Industry

5.1 FAA Use Case
For this analysis, the team focused on three critical parts for a legacy air traffic control system for the
FAA which are difficult to procure, have a critical inventory, which the business case team is tracking for
work-arounds, and that drive system obsolescence. The air traffic control system is used by controllers
to provide situational awareness, not separate aircraft, but it does provide a means of informing
controllers without leaving their workstation and helps them to efficiently use the tools around them.

The data our analysts used to estimate system obsolescence, end-of-life, and lifecycle sustainability is
provided by the Logistics Center and is data they use to estimate demand, existing inventory, and
depletion of that inventory. However, what appears to be very comprehensive data, when under closer
examination of both the data results and sources reveals a more complicated situation of a lack of data exchange, challenges in data collection, free text recording, and unintended parts return practices. On the surface, the data used to estimate demand appears definitive. After examining the underlying assumptions, the data is inconsistent and not precise.

5.2 Huge Infrastructure of Hardware & Software Systems

The FAA manages a huge infrastructure of air traffic operations, providing hardware systems to support navigation, automation, communications, safety, program management, technical operations, and surveillance infrastructure across the entire United States and extending to the borders with other countries. This infrastructure is designed to support air traffic operations for the National Airspace (NAS) need to track all aircraft operations, ensure safety, and provide efficient ever-improving flight operations across the U.S.

Air traffic systems for controllers operate on high-bandwidth software systems that are integrated with safety, surveillance, weather, and automation systems, constantly informing controllers of flight conditions, airspace constraints, and traffic. FAA program offices bring forward large infrastructure programs which are both hardware and software based and required to operate at near 100% availability. Estimating the legacy system sustainability is critical to provide an ongoing concern and maintain the safety of the NAS. Accurately assessing sustainability, obsolescence and investment timing is critical to manage capital constrained portfolio budgets used to fund more than $3B in capital projects annually.

Program offices are asked to develop robust sustainability analyses on legacy systems to prove the value, need, and urgency of infrastructure replacement systems and to justify business cases. The cost estimators responsible for these analyses must gather the right data, assess the validity and confidence in that data, and calculate system end-of-life and the cost to sustain the system.

5.3 Enormous Logistics Systems, Maintenance, and Supply

To manage such a robust enterprise as the FAA does, large logistics, maintenance, supply, and configuration systems help operate and sustain operations, make repairs, and supply replacement parts to the field.

Logistics & Supply

The FAA has a logistics system with large databases and centralized warehouses used to manage the parts supply in the NAS. The agency is currently upgrading the legacy system into a modern ERP system to manage supply and conduct predictive analyses. Each time a system in the NAS fails, the FAA takes locally stored parts from storage to the field location to fix the system failure, and the Logistics Center backfills the locally stored spare to provide adequate and optimized field inventory to meet future repair needs.

At the time of repair, the field is supposed to return the broken part to the Logistics Center for repair and replacement, and the Logistics Center records the parts being returned as parts demand. However, when the field has excess parts at a field location and is confident based on past failures that they have a sufficient supply of parts already at the field location to meet their needs, they might delay sending the broken part back and using “store credits” (a financial compensation to the Logistics Center for new replacement parts) to restock broken parts in the field. By the time the field does decide it needs to
send parts back for a restock in the field, they may have collected 3-5 broken parts to send back at once over many months, instead of sending parts back right when the failed. As a result, parts returns no longer correlate with actual failures, and the actual failures might have occurred in a different year. Using returns alone, the Logistics Center cannot consistently calculate actual failure metrics, like Mean Time Between Failure (MTBF). Diagram 1 depends this data flow and parts’ returns used a proxy for actual failures and in estimating spare parts demand for infrastructure investment decisions.

**Maintenance**

At the time of failure, the maintenance organization responsible for assigning, tracking, identifying, fixing, and restoring NAS operations during planned and unplanned outages conducts maintenance logging using separate systems than the Logistics Center uses for supply. These maintenance systems allow field personnel to assess and record failures in the field using non-standard recording practices, identifying the system and the parts via “fee text” or open fields, which do not necessarily enforce recording the same word for each system, part, or level of the part replaced. As a result, using the logging system, it is very difficult to track parts failures and system outages at the time of failure.

