COMBINING TRADESPACE EXPLORATION WITH SYSTEM DYNAMICS TO EXPLORE FUTURE SPACE ARCHITECTURES

by

Paul A. La Tour

B.S. Electrical Computer Engineering
Purdue University, 2005

M.S. Systems Engineering
Air Force Institute of Technology, 2011

Submitted to the Institute for Data, Systems, and Society
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Engineering Systems

at the

Massachusetts Institute of Technology

June 2016

© 2016 Massachusetts Institute of Technology. All rights reserved.

Signature of Author……………………………………………………………………………...
Institute for Data, Systems, and Society
May 23, 2016

Certified by…………………………………………………………………………………………...
Daniel E. Hastings
Cecil and Ida Green Education Professor of Engineering Systems and Aeronautics and Astronautics
Thesis Supervisor

Accepted by…………………………………...……………………………………………………………
Sheila E. Widnall
Institute Professor and Professor of Aeronautics and Astronautics
Committee Member

Accepted by…………………………………...……………………………………………………………
David W. Miller
Jerome Hunsaker Professor of Aeronautics and Astronautics
Committee Member

Accepted by…………………………………...……………………………………………………………
John N. Tsitsiklis
Clarence J. Lebel Professor of Electrical Engineering
IDSS Graduate Officer

COMBINING TRADESPACE EXPLORATION WITH SYSTEM DYNAMICS TO EXPLORE FUTURE SPACE ARCHITECTURES

By

Paul A. La Tour

Abstract

This work proposes a merger of Tradespace Exploration with System Dynamics modeling techniques in a complementary approach. It tests the value of this mixed method for modeling the multiplicity of inputs and complexity of feedback loops that affect the cost, schedule and performance of satellite constellations within the Department of Defense. The resulting simulation enables direct comparison of the effect of changing architectural design points and policy choices with respect to satellite acquisitions and fielding. A generation-over-generation examination of policy choices is made possible through the application of soft systems modeling of experience and learning effects. The resulting model enables examination of possible futures given variations in assumptions about both internal and external forces on a satellite production pipeline. This thesis performs a policy analysis examining the current path of the Global Positioning System acquisition and compares it to equivalent position navigation and timing capability delivered through a variety of disaggregated options while varying: design lives, production quantities, non-recurring engineering and time between generations. The extensibility of this technique is investigated by adapting the model to the mission area of Weather and Climate Sensing. This thesis then performs a policy analysis examining different disaggregated approaches for the Joint Polar Satellite System, focusing on the impact of complexity. Discussion of factors such as design choices, context variables, tuning variables, model execution and construction is also included.

Executive Summary

This work develops and implements a merged modeling approach utilizing the tools and techniques of Tradespace Exploration (TSE) and System Dynamics (SD) to investigate Department of Defense (DoD) space systems acquisitions across multiple generations. It is industry practice to use TSE to investigate the cost and performance of varied design points. It is hypothesized that a SD model can be linked to a TSE model to create a merged model that takes advantage of the ability of SD to predict change across time. The SD model which was developed tokenizes the production of satellites through a pipeline abstracted to represent satellite acquisition in the DoD. This method enables modeling the multiplicity of inputs and complexity of feedback loops that affect the cost, schedule and performance of DoD satellite constellations, as well as enabling policy testing. A generation-over-generation examination of policy choices is made possible through the application of soft systems modeling of experience and learning effects on design points and then evolving these decisions over multiple generations. The statistical validity of the SD model is assessed through standard statistical tests; the error associated with matching five historical reference modes is similar to and often better than that of existing cost models.

The merged model is developed and tested with data from the Global Positioning System (GPS) program of record. The model is asked to project the likely acquisition path over the next four decades. The model operates under assumption sets that favor the existing, highly aggregated GPS satellite design. Results indicate that continued purchase of satellites with design lives of 15 years is acceptable. Additionally, purchases in blocks of 12 is optimal. If purchasing blocks of 24, it is true that satellites 13 to 24 may be cheaper to construct, but the age of technology associated with these satellites becomes so great (potentially 16 to 24 years), that the cost for required upgrades make the following generation more expensive. Over multiple generations four block buys of 12 is a better implementation than two blocks of 24. Cost of GPS acquisitions can also be reduced by upgrading the bus technology in one block and payload technology in the next. This leads to an initial increase in Non-Reoccurring Engineering and Integration and Tests cost, but lowers the overall acquisition costs over multiple generations.

Various policies of payload disaggregation are also examined by the model. A split between a military and civilian GPS satellite, effectively doubling the number of GPS satellites, is likely initially to raise costs over the current GPS satellite program on the order of ~22%. While this split would, over multiple decades, increase the efficiency of the satellite acquisition process, it would likely never provide better than a cost-neutral acquisition. This approach is highly unlikely to benefit from learning effects and will not improve the health of the GPS production pipeline.

A disaggregated approach splitting the GPS constellation into three satellites is also found to be cost neutral against current GPS plans. While dollar cost savings are not possible (as learning effects do not take hold), a three-way disaggregation does deliver between 25 to 35 percent more years of operational capability to orbit for the same price. While this is promising, any attempt to hold back extra capability until it is needed erodes potential gains from learning across generations.

A fully disaggregated approach, where each satellite carries one payload, would place between five and seven times as many satellites on orbit. With the construction of this many satellites, learning effects do take hold and it is possible to reduce production costs in future years. While this implementation increases life-cycle cost between 12 and 20 percent over the current GPS plan, this program has very little risk of failing to deliver capability to orbit on time—an objective the current GPS acquisition plan has struggled to achieve. It is also unclear if the 2x or 3x disaggregated approaches can accomplish this.

A survivable disaggregated architecture with four (growing to six) more satellites on orbit is possible for the GPS constellation at a cost increase of 40% over the baseline for the first generation (the time period equivalent to building 12 standard GPS satellites) and 30% thereafter. The cost may be somewhat lower as these numbers do not assume any part commonality among designs despite the fact that part commonality is highly likely. In this work survivable disaggregated architecture was implemented as:

- Satellite 1: L1 and M1 signals
- Satellite 2: M1 and L2 signals
- Satellite 3: L2 and M2 signals
- Satellite 4: M2 and L1 signals

With this configuration the gain in survivability is dramatic: any one satellite can cease operations with no degradation in performance of the constellation. The constellation can operate with no loss in performance with up to 25% of the satellites lost. Beyond a loss of 25 percent, capability may degrade gracefully since the loss of additional satellites creates coverage gaps only with respect to the signals on the buses lost. Furthermore, as many ground receivers make use of multiple signals, even this loss may not fully degrade capability to the end user. It is also possible that satellites could be moved within their planes over a short (multi-day) time period to cover gaps to operate at acceptable levels even near 50% constellation strength.

Production of satellites for survivable disaggregation is at a rate between four and six times faster than current; satellites would roll off the production pipeline at a rate of three every two months. Satellites which are substantially smaller than existing designs means faster production times and less time before lessons flow back and enhance a future round of production. This approach also enables the ability to replenish in a targeted manner, and more risk-reduction/capability maturation missions can be achieved as extra space is available on some of the satellites with less payload mass (e.g., flying an extra next-generation atomic clock, or key components for a new signal generator). In short, such an implementation would improve the efficiency of GPS satellite acquisitions. If model bias are relaxed, to include benefit for part commonality and ease of constructing smaller satellites and less on orbit operational costs, then activity levels between four and five times the current level possess the change for learning effects to trump additional life-cycle costs.

The extensibility of the merged model technique is investigated by adapting the model to the mission area of Weather and Climate Sensing. Results show the technique can be used to generate insight about another satellite acquisition program in another mission area. This adaption indicates that this technique might possess further extensibility to other domains, where

cost and performance models exist and a system dynamics model might be made to abstract human behavior.

Across future generations of the Joint Polar Satellite System (JPSS) learning effects and cost savings are most likely if a disaggregated approach is adopted that implements a common bus and places the equivalent sensor capability on three busses (3x disaggregation). With this configuration, each bus hosts up to 400 kg and a fourth satellite is added in later generations in anticipation of additional desired capability. Costs are anticipated to rise six to eight percent over the JPSS baseline for the first two generations (approximately seven to 10 years per generation) and thereafter are reduced ten percent relative to the JPSS BATNA (fully aggregated implementation). While costs are not reduced over the planned JPSS program, the minor cost increase is expected to deliver 60 to 85 percent more capability to orbit during the same time period (more sensors for the same cost). Disaggregation beyond this level is less appealing: it is associated with increases in on-orbit and data processing costs as well as a loss of commonality among bus designs. Disaggregation to two busses is insufficient to capitalize on learning effects over multiple generations, and hence unable to reduce costs relative to the current JPSS program.

Acknowledgements

Table of Contents

List of Figures

14

15

List of Tables

1   Introduction

Space missions are an exceptionally difficult enterprise with substantial barriers to entry, including formidable requirements for reliability, high degrees of complexity and automation, and substantial infrastructure requirements. The ride to orbit is a risky and expensive controlled explosion, and the operating environment of space is exceedingly harsh, far from conducive to the technologies and standard design paradigms used by industries on Earth. Nevertheless, space has now been open to human activity for more than 50 years and technology has progressed significantly since Sputnik and the Cold War space race.

There has been no lack of investment in space operations as applications for satellites and space-based services have steadily increased, moving beyond original military and government applications into commercial enterprises. Based on experience with the development of other industries (e.g., semi-conductors, copiers), many expected that space technologies would become progressively less expensive and require less time to develop and manufacture as the industry matured. This was part of the underlying logic in aligning Department of Defense (DoD) practices with commercial practices and breaking from traditional Military Standard or "Mil Spec," when in 1994 then Secretary of Defense Perry stated that "moving to greater use of performance and commercial specifications and standards is one of the most important actions that DoD must take to ensure we are able to meet our military, economic, and policy objectives in the future" (Perry, 1994). The opposite has occurred, however. Almost all major space programs and businesses have experienced rising costs and lengthening development timelines over the last few decades (Wertz J. , 2013).

This may be a result of building for an unforgiving design point associated with very little margin for error: a single unexpected failure of one spacecraft or component could cause a devastating loss of capability or performance for years. A design point which cannot afford any failures requires extra work and engineering to obtain reliability. As the demands for quality increase, the required level of excellence can be obtained only through an ever-increasing and ever-more-complicated sequence of best practices. Rising costs and increasing time may also be, ironically, associated with an industry focus on minimization of total life-cycle cost. A review of the industry reveals that the designs of space systems have nearly unanimously converged at massive, complex, and long-lasting spacecraft (Saleh J. H., 2008), with one key driver of this trend being the minimization of the cost per operational day. Such vehicles are more costly and require increasingly long timelines to design and build. Low production numbers cannot gain quality through process, but must obtain it through extra engineering, design, and testing. In addition, they are associated with a strong aversion to the use of new methods or technologies (which might be less expensive or shorten production time), due to the risk involved in fielding first-of-a-kind systems.

Wertz believes the space industry is caught in a spiral, where higher costs lead to longer schedules and fewer missions, which lead to a demand for higher reliability and longer design lifetimes, which then lead back to higher costs (Wertz J. , 2011). Consistent with this observation, the next generation of all major unmanned DoD constellations: Global Positioning System (GPS), Space Based Infrared, Space Weather, Terrestrial Weather, and Communications are planned to be longer-lasting, more capable, larger variants of existing constellations.

As would be expected, the DoD views space architecture and assets as important aspects of national security. Confronted with increasing costs and timelines, it has proposed a variety of

possible strategies: improving the acquisition process to smooth out pipelines, disaggregating assets to artificially inflate activity, subsidizing launch activities, incorporating more prototypes into the development pipeline, and changing the design life. Many of these ideas are designed to work in conjunction with each other, based on the observation that other high-tech industries, including airlines, medical equipment and chip manufacturing, have successfully used various combinations of these policies to improve their posture.

Unsurprisingly, the DOD also considers the United States Space Industrial Base's capability, and the procurement and operation of space assets, to be an issue of national security (Bureau of Industry and Security, February 2014) (Memorandum from the Under Secretary of Defense: Acquisition Technology and Logistics, 2013). The latest guidance from the DoD advises acquisition professionals to consider the "should-cost" of the program, the relationship of the program to the industrial base, and the maturation of enabling technologies within the technology cycle (Under Secretary of Defense Acquistion Technology and Logistics, 2015). This line of thinking hypothesizes that the design of spacecraft constellations and the demands placed on space architectures are causally linked to the health of the United States Space Industrial Base: specifically, which systems are requested and when they are requested leads to different maturation within the space industrial base. This creates an environment in which both the operation and production of space assets can improve or degrade over time, based on the acquisitions requested by the government. Various metrics have been employed to operationalize the concept of health including: number of companies in the industry, number of satellites constructed, number of rockets launched, amount of capital committed, and opinions on future outlook (National Security Space Office, 2007).

In sum, the raw costs of obtaining space-based capability have risen, rather than declined over time, and the physical number of satellites being launched has not significantly changed, leading to a feeling that progress has stagnated. The DoD, along with industry experts, have proposed a number of possible strategies to improve this situation. This work seeks to develop a model that recognizes the multiplicity of inputs and complexity of feedback loops affecting the cost and scheduling of satellites. This model will be used first to predict what might happen in satellite acquisitions if current trends continue. Then the model will be used to examine the effect of various strategies suggested to reduce ever-increasing costs and time-to-launch. It will also directly compare the futures predicted given variations in assumptions about both internal and external forces on the space industry. The model will be developed and tested in the context of GPS and then extended to Weather and Climate Sensing satellites.

1.1 Background: Definitions of Key Terms

1.1.1 Distributed Space Systems

A distributed system is one which requires multiple assets to perform its mission. One definition states that "Distributed space systems are multi-satellite systems that work together in order to perform a unified mission" (Kitts, Pranajaya, Townsend, & Twiggs, 1999). A more precise definition states: "Distributed Space System (DSS)—An end-to-end system including two or more space vehicles and a cooperative infrastructure for data acquisition, processing, analysis and distribution" (Gurfil, 2015). For example, the satellite which provides DIRECTV to the continental United States is not a distributed system, as it performs its function with only one satellite. GPS is a distributed system because multiple assets are required to perform its operational goal.

Performance metrics for distributed systems are tied to the level of distribution found within the system; typically, more assets are linked to higher performance.

1.1.2 Aggregation and Disaggregation

With respect to space systems, disaggregation refers to spreading capability across multiple assets. A disaggregated space system could in theory be aggregated and suffer no change in performance under normal operating conditions. If aggregation of assets leads to a change in performance under normal conditions, then distribution is the parameter that is changing rather than aggregation level. Disaggregation impacts the acquisition of space assets as it splits fabrication into smaller units of work and in theory lowers the complexity of the individual satellite. Overall system complexity could change, though disaggregation does not have to affect this. Disaggregation with respect to space systems can improve different performance metrics than distribution, as noted in the United States Air Force (USAF) document, "Disaggregation improves mission survivability by increasing the number and diversity of potential targets" (Air Force Space Command, 2013).

In this work, disaggregation refers to the splitting of payloads across multiple busses. Other work, including the Defense Advanced Research Projects Agency's (DARPA) now defunct F-6 (Ferster, 2013), has also examined disaggregation of bus functions; this is outside the scope of this effort and designs where less than one capability is provided per individual satellite are not considered. The GPS system is currently a highly aggregated space system with current assets hosting seven or more signals on a single bus. Splitting payloads across two or more busses would disaggregate the GPS system while maintaining its level of distribution.

1.1.3 Classes of Variables

In this work, three primary classes of variables are discussed: Design Variables, Context Variables and Tuning Variables.

- Design Variables are those over which a decision-maker has complete control and can change. These lead to the construction of what is known as the design vector in Tradespace Exploration (TSE). (Discussed in more detail in Chapter 1.) Within TSE, design points are the specific elements contained within the design vector and are one possible enumeration of the design variables.
- Tuning Variables are requirements of the modeling and abstraction process—as a model cannot encompass all concepts and ideas nor can a model possess the same fidelity as the real world. These variables must be selected such that results are in line with real-world experience or are required to tie to abstract concepts together. These variables, which are intended to compensate for some errors (typically omission of elements from a model) can be sources of other error and are traditionally the first assumptions to be examined in validation of any modeling effort. (The role of this class of variable is discussed further in Chapter 3.)
- Context Variables represent change over time and may be represented as discrete or continuous. These variables are traditionally considered exogenous to TSE efforts. Within System Dynamics (SD) modeling efforts, context variables may be exogenous or endogenous to the model and changes in one will likely lead to changes in another over the time of model evaluation. (This is further discussed in Chapter 6.) These variables and their effects will be derived from available data sets and trend lines.

1.1.4   Best Alternative to Negotiated Agreement (BATNA)

The model representation of the historical GPS program of record and the plans currently in place to construct the next GPS constellation will be referred to as the Best Alternative to Negotiated Agreement or BATNA (Fisher & Ury, 1981) or GPS BATNA. If no new agreement within the USAF, DoD and congress is reached, the GPS constellation is likely to continue on the path listed above and as on government websites. As such, when modeling alternate architectures with different value propositions, one might consider the GPS program of record as a BATNA against which to compare other candidate architectures. The GPS IIIA, as outlined in 2008, will be the GPS BATNA to which other architectures which might have been proposed in 2008 are compared. Future proposed changes to the GPS constellation will use the existing upgrade plan for GPS as a BATNA against which to compare potential future architectures.

The same approach will be taken for the Weather and Climate Sensing mission area. The Joint Polar Satellite System (JPSS) and precursor programs of North Polar-orbiting Operational Environmental Satellite System (NPOESS) and Defense Meteorological Satellite Program (DMSP) will be considered as the JPSS BATNA. Other implementations in 2010 and later of Weather and Climate Sensing satellites will be compared to the JPSS BATNA.

1.2 Background: United States Space Industry Trends

On the basis of developments in the computer and smartphone industries, one might expect that the cost and mass of the typical spacecraft would have decreased in the last two decades, or at least remained mostly constant, and the replacement cycle to have become shorter. By and large, however, these changes have not occurred. Almost unanimously the major trends in spacecraft manufacturing have been towards more expensive, larger, longer-lasting vehicles. This can be seen in Figure 1-1 and Figure 1-2, which present the design lifetimes and launch masses of civil, commercial, and military spacecraft launched to geosynchronous orbit over the last two decades by the United States (Union of Concerned Scientists, 2014). The data implies that improved performance has come not only from increases in cost and size but that decision-makers have elected to gain additional capability beyond technology advancement through increasing cost and mass. The trend lines strongly suggest that space systems are still evolving and have not reached equilibrium or converged on a design.

Saleh has shown that the cost of spacecraft increases with extended design life, but that cost-per-operational-day estimates decrease with longer-lasting vehicles. While diminishing returns occur after a design life of approximately eight years (Figure 1-4 and Figure 1-5), extending design life continues to offer decreases in cost per operational year (Saleh J. H., 2008).

On the basis of either general advances in technology or the observation of more expensive, larger and longer-lasting spacecraft, one would expect the power and performance of spacecraft to have improved. Indeed, the average power of spacecraft over the last several decades fits an exponential growth curve. (See Figure 1-3.) Using power and mass as proxies for spacecraft performance, it is evident that performance too has increased. In sum, designers of spacecraft architecture have consistently opted for higher-performing, longer-lasting, increasingly massive space vehicles (SVs). It seems likely that selection of this design point is encouraged by the acquisitions process in conjunction with funding mechanisms. Space is still primarily a government activity, as the majority of funding is provided through government mechanisms these

trends are driven by government decision making, indicating the government possesses some control over these trends (National Security Space Office, 2007).
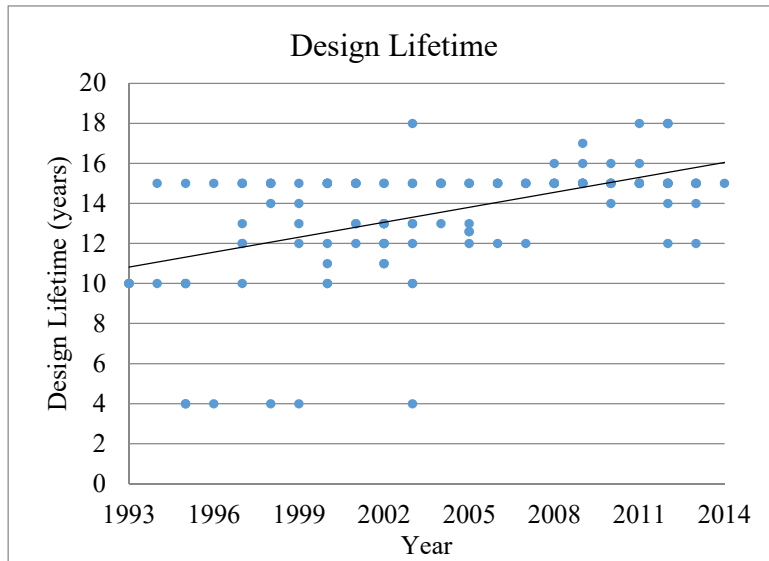
Figure 1-1: Design Lifetimes of Active Geosynchronous Spacecraft over the Last two Decades (UCS, 2014)
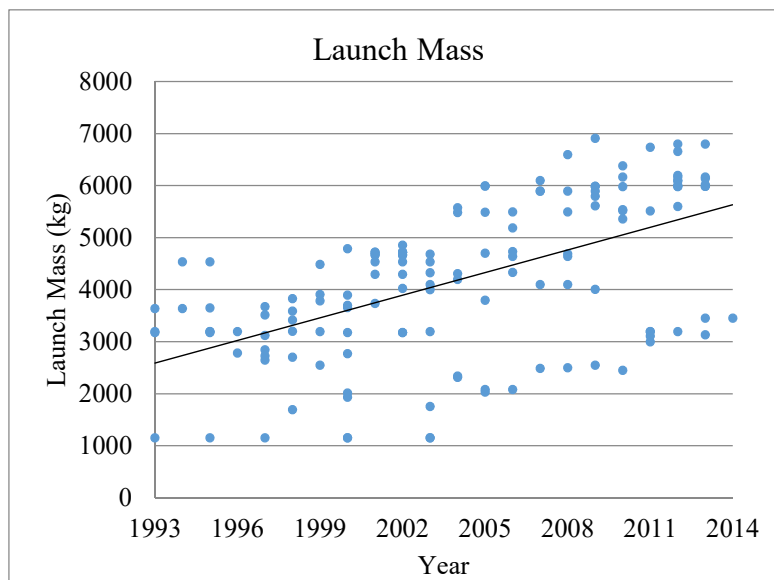
Figure 1-2: Launch Masses of Active Geosynchronous Spacecraft over the Last two Decades (UCS, 2014)
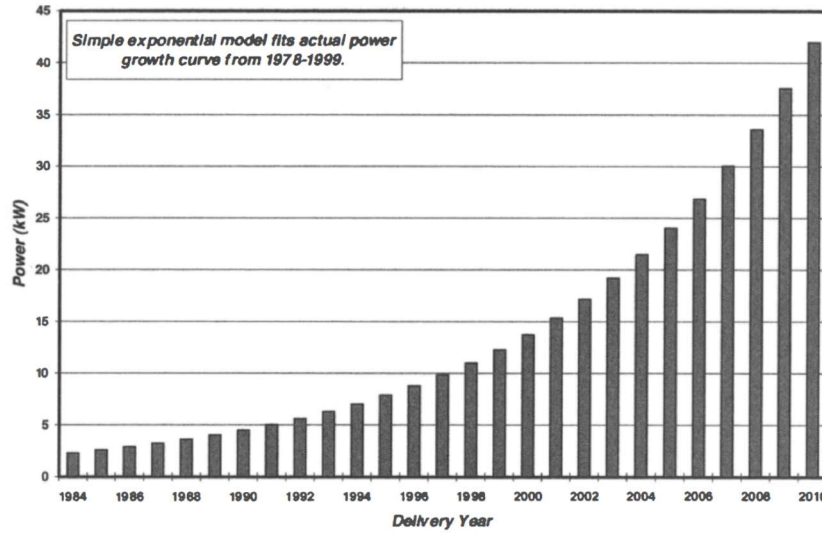
Figure 1-3: Increases in Average Power of Geostationary Spacecraft (Jones and Spence, 2011)
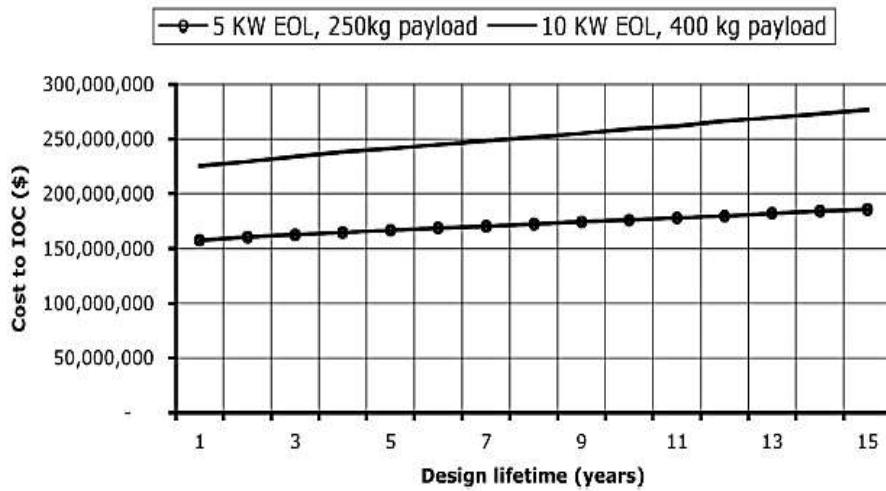
Figure 1-4: Cost to Initial Operating Capability (IOC) as Design Lifetime Is Increased (Saleh, 2008)
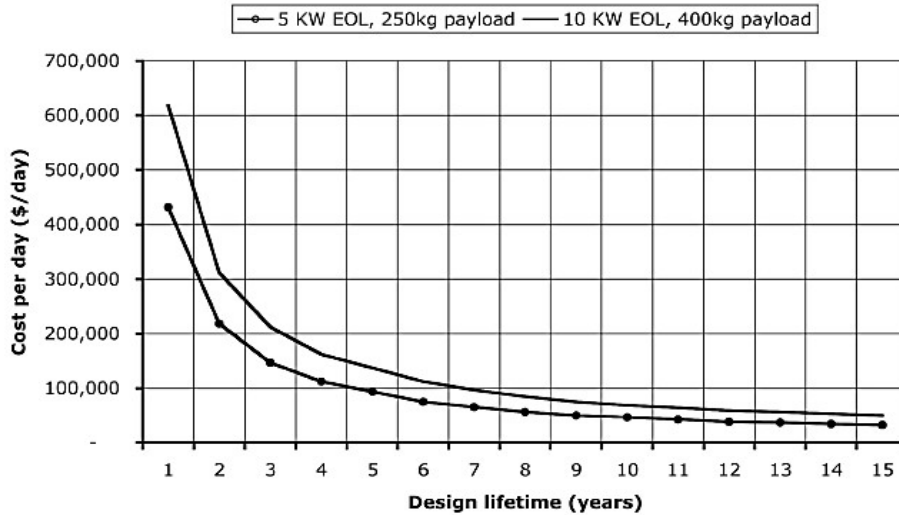
Figure 1-5: Cost per Operational Day of Spacecraft as Design Lifetime Is Increased (Saleh, 2008)