5.4 **Stovepipe Systems – Not Integrated**

In addition to the agency practices that make data integrity challenging for cost analysts and program managers assessing parts and system sustainability, the three major supply chain systems which record data to maintain the NAS are separate unintegrated systems in maintenance, supply, and configuration. These systems are currently separate in-house developed or COTS products that do not share interfaces and which only periodically share data, so data collected from one source about the same maintenance action is not reconciled with data collected in another way for the same incident.
5.5 Data Collection Compromised
Most analyses of maintenance actions and sustainability studies are conducted to track when, what, and how failures occurred to estimate future failures and how long a system can be sustained before replacement. However, the maintenance data recorded in the field is not standardized since it is recorded in open fields with free text that is subject to the level of detail and parts and systems names the technician wants to provide. Two technicians might label the same system or part with a slightly different name to record the maintenance action and what was repaired. Others might omit the part name or the system from which the part was removed. Using maintenance data alone in this case is difficult to track parts failures with any accuracy, unless there were a key to interpret the name and recording preferences of each specific field technician.

5.6 No Authoritative Failure Data Source
In addition, data used to estimate failures, inventory depletion rates, repair forecasts, and sustainability can be collected using the non-standard maintenance recording data or through data collected from the Logistics Center. Since the data collection sources are stove piped systems, they each collect data about failures and maintenance events, and it is up to the cost analyst to choose data from a particular source or from multiple sources to reconcile. Having no one authoritative source of data makes failure data analysis challenging and non-repeatable.
5.7 Data Interpretation as Important as Data Collection

Just as important as collecting data from different sources and databases, understanding what is collected is even more critical. Knowing from where data originates, how it is collected, and under what protocols is critical to understand how definitive or what sort of confidence should be applied to the data collected. If a data set provides only part of the story and omits other failures, understanding that would require the analyst to complete the data set using another source or extrapolate the sample data set to a larger view.

By understanding the data and how it is collected, analysts can better interpret the data, apply risk, and potentially develop new types of analyses to refine and improve data fidelity.

5.8 Data Drives Analysis

The data analysts collect to estimate legacy system sustainability, end-of-life, and lifecycle cost drive:

- Investment decisions – future and current capital investments and portfolio analysis,
- Predictive Maintenance – Future maintenance actions and the prioritization of maintenance activities,
- Systems Obsolescence – When current systems can no longer be sustained,
- Cost Estimates – Estimates of operational costs for business cases.

5.8.1 Investment Decisions

A government supply chain system is the primary source for the analysis of the sustainment of legacy infrastructure systems to determine when they should be replaced and when they can no longer be sustained.

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 Diagram 2). For an agency like the FAA, this could represent a reduction in flight operations or a safety risk.
5.8.2 Predictive Maintenance
A government supply chain system and its data are sources of agency predictive maintenance. By understanding what fails when, agencies can forecast or anticipate what parts or systems might fail in the future and can proactively replace systems before they fail, transforming supply chain and maintenance operations from reactive environments to proactive maintenance entities. Unintegrated or partial data sets can compromise the ability of supply chain analysts from accurately employing practices of predictive maintenance. And, the ability to parse and improve fidelity of information can be transformation in maintenance operations.

5.8.3 Systems Obsolescence
Supply chain systems are also used to predict system obsolescence and when an agency should plan to replace hardware and software systems according to an ongoing schedule. Understanding which systems and configurations reach obsolescence sooner may play an important role in deciding which manufacturer or configuration should be standard across the NAS.
5.8.4 Cost Estimates for Business Cases
Finally, and critically important to the cost estimating profession, supply chain systems and their associated data are a primary source of estimating operational costs for legacy system cost estimates. The FAA and other civil agencies use legacy system cost estimates as a baseline and point of comparison for their capital investment cost estimates. They are also used as a comparative cost avoidance reference point and a measure of overall lifecycle agency cost. Estimating the frequency of parts failures, their replacement costs, and carrying inventory cost are important to accurately develop a bottoms-up legacy cost estimate.

6 Cost Estimating Process & Failure Analysis Methodology: Data Analysis from Multiple Non-Definitive Sources

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 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. Define parts by expendable and Exchange & Repair (E&R) to define which ones are sustained and which ones the agency discards.
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 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:

1. **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

3. **Historical Demand** – Use Logistics demand data from parts 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.

6. 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
### Diagram 3: Example of Demand Profile of Hardware System – Single Source Data Estimate of Historical Demand (Step 1)

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Diagram 4: Estimated Failure Growth Rate Based on Historical Failure Growth Trends & Forecasted Demand (Steps 2-5)
Diagram 5: Annual Non-Cumulative Annual Inventory Replacement Requirements (Negative Value = Needed Procurement of Parts)

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6.1.2 Non-Standard Data
If the FAA’s Logistics data was recording demand at the time of failure with standardized system and parts’ recording, the data in this analysis would provide accurate forecasts of future sustainment needs. Even with accurate data, failure growth rates can suddenly accelerate at the end-of-life, replicating a bathtub curve for parts’ sustainment.