Some authors have noted that a design point of higher-performing, longer-lasting, increasingly massive space vehicles seems somewhat at odds with risk preferences. Richards writes that this design point negatively affects the health of the United States Space Industrial Base and places space systems in a riskier position, as any failure is catastrophic and requires years for recovery (Richards M. G., 2009). Clearly, larger systems have more redundancy and are themselves better able to survive perturbations. Nonetheless, this invites other risks e.g., putting all your eggs in one basket. While one would hope that every satellite put on orbit would arrive without issue, history notes otherwise: in the last 4.5 years, seven Proton rocket engines (Russia's and by extension the international community's workhorse launch system) have failed to place their payloads in orbit, the Indian Mars mission almost failed due to an upper-stage burn failure, a United States GPS satellite limped to orbit, the last two Galileo satellites were put into an elliptical orbit and Russia lost its most expensive, state-of-the-art communications satellite. In some of these cases redundancy or extra capability was able to salvage some system utility, but not in all cases. The Space Industry may have reached a tipping point where continual increases in system size and design life may no longer result in overall gains.
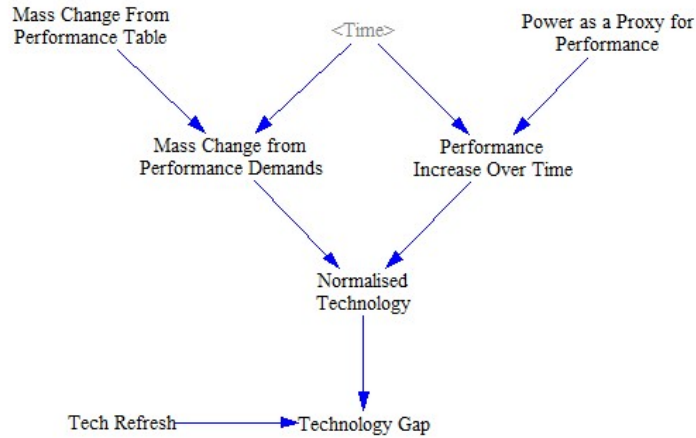
Figure 1-6: Normalized Technology-Performance Computation
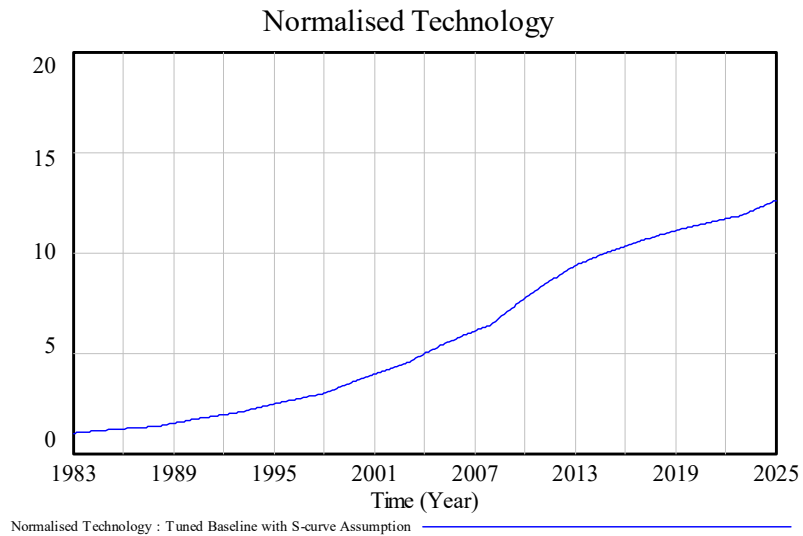
Figure 1-7: Normalized Technology-Performance Curve

The data in Figure 1-2 and Figure 1-3 can be combined to obtain insights about the advancement of underlying technology. Figure 1-7 shows how the change in mass over time and the variable of power (measured as watts) in communications satellites over time can be used to compute a normalized Technology Growth or Technology-Performance curve based on the logic of Figure 1-6. Dividing the Power of the average communications spacecraft (watts) by the Change in Mass (kg) of the average communications spacecraft results in a normalized metric of the impact of technology over time. One can think of this as the change in potency or efficiency of spacecraft over time, where power is a single variable for performance. Over time more power can be placed in a single satellite of equivalent mass. This is one way to compute the impact of technology over time on performance of communications satellites. The graph also indicates a growth rate of technology that is non-linear and may be approximated by a quadratic (or even potentially, an exponential) function.

32

The trend line in Figure 1-7: Normalized Technology-Performance Curve represents the industry as a whole, however, a constellation of satellites or an individual satellite design will need to update or refresh its technology whenever a new satellite is required. An underlying assumption is that satellites are built by companies which do not share technology with each other, but do draw technology and expectation of capability from the same general pool of knowledge. This seems a reasonable approximation of the industry which operates in a trinity of the Government (DoD), The Aerospace Corporation, and system integration contractors (e.g., Boeing, Lockheed Martin, etc.). Each organization knows the general trends in capability and exogenous technology but typically must refresh its technology for each new satellite design, based on technology maturation both inside and outside the space industry.

Figure 1-8 depicts the normalization of such a Technology Growth curve to technological update events. When a "tech-refresh" or Non-Reoccurring Engineering (NRE) payment is made with respect to this set of technology the growth curve is re-baselined and set back to zero. This is one way of visualizing (a simple model) how much technology may have matured over a time period. Other evaluations can be performed on technology-over-time variables and will be considered in Chapter 2.
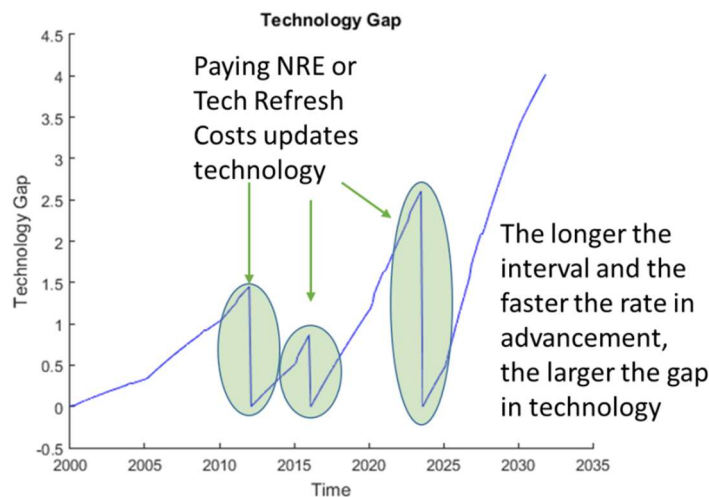
Figure 1-8: Normalized Technology-Performance Curve Re-baselined at Tech-Refresh

The problem of fielding high-performance space systems in a cost-effective manner has been tackled for over thirty years. It appears space has reached a crossroads in development where cost reduction can no longer come from increasing design life—there is an upper limit on how long a physical asset can maintain operation without servicing. With future reductions in funding (based on funding projections), gaps in DoD space capability are a realistic possibility in weather and environmental monitoring (United States Government Accountability Office, 2012) (Office of the Federal Coordinator for Meteorological Services and Supporting Research National Space Weather Program Council Joint Action Group for Space Environmental Gap Analysis, 2014).

Current spacecraft perform exquisitely and reliably once on orbit, however, due to their enormous cost there is no room for failure. The development schedules required to build, test, and deliver new spacecraft now typically extend a decade or more. Cost and schedule overruns on new

spacecraft are the norm, and the United States Space Industry as a whole has exhibited a high degree of consolidation and monopolization as firms chase larger and lengthier contracts (Wertz J. , 2011). This leads to a core question for analysis: what are the advantages and disadvantages of this path?

Advantages of the current implementation appear to be:

- Known and successful implementation
- Minimizes cost per operational year given current context
- Likely continues to work given current context
- Economies of Scale
    - ◆ Satellite bus to payload ratio (in favor of more payload and less overhead)
    - ◆ Minimizes number of launches
    - ◆ Fewer assets to control on orbit; fewer operators at console
    - ◆ Fewer acquisition efforts; in theory, less human overhead
    - ◆ Fewer physical assets; in theory lowers complexity

Disadvantages appear to include:

- More complexity per satellite
- More rigorous and longer testing required
- Long design life of satellites leads to slow rates of tech refresh; lengthy reliance on old technology
- Low chance of capturing learning effects
    - ◆ Knowledge becomes obsolete before replacement of assets; low chance of cross-generation learning
    - ◆ Actual performance data indicate no savings on replication cost inside a block or generation
- Large gaps in time between satellite generations means that subject matter experts are not likely to be available for a more than one generation (people will experience only a small number of programs), and that book knowledge is likely out of date
- Every block of satellites built is a "one off" or first experience, and production seems to only improve at the very end of the production run
- Single failures result in large setbacks

1.2.1   An Engineering Systems Problem

An Engineering System problem is an issue that possesses economic, technical and social aspects. The problem of fielding and sustaining space-based capabilities is such a problem.

1. Economic: Space systems are national assets; our economy and security depend on space-based services. Yet, the sustainability of and ability to deliver current capability for the next ten years may not be possible given current budget projections; this is a resource constrained environment. General Hyten, Commander of Air Force Space Command (AFSC), says 2016 "scares him," because we will not be able to replace our assets as quickly as they wear out; gaps are now projected that cannot be plugged. (Gruss, 2014)
2. Technical: The Space Industry provides both a pull and a push to technology. The Space Industry has spun off many technologies which have been beneficial to other sectors of

the economy and the Space Industry has grown with the technological revolution of the digital age. Satellites and rockets are at the very front of humanity's technological prowess. Space technology, however, is not a "silo." Advances in communications, power systems, and data processing from external industries must also be incorporated into the next generation of systems.

3. Social: Possibly the most difficult aspect of the Space Industry is the *human* endeavor of contracting, building, launching and maintaining space assets. A growing stakeholder problem is also emerging as the distinction between military asset and national infrastructure softens. For example, GPS was developed to report the location of nuclear detonation, not calculate the optimal path to a coffee shop. The DoD is undergoing substantial changes in its acquisition process to cope with the growing complexity of large acquisitions programs, many of which are in the space domain (Under Secretary of Defense Acquistion Technology and Logistics, 2015). This Social problem also bridges the Economic problem where funding streams come from the President's Budget and if not approved in time can cause shock to the acquisitions pipeline.

1.2.2   Simplified Example: Galileo versus GPS

While investigating these research questions is highly complex and requires the distillation of a substantial amount of literature, experience, and theory to properly abstract and understand the nature of this sociotechnical system, a simple model might provide insight in defining system boundaries and key variables. The simplest model for evaluating such a question might compare GPS and Galileo, the European Space Agency's implementation of a position navigation and timing (PNT) satellite constellation, on three variables using linear equations.

The GPS solution (Block IIIA), for which development began in 2008, could be characterized as:

- Cost per copy: $224M
- Design life: 15+ years
- 7 signals

Galileo could be characterized as:

- Cost per copy: $30M
- Design life: 12 years
- 3 signals

It should be noted that the actual values vary by source and these values are for illustrative purposes only. Computation of the ratios of each variable would yield a model that can compute which implementation delivers the same capability for the lower cost per year.

- $224M/$30M = GPS is 7.5 times the cost
- 15/12 = 1.25 = GPS lasts 1.25 times longer
- 7/3 = 2.33 = GPS delivers 2.33 times the capability

On a per-signal basis, considering only the replication cost of the satellites, GPS delivers 1.25 times the lifetime and 2.33 times the performance for 7.5 times the cost. This simple comparison indicates that from a replication stand point GPS is worse than the Galileo implementation of PNT by a factor of ~2.5. This three-variable analysis is clearly simplistic as its system boundary is

drawn only at the replication of satellites (assuming that performance is actually equivalent), and it lacks consideration of research and development, launch vehicles, ground support, the operational reality of satellite acquisitions and operations, and the fact that most GPS satellites last 1.5 to 2 times their design life (Lockheed Martin, 2015).

Nonetheless, it is intriguing that these two design points may be far apart and if they are, what is the reason for the poorer evaluation of GPS? Complexity? On-orbit operations costs? Launch costs? It seems unlikely that GPS is 2.5x "worse" than Galileo based on a cost-to-performance ratio, but it is intriguing. In the calculation above, the element of time is included through design life in the cost-per-year metric. An important element missing from this calculation is the numerous other effects that time brings. Over time technology will change, industrial bases will emerge, and humans should become better at designing and producing space systems. These elements would, however, favor the Galileo design point rather than GPS.

Expanding this model into an engineering systems problem requires extending the boundary to the Space Industry which produces and supports this system, as well as connecting with other satellite programs and the larger sphere of space systems design. As shown in Table 1-1, based on the raw number of satellites produced over 40 years, GPS's current implementation would produce 64 satellites; an average of ~1.5 per year. Galileo's smaller, three-signals-per-satellite bus would need to produce 27 satellites to match the equivalent capability of one GPS satellite over the same time period (assuming three Galileo satellites could deliver the same performance and last 12 years each). If GPS were to adopt the Galileo-sized design point, it would increase the number of satellites required to perform the mission. The Galileo-sized design point turns production for GPS satellites from two per year to one every two months.

Table 1-1: GPS vs. Galileo-equivalent Average Satellites Built per Year

Year	0	5	10	15	20	25	30	35	Total	Average Built Per Year
GPS Satellites Ordered	8	8	8	8	8	8	8	8	64	1.6
Galileo Satellites to Match GPS Signals	27	27	27	27	27	27	27	27	~240	5.4

This would reduce current economies of scale, requiring more bus mass to support the same payload mass. But would the extra activity required create enough learning that the benefits could overcome the loss in economies of scale in design life, a decrease in the payload-to-bus-mass ratio, and an increased number of launch vehicles? If this is not possible, it would still be useful to know how much more this design point would cost as it is associated with other benefits. These benefits may include a more robust industrial base, a greater ability to replenish in the event of catastrophe, and potentially increase survivability of some PNT capability in the event of loss. Considering that as of 2012 GPS was estimated at a value of $1.6 trillion to the economy (Henttu, Izaret, & Potere, 2012), paying extra to ensure this capability may be acceptable. Such considerations change the analysis from one concerned only with satellites to one that considers satellites and the industry which produces them. Having now drawn the system boundary at not only the lifecycle but also

the replication of the system and delivery of the next generation of satellites, the scope of the problem becomes unwieldy for a human mind.

While this mental exercise provides an initial insight into concepts and variables, it gives no insight into other possible solutions or how one might evaluate all the other options between and beyond these implementations. Chapters 2 to 4 will build a model of sufficient fidelity that such a comparison can be made. In each of these chapters this comparison between the GPS BATNA and the Galileo-sized approach or 3x Disaggregation will be made; each time adding a new dimension to the examination.

1.3 Level of Analysis and Modeling Boundary: Satellite Constellations and the United States Space Industry

This work seeks to create a predictive model for the purpose of examining future development of space assets. For the purpose of examination this work implements an abstraction of the acquisition and development of space systems as represented in Figure 1-9. This figure shows that at the highest level, Industry continues to evolve and develop technology and processes; this will occur regardless of events inside the Space Industry. Some of the technologies developed may be used by space systems and come in many forms: physical (e.g., solar cells), software (such as communications protocols), and even processes (such as test and evaluation). A subset of Industry is the Space Industry, which produces technologies specific to space assets such as: rockets, satellite busses or ground control stations. These are systems or technologies that will not evolve through activity outside of the Space Industry; however, some of these technologies may spin off and be used by external industries just as the Space Industry makes use of other industries' technologies.
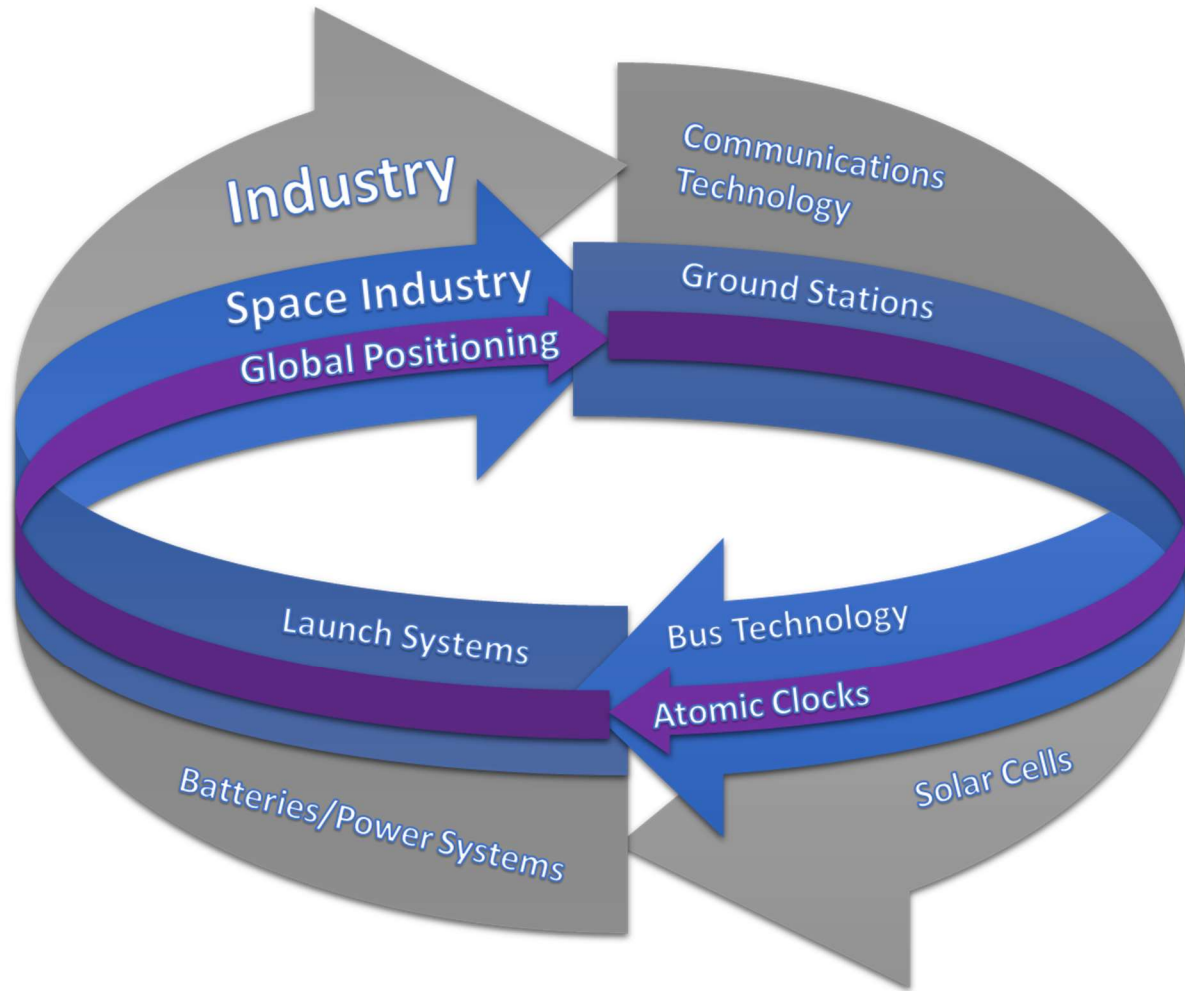
Figure 1-9: Model Representation of Space Acquisition and Development

Within the Space Industry there are several different ways of functionally decomposing activity. One might view all space activity as either observing (imaging) or transmitting (communicating). Another decomposition might be Government versus Civilian Activity. A third decomposition could be through functional areas defined by budget and funding such as communications, weather, imaging, position navigation and timing, etc. The model developed in this work implements this third world view, a decomposition by functional area. It focuses, as seen in Figure 1-9, on one specific component of the Space Industry, GPS, which makes use of technologies specific to the Space Industry but also develops capability used only for GPS satellites. Lessons learned and technology developed within the GPS sector of the Space Industry may be beneficial to other elements of the Space Industry and by extension Industry as a whole.

To examine the impact of high-level design decisions on space-acquisition projects, as well as on overall Industry over multiple years, an appropriate a level of analysis must be identified from the possibilities of:

- Payloads, Satellite Buses, Launch Vehicles and Ground Operations
- Satellites
- Satellite Constellations

- United States Space Industry
- United States Industry

It appears that an appropriate level of analysis for this research is *satellite constellations,* because constellations are the units of analysis which form the overall United States Space Industry. While the United States Space Industry includes many diverse actors and stakeholders, from civil agencies to the military to commercial entities, this analysis seeks to examine industry-wide trends and their impact on satellite constellations. Trends in spacecraft design are not an issue affecting a single firm or entity, but rather an industry-wide phenomenon with ramifications for all stakeholders.

This decision defines the boundary for both the research and the modeling effort. Setting the level of analysis also leads to the definition of what is exogenous, or outside the control of the model's feedback structures (e.g., Launch Costs or Part Commonality) and what is endogenous, or should be included as internal variables in the structure. Having set the level of analysis as satellite constellations (and first examined the GPS constellation and second, Weather and Climate Sensing) within the United States Space Industry, the model developed for this analysis focuses primarily on their construction and upkeep, and tracks some of the effects that this activity has beyond the constellation. This implies that activities in the overall United States Industry are exogenous to the model structure, and that individual satellites are beneath the level of analysis. The latter, however, is problematic as changes in satellites also change in satellite constellations. The design of satellites undoubtedly impacts the Satellite Constellations that they are a part of.

To combat this discrepancy in level of analysis, this work will use modeling approach that is capable of modeling both the production of a satellite constellation and the satellite designs which comprise the constellation to capture the salient impacts of both individual satellites and overall production trends. The utility of such an arrangement are discussed in Chapter 5.

1.4 Elements of this Problem as Defined by System Boundary

For the model to be an accurate abstraction of the world it must contain certain elements. Inclusion of other factors may improve the fidelity of the model, but at minimum the following must be captured to model the unmanned United States space-acquisition system:

1. The acquisition process for space vehicles
    a. The request of space vehicles
        i. A block purchase
        ii. A new development effort
    b. The design and cost of space vehicles
    c. The design of payloads or sensors
    d. The performance of space vehicles
    e. The production of space vehicles
    f. The deployment and depletion of space vehicles.
2. The concept of learning
    a. Within a single program (In-Generation Experience and Learning Effects, Static Efficiency)
    b. Across Generations of programs (Across-Generation Experience and Learning Effects)
3. The "health" or capability of the Space Industry

4. Policies in space architecture design:
   a. The current design point
   b. The concept of disaggregation
   c. Economies of scale
5. Cost
   a. Cost of Space Vehicles
   b. Cost of Launch Vehicles
   c. Operating Cost
   d. Non Recurring Engineering (NRE) Costs
6. Technology and Performance
   a. Changes in requirements over time
   b. Changes in technology over time to deliver performance

In Chapters 2 and 3 additional elements for inclusion are defined and the mechanisms of their inclusion outlined (Chapter 4 validates the work of Chapter 3 against historical reference modes). In Chapter 5 the model's ability to incorporate the above elements is verified across the previous three chapters' work, ensuring we have built the model as intended.

1.5 System Dynamics (SD)

1.5.1 Overview

While SD derived from control theory and was first outlined in the 1950s by Jay Forrester (Forrester, 1961), it was only with the arrival of modern computer systems that the capabilities of this method and its applicability to a diverse set of problems was fully realized. In the 1980s the ground work was laid for a SD methodology that would enable examination of a diverse set of problems and enable inquiry into human systems (Wolstenholme, 1983). Wolstenholme reasoned that SD is "capable of assisting with practical problem definition, analysis and change in a wide range of systems and…[has]…a potential to provide a more significant contribution to current general system practice" (Wolstenholme, 1983). The processes of SD not only aid in providing a qualitative description and evaluation of a complex system (through the visualization of causal feedback loops affecting quantifiable stocks, inflows, and outflows), but also allow modelers to arrive at quantified descriptions and solutions to system problems. Using SD to identify and resolve complex issues has also been shown to grant modelers and clients a better overall understanding of complicated systems: affording insights which had not been arrived at using other methodologies and the ability to turn model results directly into policy.

Sterman provides a seminal description of the underlying reasoning and justifications for SD modeling in his 1994 article, "Learning in and about complex systems" (Sterman, 1994). He describes the SD worldview as one in which decision-making is a constant iterative process, influenced by information feedback and the decision-makers' own mental models and beliefs about the system. Sterman also describes the way in which humans are typically unable to fully visualize the causal relationships among the many disparate variables in a system, and may not recognize the ways in which certain decisions bring about unintended consequences (especially when there are significant delays in the realization of those consequences).
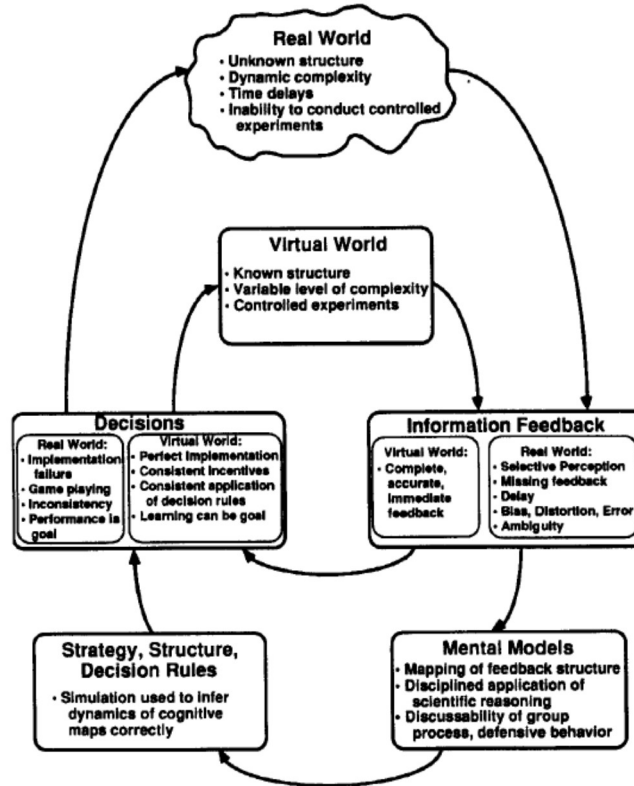
Figure 1-10: System Dynamics Ontological and Epistemological Framework (Sterman, 1994)

The Systems Dynamics Society outlines SD as a *methodology* as well as a model. The Society focuses on the word model because that is the final output or product of SD but they clearly describe multiple methods of data gathering in development of the model.

> *…System dynamics modelers not only use traditional econometric methods to estimate model parameters using quantitative data, but also routinely augment those methods with qualitative research methods including use of archival documents, interviews, and ethnographic methods and direct observation of decision making and organizational processes. Model testing involves quantitative assessment of the ability of the model to reproduce the behavior of the system of interest, and a wide range of additional tests including structure assessment, dimensional consistency, extreme condition, behavior reproduction, surprise behavior, sensitivity analysis, and system improvement tests.* (System Dynamics for Academia, 2014).

This definition is in line with *methodology* defined as a "Structured set of guidelines or activities to assist people in undertaking research or interventions" (Mingers & Brocklesby, 1997). The structure of a SD approach is a repeatable sequence of events which iteratively improves upon the model in a spiral fashion.

Pruyt (Pruyt, 2006) outlines the SD research cycle via a causal loop diagram—which is in fact a *tool* for SD modeling. Figure 1-11 shows Pruyt's conceptualization, including the way in which the researcher incorporates external data and his/her own mental model of the world and then simulates iteratively to converge on a better approximation to the system under analysis.

41
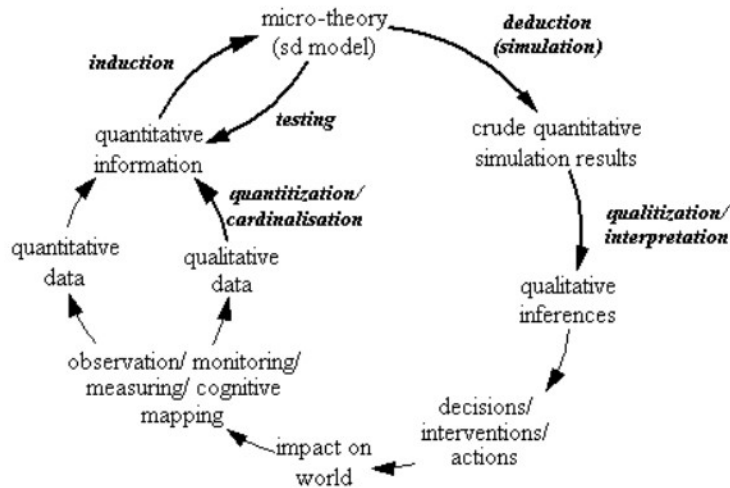
Figure 1-11: The System Dynamics Research Cycle (Pruyt, 2006)

In sum, SD modeling is a means of capturing relationships among system variables as well as simulating the effects of external variables (such as policy changes and management decisions) throughout an entire structure (Sterman, 1994). When implementing SD at this level, SD is a *method*. This is classified as a method within the definition that a method is a "Structured set of processes and activities that include tools, techniques, and models that can be used in dealing with the problem or problem situation" (Mingers, 2000).

Lane and Oliva, following from Wolstenholme, define the structure for a SD method and they list the major steps as follows (Lane D. , 1994):

1. Learning about the problem situation: gathering information about the driving variables, decision-making process, client relationships, typical delay times, etc.
2. Model building: constructing a working model of the complex system's structure and feedback loops, based on the situation described by the client(s) in Step 1.
3. Using the model in the problem situation: validating the model by confirming that it returns realistic reference modes (trend lines), and then exploring policy solutions to ameliorate the problem(s).

This merged SD methodology starts with a problem using deductive techniques for theory building, is refined iteratively with multiple data sources, and finally, is inductively validated against reference modes to provide a method for inquiry about system performance over time. Lane and Oliva continue by merging the two halves of SD, deductive research for theory generation (step 2 above) and inductive model simulation for evaluation of policy (step 3 above) into a unified theory called "Holon Dynamics." A "holon" is constructed using SD and changes to this initial holon are then simulated (Lane & Oliva, 1998). In deductive SD work, empirical data is not typically considered critical for theory generation, however, data are critical in tuning a specific model to capture real world values, not just inflection of curves. System dynamists using holon dynamics must construct a world view from objective data available in the problem space rather than mental models. After initial construction, aspects of the model may be changed to observe the effects on the system of potential changes in policy or other external forces. In this approach the model representation of the world (system under examination) can be altered and the

changed model then compared to the initial run as a way of examining change; this is the core principle of the "same but different" idea in Holon Dynamics.

1.5.1.1   Stock and Flow Simulations

In System Dynamics modeling two primary structures exist, stocks and flows. Stocks act as a store of memory and record a "level" over time. Flows act upon stocks and represent the instantaneous change to a stock at a moment in time. A simulation is comprised of causal loops where stocks and flows interact with each other over time. Causal loops or feedback loops and the strength of their interactions with each other is typically dictated by the time constants associated with each flow. Thus, the time-constants control the speed at which flows change the levels of their associated stocks. While a model may poses variables to simply computations, execution of such a simulation only occurs with respect to the stocks and flows of the model. Model execution results in stocks and flows attempting to reach an equilibrium, unless modified by an exogenous force.

1.5.2   Examples of Applications of SD

One implementation of SD to a complex socio-technical system is Ellis' application to the United States Coast Guard (Ellis, 2001). The Coast Guard embedded a team of operations researchers into the design process for the next generation of Coast Guard operations. During this three-year effort (1998-2001), the team collected data and constructed models incorporating requirements from various stake holders. Then, they constructed a SD model which was used not only to inform decision-makers of the overall picture of Coast Guard operations, but also to aid in the development, implementation, and optimization of new logistical systems.

Other examples of using SD methodology to understand human interaction with technology include: examination of operating room procedures through the lens of reinforcing and balancing loops (Morrison, Rudolph, & Carroll, 2008) and within a case-study approach, exploration of how multiple shocks to a system can lead to disaster (e.g., airplane crashes) (Rudolph & Repenning, 2002).

1.5.3   SD and Statistical Techniques

Tools such as regression analysis, or other traditional linear modeling efforts could be applied to analyze satellite construction data. Regression and other modeling efforts, however, fall short in their ability to capture the interactions that this research intends to observe. Regression analysis likely could describe the changes in available data; however, it provides no path to understanding data which cannot easily be measured (e.g., there is no historical data for "experience" or for "learning curves"). Additionally, regression models have difficulty capturing capture feedback loops and oscillatory functions if discrete events occur. SD assists in this process as it provides a technique for backing out the likely "level" of such abstract concepts. Traditional cost and performance approximation models, as laid out in the SMAD (Wertz, Everett, & Puschell, 2011) are useful for understanding the cost and performance of satellites or even constellations of satellites. Yet, these techniques cannot explain how one constellation effects the construction of another, and provide no insight into how decisions today impact the choices that will be available in the future. These techniques also typically rely upon single static optimization at a point in time; as space acquisition is an evolving human endeavor any approach which leaves out the human element across time is missing a large piece of the model. SD allows for construction of a model that can be tuned to fit the mental model of a diverse set of people and be coupled with abstract

concepts in a way not possible in traditional cost and performance modeling. Standard statistical tools are not, however, discarded when evaluating the validity of model outputs. Tests for goodness of fit and error are available and will be implemented and examined in Chapter 3.

1.5.4   Grounded Theory (GT) in Relation to System Dynamics

SD as both an inductive and deductive methodology is similar to Grounded Theory (GT). GT is first outlined in Glaser's 1967 work, "The discovery of grounded theory," and further expanded in later publications (Glaser B. , 1998). Glaser's approach proposes four stages; these stages and their corresponding elements in SD include:

1. Coding or anchoring the key points of data to be gathered.
   a. In SD this is seen in activities such as causal loop diagramming or other brainstorming efforts where key metrics or variables and their linkages to each other are documented.
2. Concepts or collecting codes into similar bins that allows for grouping of data.
   a. In SD this occurs in the clustering of similar concepts into variables for inclusion in the model under development.
3. Categories or placing concepts in broad groups that are used to generate a theory.
   a. In SD this is comparable to closing loops, or gaining understanding of how one activity returns to influence the original activity over time. Each loop in SD is a theory to the causal nature of interaction between two or more concepts or variables.
4. Theory or collecting categories that describe the subject of the research.
   a. In SD this is the dynamic interaction among several feedback loops of both balancing and reinforcing nature, which would illuminate the nature of the system under examination as either stable or oscillatory.

When examining SD through the lens of GT at least three threats to validity of SD become apparent: the role of generic structures for evaluating a problem, the method's ability to extract the necessary modeling information from a qualitative data set, and the ability to interpret the specific outputs and iteratively reconcile discrepancies (Akcam, Guney, & Cresswell, 2011). With respect to the first of these threats, while using generic structures can hinder the modeling of specific elements of a problem, it can also be a great strength. Modern SD models can be generated quickly by using "molecules" or basic building blocks of code (Hines, 2005). The practice of using generic structures which are then tailored to a specific problem has become accepted practice and is supported by the System Dynamics Society (System Dynamics for Academia, 2014). The other two concerns are addressed when the model is inductively tuned and fit metrics are produced (Chapter 4). Two examples of combining SD with GT can be found in (Black, Carlile, & Repenning, 2004) and (Laws & McLeod, 2004). GT as both an inductive and deductive method constructs models in a very similar fashion to the process of a SD model and its influence on this work is detectable in Chapter 3.

1.5.5   Data Sources

Yin's work on case studies notes the importance of collecting data and information from multiple sources to aid in the identification and analysis of trends as well as enable predictions of future trends (Yin R. K., 2014). This is a very similar to the preferred SD methodology outlined by the System Dynamics Society (System Dynamics for Academia, 2014). Yin lists six primary sources of evidence: documentation, archival records, interviews, direct observation, participant observation and physical artifacts. For this thesis these are operationalized as:

1. Documentation: Each completed program produces a series of reports for each milestone and a flight certification. Risk management is a large part of these documents. Also AIAA journal/conference publications contain substantial information about technical justifications for program decisions.
2. Archival Records: Databases e.g., Defense Technical Information Center.
3. Interviews: The acquisitions process is well known, nonetheless after construction of this model it could be taken to senior decision-makers and their opinion of its abstraction requested. While the modeling technique was briefed to the Aerospace Corporation Modeling Division in Los Angeles on Dec 11th 2015, this does not qualify as conducting an interview per the case study methodology.
4. Direct Observation: Useful for deductive model building.
5. Participant Observation: One could sit in on meetings of the Milestone Decision Authority or hear quarterly updates to a Program Executive Officer (PEO Space). An individual could also run a DoD acquisition program to learn the specific issues associated with acquisition. Normally, it would be unrealistic to expect a researcher to actually acquire and put satellites in orbit, however, in this situation the author was a Program Manager for a DoD satellite acquisition for over two years (La Tour, Frazier, Sondecker, & Abramowitz, 2011).
6. Physical Artifacts: Satellites exist and are supported by program offices, as such they can be studied in situ for theoretical versus actual performance.

Yin also notes the need for triangulation, or the use of multiple sources of evidence when applying the case study approach (Yin R. K., 2014). This also aligns well with the SD methodology, as multiple sources that provide justification for a causal loop strengthen the rationale for including it in the model. For this analysis, the deductive process (or theory crafting) will rely heavily upon documentation, archival records, and physical artifacts.

Homer writes extensively about the need for "reference modes" for both tuning and calibration; i.e., sources of sufficient raw data to align the outputs of the model to the real world (Homer, Structure, Data, and Compelling Conclusions: Notes from the Field, 1997). Tuning grounds a SD model in the correct domain as well as enabling better communication of results to individuals who work in the domain, as the variables will be in the units expected. For this analysis, documentation, archival records, direct observations and physical artifacts are used as sources for model calibration. Once the model has been adequately calibrated in the language and units of space acquisition the model can be used to test and explore policy.

1.6 Tradespace Exploration (TSE), Multi-attribute Tradespace Exploration (MATE), and Epoch-Era Analysis

TSE, well-articulated by Ross and Hastings (Ross & Hastings, 2005), but broadly developed as a field over the last two decades, is a tool for merging cost and performance models into a problem that can be analyzed by a computer. As the name suggests, TSE builds a space of solutions from a set of design points. A computer applies cost and performance models to calculate the associated cost and utility of the various resulting systems to form a Tradespace of candidate solutions for further evaluation. Typically the modeler examines the resulting design points or solutions close to the Pareto front when plotting cost against utility. These are said to stochastically dominate the other points from either a cost or performance perspective, and as such are the designs

of greatest interest. Clusters of design points are also typically of interest for investigation as they illuminate specific trades that are occurring, suggesting a high correlation among specific design variables.

Successful acquisition of space systems requires the satisfaction of many variables including both cost and performance, from the perspectives of multiple stakeholders. The technique of Multi-attribute Tradespace Exploration (MATE) has often been used to assist with management of the multiple variables associated with satellite design. To address the various attributes of designs and performance across time, MATE can be combined with another concept, Epoch-Era analysis, to consider context and uncertainty (Ross & Rhodes, 2008). Epoch-Era analysis includes temporal calculations in the evaluation of candidate systems by first defining a set of systems (as in MATE), then computing the performance of candidate systems relative to the exogenous context variables. A set of solutions and their performance under a set of conditions or assumptions is referred to as an "epoch." If these same design points are tested against different context variables, this creates a different epoch, and it is expected that the performance of the various systems will change.

Era-level analysis arises from an ordering of epochs and examination of the performance of candidate solutions across a sequence of epochs. This is illustrated in Figure 1-12. Through an ordering of epochs, the "goodness" or performance of a system across a specified set of times and conditions can be evaluated and a combined utility value computed.
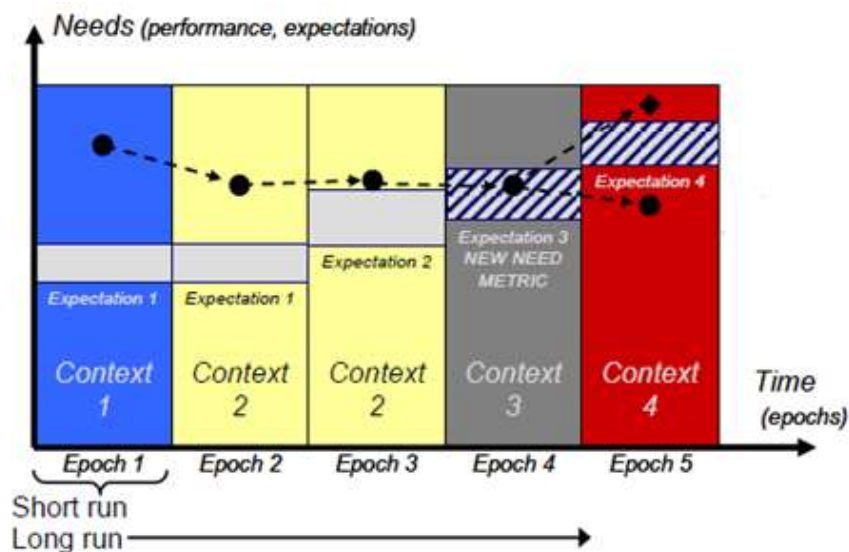
Figure 1-12: Epoch-Era Analysis Reveals the Performance (including affordability) of a System Through a Sequence of Varying Contexts, Illustrating Potential Lifecycle Value of the System (Ross & Rhodes, 2008)

Epoch-Era analysis may be a useful approach to examining the acquisition and performance of satellite architectures over time. In theory, constructing eras allows a combination of the existing body of work in cost and performance models and extension of this analysis across different orderings of future possible scenarios. The work also often focuses on examining specific "ilities" or emergent properties. For example, naval ships were designed for affordability (Schaffner, Ross, & Rhodes, 2014) (Schaffner, Wu, Ross, & Rhodes, 2013), modularity (Shah, 2004) and survivability (Mekdeci, 2013). Work in this area included the development of specific survivability

46

metrics (Richards M. G., 2007). This body of work indicates that Epoch-Era analysis is robust for answering a variety of performance questions across time and across different domains. It also allows an examination of both the macro variables, in terms of large industry factors varied through exogenous parameters, and the micro elements, in the form of individual satellite design points. Epoch-Era analysis has proved amenable to inclusion of other techniques such as portfolio theory (Vascik, Ross, & Rhodes, 2014). This existing method for evaluating systems under uncertainty and context serves as a valuable beginning point for analysis, however, ultimately this work will deviate from MATE and Epoch-Era analysis replacing MATE with a single variable and Epoch construction with the SD model.

1.7 A Combined Model

As noted above, TSE is an appealing method for evaluating design issues associated with satellite payloads, buses, and architectures. The technique has already been applied to satellite systems. For example, it was used to evaluate Space Based Radar (Spaulding, 2003) over a decade ago and since then many others [authors] have refined the process through evaluating other large systems. TSE allows for evaluation under a cost ceiling as prescribed by the Better Buying Power initiative of the DoD (Under Secretary of Defense Acquistion Technology and Logistics, 2015) (Carter & Mueller, October 2011). With the inclusion of Epoch-Era analysis the modeler has the ability to consider performance over various time periods, given assumptions about various exogenous conditions.

SD is also a proven method for understanding a high-level abstraction of causal interactions over time. Currently, the System Dynamics Society believes that the goal of SD is "a focus on endogenous explanations for dynamic phenomena. Dynamics are explained as arising primarily endogenously within the boundary of a model from the interactions among the elements and actors in the system, rather than from exogenous inputs" (System Dynamics for Academia, 2014). Such an approach is consistent with the goal of drawing the system boundary at the level of the United States Space Industrial Base, and a belief that design and human preferences have driven the current design point. SD differs from Epoch-Era analysis as a tool for evaluation across a time period. In Epoch-Era analysis exogenous variables or assumptions would be changed and future time periods (epochs) are not based on events in previous time periods (epochs). In contrast, in SD, as time is continuous, past performance influences future outcomes, and sequencing or ordering of events matters.