However, the Logistics Center’s estimate of demand is not a one-for-one correlation with parts’ failures. At the FAA, when preventative and corrective maintenance is performed and failed parts are replaced from locally stored inventory, the maintenance region sends back the broken part (NSN) and requests a new part from the Logistics Center to replace the part used from local inventory. If each field location were to send back parts for repair or replacement from the Logistics Center at the time of failure, parts requests of the Logistics Center would be a good proxy for the time of system failure and for demand.

Instead, sometimes, field locations have an extensive local inventory of spare parts, and instead of immediately ordering replacement parts from the Logistics Center, the field might accumulate broken parts locally as it draws down local inventory. After several months of failures, the location might send back multiple parts to the Logistics Center for repair or replacement. This type of return of parts is not an accurate assessment of when systems or parts failed, and when incorporated into the overall demand forecast, it skews the collection of historical failures and misinforms the trend analysis used to generate forecasts of future demand.

6.1.3 Non-Normal Trend Analyses – Choppy Year-to-Year Because Failure Data Is Inaccurate and Misappropriated by Year
With the noise introduced to demand projections by the uncertain parts returns from NAS parts’ failures, historical failure demand is choppy from year-to-year and is best smoothed out using two or three-year demand averages to forecast annual demand. If broken parts are stored locally until local inventories are depleted and then sent back to the Logistics Center for replacement, the timing of the parts return and the actual failure date could deviate by more than a year. Without using a two or three-year moving average, failure trends might be impossible to see.

6.1.4 Data Source Limitations/Subjectivity/Interpretation
One of the reasons the FAA uses parts returns as a proxy for parts demand is a result of the agency not collecting standardized part-level failure data during maintenance recording and because there is no data exchange between the logistics and maintenance systems. Each system is stove-piped, and the failure data that is collected is recorded in “free-text” fields with maintenance technicians record as much or as little about a system or part as convenient. Different field technicians might record the same system using slightly different system names, and parts’ repairs and replacement might be omitted altogether. Using maintenance recording data alone would not be sufficient to measure demand.

6.1.5 No Definitive Source of Data – Multiple Sources of Data, All with Shortcomings
While the Logistics Center “supply-based” historical demand data estimates are subject to parts’ return delays and choppy forecasts, analysts who try to interpret and track demand based on maintenance recordings might outright miss failures based on naming convention. Neither data source is fault-free,
and neither data source is considered authoritative. Using Logistics demand data and the previously described methodology for estimating future demand and projecting spare parts’ needs over the life of a business case is still the most accurate way to project future parts’ demand and estimate system sustainability. However, is there a way to improve or supplement this demand data?

6.1.6 Short of Revamping Databases and Standardizing Data Collection for Maintenance Recording, How Can Cost Estimators Provide Accurate Analyses and Estimates?

The objective for legacy system sustainment analysis and estimating parts’ demand should be to:

1. Develop a repeatable “how-to” process for analyzing using one data source from the Logistics Center as defined in section 6.1.1,
2. Improve that data and information by correlating the same maintenance actions that make up demand and estimating their actual failure dates by combing through the maintenance data logs and interpreting data in the “open” free text fields,
3. And, finally, refining estimates of demand from maintenance logs by collecting the context provided in maintenance summaries.

If analysts realize that a primary data source of failure and system sustainment analyses is incomplete or inaccurate, supplementing this data source with second set of data collected differently or in the case of the FAA “upstream” of the Logistics data can add fidelity and improve forecasts.

7 FAA Business Case – Using Two Incomplete Data Sources to Improve Sustainment Forecasting

In this business case, we conducted a full sustainment analysis for an operational air traffic control legacy case program:

1. We collected historical failure data and inventory from the Logistics Center,
2. Analyzed the data and generated failure growth rates using two-year moving averages,
3. Forecasted annual parts demand,
4. Analyzed each NSN’s procurement’s needs and means of procurement for lifecycle sustainment,
5. And, estimated the cost of sustainment and spares procurement.

To improve the fidelity of the demand data and forecast, for a select number of parts – trackball, modems, and timecards (clocks) – we compared the data collection in free text “open” fields in the maintenance logging system to the same failure data collected as parts returns to the Logistics Center.

While the data collected by the maintenance logging system does not list each NSN like Logistics Center data does, by utilizing word search techniques, topic analysis, and word associations, we could add fidelity to the failure analysis provided by one incomplete data set alone.

7.1 2nd Source Data Analysis Using Word Associations & Topic Analysis Across Free Text to Improve Single Source Data Integrity

To improve the integrity of the demand data we collected to estimate spare parts demand to sustain an aging legacy infrastructure program at the FAA, we examined another incomplete data source from a maintenance log database. This way, we could search across text fields for parts numbers, system names, component nomenclature, and associated words that field techs might write in the larger context of the maintenance action.
The challenge is that in free text fields, technicians do not necessarily:
- Record NSN part numbers as a reference to what part was replaced,
- Use standardized nomenclature to describe the system or part which failed,
- Define the system fix using the same words,
- Or spell standard system or parts names in the same way.