Having examined TSE and SD it is valuable to compare their approaches side by side to understand on what levels they operate in unison as well as where the techniques complement and contrast each other. This assists in understanding if a merger is possible at each level of the methodology.

Table 1-2: Merged System Dynamics and Tradespace Exploration as a Mixed Methodology

Mixed/Meta Methodology	Merged SD and TSE	
Multi Methodology	Soft SD Methodology	
Methodology	SD,	TSE

	"Soft Systems," "Holon Dynamics"	
Methods	Inductive Deductive	Multi-Attribute Tradespace Exploration (MATE)
Techniques	Causal Loop Diagrams, "Molecules of Structure"	Epoch-Era Analysis, Utility Functions & Pareto Analysis
Tools	Vensim & Lookup Tables	Matlab, C++, Cost Models and Performance Models

This work proposes a combined approach that fuses a SD model of the Space Industry with a TSE model of a satellite program as a means to examine the evolution of a satellite acquisition program over time. To implement this proposal the approach must work across all levels as laid out in Table 1-2. The tools selected must be able to work with each other, as this is a modeling approach it is thus required that Vensim be able to interact with and pass data to existing satellite cost and performance models. The techniques for developing both models and processing the resulting data must also be able to work in conjunction with each other. This is an area of particular focus as System Dynamics typically plots results across time and TSE usually produces results at a point in time. The methods for determine validity in each respective domain must also be aligned such that they do not invalidate the results of each other. If across each of these layers the respective tools, techniques, and methods can be reconciled then a mixed methodology may be possible. In this thesis a technique for merging across all levels is constructed. As this work only examines a single set of models (DoD space systems acquisitions) it is not appropriate to title this work a "mixed method" as this would imply that the work is inherently applicable or extensible across multiple domains. In the future, additional work may lead towards best practices in such merged modeling and eventually an official mixed methodology, for now this thesis describes one possible technique for doing such.

1.7.1   Possible Advantages of this Approach

A merged SD/TSE model broadens the concept of system beyond the satellite constellation on orbit to incorporate the apparatus required to replenish the constellation and include elements of the industrial base as well as trends in space capability. Using both methods in a single simulation capitalizes on the strengths of each: the bottom-up cost and performance evaluation of TSE, and the top-down abstraction of a SD Stock and Flow model. The combination allows examination of many proposed approaches to future acquisitions under a number of assumptions about future conditions, both those incurred through exogenous conditions, and those resulting from endogenous interactions among elements of a space architecture.

The possible advantages of the combined approach include:

- By creating a SD model, the technique incorporates an external body of knowledge that may be hard to translate into computer code but translates easily into a Stock and Flow or causal loop structure.

- A SD model provides a more systematic method for selecting constants, exogenous parameters and context variables for a TSE model, as opposed to relying on a modeler's or expert's opinion in picking a static constant.
- A SD model captures the iterative nature and interconnectedness of internal and external variables across time, allowing for an examination of the more likely future scenarios when computation complexity is a concern.
  - Traditional epoch construction relies on the modeler to predict the sequence of epochs before computation starts in the creation of Eras.
  - The SD model automatically constructs a representation of future conditions based on the change in context that occurs across time as specified by the modeler. This enables the changes of context to be incorporated with the causal mechanisms of the SD model.

This merged approach offers one other unique capability. Because the evolution of a specific system is tied to the evolution of the pipeline that produces it, this approach can model the interaction between the pipeline as well as the impact of individual satellites inside the constellation being represented. This capability arises from modeling the causal interaction between causal trends and the effect on a specific architectural implementation while accounting for time delay and the reality associated with specific satellite designs. The system boundary of the satellite production pipeline can be modeled in SD, while the specific architecture under examination can be modeled within TSE and SD.

1.7.2   Multiple View Points

From the standpoint of system dynamists, this approach uses TSE as a way to size discrete inputs into a production pipeline; in this case the ordering of satellites and their requirements (cost, mass, etc.). From the perspective of the user employing TSE, SD serves as a way to determine the exogenous levels and inputs required for the determination of what is an appropriate assumption in replication costs based on the architecture proposed. The SD model also serves as a way of enabling continuous functions for context or assumptions; in traditional Epoch Era Analysis context or assumption variables are discrete. The use of the SD model replaces the construction of Epochs and the sequencing into Eras is folded in as well. There is also the perspective of a control module: this approach makes use of both tools to construct an analysis of possible satellite procurement sequences and suggest a set of decisions across time to reach an optimal future after examining a wide range of designs.

1.7.3   Steps for Model Construction, Validation and Application

The problem defined here is a complex socio-technical system that evolves over time. Having selected a variety of tools and techniques for evaluation of a problem space, a method must be proposed to incorporate and properly align modeling efforts. One step has already been performed: defining the system boundary. In subsequent chapters the remaining steps as listed below are performed. The technical implementation of these steps is illustrated using GPS as an example.

1. Define System Boundary and Level of Analysis
   a. What is exogenous and outside of model boundary
   b. What is endogenous and can be represented by trends over time
   c. What is endogenous and can be controlled by decision-makers
2. Construct Point-in-Time TSE
   a. Construct Tradespace with design variables to produce design vector

b. Evaluate performance model(s)
c. Select appropriate cost model(s)
3. Create SD Model for Time Period to be Evaluated
a. Causal Loop Diagram based on literature review (assists in identifying key variables)
b. Simulate Deductive Model
c. Tune to Inductive Model
d. Determine context variables and implementation
4. Link TSE with SD
a. Determine loops that pass through the TSE and control module
b. Determine impact of stocks on TSE cost or performance modules
5. Execute Evolutionary Planning on Desired Design Vector
a. Re-run simulation varying context curves
b. Re-run simulation varying tuning parameters/assumptions
6. Evaluate Results

1.7.4   Implementation

Construction of the model makes use of two primary programs: Matlab (Mathworks, 2015) and Vensim (Ventana Systems Inc, 2015). TE, MATE, and functionality based on Epoch-Era analysis are implemented in Matlab. Vensim DSS is delivered with a Dynamic Link Library (DLL) which enables external commands to be sent to Vensim. For this effort, wrappers were written in Matlab to pass the specific desired commands to be executed by the Vensim model during execution, and SD functionality was implemented in Vensim. Vensim was also used as an easy way to represent trends since it possesses an easy-to-use interface for implementing look-up tables (particularly useful in developing the model).

1.8 Research Questions

1.8.1   Methodological Research Questions

This work seeks to develop a predictive model to compare various acquisition strategies over time. Many tools and techniques are available for building such a model. SD provides a high level of abstraction for investigation of such problems. Its shortcoming is its inability to validate solutions against real world physics and cost models where discrete points represent an exact absolute solution, rather than a change relative to a baseline. TSE is good at evaluating cost and performance of candidate systems at a specific point in time under a specific set of assumptions. It, however, offers no direct means to evaluate the system under examination across time, other than making abstract assumptions about future world conditions set through the means of exogenous context parameters and re-computing a utility function. TSE specifically lacks the ability to model iterative interplay between variables or causal changes over time; SD possesses these capabilities.

Both of these techniques have been developed over the years in response to specific questions and the needs of modelers. Both appear able to speak to the issues affecting the construction and fielding of satellites, though they do so at different levels. This leads to a methodical research question:

- Can SD techniques be merged with TSE techniques to create meaningful combined models and outputs for exploratory purposes?
  - ♦ Can a combination of existing SD and TSE techniques overcome their individual limitations through a complementary implementation and grant deeper insight into satellite acquisitions?
  - ♦ Specifically, can a complementary implementation provide new insights into the health of a satellite production pipeline over multiple generations and compare the outcome of different architectural implementations across time?

This thesis presents a technique for merging the strengths of TSE and SD into a single executable model to track cost, performance and time of satellite acquisitions in a single model. This technique will be tested with GPS satellite production, to evaluate its accuracy and usefulness. The model is then applied to a Weather and Climate Sensing constellation to investigate the extensibility of this technique.

1.8.2   Policy Research Questions

The USAF is investigating disaggregation, among other possible changes, as an acquisition strategy. Before committing to such an architectural change, more information is required (Gruss, 2014). Gruss cites the recent GAO report stating, "Until more knowledge is gained, disaggregation will not only remain inconclusive, but poorly informed decisions could be made in the interim." The USAF wants to know how a concept like disaggregation will influence both the operations and fielding of space assets. This work seeks to answer this question and others, including:

- Will the current acquisition approach improve, degrade or leave unchanged, the health of the GPS production Pipeline over the next thirty years?
  - ♦ The health of Weather and Climate Sensing?
- Does a reasonable design point or set of points exist that leads to improvement in the cost or performance of the GPS production pipeline over the current design point?
  - ♦ To the Weather and Climate Sensing mission?
- How do different design points change the posture of unmanned U.S. space assets with respect to survivability, replenishment, and capability maturation?

One might also consider that current space acquisitions are the optimization of large economies of scale for space systems. If the current design point is hypothesized to be the maximization of economy of scale with little or no benefit from learning effects, then we might like to know:

- Under what conditions does more activity, generated by disaggregation or through other means, lead to capitalization on learning effects that yield benefits greater than the potential losses in economies of scale when shifting from the current design point?
  - ♦ How do different assumptions measured through exogenous context variables affect this result?

1.8.3   Example Policy to Be Examined: Global Positioning System (GPS)

The United States-sponsored GPS is a worldwide Position Navigation and Timing (PNT) solution that operates through synchronized clocks in mid-earth orbit (MEO). The current GPS

solution uses ranging signals to determine the distance between a receiver on the ground and satellites in orbit. While many signals are currently used for PNT, the signals currently broadcast are known as:

- L1 at 1575 MHz: a signal for civilian navigation and Coarse Acquisition of signal (C/A), this is the original legacy signal
- L2 or L2C at 1227 MHz: the second civilian signal for increased precision on civilian receivers when used in conjunction with the L1
- L3 at 1381 MHz: used to enforce nuclear test ban treaties
- L5 at 1176 MHz: the third signal proposed as and implemented for "safety of life" for aeronautical navigation
- M1: the first military signal at L1 frequency with unique code
- M2: the second military signal at L2 frequency with unique code

Upgrades to this system are currently planned in future generations with:

- L1C at L1 1575 MHz: a fourth civilian signal for increased accuracy
- L4 at 1379 MHz: being studied for additional ionospheric correction capability.
- Crosslinks among GPS satellites to assist in clock correction
- Spot beams to produce higher power signals in specific areas of interest

The European implementation of a PNT system, known as Galileo, has planned for operation of three signals. Due to international agreements developed by the International Committee on Global Navigation Satellite Systems, two of the signals operate at the same frequency and transmit information in the same fashion as the United States' GPS system. The performance of these signals is the same from the standpoint of the end user/receiver.

- E1 at the same frequency as the L1
- E5 at the same frequency as L5
- E6 at 1278 MHz a capability unique to Galileo

There is currently debate about the implementation of the GPS versus Galileo design points with respect to value delivery. This debate arises when the metric comparing value delivery is "signals compared on a cost-per-operational-year basis." The GPS system possesses many more signals as well as large economies of scale with its physically larger satellite design. If, however, the United States desired equivalent capability and built the GPS system at the same design point as a Galileo satellite (smaller and shorter lived and by extension disaggregated), second-order consequences such as faster technology replenishment, reduced complexity in satellite design, larger production quantities and the potential for learning effects *could* mean that a Galileo-class satellite would be superior decision. This work will compare these two approaches and many others, under varying conditions over the next 30 years to determine which future pathways result in the highest performance, lowest cost and easiest acquisition.

1.8.4 Example Policy to Be Examined: Weather and Climate Measurement

Unlike GPS, which has a known working solution, Weather has had difficulty deploying effective capability. Going forward, Weather has no requirement or expectation for 100% satisfaction in delivering all requested capabilities. Weather payloads are typically earth observing

(optics) and have radically different costs of development and production. The primary payloads for the NPOESS program include:

- Visible Infrared Imaging Radiometer Suite (VIIRS) (NASA, 2016)
- Conical Scanning Microwave Imager/Sounder (CMIS) (Chauhan, 2003)
- Cross-track Infrared Sounder (CrIS) (NASA, 2016)
- Advanced Technology Microwave Sounder (ATMS) (NASA, 2016), (Blackwell, Cull, Czerwinski, Leslie, & Osaretin, 2012)
- Earth Radiation Budget Sensors (ERBS cross-track scanning, ERBS-biaxial scanning)
  - ♦ Many of the estimates for ERBS were based on its heritage from CERES and on JPSS CERES is being flown. (ESA, 2016)
- Ozone Monitors (OMPS-Limb, OMPS-Nadir) (OSCAR, 2016), (NOAA, 2016)

The model developed in this work will allow a re-test and extension of the work by Morgan Dwyer in her thesis (Dwyer, Feburary 2015). First, her results with respect to disaggregation can be re-evaluated within this model. Second, her analysis, which does not evaluate "goodness" beyond a single point in time, can be expanded by this model to examine the impact of design choices in 2010 on systems and implementations over the next 30 years. Finally, implementing this model allows consideration of a much larger set of context variables and design points to evaluate a larger set of possible future weather constellation implementations than were present in her work on disaggregation of systems.

1.9 Thesis Organization

This thesis is divided into 10 sections. The Introduction lays out the background, research questions, existing methods and literature, and proposes an approach to investigate the thesis questions. Chapters 2 through 4 serve as a method section and discuss construction of a model merging SD and TSE with associated literature and background embedded as needed. Chapter 5 documents how the merged model was constructed. Chapter 6 contains the results of the model constructed in Chapters 1 through 5, and Chapter 7 tests the consequences of changing of variables to challenge assumptions. Chapter 8 changes the domain from PNT to Weather and Climate measurements and modifies the work in Chapters 2 and 3 to accommodate the change in domain. Chapter 9 contains policy recommendations for future Weather and Climate Sensing efforts when examined through the lens of the tools and techniques outlined in this thesis.

This work implements a merged modeling approach. The underlying rational is that the TSE model will validate with the "tokenization" of satellites in the SD model, and the SD model will capture elements of time and human learning not capable of being represented in TSE. Chapter 5 develops the method to merge SD and TSE relative to the representation of the world shown in Figure 1-9. The argument is made that the tools and techniques provided through a SD approach are well suited to investigate the causal nature and development of an industry which can be abstracted to a set of key variables and metrics. Furthermore, SD is well suited to understand the impact of time and strength of time delays within a context of interest while complementing the cost and performance modeling capabilities found in TSE.

After describing the implementation and execution of this model, the various outputs and products of the model are described and interpreted for real world value in Chapter 7. Chapter 7 also discusses additional investigations which might be performed and other techniques which

could be used in conjunction with this combined model to gain deeper understanding. Having displayed and discussed the products output by this method Chapter 8 replaces the TSE cost and performance models associated with the GPS constellation with those of Weather and Climate Sensing satellites. Chapter 9 then extends this modeling approach to answer questions about a new Weather and Climate Sensing constellation.

- Chapter 1: Introduction
  - ♦ Satellite Systems, Standard Modeling Practices, Previous work
  - ♦ System Dynamics, Tradespace Exploration, Space Systems Modeling Techniques
- Chapter 2: Tradespace Exploration for a GPS Constellation
  - ♦ Definition and Construction of a design vector for GPS policy examination
  - ♦ Impact of Change in Policy or Requirements on Payload Selection and Alignment
  - ♦ Application and inclusion of Existing Models in research
- Chapter 3: Deductive System Dynamics (SD) Model for an Acquisitions Pipeline
  - ♦ Existing work on pipeline and modeling learning effects in System Dynamics
  - ♦ Translating Policy and Acquisition Process to construct a GPS pipeline model
  - ♦ Create Causal Loops which represent large forces in the space industry
  - ♦ Initial simulation of specific model components
  - ♦ Insights from System Dynamics Work (Understanding the Impact of Time)
- Chapter 4: Inductively Tuning the GPS Pipeline System Dynamics Model
  - ♦ Tuning Model to Match Observed Data, Goodness of Fit/Validity of Results, Sensitivity of Model to Changes in Parameter Values
- Chapter 5: Mixed Model, Merging System Dynamics with Trade Space Exploration Techniques
  - ♦ Tools, Techniques, Flow Control, Computer Memory and Software Interface Management of merged technique
- Chapter 6: Policy Testing on GPS Acquisition Pipeline
  - ♦ Compare GPS Program of Record Predictions to Model Results of Policy Changes
  - ♦ Investigate results of changes in design vector consisting of: various disaggregated approaches, design lives, Non-Recurring Engineering and order quantities.
- Chapter 7: Varying Assumptions on GPS Policies
  - ♦ Change exogenous variables (assumptions) and examine the impact of part commonality and launch costs over time.
  - ♦ Change funding profiles to examine if learning effects enable cost savings.
- Chapter 8: Modeling Weather and Climate Sensing Satellite Acquisitions
  - ♦ Adapt and retune model to Weather and Climate Sensing
  - ♦ Examine impact of complexity on architecture design and causal loops
- Chapter 9: Policy Testing for Weather and Climate Sensing Satellite Acquisitions
  - ♦ Model JPSS satellite program
  - ♦ Construct policy recommendations for a future Weather and Climate Sensing constellation
- Chapter 10: Conclusions and Future Work

2 Tradespace Exploration for a GPS Constellation

This chapter constructs a Trade Space Exploration (TSE) model for the evaluation of GPS constellation designs. As documented in the Introduction, TSE is a well-defined and often implemented methodology for investigating tradeoffs between cost and performance of a system. The most relevant of these includes the original paper by Ross on the Terrestrial Observation Systems (TOS) [the seminal work (Ross, Diller, & Hastings, 2003)], a satellite space radar system (Ross, McManus, Rhodes, Hastings, & Long, 2009), Distributed Satellite systems (Corbin, 2015), On Orbit Servicing (OOS) (Putbrese, 2015), and survivability of space vehicles (Richards M. G., 2009). The method implemented for construction of this model is based upon the literature outlined in the Introduction and existing best practices for MATE modeling. Figure 2-1 depicts the computational flow of the model developed and evaluated in this chapter.
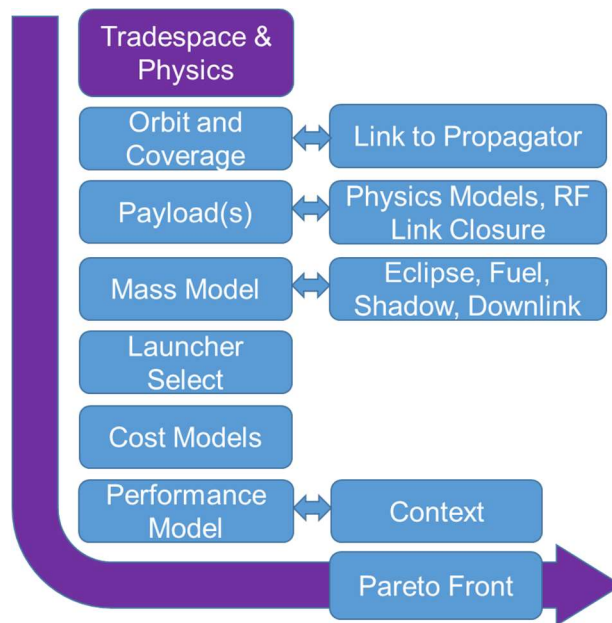
Figure 2-1: Execution Sequence of TSE model

2.1 Initial Code Base Development

The model's original code base was developed for a class project for ESD.77 by Mike Curry (Curry, 2014). This project was designed to perform a TSE of a Low Earth Orbit (LEO) earth-imaging satellite or constellation dubbed OREOS or, Operationally REsponsive Observation Satellites. This work compared the cost of a system against a utility function comprised of image resolution, time to re-visit a specific point, percent of global coverage, and longest time to re-visit any point.

The design vector fed into the TSE model for the OREOS project contained:

- Inclination
- Altitude
- Number of satellites per plane
- Number of planes

- Design life
- Maximum grazing angle of the optical payload
- Aperture size of the optical payload
- CCD Size
- Type of optical payload

The utility of such a system was defined as an even weighting of five variables compared against the cost of the system. The utility function needed to be constructed such that the potential trades could properly be investigated. The set of weights could have been examined and the change in weights mapped to the change in utility delivered:

1. Minimizing lifecycle cost (affordable)
2. Minimize gap/revisit time (low latency)
3. Minimize resolution (m/pixel) (high resolution)
4. Maximize time in view (near continuous)
5. Maximize global coverage (arbitrary location)

This created a Tradespace where the size and orbit of the satellite(s) varies across a region of interest as determined by the design vector. This enabled the cost and performance of the resulting design points can be compared. The value of this construction of a Tradespace lies in its ability to assess the effect on performance of moving from single to multiple satellites and the cost of increasing from one orbital plane to two or more. The findings primarily link the re-visit rate and coverage to the number of satellites and the desire for polar orbits. They also establish a complex trade-off among altitude, design life, resolution of image, and size of the space vehicle.

Hastings, La Tour, & Putbrese (2015) subsequently revised and improved this code was then for study of the value of an on-orbit communications infrastructure. Specifically, this work examined the value, to existing or future on-orbit assets, of improved communications given an on-orbit communication infrastructure as opposed to access to only a select set of terrestrial downlink locations. Results were presented at the Big Sky Conference, Montana, 2015 (Hastings, La Tour, & Putbrese, 2015). Part of this work is also included in Putbrese's thesis (Putbrese, 2015), examining the value of on-orbit infrastructure (OOS).

The design vector for study of a LEO Communications Data Relay Infrastructure contained more variables than OREOS; where the satellites in the infrastructure are referred to as the servicing satellites and satellites making use of the infrastructure are referred to as serviced:

- Altitude
- Number of satellites
- Inclination
- Number of per orbital-plane
- Ground stations available to servicing space vehicles
- Ground stations available to data relay infrastructure
- Cross-link speed to serviced satellites
- Inter-link speed between servicing satellites
- Downlink speed of servicing satellites

This established a two-body problem where a need exists to consider the utility of the serviced space vehicles in presence of the infrastructure and without the infrastructure. The utility of the

servicing infrastructure needed to be considered in context of the serviced space craft. The serviced space craft, for example an imaging system, delivers utility in more than just communications; it also considers the quality of the image. As such the change in utility with respect to the serviced spacecraft in presence of the infrastructure can only change utility metrics associated with its delivery of product (the downlink of images). The utility of these satellites was assessed based upon an even-weighted utility function of six variables:

1. Additional data serviced satellites can downlink per day
2. Percent of day serviced satellites can be in "instant" contact
3. Percent of day serviced satellites can communicate with infrastructure
4. Total bandwidth per day of on-orbit infrastructure
5. Average delay of serviced satellites versus unserved satellites
6. Worst case delay of serviced satellites versus unserved satellites

Another utility had to be constructed for the serviced space vehicles to determine the utility to them, the details of which can be found in the paper. This work resulted in the creation of a trade space where the orbit, number of satellites in the constellation, and the performance of each satellite can be compared against the life-cycle cost of such an infrastructure and the value delivered to serviced space vehicles. Results indicate that a design of a single halo or ring of between 16 and 32 smaller satellites in a single plane would likely be the most cost-effective implementation. This enables examination of infrastructures and identifies the cost points that deliver sufficient bandwidth and communications time to a serviced vehicle. These data can inform policy makers on the desirability of implementing such a system from the perspective of serviced vehicle owners and allow them to determine if they are willing to pay the increased costs for increased performance.

Clearly, constructing a point optimization to examine the tradeoffs among different design approaches for GPS satellites is feasible based on existing cost and performance models. In both the OREOS and Data Relay Infrastructures Tradespace Exploration studies, the design vector and the utility function were tailored to the problem and the specific tradeoffs being examined; extending the TSE model to the GPS constellation will be no different. Creation of a TSE model capable of investigating the revised model's capabilities is documented in the remainder of this chapter. As one goal of this work is to merge the created Tradespace with a SD model, throughout this chapter it will be noted where changes are made to traditional TSE practices and how this combined-model will contribute to investigation across time. Key variables associated with each module, listed above in Figure 2-1, are listed in this chapter to give an understanding of the fidelity associated with the model.

2.2 Construction of a TSE Model for GPS Satellites

2.2.1   Design Variables

TSE is capable of examining many aspects of potential GPS solutions, however, based on the research questions of this work, the following four variables were encoded for the initial design vector which are defined here, for the remainder of the chapter variable definitions can be found in Appendix A Variables and Definitions in TSE model:

Design Vector: {Design Life, Payload Alignment, Number of Satellites to Be Produced, NRE Update}

1. **Design Life**: Typically, longer-lasting satellites weigh more but require a less-than-linear increase in the amount of mass to achieve increased design life (Saleh J. H., 2008). Since the GPS constellation is not a one-off design but rather a pipeline which requires replenishment, the design life also influences the rate at which satellites are ordered, and the time between technology refresh. As each space vehicle requires a rocket in order to reach orbit, the longer the design life the fewer rocket launches required in the same time period.

2. **Payload Alignment**: One of the research questions asks about the consequences of different architectures rather than the current implementation. Table 2-2 outlines a set of different potential payload-to-bus alignments looking at the concept of disaggregation. The design vector will be populated with these configurations. This variable also changes as a function of the level of performance required. If more or less capability is desired by the constellation, payloads can be added or subtracted if this is the type of performance desired for examination. When considering evaluation at different time points, within the context of GPS, as every satellite must possess the signal for global coverage every satellite for it to be meeting the performance threshold. From the perspective of TSE, block buys of satellites all possess the same signals, however, this does not mean that the overall constellation possesses the capability. For example, a block buy of eight satellites possessing a new signal will not grant the performance to the entire constellation until at least 24 of those satellites are on orbit. This is a hard performance metric to examine from the perspective of TSE as it does not know what capability previous generations of satellite possess, nor when previous satellites exceed their design lives. From the perspective of System Dynamics this performance metric becomes easier to examine as individual satellite launches can be tracked over time.

3. **Number of Satellites to Be Produced**: GPS procurement is typically performed in block buys. The number of satellites inside a block relates to economies of scale in production as well as possible learning effects. The greater the number of satellites produced in a block, the less NRE cost per satellite. One research question asks about learning effects on satellite production, inclusion of this variable in this design vector enables examination of this query. This variable will also influence the Tradespace with respect to launch and on-orbit costs since the number of satellites launched does not linearly impact launch and support costs.

4. **Non Reoccurring Engineering (NRE) Update**: While the first three variables are easily understood within the context of TSE, NRE is a model representation of updating the technology of satellite design, while not changing any other performance metrics. This is an illogical action as one would naturally want to gain performance if paying a technology refresh; if the payload alignment variable is changed over time then this automatically is invoked. Within standard TSE this variable is not useful, however, when this model is merged with a SD model (Chapter 5) it becomes useful for two reasons. First, it allows investigation of the impact of spending money on technology updates and changing the time between technology refresh events. Second, it permits investigation of the specific questions, "What if instead of refreshing technologies, additional units of previous design are produced? What are the short-term and long-term impacts with respect to cost and technology?" When a TSE model is run, if NRE Update is set to "Yes," the model

58

considers this to be a new acquisition and behaves as a standard TSE model with only the first three variables. When NRE Update is set to "No," the model considers this to be a replication activity based on preexisting acquisition activity and in order to execute requires assumptions about the previous generation's production activity.

In comparison to the previous works which implemented MAUT and weighted utility functions for evaluation, this work will only implement one variable: cost per operational year. Thus, for this investigation and model execution, satellite performance will be fixed and all systems under investigation will be designed to have performance equivalent to the existing GPS program of record or BATNA. (Recall that in the Introduction the GPS program of record is referred to as the BATNA, as any change would be from the current plan.) As the performance of GPS constellations is already known, designing different systems to match performance is different than in a traditional TSE. Traditionally performance would be allowed to vary and then plotted against cost to create the Pareto front. In this instance, performance is considered as a design to specification as opposed as an output from the model. This implementation is appropriate and does not pose a threat to the validity of this approach since it does no more than limit the size of the resulting Tradespace. Future work will not be precluded from adding complex utility functions or changing satellite-performance, but for developing this technique it is helpful to begin with a simpler comparison.

The decision to limit the utility function to the single variable of cost per operational year also comes with a possible benefit for testing the combined-model proposed in this thesis, as it enables a direct comparison. In traditional TSE, the model output of a weighted utility function cannot be compared with another model's utility function if parameters are varied. This is because a utility function in TSE is a dimensionless variable. Because cost per operational year is not a dimensionless variable, but rather is $M FY 2010 dollars, two outputs can be directly compared.

This becomes important, not for comparing calculations for the first generation of satellites, but for future generations. Because two of the variables in the design vector, Design Life and Number of Satellites to be Produced, directly change the future time (year) at which the next design (TSE run) occurs; each "future" output by the model produces different timelines for procuring satellites. This is an important issue, one which the combined model approach will be able to investigate. Consider a future where a constellation is ordered in 2024 versus one where the constellation is ordered in 2026. An analysis of the cost between 2008 and 2025 would be heavily influenced by the spike that would occur in 2024. The spike would arise from the large amount of NRE that would be required in 2024 for a technology refresh. For the future scenario where the constellation is ordered in 2026, no such cost spike would be visible. While any human would be able to see it coming, the model would not. The variable of cost per operational year enables cost comparison across a time period. This is computed by dividing the total lifecycle cost based by the number of years of capability granted (the design life). In this example, the cost in 2024 would not be the huge spike associated with a new acquisition, but just the average cost of one year—2024 to 2025. In Chapters 4 and 5 graphical comparisons of different runs are overlaid using this approach of comparing cost per operational year.

Based on this single variable utility function, if one system possesses extra emergent capability and a different cost per operational year, the modeler will conclude that the difference in cost between the BATNA and the other system is the cost of the additional capability (or emergent capability). Specifically, some of the systems under initial observation may possess

superior reconstitution, survivability, or another "ility." The "survivable" design in Table 2-2 and Table 2-3 possesses additional ability to maintain full capability in the face of missing satellites up to 75% of full constellation strength. This design will likely cost more than the GPS BATNA design (it actually does, as shown in Chapter 5), but when compared at equal performance the difference in cost per operational year can be understood as the cost of purchasing survivability in this design. Policy makers can judge the value of this increased performance for a known cost. This is a less formal way of presenting results than a Pareto front. Typically in TSE, the combined utility function is plotted against the lifecycle cost the system being examined. Those designs with either a higher utility score or lower cost than any other design are said to stochastically dominate the other designs and are found on what is known as the Pareto Front (Ross, Diller, & Hastings, 2003). Future work could construct a better defined utility function, such as the ones for the OREOS and On Orbit servicing examples and produce such a product.

For the purpose of illustration and focus on the research questions of this work, in Chapters 2, 3 and 4, the design vector contains the four design variables listed above. In this chapter, additional variables and their inclusion in the TSE model are presented with the goal of illustrating the amenability of the merged modeling technique to larger design vectors. Not every variable computed in the TSE model is documented in this chapter, however, the resolution and function of each component in this TSE model will be made clear.

2.2.2   Assumptions and Context Vector

The next set of variables include the assumptions and context variables. These are variables which might be considered exogenous to the TSE model, those over which the designer has little to no control. The TSE methodology calls for sensitivity analyses and changing assumptions to test the impact on model results as well as testing the performance or cost of a system under context change. As the ultimate goal of this technique will interface with the assumptions made in a System Dynamics Model, outlined in Chapters 2 and 3, it will be important to ensure the two-tiered combined model possess the capability to track assumptions across both models. In a traditional TSE effort an assumption vector is constructed; in the technique of Epic-Era analysis a context vector is constructed. As this work seeks to investigate future outcomes, and has been tuned to match historical outcomes, it is fair to state that all future changes are assumptions. As such the Context and Assumptions vector will operate in this model as a single structure which may be varied to influence model results. From the perspective of the TSE model these are assumptions and the model has no knowledge of how these variables were constructed; it inserts them into the appropriate equations and calculates. Varying of these parameters is conducted in Chapter 6; they are defined here:

Context Vector: {Year, RF Configuration, Mass Model Tuning, NRE Cost Model Tuning, Production Cost Model Tuning, Launch Costs, On-Orbit Operations}

1. **Year**: The year of execution; this variable works as an 'unlock' function where at a point in the future a new assumed capability becomes available. This also functions as an axis for comparison against.
2. **RF Configuration:** This variable represents a class of assumptions, an example of which can be found in Appendix A Variables and Definitions in TSE model. The implementation and the interaction with this set of assumptions is explained below in the Payloads section of this chapter. This is not a single assumption but influences the radio frequency (RF) environment in which the payloads, downlink, and potential crosslinks operate.

3. **Mass Model Tuning:** If the mass models outlined in Mass Model section of this chapter produced does not match the real world satellites, as the equations work for generic communications satellites and the GPS constellation is more than just a communications satellite, this can provide an additional constant to compensate. In all executions this tuning parameter is not used; however, it is not unreasonable that this variable might be used (might have been needed) in conjunction with the 'Year' variable to extrapolate a reduction in mass for equivalent performance. The implementation of such an historical curve was seen in the introduction.

4. **NRE Cost Model Tuning:** In the Cost Models section the NRE cost of satellite design is outlined. This variable would enable tuning of the model results if the model did not accurately predict the cost of the GPS constellation. However, as the models employed computed the GPS IIIA NRE cost to within a reasonable level, this variable was not employed. The model does make use of this variable in the event that the time interval between NRE events changes, as a way to track the interaction between the design vector's "NRE Update" and the "Year" variables in the model.

5. **Production Cost Model Tuning:** In the First Production Unit section the way additional unit cost is computed is examined and it is noted that this assumption has large impacts on model results. Examination of how additional unit cost is computed is be required and this variable enables such examination.

6. **Launch Costs:** In the event that launch cost either increases or decreases in the future, a modification to the values in the Appendix E Launch Vehicle Database Delta IV would be required; this variable enables such a modification. This variable will be especially important as the cost of rockets ties heavily to overall system cost and is a possible driving force in current design points.

7. **On-Orbit Operations:** This variable allows the model to test the cost impact of adding additional satellites to a constellation. It is possible that each additional satellite adds a flat cost per additional unit. It is also possible that each additional satellite added to the constellation costs incrementally less. It is even possible that due to higher complexity, additional satellites add to the constellation cost incrementally more or create a discontinuous increase as entire new stations (hardware) must be procured and maintained. As little data about on-orbit cost in flying large constellations is available, being able to test the impact of such possible scenarios across time is important to costing potential architectures.

2.2.3 Orbit and Coverage

For initial efforts, the orbit for all constellations has been fixed to the existing altitude, number of planes and inclination of the existing GPS constellation (commonly referred to as a walker delta constellation 56°:27/3/1 for degrees, satellites, planes and spacing). None of these variables are included in the design vector listed above. Yet, for completeness and validity, orbit and coverage must be incorporated within the model. Consequently, if requested, the design vector is capable of computing:

Coded but Excluded Design Vector: {Altitude, Inclination, Number of planes equally spaced around the right ascending node, Number of Satellites, Number of Satellites per Plane}

For the majority of the results (contained in Chapter 5), the work assumes a fixed orbit equivalent to the existing GPS constellation such that a disaggregated approach would fly in a loose formation but the same location as an existing GPS satellites. The reason for turning off the orbital propagator for the majority of design points is the time complexity for this modeling approach. In Chapter 4 computational issues are examined in detail and it is noted that with a full orbital propagator only 400 design points per day per CPU core can be examined. This is in line with other work on orbital simulation and modeling where years of computational time are required (Legge, 2014). Future models will likely be able to bypass this CPU limitation by offloading orbital propagation calculations to Graphical Processing Units (GPUs) which are specifically designed to perform large amounts of parallel floating-point calculations and matrix operations.

When activated, the Orbit and Coverage model performs the following sequence to investigate the satellites' orbit in the design point:

- The Earth is represented by a spheroid composed of 2,000 points on its surface.
    - While all orbits are assumed to be circular, this does not equate to perfect circles (due to the inclusion of Earth oblations and perturbation). The orbital propagator's computation of a circular orbit is not the same as simply placing a circle around a model of the earth.
- The model is set to run for a 24-hour period, on the Julian date represented by 1 January 2014. This was tested and found to be a sufficient time scale to analyze the performance of spacecraft at the GPS orbit of ~22,000 km orbiting approximately twice a day in an approximate 12-hour orbit.
- As GPS possesses the requirement of full planetary coverage 24 hours a day, a single day is a sufficient time period for analysis.
- Since the antennas for GPS payloads are sized to cover the width of the earth from Middle Earth Orbit (MEO), all points on the spheroid which possess line of sight to the satellite (minus 10 percent for clearance of obstructions) are considered able to receive the GPS signal.
- The script executes one-minute time steps, solving for a satellite's or a constellation's position and velocity over the Earth after each step.
    - At each time step through the 24-hour time period (1440 minutes), each of the 2,000 points on the globe is assigned a value of "1" into a matrix if the point on the Earth possesses line of sight to each satellite in the GPS constellation; otherwise, a value of zero.
    - The matrix is the number of satellites on orbit times 1440 (e.g., 1440 x 27).
    - After execution, the matrix can be summed across all the 1440 time points (vertically summed to a 1440 x 1 matrix). If the summed matrix possesses more than three satellites in view, then that point on the spheroid is said to have visibility. If any value in the final matrix is less than three (and preferably four), the constellation does not meet its design requirement.
    - When investigating spot-beam payloads and their coverage, capability is represented by percentage of the globe covered or visible, and a different utility function needs to be computed.

The orbital propagator's performance was validated against several sample cases of Systems Toolkit (STK) simulations (using the STK as a gold standard), and was shown to achieve the necessary fidelity and resolution to provide for effective analysis. The goal of this research was not to work on satellite orbitology, however, it must prove compatible with existing orbital modeling practices in TSE, which has been achieved.

- Corbin's thesis (Corbin, 2015) explains how it is possible to link a Matlab TSE model to STK. This model possesses the ability to interface in the same way if a higher fidelity orbital model is desired.
- STK is preloaded with the current almanac of GPS satellites and as such serves as a "gold-standard model" test for comparing another orbital propagator.

2.2.4 Payloads

2.2.4.1 Link closure to ground

One important physics model for sizing a GPS satellite is the link closure algorithm. A GPS satellite is a communication satellite that must close link with a ground receiver (e.g., a cell phone, or other navigation-enabled device, and specifically the GPS receiver within the device). This requirement, given assumptions about data rate, path loss, antenna design, and other design parameters ultimately results in a power requirement for the transmitter. This power requirement in turn sizes the power system and has great impact on the overall size of a communication satellite. For the GPS example, the link budget is calculated from the equations listed in the Space Mission Analysis and Design Handbook (Wertz, Everett, & Puschell, 2011), a method that has been validated by comparing Iridium's theoretical performance versus actual performance (Chang & Weck, 2004). Tuning parameters and variables are derived from the GPS standard, listed on the gps.gov website (Global Positioning Systems Directorate, 2014) as well as other online sources and fact sheets (Los Angeles Air Force Base, 2015) (Lockheed Martin, 2005). Information comparing relative sizes and costs of specific payload components between the GPS and Galileo implementations are also available online (Curiel, 2015).

The website gpsinformation.net (Mehaffey, Yeazel, Penrod, & Deiss, 2015) also lists computations to solve for the amount of power in spectrum required to close the link between a GPS payload and the GPS specification as listed on the government website, given a reasonable set of assumptions (Global Positioning Systems Directorate, 2014). These computations enable sizing of the hardware required to support the power requirements for each of the signals (Payloads) on a GPS satellite. This in turn allows for computations encapsulating the size of the overall space craft required to support these power requirements.

The full computational script for link closure is found in the Appendix D RF Link Closure Code. This script can also be used if assumptions about data rate, antenna size, and other parameters are changed to compute the communications system for Telemetry, Command and Control as well as the construction of various cross-link payloads. Another required change for cross-link payloads will be the loss calculation through the atmosphere, as there is no atmosphere in a MEO to MEO calculation; this is usually approximated as a three decibel (dB) loss. The range for the cross-link is set as the distance between two satellites in the same plane, not the distance between the constellation and earth. Here is an example of a simple calculation to determine link closure for a GPS signal based on the L1 C/A power listed at 25.6 watts: (Mehaffey, Yeazel,

Penrod, & Deiss, 2015). The gain of the operational GPS system is listed as 13 forward antenna gain in decibels (dB) for a Block IIR satellite and the L1 C/A payload (GPS.gov.).

- This would imply a power of ~500 watts or 27 decibel watts (dBW) in spectrum. This is calculated based on equivalent isotopically radiated power.
- As the GPS satellite is orbiting at ~22,200 km there exists a free-space loss of 182 decibel watts dBW relative to 1 watt at the GPS transmitter. Semtech lists the free-space loss equation and provides another source for computation. (SEMTECH, 2007)
  - ♦ It is important to identify the free-space loss component of this calculation and ensure it properly considers the atmosphere as the atmosphere adds loss beyond free-space.
- Since both the power in spectrum and free-space loss are in decibel watts, they can be subtracted (27 minus 182) to compute the power at earth's surface of –155 dBW.
  - ♦ Due to background radio frequency (RF) noise, the minimum strength listed for link closure is 160 decibel milliwatts (dBm).
  - ♦ These computations also assume a "top-hat" or even distribution of power around the 1575.42 megahertz (MHz) L1/ CA signal; this is not perfectly true as the power follows a Gaussian distribution; but such an assumption is acceptable for this class of modeling.

The same type of computation can be made in reverse for every signal. Given the required power in spectrum, the amount of power (in watts) which a transmitter would require to meet link closure at earth's surface can be computed (solved for as a system of equations). Similar to the orbital propagator, it is not critical for this model to simulate reality perfectly; however, it is critical to show that this method is supported by existing RF models and existing space hardware. In this respect, the model is able to create a reasonable set of parameters for sizing a space vehicle; such as the ones listed in the above example for the L1 C/A payload.

This varies slightly from traditional TSE where one might chose to vary the type of antenna, or even the power output by the transmitter. The change in performance of these satellites might then be captured in the resulting dBW of the signal at earth's surface, where anything less than ~160 dBW would be considered a failure to meet the constraint of link closure. Signal strength greater than ~160 dBW would be considered a design with superior performance; and in an associated utility function could be given a weighting relative to this performance level and the desirability of such an increase. However, as these variables are not under examination, and the performance required is already known, this computation remains an equation to be solved within this model. This modeling decision excludes antenna and transceiver design from the Tradespace, however, including these computations when modeling the spacecraft enables validation of the design point with respect to existing physics models. Inclusion of this performance model ensures that the designs produced are able to deliver the required performance with a reasonable level of fidelity. For spot-beam payloads the requirement is listed as ~20 dB stronger at earth's surface, which will be achieved through higher gain directional antennas combined with a higher power-output for the transmitter. Consequently, the requirement for the spot-beam payload was set at 138 dBW with an assumption of a 44 dB antenna. (Wayana Software, 2016). According to the Los Angeles Air Force Base (LAAFB) webpage, the gain for M-Code is +10 dB; exact specifications on power and antenna are unknown. (Los Angeles Air Force Base, 2015)

After these physics models compute the power required for the transmitter, these power requirements can be fed into a spacecraft sizing module. The power requirement also gives insight into the mass of the various payloads (Wertz, Everett, & Puschell, Space Mission Engineering:

The New SMAD, 2011). If desired, the model could be enhanced by approximating the size (mass) of the antenna based on the gain required.

2.2.4.2   Command and Control

Each GPS satellite is capable of communicating with any visible ground station, subject to a minimum elevation angle of 10 degrees (an assumption required for skyline clearance). According to government websites there are a total of 12 Command and Control (C&C) sites which could be used to communicate with GPS satellites (GPS.GOV, 2015). To calculate times when a GPS satellite can communicate with these 12 ground stations, a computation nearly identical to the Orbital Coverage model is used, though the assumed values (data rate, gain, power, etc.) in the Appendix C Example RF Configuration File (Class and Variables) are changed.

- 12 of the 2,000 points on the spheroid representing Earth are marked as C&C sites.
- If a satellite possesses line of sight to the control site (minus 10% elevation as computed relative tangential to Earth's surface), the control site is considered able to communicate with the satellite during that time step.
- The visibility for each individual satellite to each ground station must be computed individually in a 1440 x 12 matrix to represent one minute for each satellite and the 12 ground station locations.
  - ♦ For a constellation of size 27 satellites this implies a matrix of size 1440 x 12 x 27 must exist to compute contact times for the entire constellation.
  - ♦ Due to the large size of such a vector, having the orbit constant assists in reducing the time complexity of the problem.

Two key variables in sizing the transmitter are:

- **The Downlink Rate**
- **Percent Contact Time with Ground Stations**

2.2.4.3   Cross-Links

One planned upgrade to the GPS constellation is the implementation of cross-links, or a means of communication from one GPS satellite to another. The implied performance increase lies in the fact that communication is possible with any satellite in the GPS constellation as long as a ground link exists with at least one satellite. This model is designed to evaluate this implementation.

The addition of cross-link capability is achieved in TSE by adding a new payload to the capabilities list. Based on performance requirements, the associated mass and cost can be computed. The major variables which need to be considered in evaluating such an implementation are listed here but defined in Appendix A Variables and Definitions in TSE model:

- **Cross-link**
- **Cross-link Data Rate**
- **Cross-link Range**
- **Cross-link Transmission Power**
- **Cross-link Mass**
- **Inter-link Data Rate**

2.2.4.4   Payloads Placed on GPS Satellites

As noted in the Introduction, five GPS payloads already exist and the cost and mass of these payloads are well known. Possible approximations for the associated mass, power, and cost for each proposed GPS payload are shown in Table 2-1.

Table 2-1: GPS Payloads and Associated Mass, Power and Costs

Payload Name	Payload Mass (Kg)	Payload Power (watts)	NRE Cost ($K)	Reproduction Cost ($K)
'L1'	50	50	100,000	10,000
'L2'	200	200	200,000	20,000
'L3'	300	300	0	20,000
'L5'	200	200	100,000	10,000
'M1'	50	200	250,000	15,000
'M2'	500	1200	250,000	20,000
'Atomic Clock'	50	100	0	10,000
'L4'	200	200	100,000	10,000
Cross-link	Varies	Varies	Computed as RF Payload	Computed as RF Payload
Spot Beam	Varies	Varies	Computed as RF Payload	Computed as RF Payload

Note1: 'L1' and 'L2' include L1 C/A and L2C in capability for all future designs.

Note2: For the purpose of this analysis the 'Atomic Clock' payload is added to each satellite based on the design life of the satellite being produced. For every five years of design life desired, one 'Atomic Clock' payload is added: 5 years = 1 through 20 years = 4.

Note3: Values in table intentionally rounded to nearest significant figure; actual computations do not round inside Matlab code execution.

Table 2-2 summarizes the GPS program of record or BATNA in a single GPS satellite with all the payloads available in 2008, and outlines a set of potential payload-to-bus alignments, showing various payload alignments available. These alignments attempt to create performance equivalent to that expected from the GPS constellation in 2008. It is possible that even more optimal alignments might exist, and certainly other options are available, however, this set of design choices is sufficient to examine the capability of the merged model and proposed techniques. Based on this configuration, full aggregation places all capabilities on a single bus, and the greatest disaggregation examined is one signal per satellite. Adding additional payload-to-bus alignments is accomplished by updating the payload alignment code, listed as Payload(s) in Figure 2-1, and re-executing the code.