This lack of data standardization results in likely missed recordings of failures when examining this data alone. Using new data mining techniques, queries, and topic analysis, we were able to explore inconsistencies and potentially improve the demand data we collected from one incomplete data set alone.

### 7.1.1 Queries & Word Variations

For the trackball hardware component, we searched over a three-year period, filtering our data queries using the standard system name in text. This reduced the number of records by more than 50%. However, there is still risk that technicians might not have used the hyphen when spelling the system name or might have used a more generic description. The result of filtering by the official system name is that we might filter out actual historical failures and might not be able to match the recorded demand from the Logistics Center.

While we understand that the Logistics Center demand data timing might be off, especially if some locations collected an aggregate number of serviceable parts before returning them to the Logistics Center, unlike E&R parts which are repaired at the FAA Logistics Center, expendable parts would not be returned, and the field would be more likely to process a replacement part request. The trackball is an expendable item, so we would anticipate (except for potential timing discrepancies) for the number of failures and demand to be the same by year for each data set.

When querying on “trackball” over a single year (2017), the maintenance logging database text search only yielded five records. However, when reducing that word search to a smaller (but still unique) word choice and using “track,” our query generated an additional record where the word was spelled “TRACK BALL” as two separate words. Using the first query where we spelled trackball as one word, we missed a real record of a repair and part replacement. Changing the search word again to “ball” yielded still one more failure result when the word “slewball” was recorded in the free text field. By examining the location and identity of that failure, we determined the failure referenced was also a trackball, but listed with a different nomenclature.

Comparing the number of failures to the Logistics annual demand number, the maintenance logging data was half the number of records as estimated by the Logistics Center. Reconciling those would require understanding which parts actually failed in a given year and did not roll over to the next one. A larger aggregate sample size of years might resolve that. And, if the FAA system were spelled differently by any user, the maintenance logging system records might have been more comprehensive.

### 7.1.2 Associated Word Descriptions and Topic Analysis

While topic analysis is a machine learning technique that analyzes text data for word clustering and related words to which we can associate our target data, the same outcome can be achieved manually via querying and analysis. In the absence of writing algorithms, we analyzed the modem parts and the
word associations. By querying/filtering on “modem” in 2017, we generated 17 records of failures, the same number of failures recorded by the Logistics Center for the same part.

However, on further examination of the descriptions and the action words around the modem summary, we could differentiate between modems that were just “reset” and those which were explicitly “replaced.” Reset modems were not necessarily replaced by a new modem in inventory, so the number of modem failures recorded may have been the same demand estimated from the Logistics Center, but the actual failures of those parts is likely a subset of that total. In addition, parts that failed may not actually be broken, and the Logistics Center tests returned failed parts before restocking serviceable stock at the Depot Logistics Center. By further examining and analyzing the nomenclature and searching across like words – “reset” and “replace” – we might be able to identify additional records or we can eliminate a percentage of these failures by instead recording an aggregate amount as only modem “resets” and not inventory depletion.

7.1.3 Word Descriptions
For the final part analyzed, we searched for the legacy system timecard, also called a “clock” or “CCA” (circuit card assembly). We discovered four records in 2017, just one more than was recorded as 2017 demand using Logistics Center data alone. We generated no records using the words “timecard” and “clock,” but we generated four records, three of which were replacements when querying “CCA.” Since one of the repairs was generated in October, there is a chance that a demand as calculated from the Logistics Center had a timing delay, and one of that year’s failures might have been recorded in the subsequent year.

8 Conclusion
Sometimes in government agencies, cost estimators are presented with incomplete data sets from which they must generate forecasts and conduct predictive analyses. In major government infrastructure capital investments, the FAA cost estimating and business case team generated a methodology for conducting legacy sustainment and obsolescence analyses to estimate a system’s end-of-life and the date by which it might risk loss of service. This analysis was conducted with the premise that the demand data collected to estimate historical parts failures and from which a forecast of future failures could be generated is accurate and not clouded by inconsistent agency practices. However, when estimating parts demand at the FAA, analysts must consider that not all spare parts are returned to the Logistics Center right after failure, and the timing for demand might be skewed depending on the practices and spares inventory at certain locations.

By supplementing one incomplete source of demand data with a second source of data, the team was able to reconcile some parts demand records and improve the fidelity of sustainment analyses. By using topic analysis and other text data analysis techniques, the program office could add context to system failures and parts demand and improve sustainability forecasts.

Adding these techniques to business cases and investments that utilize incomplete data sets, cost estimators and program offices will be able to make better informed decisions about infrastructure investments and the timing of those investments.