Table 2-2: Generation 1 Payload Alignment

Configuration Name	Payload Alignment
GPS Program of Record (BATNA)	SV1 = L1, L2, L3, L5, M1, M2
Military & Civilian	SV1, Military = M1, M2, L3 SV2, Civilian = L1, L2, L5

3x Disaggregation	SV1, Military = M2
	SV2, Old Military = M1, L3
	SV3, Civilian = L1, L2, L5
Survivable	SV1: L1 & L2 + L3
	SV2: L2 and M1 + L3
	SV3: M1 & M2
	SV4: M2 & L1
Full Disaggregation	SV1 = L1+L3
	SV2 = L2
	SV3 = L5
	SV4 = M1
	SV5 = M2

2.2.5   TSE Model Runs to Assess Future Capability

As outlined in the Introduction, future GPS satellite designs are planned to have upgraded capability in the form of additional signals, cross-links, and spot beams. Table 2-3 outlines how a second TSE model execution could replace the alignments of payloads in Table 2-2 (a representation of GPS construction in 2008) with updated or increased performance designs at a future date. It is important to note that with this future-oriented execution of the TSE model any point or assumptions in the design vector can change. The computed future generation may add all of the new payloads (spot beam, cross-link, L4 signal), add a combination of the payloads, or none at all. In theory, the rate at which capability is added is likely to have an impact on the development of the GPS program. Examination of time-sequenced upgrades and their impact on the production of satellites is, however, beyond the capability of a TSE model since TSE considers only the sizing and costing of satellites based on given input and has no knowledge that trades might exist across time. Nonetheless, the TSE model can be rerun with the additional capacity added and the potential cost and size of such a satellite defined by a set of assumptions similar to those in Table 2-3: Generation 2 Payload Alignment. When considering future GPS implementations, the proposed upgrade plan is now referred to as the BATNA, as even though no such satellites exist, the existing plan is the baseline against which all other potential plans are compared.

Table 2-3: Generation 2 Payload Alignment

Configuration Name	Payload Alignment
GPS Program of Record (BATNA)	SV1 = L1, L2, L3, L5, M1, M2
Military & Civilian	SV1, Military = M1, M2, L3, Cross-link, Spot Beam
	SV2, Civilian = L1, L2, L5, Cross-link
3x Disaggregation	SV1, Military = M2, Cross-link, Spot Beam
	SV2, Old Military = M1, L3, Cross-link
	SV3, Civilian = L1, L2, L5, Cross-link
Survivable	SV1: L1, L2, L3, Cross-link

	SV2: L2. M1, L3, Cross-link
	SV3: M1, M2, Cross-link, Spot Beam
	SV4: M2, L1, Cross-link, Spot Beam
Full Disaggregation	SV1 = L1+L3, Cross-link
	SV2 = L2, Cross-link
	SV3 = L3, Cross-link
	SV4 = L5, Cross-link
	SV5 = M1, Cross-link
	SV6 = M2, Cross-link, Spot Beam

In a third or fourth generation even further into the future, a similar computation for payload alignment and increased performance cannot be continued as neither capabilities nor requirements have yet been defined by the government. While the model cannot create a specific design to an unknown specification, performance comparisons can be achieved as follows:

1. Assume that no more performance will be required and that technology will simply be used to reduce the mass of the GPS satellites. This will produce identical results, as the code possesses no stochastic elements. This is not useful in the context of TSE, however, as noted when merging this approach with SD (Chapter 4), this may become useful since keeping the model static can return information if the overall model has reached equilibrium, or if change in the SD model will occur if change in requirements does not. The utility of such an approach is clearly seen when examining the "Full Disaggregation" configuration.
2. Assume that performance will continue to follow a linear regression model with respect to the mass of GPS satellites and number of payloads added each generation.
3. Create dummy payloads and attach them to the payload configuration future options. For example, a payload "Dummy 1" (D1) could be added to Table 2-1: GPS Payloads and Associated Mass, Power and Costs with the same mass, power and costs as the M2 signal. This would be the same as assuming the military would want an increase in capability in the Block IV design equal to that desired in Block III.

These assumptions are more relevant to policy choices than model development, as the model is indifferent about any such assumptions. From the perspective of the TSE model all that matters is that it executes the design vector it is given and is able to create and cost the appropriate satellites and associated architecture based on requirements and assumptions. In Chapter 4, the rules imposed to constrain design vectors based on past design vectors are discussed in the context of model execution. The model is equipped to handle all three approaches to handling future requirements, depending on modeler preference.

2.2.6 Mass Model

Mass models and estimating techniques for unmanned satellites are typically regression models which divide a satellite into eight major subsystems. These subsystems can be tailored and sized based upon the mission and capability desired for the satellite under examination. The models used in this thesis can be found in the Space MAD (Wertz, Everett, & Puschell, 2011). Additional information about mass estimation can be found in NASA's *Cost Estimating Handbook* (NASA, 2010) and the USAF's *Satellite Cost Models* (SAIC, 2010) which provide regression models of

historical satellite masses and the relative percent of that mass which comprises each subsystem required to support the specific payloads. This section outlines the mass model's major variables and construction.

2.2.6.1   Primary Subsystems

Based on existing satellite modeling and representation techniques the primary subsystems used in functional decomposition of communications satellites are listed here and defined in Appendix A Variables and Definitions in TSE model:

- **Structure Mass**
- **Thermal Mass**
- **TTC_ Mass**
- **CDH Process Mass**
- **ADCS Mass**
- **Closeout Mass**
- **Power Mass**
- **Payload Mass**

2.2.6.2   Power System

The simplest approximation for the power requirement of a GPS satellite could be based upon the single variable of total mass of the payloads. For the model developed in this work, however, a comparison of power required against a regression line of the average mass for historical communications spacecraft is insufficient. This calculation is performed for an initial estimate of the power required, and the bus is sized with this rough calculation in place rather than using iterative adjustments to the satellite design, in which increased power mass increases other relative masses. This work implements a series of higher-fidelity component specific power models for the computation and model representation of the power demands of the GPS satellite.

Power need is one of the most important elements of this class of space vehicle. The developed model breaks down power requirements in alignment with the major subsystems listed above:

- **Thermal Power**
- **ADCS Power**
- **Processing Power**
- **Transmission Power**
- **Average Transmission Power**
- **Propulsion Power**
- **Bus Power**
- **Payload Power**
- **Total Power**

With Total Power required by the satellite computed, the required size and mass of the power system can be computed from consideration of:

- **Solar Mass**
- **Power Distribution and Regulation Mass**
- **Battery Mass**

- **Solar Type**
- **Average Cosine Loss**
- **Solar Surface Area**

After computing Total Power-System Mass, the model replaces the initial estimate with this more accurate calculation. The model is also capable of computing the rough length, width and height of a satellite based on its mass and assumptions about the general ratio and density of existing GPS satellites. This information can be used when attempting to fit multiple satellites inside the faring of a launch vehicle. The current model could be enhanced to achieve more accurate sizing results if further analysis of multiple launches on single satellites is desired.

2.2.6.3   *Propulsion System*

The size (mass in kilograms [kg]) of the space vehicle, as well as the design life are the major factors in sizing the propulsion system for any satellite. With each of the eight subsystems sized and the design life specified in the design vector, an appropriate propulsion system can be designed. Consideration to the overall design is also given for additional power required for propulsion systems.

In the GPS program of record, capability of the propulsion system is listed as the liquid apogee engine for final orbital insertion, the five foot-pound thruster for large on-orbit maneuvers and the .2 lbf thruster for attitude and station-keeping (Gibbons Media & Research LLC, 2015). (Note: Los Angeles Air Force Base lists a different set of thruster specifications containing 12 small thrusters based on the A2100X design on Lockheed's spec sheet). In this model the propulsion system is sized based on the regression models and approximate mass required derived from MEO and GEO satellites already in existence. Thus, the mass of the propulsion system adopted for this work is part of the TSE computation and increases or decreases in relation to the mass and design life specified for the space vehicle. This model and associated TSE implementation could be expanded and enhanced by enabling different specific configurations of propulsion systems. This improvement may give better fidelity for the mass requirements of propulsion for smaller space vehicles, since the regression models implemented are based on the design of large satellites. It is also possible that new propulsion systems with higher efficiency could change this set of equations and could be set in the context variable as an option beyond a specified year. The following variables are computed and solved for based on the Design Vector and defined in Appendix A Variables and Definitions in TSE model:

- **Propulsion**
- **Delta V Lost to Drag**
- **Delta V for Maneuvers**
- **Propulsion Mass**
- **Fuel Mass**
- **Apogee Kick Motor**
- **Kick Motor Mass**

2.2.6.4   *Total Mass*

Having computed the approximate mass of all satellite subsystems, with additional fidelity provided to payloads, power requirements, and propulsion the total mass can be computed as a sum of all the subsystems as outlined above.

- **Dry Mass**
- **Wet Mass**

2.2.7   Launcher Select

Each design point possesses a different number of satellites to be placed on orbit. Once the mass of the satellites to be launched and the total mass of the constellation have been computed, appropriate launch vehicles can be selected. If there is to be only one satellite per launch vehicle, this problem is trivial. Yet the model must be robust enough to handle constellations where many satellites may be placed on a single launch vehicle. The model must also be able to handle anticipated changes in launch capability over the time horizon of investigation. The problem is heuristically similar to the knapsack problem where 'n' number of objects must be placed into 'k' number of bags. This problem becomes even more complicated if the 'n' objects possess different masses and the 'k' bags possess different carrying capacities. In this case the 'n' objects are satellites for a design point, and the 'k' bags are available launch systems. Several knapsack-solver programs are available on the MathWorks File Exchange (Petter, 2009). These functions implement dynamic programming as a method for combating the time complexity of this Non-Polynomial or "NP" hard problem. Because each design point varies the mass of the satellite(s), the routine must be invoked for each design point. The computation delivers the appropriate number of rockets required to launch the design point under consideration.

The Matlab tool kits contain a detailed list of launch vehicles including American, European, and Russian, both historical and current. The assumption underlying the results in Chapter 5 is that for the GPS constellation, only American rockets would be possible solutions. This results in five rocket variants.

One could vary this assumption and include the European Ariane launch system; however, based on the data in the database used, it appears that Ariane is stochastically dominated by Atlas and Delta variants. In Chapter 5, the impact of a new entrant—potentially a SpaceX rocket—or a change in launch costs due to political instability are analyzed. From the standpoint of the TSE model this is achieved through an implementation that "unlocks" new options within the knapsack solver based on the "time" or year of execution. In Chapter 5 the model's ability to examine assumptions is increased when this context variable is paired with the execution of the SD model. Five variables form the assumption space around the launch costs in delivering the modeled space vehicles to orbit:

- Launch Vehicle
- Number of Launch Vehicles
- Maximum Space Vehicles per Launch Vehicle Allowed
- Maximum Space Vehicles per Launch Vehicle
- Excess Launch Capacity

The model assumes that the launching of satellites will follow a sequence such that in the event multiple satellites are placed on one launch vehicle, they will require insertion into a single plane. Currently, one GPS satellite is launched per rocket. One future option may be to dual-launch GPS satellites, placing two satellites in orbit using one large launch vehicle. In the event of disaggregation and smaller satellites, a cost-affordable solution would almost invariably mandate the ability to launch multiple satellites on a single launch vehicle. SpaceX placed 11, 173 kg

satellites and one mass simulator into LEO on a single rocket and Iridium was placed into LEO with between six and eight satellites per launch vehicle as early as 1996; however, no such launches have been performed for MEO. (ORBCOMM, 2015). While it is conceivable that as satellites are launched to replace failing capability on orbit, extra launch vehicles might be required, this type of analysis is beyond the scope of this model's current implementation. It is likely that a model to include this type of computation would require inclusion of an "Agent-Based" approach, where each satellite is tracked in its respective orbit; this could be examined in future work.

2.2.8   Cost Models

Cost models and cost-estimating techniques for satellites are found in the Space Mission Analysis and Design Handbook (Wertz, Everett, & Puschell, Space Mission Engineering: The New SMAD, 2011). Additional information about cost estimation can be found in NASA's *Cost Estimating Handbook* (NASA, 2010) and the USAF's *Satellite Cost Models* (SAIC, 2010). These provide regression models based on historical costs for predictive modeling efforts for space systems.

The cost model in this work implements two key cost calculations: one computing the theoretical first unit cost and the second computing the cost of the first production model. The models have also been tuned for communications satellites. In Chapter 6 when Weather and Climate Sensing satellites are investigated, these models must be changed as costs associated with communications satellites are historically different than LEO weather satellites. The model implements a third cost calculation in the event that the satellite being procured weighs less than 500 kgs, which occurs with some highly disaggregated designs having shorter design lives.

2.2.8.1   *Theoretical First Unit*

As with the mass models, the values associated with each of the eight subsystems of the satellite under construction are independently calculated and then summed. First, the costs of the theoretical first unit are computed; this calculation includes other programmatic elements beyond the satellite itself (e.g., program management, integration and test, residual equipment). All costs are computed in $K FY 2010 dollars and the model does not implement a discount rate or a computation against the time value of money:

- **Structure and thermal management costs**
- **ADCS costs**
- **Power generation, distribution and regulation system costs**
- **Propulsion Systems costs**
- **Telemetry Command and Control costs**
- **Logic Processing Systems (CPUs and control software included)**
- **Payload costs summed for all payloads to be attached to the bus**
- **Integration and Test Costs**

The summation of all costs results in the Total Cost for the theoretical first unit and all Non-re-occurring Engineering (NRE) costs associated with this first unit. The model also possesses a variable "Part Commonality" in the event that the Payload Alignment selected is a disaggregated approach. It is highly likely that in the event two or more satellites are produced, at least the buses will possess similar components and not require a unique design. For the initial calculations

(Chapter 5) this variable is inactive. As this is a reasonable assumption to challenge, the impact of assuming part commonality is examined in Chapter 6.

2.2.8.2   *First Production Unit*

After the first unit is costed, the first production flight can be costed. Due to the reuse of software and physical designs and substantially reduced cost, the computation of the cost for the first production unit relies on a completely different regression model than the theoretical first unit but relies on the same variables since the underlying design point has not changed. The summation of all costs results in the Total Cost for the First Production Unit.

2.2.8.3   *Total Cost and Cost per Operational Year*

Typically, satellite cost models implement a learning curve formula to calculate the cost reduction in replication of space assets between the second and 'nth' unit. As outlined in the Space Mission Analysis and Design Handbook (Wertz, Everett, & Puschell, 2011):

$$s = \text{replication modifier an arbitrary constant from .9 to 1}$$

$$B = 1 - (\frac{Log\left(\frac{1}{s}\right)}{\log(2)})$$

This equation becomes the constant to which the Number of satellites to be produced is raised

$$L = (Number\ of\ satellites\ to\ produce - 1\ )\verb|^|B$$

The "–1" is included in this equation to remove the Theoretical First Unit since its cost has already been accounted for in the NRE computation.

$$Cost\ of\ Aditional\ Units = First\ Production\ Unit\ Cost * L$$

The computation is completed by multiplying the value L by the cost of the first production unit, essentially scaling the cost of every satellite to the average cost. One drawback of this approach is the large impact of the assumption behind the s value or "replication modifier constant." For example, if we compare a 3x disaggregated approach versus the GPS BATNA: in the GPS BATNA 24 satellites are produced, while in the 3x disaggregated approach, 72 are constructed. Selecting an s value of .98 (weak learning) ensures that the BATNA is cheaper to construct. Selecting an s value of .92 (relatively strong learning) ensures—across a wide range of assumptions—that the disaggregated approach is cheaper. In short, this single assumption/variable possesses the ability to change the outcome of the analysis. Even a small difference in the variable will have a major effect. Selecting a proper value for s is even harder in an environment of few large-production satellite constellations. In Chapter 4, the SD model will replace this calculation with a Stock and Flow model and enhance the accuracy of this variable's computation. Because this single variable possesses the ability to reject the entire model's validity in its ability to analyze the concept of a learning effects, without solving this problem trust (and consequentially usefulness) in model outputs could not be obtained. One of the reasons this thesis is investigating the proposed merged method, linking SD with TSE, is to develop a method to better examine this cost computation.

To compute the total system cost: the total cost of the theoretical first unit and all production units, along with all launch costs and on-orbit support costs are summed. This yields the total cost of the block buy for manufacturing, fielding and operating over the system's entire design life.

Cost per operational year can be obtained by dividing the total system cost by the design life. Over 75 cost and performance metrics tied directly to spacecraft sizing and design (computed in the Physics Model) are included in the final determination of each individual spacecraft's cost.

2.3 Model Outputs for BATNA

From the perspective of the TSE module, all assumptions or context variables are exogenous tuning parameters. To model results at two different time periods, two different sets of context variables are constructed. Table 2-4 presents two model runs. In the first, the year is set to 2008. The second is set in the future, in 2020.

The Design Vector for the first run is:

Design Vector: {Design Life, Payload Alignment, Number of Satellites to Be Produced, NRE Update}

Design Vector: {15, BATNA, 8, 1}

This indicates a design life of 15 years, designing the model representation of the GPS program of record or BATNA in the year 2008, a request to build eight satellites and that this is a new design implementing a technology (NRE) refresh.

The Design Vector for the second run is:

Design Vector: {15, BATNA, 8, 0}

This vector indicates that for the block buy of eight satellites in 2020; no performance updates or increased capability would be requested.

The Assumption and Context Vector for 2008 is structured as:

Assumption & Context Vector: {Year, RF Configuration, Mass Model Tuning, NRE Cost Model Tuning, Production Cost Model Tuning, Launch Costs, On-Orbit Operations}

Assumption & Context Vector: {2008, 0, 0, .95, 1, 1}

This instructs the model that it has access to technology available in 2008, is to make no modification to any mass models, make no modification to any NRE cost models, use a cost replication factor of .95 for the s value in additional units, fixed launch costs as contained the database of launch vehicles, and assume each on-orbit asset comes at a fixed cost.

The Assumption and Context Vector changes nothing beyond updating the year to 2020:

Assumption & Context Vector: {2020, 0, 0, 95, 1, 1}

The values selected for these vectors are those associated with base case assumptions, i.e., are the values associated with the BATNA. In Chapter 6, these assumptions will be challenged and the impact examined. The model output displayed in Figure 2 represents two TSE design points in two different TSE model runs based on the two Assumption & Context Vectors listed above. The only change between the two model runs is the year of execution, 2008 versus 2020. This different context variable shifts the design vectors pool of Payload Alignments from which it selects. In the green columns the Payload Alignment is the BATNA selected from Table 2-2, in the teal columns the model executes using the BATNA Payload alignment as contained within Table 2-3. This shift

in context implies a higher demand for performance and the second set of satellites includes the additional capability represented in Table 2-3.

Table 2-4: Model Output for Two Blocks of 24 GPS Satellites Under BATNA Payload Alignment Variable

	Variable	GPS BATNA		Variable	GPS BATNA
1	Program Start (Year)	2008	1	Program Start (Year)	2020
2	First Production SV Launch (Year)	2015	2	First Production SV Launch (Year)	2028.375
3	Gen #	Gen 1	3	Gen #	Gen 2
4	Design Life (years)	15	4	Design Life (years)	15
5	NRE This Generation	1.57e+06	5	NRE This Generation	1.96e+06
6	Cost 1st Production	2.19e+05	6	Cost 1st Production	3.33e+05
7	Replication Costs (TSE)	3.45e+06	7	Replication Costs (TSE)	5.25e+06
8	Replication Costs (SD)	4.80e+06	8	Replication Costs (SD)	7.68e+06
9	Launch Costs	2.67e+06	9	Launch Costs	2.67e+06
10	Ops Costs	1.46e+06	10	Ops Costs	1.45e+06
11	Cost Per Year Total	8.75e+05	11	Cost Per Year Total	1.01e+06
12	Cost Per Year Gen	8.75e+05	12	Cost Per Year Gen	1.15e+06
13	SVs Ordered this phase	24	13	SVs Ordered this phase	24
14	Equal Capability Dry Mass (kg)	3.55e+03	14	Equal Capability Dry Mass (kg)	4.24e+03
15	Equal Capability Wet Mass (kg)	6.11e+03	15	Equal Capability Wet Mass (kg)	7.29e+03

The variables summarized in Table 2-4 are defined in Appendix B Variables and Definitions of TSE Model Outputs. An important variable not listed above is the expected expiration of the generation once placed on orbit. While one might conclude that satellites expire after their design life is exhausted, as all satellites are not launched at once, this gives little planning or policy assistance concerning when satellites will be needed. In Chapter 2 and 3 the System Dynamics model will be used to track the launch, on-orbit capability, and exhaustion of satellites, enhancing this model and indicating when the next generation must be produced to maintain constellation strength.

2.4 Model Comparison to GPS Program of Record

Once model outputs are available, it is important to check the reasonableness of the outputs of various payloads and alignments. (It took over a month of debugging to achieve this.) Once the model is found to be a sufficiently accurate representation of reality, one can compare predicted design points (TSE outputs) against real world GPS IIIA satellites currently under development. Comparisons are not made, however, with the values of actual GPS III satellites currently under production but with the model's representation of the GPS III constellation. Before these comparisons can be made the Model outputs must first be validated against the actual GPS III constellation as seen in Table 2-5. This approach improves the validity of relative comparisons of a tested design point versus the baseline, as any errors in the model are present in both the GPS III model representation of the BATNA as well as in any other design point. In theory, the errors cancel out, enabling a pair-wise percentage comparison between the different designs. While not all values for the GPS IIIA in production are available for comparison, the most critical (high-level) variables are available online (Los Angeles Air Force Base, 2015) (Lockheed Martin, 2014) (Airforce Technology, 2015) (Kasper & Balle, 2014).

Table 2-5: GPS Specifications Compared to Model Outputs

Variable/Metric	GPS IIIA (Actual)	GPS IIIA (Model)
Dry Mass	3680 kg	3574 kg
Wet Mass	7100 kg	6342 kg
NRE Cost (First Unit)	Listed $1.5 (overrun $1.7B)	$1.56 B
Production Cost (Replication Cost)	$224M	$219M
Power Size	307 ft2 (28.5 m^2)	33 m^2
Total Power	4,480 Watts EOL	5061 Watts EOL
Design Life	15 Years	15 Years

Table 2-6: GPS Future Block Specification Compared to Model Outputs

Variable/Metric	GPS 2020 (Actual)	GPS 2020(Model)
Dry Mass	4,764/5003 kg	4236 kg
Wet Mass	8,115/8553 kg	7237 kg
NRE Cost (First Unit)	Unknown	$490M More/Over Block IIIA NRE (total $2.05B)
Production Cost (Replication Cost)	Unknown $224M+	$330M
Power Size	307 ft2 (28.5 m^2)	37 m^2
Total Power	4,480 Watts EOL	5490 Watts EOL
Design Life	15 Years	15 Years

2.5 Discrepancy Analysis

As any model is an imperfect abstraction of reality, the predicted results are not expected to be in perfect alignment with the actual GPS IIIA design specification. Nonetheless, some sources of discrepancy can be uncovered by looking deeper into the code execution associated with major divergences. There are four key areas of inconsistency.

1. The heuristic mass model used for the weight of the propulsion system and the amount of fuel for the propulsion system appears to predict a value less than in actual GPS designs (roughly 10% less). A correction factor could be applied, however, this will not be implemented as such a tuning would cascade into other design points as well. It was reasoned that keeping this error in the model was better than tuning it out and then not understanding how this tuning might impact different "Payload Alignments" in the design vector for other points in the Tradespace.

2. The production cost model works very well for the GPS IIIA, however, the cost rises substantially when adding the L4 signal, cross-inks and spot beams. The model does not predict that these satellites will cost anywhere near $224M in production. The reason for this likely stems from the implementation of the M2 signal: the model associated spot beams with as much cost as the M2 signal itself. The model has been adjusted to teach it that adding spot beams was not the same as adding an entire M2 capability.

3. According to the fact sheet, battery systems are nickel hydrogen (NiH2) for the GPS BATNA, however, the model assumes lithium ion to be available as a viable option in

2008. This makes the modeled GPS IIIA design weigh less than in reality. The Assumption and Context Vector could be altered to lock out the option of lithium ion in 2008, which would increase the battery mass and bring the model closer to reality. This, however, was not implemented as the disaggregated approaches made use of lithium ion batteries, and in all computations the initial desire is to bias the model against disaggregated implementations.

4. The model expects slightly more power at End of Life (EOL) will be required than is listed on the GPS IIIA specification. Similarly, the model predicts a need for a larger solar foot print than is listed on the GPS specification. It should be noted this capability is well within the capability of the Lockheed A2100X Bus line of products. The discrepancy in the additional power required is due to the M2 signal. The bus was sized per the +20 dB requirement rather than the +10 dB performance assumption. At +20 dB the M2 signal requires on the order of ~1200 watts, by far the largest power draw of any payload. While this is a lot of power for a single payload, it is not completely unreasonable and as such was not tuned through the Context Vector. It is also possible that the efficiency of the solar panels is higher in reality than the model, or the degradation rate of the solar panels slower in reality. Such factors are not publically available, so reasonable values from the SMAD have been used in place. With so much uncertainty the model is left as is with this error intact and noted.

Even with these discrepancies, the TSE model reasonably approximates the high level variables of the GPS IIIA satellite design currently in production.

2.6 Model Program of Record Compared to Model 3x Disaggregation

The GPS BATNA was constructed as a design point inside this TSE model. It can be compared to the theoretical Galileo implementation of GPS outlined in the mental exercise in the Introduction.

Table 2-7: Model Output for Two Blocks of 72 GPS Satellites Under 3x Disaggregated Payload Alignment Variable

	Variable	GPS BATNA			Variable	GPS BATNA
1	Program Start (Year)	2008		1	Program Start (Year)	2020
2	First Production SV Launch...	2015		2	First Production SV Launch...	2025.125
3	Gen #	Gen 1		3	Gen #	Gen 2
4	Design Life (years)	15		4	Design Life (years)	15
5	NRE This Generation	1.73e+06		5	NRE This Generation	2.16e+06
6	Cost 1st Production	2.71e+05		6	Cost 1st Production	1.95e+05
7	Replication Costs (TSE)	1.15e+07		7	Replication Costs (TSE)	8.30e+06
8	Replication Costs (SD)	4.31e+06		8	Replication Costs (SD)	3.33e+06
9	Launch Costs	2.67e+06		9	Launch Costs	3.33e+06
10	Ops Costs	1.50e+06		10	Ops Costs	1.92e+06
11	Cost Per Year Total	8.50e+05		11	Cost Per Year Total	8.72e+05
12	Cost Per Year Gen	8.50e+05		12	Cost Per Year Gen	8.94e+05
13	SVs Ordered this phase	72		13	SVs Ordered this phase	72
14	Equal Capability Dry Mass (...	3.86e+03		14	Equal Capability Dry Mass (...	4.56e+03
15	Equal Capability Wet Mass ...	6.64e+03		15	Equal Capability Wet Mass ...	7.84e+03

As the equivalent capability of the GPS BATNA has now been spread across three satellites, an exact comparison for mass and power is not possible. Instead the total combined mass and power of the three satellites is listed in Table 2-8 and Table 2-9.

Table 2-8: GPS IIIA BATNA Compared Against 3x Disaggregation

Variable/Metric	GPS IIIA 2008 (Model View)	GPS IIIA 2008 (3x Disaggregated)
Dry Mass	3574 kg	3860 kg
Wet Mass	6342 kg	6640 kg
NRE Cost (First Unit)	$1.56 B	$1.73B
Production Cost (Replication Cost)	$219M	$271M
Total Solar Size (m^2)	33 m^2	41.4 m^2
Power Size (watts)	5061 watts EOL	5971 watts EOL
Design Life	15 Years	15 Years

The GPS BATNA 2020 model representation can also be compared against the GPS 3x disaggregated approach in 2020. In Table 2-9 we find the increase in relative mass to be placed on orbit as well as the increased support power required for such an approach. Based on the assumption and context vector selected, it appears that over two generations such an approach starts to become cost competitive with the GPS BATNA on a cost-per-operational-year basis. With the traditional TSE tools this examination is difficult to visualize. Further analyses and the reason for this cost shift is presented in Chapter 5, using visualizations available in SD.

Table 2-9: GPS IIIA Next Generation Compared Against 3x Disaggregation

Variable/Metric	GPS 2020	GPS 2020

	(Model View)	(3x Disaggregated)
Dry Mass	4236 kg	4560 kg
Wet Mass	7237 kg	7880 kg
NRE Cost (First Unit)	$490M over Block IIIA (total $2.05B)	$430M over Block IIIA equivalent ($2.16B total)
Production Cost (Replication Cost)	$333M	$195M
Total Solar Size (m^2)	37 m^2	44.3 m^2
Power Size (watts)	5490 watts EOL	6399 watts EOL
Design Life	15 Years	15 Years

2.6.1   Evaluating the Design Points Performance Model

As a TSE model can pose thousands of possible design points, it is infeasible to analyze them all. Plotting tools are used to assist with evaluating large numbers of possible futures. A utility function can be used to rank the relative goodness of each implementation. As previously noted, cost per operational year is the sole basis for judging goodness, so our utility function in this model is cost per operational year.

Table 2-10 displays the output of the TSE model if only the Payload Alignment Variable is changed inside the Design Vector. Blue Points are those that are similar to the existing GPS design point implementation; red points are substantially different. It can be seen that, all else being equal, the current GPS BATNA is one of the cheapest solutions.

Table 2-10: Cost per Operational Year Based on Modification of the Payload Alignment Vector
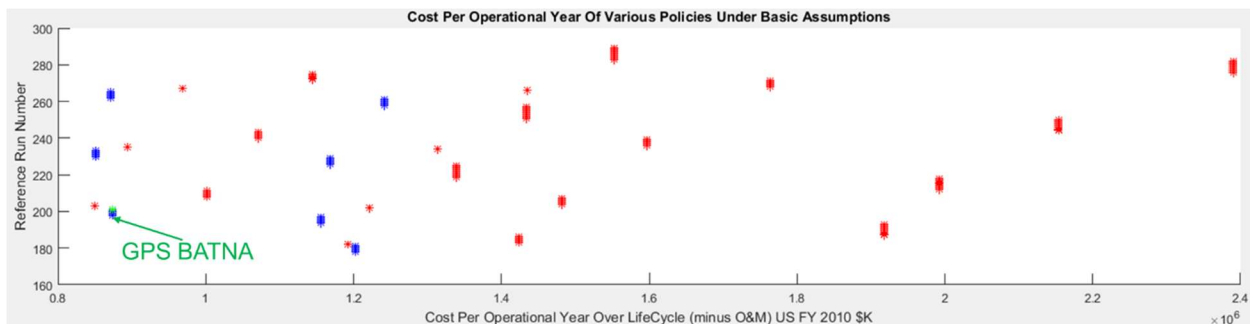
The creation of new metrics for evaluation of alternatives is not a major focus of this effort, but this work will have to incorporate existing metrics to examine the concept of survivability with respect to the GPS constellation. Richards (2007) lays out "Time-Weighted Average Utility Loss" as a primary factor to consider when equating the survivability of two space systems (Richards M. G., 2007). Richards also notes another metric worth considering when thinking about survivability: "Threshold Availability." For now comparisons will be made across the single variable of cost per operational year, and additional performance will be considered with respect to the increase in cost-per-operational year. In Chapter 5 the difficulty associated in comparing across generations is further examined.

2.7 Weather and Climate Measurement Costs

To examine Weather and Climate Sensing satellites, the largest change will be modifying the Payload Alignment vector to match the sensors for these satellites. This will also require the

implementation of a different set of cost function and capability upgrades over time. Otherwise, the model will be identical to the one laid out here; changes and validation are documented in Chapter 8.

3 Deductive System Dynamics (SD) Model for an Acquisitions Pipeline

In this chapter a SD model is constructed which abstracts concepts about government acquisitions and contractor production of GPS satellites. GPS satellites as a system are summarized as tokens representing individual satellites and the acquisitions pipeline is considered a system which produces these tokens. The SD model is constructed upon the system boundary and the elements listed in the Introduction; it works with the same scope as the TSE model described in Chapter 2. It thus examines the interplay between two systems: the production of a GPS satellite constellation and the pipeline which produces these satellites, and how external changes to architecture design change the performance of the pipeline. It models the elements of time and cost—in contrast to the TSE model, which examines cost and performance.

When SD is used for deductive reasoning or mapping causal relationships among high-level variables, the concepts are initially examined using proxy data. Such an examination forms the core of this chapter. The chapter concludes with the creation of a complete deductive SD model appropriate to the acquisition of GPS satellites. While this model is useful for understanding the relationship among various causal loops and the impact of time on the acquisition process, it has limitations because it is built on estimates and approximations. The model is able to inform only about relative, not absolute, changes in stock levels. Absolute changes can be discussed only after the model is tuned to real-world reference modes in Chapter 4.

As a deductive model represents the author's interpretation of the world, it naturally comes with biases. It is expected that in this deductive model (and the future inductive model of Chapter 4), there is a bias is toward creating systems that look like current systems. This means systems that differ from current strategies will appear less appealing, but any system that differs from current usage and appears to yield attractive outcomes can be trusted to deserve further investigation.

As the model also attempts to capture the "soft system" of experience with a mathematical model, there is no single correct implementation. To address the usefulness of the model, and defend model validity, in Chapter 4 actual data are used for inductive tuning. In this tuning, statistical fits and predictive power are examined and serve as indicators for validity of the model and its usefulness. This chapter and Chapter 4 will also note the limitations of a SD model of satellite acquisitions. It will conclude that SD alone is unable to answer the questions posed in this thesis; primarily a consequence of the "tokenization" of satellites and the model's inability to validate designs (there can be no trust that the system the SD model produces would actually deliver the performance requirement of delivering global signal coverage).

3.1 System Dynamics Methodology and Model Construction

Many authors, as outlined in the Introduction, have written about methods for implementation and creation of SD models, and the utility and applicability of SD to different domains and problems. The various methods and methodologies proposed and implemented follow a form similar to that outlined in Figure 3-1 below. Steps 1 to 3 are implemented here in Chapter 3 and Step 4 is completed in Chapter 4.

Step 1: Initial Work
- Define the problem.
- Identify variables and cluster for inclusion in loops.

Step 2: Causal Diagraming
- Cluster causal directions, variables, and high-level concepts.
- Create Stock and Flow diagrams
- Diagram exogenous shocks and external policies potential impacts

Step 3: Simulate a Deductive Model
- Simulate and test individual loops based on causal diagrams.
- Ensure trends and inflection match historically observed behavior.
- Link individually simulated loops into single model.

Step 4: Simulate an Inductive Model
- Match reference modes to model outputs.
- Use standard statistical tools to validate model outputs.

Figure 3-1: High-Level Representation

More generally, this work follows a model construction process similar to that utilized by the Sloan School of Management; a four-step process (Albin & Forrester, 1997) based on initial work by (Randers, 1980). The first two steps are accomplished within this chapter. The process of inductive tuning, and the sensitivity of the model to both assumptions and perturbations are discussed in Chapter 4. Chapters 5 and 6 contain the model response to different policies.
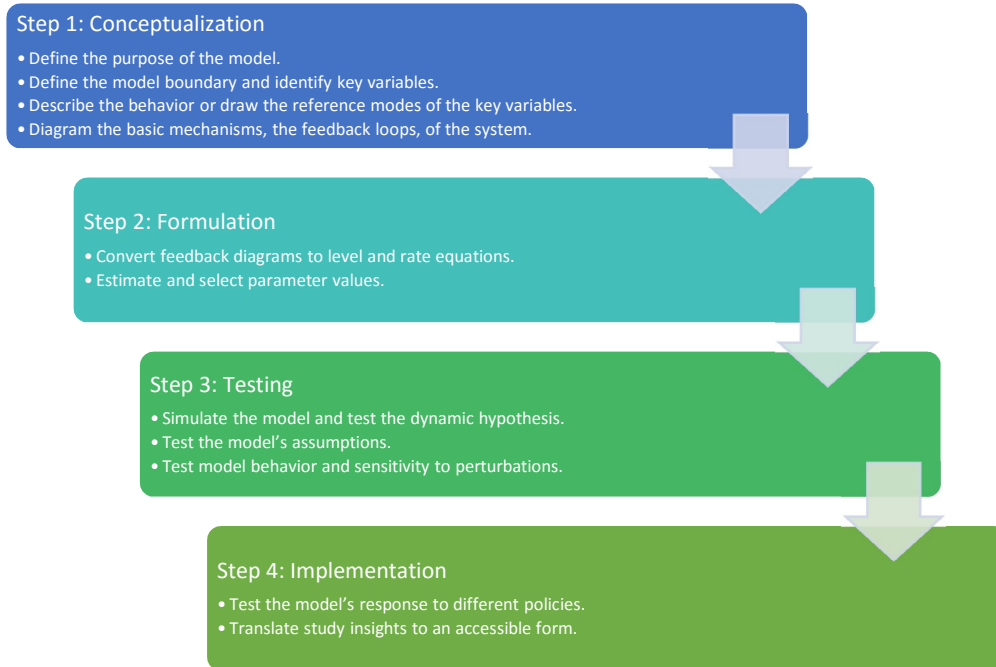
Figure 3-2: Sloan's Four-Step Process to Creating a SD Model

3.2 Model Conceptualization

The first steps in developing a SD model are to define the model and system boundaries, identify high-level variables, and link the variables to the elements of the system which they represent. Model and system boundaries have been outlined in the Introduction and Chapter 1. Specifically, this is a model designed to encapsulate the production pipeline of GPS satellites incorporating the life-cycle costs of acquiring, fielding and operating satellites. It must draw into computation the effects of experience, learning, technology and changes over time to the systems under production. While the overall work examines satellite performance inside the model boundary, in this SD model performance is characterized not by a satellite's ability to deliver signal to the earth's surface, but by the pipeline's ability to deliver and maintain the required number of satellites below a cost ceiling.

SD models do not attempt to include all interactions; they favor inclusion of the largest concepts and the differences in change between these concepts across time. Unlike the TSE model documented in Chapter 1, where nearly every component of the model can be improved by more detailed computations or more precise modeling, a SD model does not necessarily become more useful or more correct by including more variables. It is also likely that a highly complicated SD model will become unwieldy and increasingly hard to work with as more elements (causal loops) are added. A tight clustering of concepts improves the chance that the work will be useful for greater understanding of the primary driving forces in the system. It may even be that the very nature of a highly complex system, such as the GPS satellite acquisition pipeline, is so complicated that the only way to model it is with high-level abstraction and simplification. The ability to distill a complex process into a simple model is one reason why SD was selected for in this analysis.

3.2.1   Clustering Variables

Once high-level variables are identified, SD seeks for possible relationships among them. It is these relationships that form the basis of the SD analysis. Specifically, these clustering of variables seek to create dynamic hypotheses, about how one variable's change impacts another's. Within SD, relationships are usually noted as "all other things being equal," or, if one thing changes at a specific point in time and no other exogenous factors change, what change in the system will be expected due to the single change (up or down).

One relationship which will be investigated in this work is shown in Figure 3-3: the relationship between Technology and four other variables. Figure 3-3 shows that if Technology were to suddenly increase (arrow goes up), the effect on the four other variables "all else being equal," is expected to show:

- **Cost**: Would be assumed to decline because better technology is available.
- **Weight**: Would be assumed to decrease as batteries or solar cells might be more efficient.
- **Reliability:** Would be assumed to improve, since in the past better technology has led to longer component life. For example, as technology has advanced, satellite reliability has benefitted from access to better conformal coating on electronics, enhanced shielding techniques from the Van Allen Radiation Belts, and more UV-resistant systems.
- **Performance**: Would be assumed to improve since enhanced technology has in the past led to more power-efficient transceivers, additional signals, more accurate atomic clocks, and better on-orbit station keeping.

Note that these variables are represented in the abstract and do not possess units. Figure 3 illustrates only assertions about expected direction of relationships among variables in the SD model.
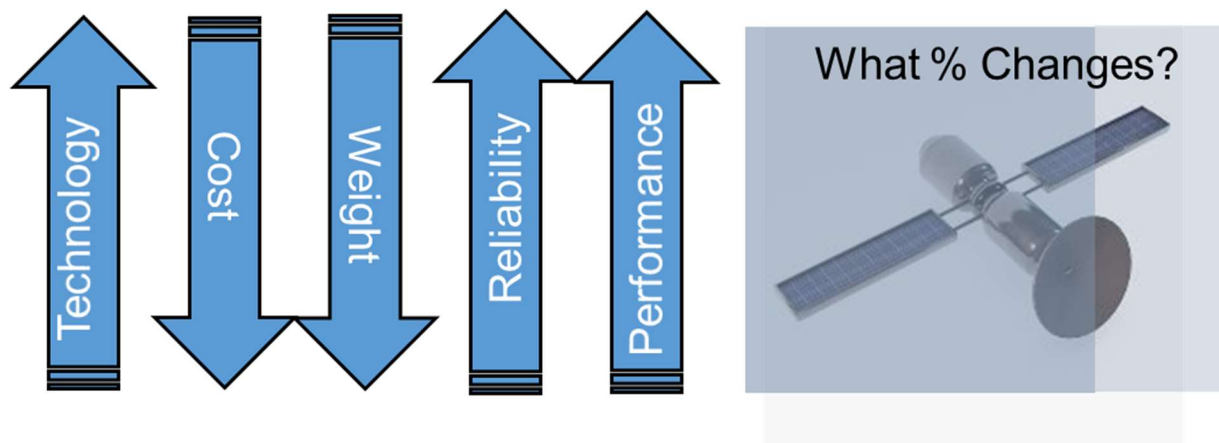
Figure 3-3: Clustering Variables Technology over Time

If an example could be found where the opposite direction of change was observed, or the direction of change was ambiguous, then Figure 3 would have to be altered. The variable for which this difference was observed would probably be split into two variables. But as no such examples have been found, for now, this is the relationship that will be investigated.

As the relationship described in Figure 3-3 occurs at a point in time (referencing the concept of "all other things being equal"), one must also ask what percent of a satellite changes across time

as technology increases? It is well established that technology and the technology associated with satellites increased from 1988 to 2008. It is also accepted that technology is current for only a set amount of time (years). Further it is observed within satellite development that some technology transfers across programs and some does not. Currently, the GPS IIIA bus is leveraging technology both in sensor payloads from the GPS II program and bus technology from Lockheed Martin's A2001X satellite product line. All of this suggests an underlying trend in technology and its rate of change over time, as well as its duration of value to satellite production. As time approaches infinity, every element of a satellite would be expected to change.

Another clustering of variables to be explored in this work is presented in Figure 3-4. An increase in the variable of Production is linked with other high-level concepts likely associated with the creation of physical satellites. Production increases have been selected as an independent variable. Similar to Technology, "all else being equal" in a potential arrangement Figure 3-4 shows what a change in Production Quantity might drive:

- The **Cost per Unit** should decrease as people get better at producing components and integrating systems.
- The **Reliability** of units should increase as fewer mistakes are made in production, and lessons learned are applied to subsequent units.
- The **Experience** of the people producing the physical assets should increase as they have more opportunity to learn.
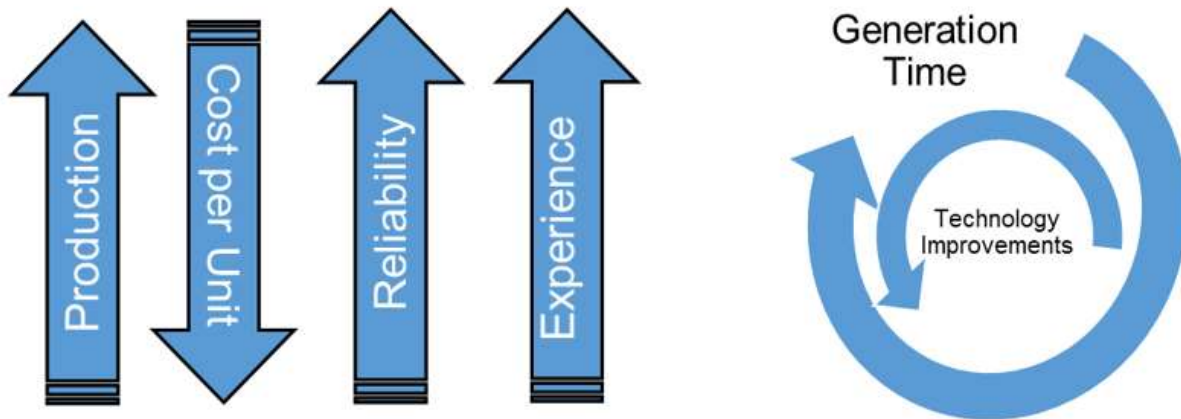
Figure 3-4: Clustering Variables: Production over Time

As with Technology, Experience is valuable for only a period of time. Experience may be considered to be a stock of value possessed by people. As people enter and exit the GPS production pipeline, Experience is lost and gained relative to satellite production. Unless satellites are produced, people cannot become experienced with the process. Also as with Technology, some Experience transfers across programs; some does not. There is also a time required to obtain Experience with process, experience is not gained when a satellite is ordered, it is reaped after it is completed and the acquisition evaluated.

Figure 3-4 also shows two curved arrows indicating change over time: one labeled Technology Improvement and the other Generation Time. Technology Improvement is the Technology variable discussed in Figure 3-4. Generation Time may be influenced by Technology

Improvement Time or it may be completely uninfluenced and based upon external human factors, or even depend upon when funding becomes available. Nonetheless, some relationship likely exists between Generation Time and the exogenous Technology Improvements occurring with respect to technologies related to satellite development. If Figure 3-3's Technology variable and its change over time is compared with the Generation Time of satellite development, it may be observed to be either faster, slower, or progress at the same rate. Figure 3-4 shows Technology changing more rapidly than Generation Time.

Experience also appears to have multiple levels. People gain experience in producing the generation under construction and also more general experience that will be helpful in building the next system. This issue of gaining experience that can be applied to the next generation has been tackled by Intel, an industry leader in microprocessor design and technology advancement (Intel, 2015). Intel uses the Tick-Tock model to secure sufficient experience to ensure high performance today and drive technology advancement tomorrow. Intel views chip manufacturing as two major areas of technology: architecture and photolithography. These represent the way a processor is laid out, and the way the processor is fabricated. Intel has decided to update each of these processes on a three-year cycle but to offset the two updates by 18 months. Thus each generation (a tick or a tock) updates only the design or the fabrication process. (See Figure 3-5.) This has the result of limiting the change to no more than 50% of the entire production, and has the benefit of being able to flow back any minor corrections at the next tick or tock. A final benefit Intel derives from this 18-month schedule is that it works well within human time. Updates every 18 months enable workers to retain experience from the last generation. As Intel is driving the development of manufacturing technology in the microprocessor industry it cannot expect to be able to transfer any technology in. This is similar to the Space Industry where the U.S. government typically must force technology development if it wishes such performance on space vehicles. Given the similarity in situations between Intel and the government, the Tick-Tock policy may be worth further examination with respect to satellites (Intel, 2015).

The Tick-Tock model through the years

Manufacturing process technology | Microarchitectures

45nm | 32nm | 22nm | 14nm

Tick | Tock | Tick | Tock | Tick | Tock | Tick | Tock

Intel® microarchitecture code name Nehalem | Intel® microarchitecture code name Sandy Bridge | Intel® microarchitecture code name Haswell

Increased performance, new capabilities, energy efficiency, and form factor advances
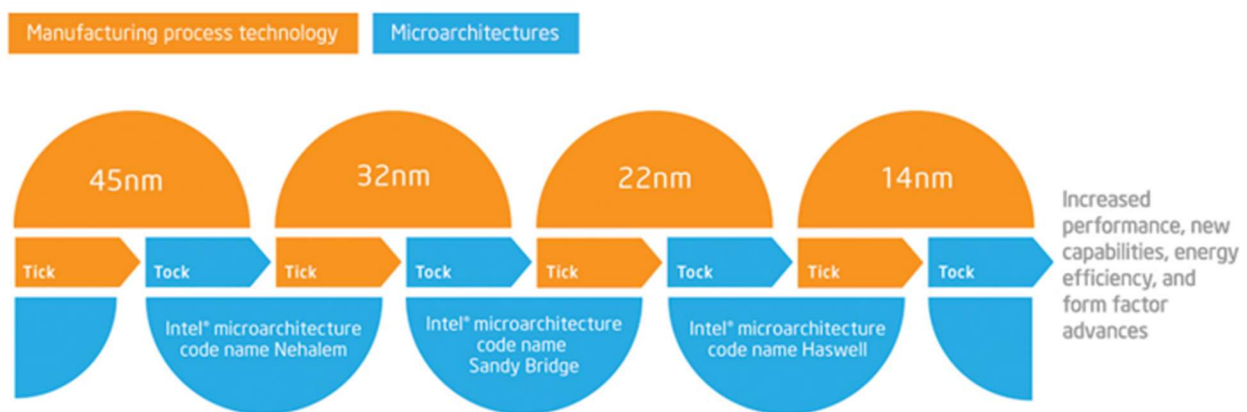
Figure 3-5: Intel Tick-Tock Model

As the government produces few units it may not be able to capitalize on a model such as Tick-Tock. The Space Industry, however, has developed a few strategies to enhance technology advancement. One policy decision is to launch a new design of a subsystem along with an older design of proven heritage. This enables technology advancement while providing redundancy. Another proposed approach is disaggregation, where functional capability is spread across multiple platforms as a way to even production and artificially inflate experience with a process.

SpaceX applied disaggregation in an approach to thrust and rocket engines. Over 12 years SpaceX built five generations of the engine: Merlin A through E. By replacing one large engine with nine small engines, some performance was sacrificed due to the extra mass required to support the engines. But small engines meant that it was easier to re-design and move to a new generation. The thrust of the engines was improved each generation so that today thrust of nine smaller engines is twice that of the initial single engine. Additionally, as of 2015, SpaceX was producing an engine every four days. This rate of production increases the ability to capitalize on learning effects. Compare this to a single large engine design which would be constructed several times a year. This experience with process may be able to drive down the cost of engineering production as Merlin engine production becomes a more repeatable process. Within the context of the variables in Figure 3-3 and Figure 3-4 one might consider that the Generation Time of SpaceX's Merlin engines is inside the Technology Improvement time of rocket engine design. It is also interesting to note that the time horizon of SpaceX implementing a new engine design to reaching learning effects and associated benefits might be considered 10 to 12 years. (SpaceX, 2015)

3.2.2 Theoretical Causal Effects of a Disaggregated Policy

Having outlined several dynamic hypotheses, in order to begin analyzing the possible impacts of a policy change such as disaggregation, it may be useful to consider how such a policy impacted another industry. Table 3-1 contains a list of possible impacts of a policy of disaggregation.

Table 3-1: Variables, Trends and Potential Outcomes of Disaggregation

Variable	Expected Change	Possible Outcome
Work in Production or Backlog of Work in the Industry	Smooth Pipeline	Right size workforce—less ramp up and down between efforts
Size of Space Vehicle	Decrease Size	Physically easier to construct
Complexity of Space Vehicle	Decrease Individual Complexity	Easier to fabricate and test, plus a potential Decrease in Production Time
Complexity of Architecture	Unknown: Increase, Decrease or Equivalent are all possible	More manageable based on other industry "design patterns" e.g., cell architecture scales well
Reliability	Shift from Highly Redundant To Herd Mentality and Replacement	Eliminate "Too big to fail"

Reliability	Increase	Get for free as in the "Toyota process"
Technology Refresh	Increase Refresh Rate	Bring in line with industry observed "half-life"
Learning Effects	Activate (not currently seen in space industry)	Substantial gains possible when cycle time inside half-life of technology.
Overhead Mass	Increase	Penalty: loss in economy of scale
Performance	Individual SVs less capable	Better for some missions (e.g., weather, imaging or LEO communications)
Catastrophic Loss (Survivability)	More Targets	Faster replenishment to capability
Resources Required	Initially cost more but less after learning "kicks-in"	Decrease over-runs in every program

The listing of abstract concepts in Table 3-1 and determination of their direction leaves the effort with an initial list of potential variables and potential causal relationships for SD modeling. The next step is to translate these concepts into causal loop diagrams. Development of these variables and their relationships is much less well defined than the TSE processes employed in Chapter 1, where well-defined systems exist for satellite construction and more than twenty years of regression models are available. This stark difference in model precision clearly illustrates the difference between these model classes and their construction origins.

3.2.3   Causal Loop Diagrams

Causal loop diagrams assist with clustering of variables and concepts as well as converting human text into a computer representation of a system. They also indicate the direction of change over time. In the Introduction, two quotes were presented which have implications for the chaining of high-level variables/abstractions over time. The first is from Wertz (2011):

> [the space industry is]…caught in a spiral, where higher costs lead to longer schedules and fewer missions, which lead to a demand for higher reliability and longer design lifetimes, which then lead back to higher costs (Wertz J. , 2011).

This quote is represented in a causal loop diagram in Figure 3-6. The quote specifically calls out the variables of: cost, design schedule, number of missions, demand, reliability, and design life. While not identical to the text, the blue arrows of the diagram clearly display the relationships among the variables.

It should be noted that this loop handles the previously discussed problem of gaps or difference between demand (request) versus actual implementation (or value of a stock) at a point in time. (The demand/request for a capability or the demand/request for a cost is not necessarily the capability or cost that is actually delivered.) In SD this is often ascribed to goal-seeking behavior

within a model. This goal-seeking behavior and the time horizon over which the gap is closed is a valuable part of analysis when considering how long a change might take.
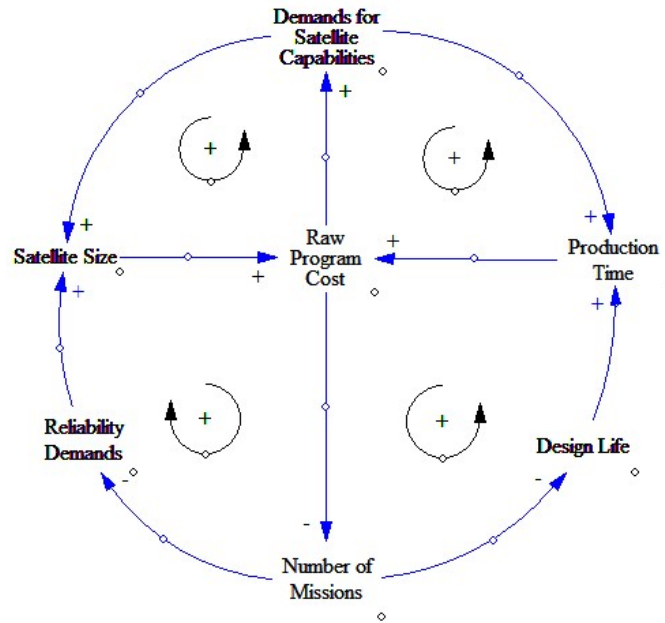
Figure 3-6: Wertz Loop

Figure 3-6 also expands Wertz's statement into four, more detailed loops and inserts intermediary variables (e.g., production time and satellite size) required for construction. These four loops link Raw Program Cost to the concepts of: Demand, Production Time, Number of Satellites, and Satellite Size in Mass. The concept of Satellite Demand or number of satellites required, and Satellite Size in Kgs are both outputs of the TSE model in Chapter 1. The other two concepts, Production Time and Number of Missions are not in the TSE model. They were not included in TSE computations as we seek to understand their change across time and TSE is a point-in-time optimization.

A second quote in the Introduction states: *...the industry moves with one key driver, the minimization of the cost-per-operational day* (Saleh J., 2008). These two quotes, combined with clustering of variables in this work and variables discussed by other authors might create a picture similar to that shown in Figure 3-7. The eventual model produced should be able to "understand" and represent each of the variables listed up until this point.

Figure 3-7: Industry Design Paradigm

It may seem infeasible to link all these concepts across time; this however is the strength of SD. Using causal loop diagraming we can combine the quote from. Saleh with the concepts from Wertz. Figure 3-8 expands the Wertz Loop to include Saleh's concept of "cost-per-operational day," operationalized as "cost per operational year" ("raw program cost" divided by design life).
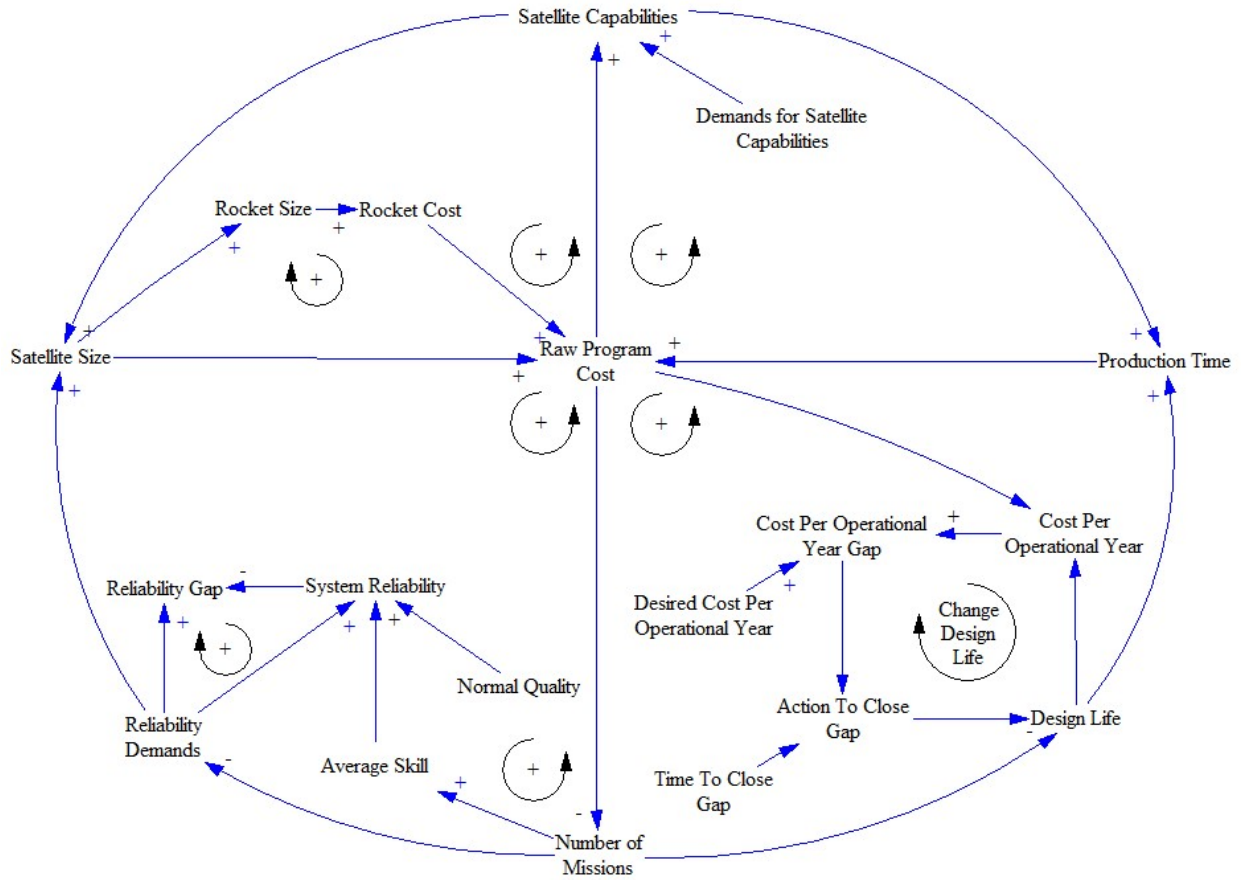
Figure 3-8: Saleh's Statement Merged with the Wertz Loop

With the inclusion of the concept of "cost per operational year," we can see the interaction between how long a program lasts and if it meets the desired operational cost per year. This particular structure is highly relevant to the current DoD acquisition paradigm since Congress sets budgets on one- or two-year time horizons.

Figure 3-8 also includes the concept of rockets and their relationship to program cost, necessary as every satellite program currently requires a rocket to reach orbit. Another enhancement to the model is the inclusion of "desired" reliability as opposed to actual reliability and the concept of an external or exogenous demand for capability. Each of these inclusions expands the causal loop diagram's ability to depict the GPS procurement system to the model boundary specified.

Figure 3-9 is the final product of this casual-loop-diagram effort. The loop now includes key structures dealing with experience, learning, technology, demands, capability, and cost. Mathematical relationships behind the causal linkages must now be determined. On the far left side a set of two material delays is included, one to show technology being transferred from the outside of the industry, and another covering technology that is "born native." This technology lasts for a time period and then expires out of the industry. Above this a ratio of technology that must be transferred into the industry versus technology that is created inside the industry as part of a satellite development program is depicted. Examination of this relationship suggests that the

more technology born native, the less that needs to be transferred in. This ratio feeds to the amount of engineering work required, implying that the more technology created inside the industry the less engineering work required to adapt external technologies (e.g., solar cells, processors, RF communications.)

Also fed into engineering work, at the top of the diagram, is a ratio of reliability. Two structures on the far right of the figure create a ratio for reliability. The logic implied here is that some reliability comes for free, based on experience, and other reliability must be paid for, or acquired through test and additional engineering. A learning curve structure like that seen in Morrison's work is depicted as a store of such experience. (Morrison, 2008)

In the center of the diagram a core Cost Loop appears. It is implemented with a variable, Production Time, which is specified by the amount of engineering work required. The logic is that if a unit of work exists, all other things being equal (specifically resources), then one unit of work extends production time by one unit of time. This would then increase the overall program cost by one unit. These values are also interplayed with the other key variables of design life and mass, for which existing mathematical relationships exist. In the diagram a single line is drawn to depict these relationships but in a functional model these relationships would be encoded in more detail (specifically those noted in the previous chapter on satellite cost and performance modeling).

This raw program cost (from the core Cost Loop) is then connected to the number of missions/satellites produced. This quantity value feeds both a pipeline of satellites at the bottom as well as the learning structure previously noted. The connection implied is that as satellites are produced the number in existence must be tracked. Also, the implication is that higher numbers of satellites will feed in more experience which will decrease cost (dollars) through decreasing the amount of engineering work required to obtain the desired reliability. This experience, like technology, will eventually expire out of the model.

The ultimate result of this diagraming activity is a representation/abstraction of reality where the concept of engineering work exists as a primary driver seen in Figure 3-9: Space Industry Causal Loop Diagram. This work is modulated by the technology ratio, the reliability ratio, and the complexity value as defined by capability desired. Exogenous factors such as increasing technology, increasing demands for capability and desired cost are included. Endogenous factors such as the amount of technology "born native" in the industry and the percentage of reliability that comes from process versus the reliability that must be engineered in are also captured. Overall this diagram places the causal linkages in line with existing satellite models, but it also suggests some new ideas about possible causal relationships; it is ready to begin simulating an actual model to test these ideas.
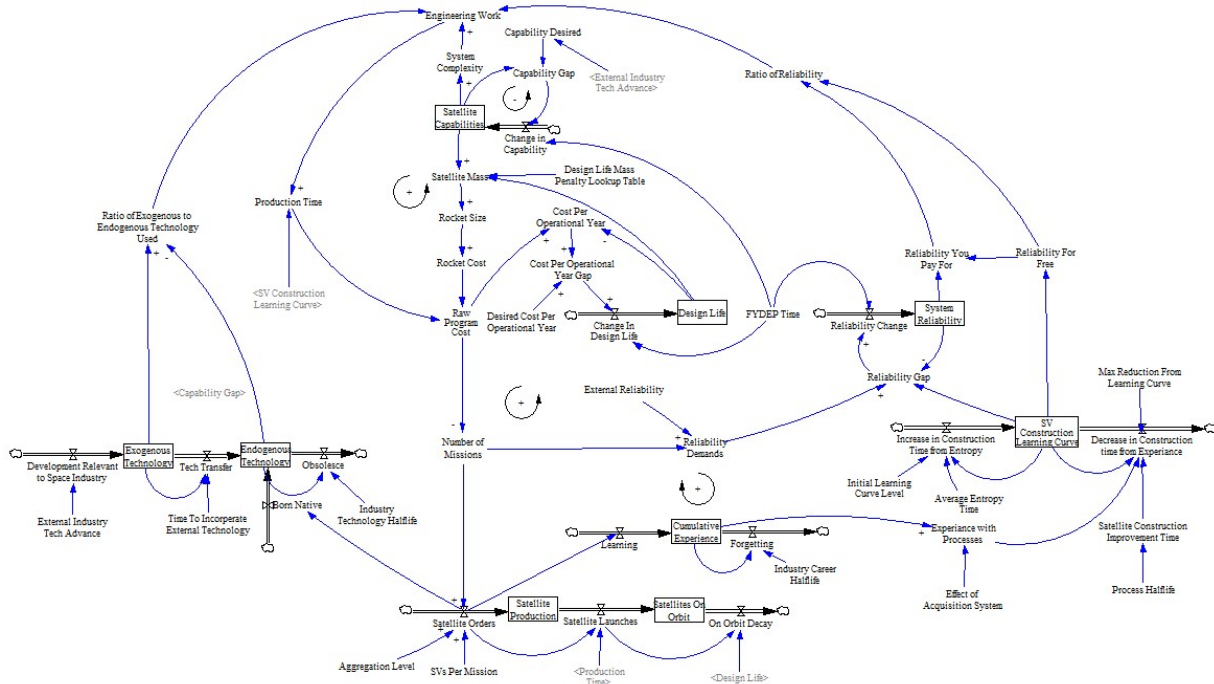
Figure 3-9: Space Industry Causal Loop Diagram

3.2.4   Stock and Flow Diagrams

Figure 3-10 presents a simple concept of a pipeline relevant to satellite production. The diagram shows an exogenous request for space vehicles (SVs), which then for a fixed period of time, specified by the variable "SV Production Time" are produced and then launched. After launch, SVs sit on orbit until they exceed their "Design Life" for which they were produced, at which point they are taken out of service. While historically satellites have exceeded their design lives, for now the model is encoded such that satellites should only last their design life; changing this assumption is examined later on. This two-stage pipeline is a high-level approximation of building and launching satellites. It must be noted that while this is written in the notation of a stock and flow diagram it is not, nor can it become a SD model. This diagram does not include any feedback loops, it only contains a linear set of equations describing states, construction and on-orbit operations of a satellite. To become a SD model, the system being modeled must possess more feedback loops than exogenous values. In this particular example, it is likely that there is a linkage between the number of satellites on orbit and requests for new satellites to be produced.

93
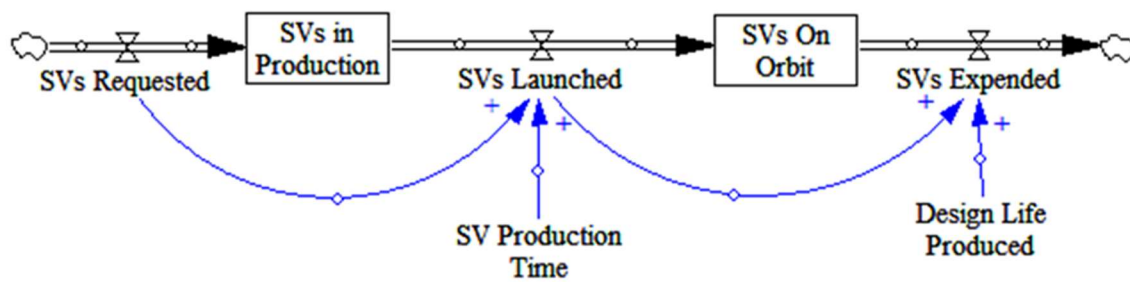
Figure 3-10: SD Model of Space Vehicle Production Pipeline

One existing SD model of a pipeline for production suggests an approach to capturing the link between the stock level "SVs on Orbit" and the required order rate. Outlined in Hines' work on "Molecules of Structure" for SD (Hines, 2005) is a basic structure intended to keep the "stock" at a specified level based on outflow rate, processing time, and desired level. This is shown in Figure 3-11. This figure also includes the concept of a "Gap" where the model is "aware" of the level that the stock should possess, the rate of decay, and the amount of material currently in production. The "knowledge" of these elements allows the model to adjust the production rate to ensure the proper stock is maintained; it is even able to factor in the processing time (how long it will take to produce these goods on average) required for this computation.
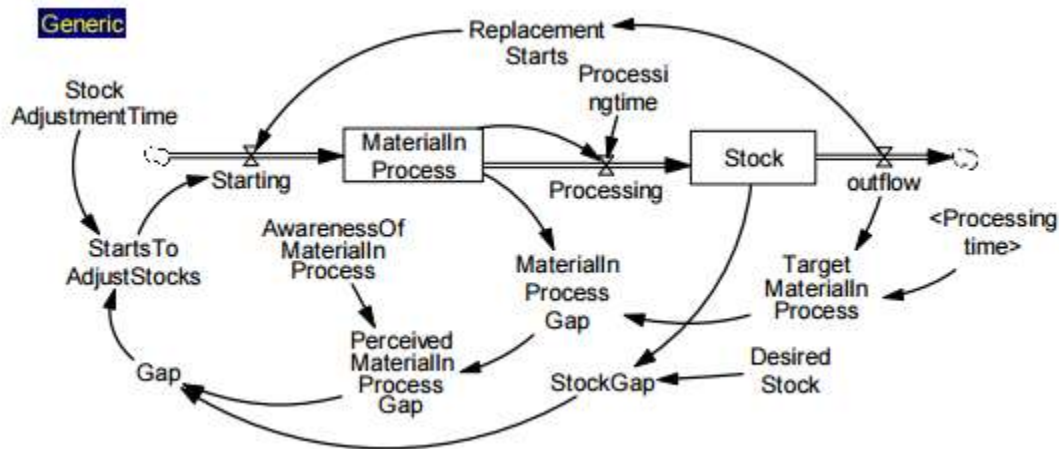
Figure 3-11: Generic Pipeline with Correction to Changing Outflow (Hines, 2005)

Table 3-2 shows lists how variables in Hines' pipeline model with correction for gaps can be adapted to the GPS pipeline given that the desired stock to keep on orbit is a minimum of 24 satellites and an objective of 27 satellites.

Table 3-2: Adaptation of Generic Model Structure to GPS Pipeline Model

Hines' Pipeline Model	GPS Construction Pipeline Model
Processing Time	Satellite Production Time
Replacement Starts	Satellite/SVs Requests
Processing	Satellite Launch
Material in Process	SVs in Production
Outflow	SVs Expended
Desired Stock	27 satellites
Adjustment to Production Starts	Replaced with secondary pipeline Figure 3-13

Three cautions should be noted when implementing such a model:

1. This pipeline model does not ensure that the desired stock will always be maintained. It is very likely that exogenous shock (in the form of changing exogenous constants) will push the system out of equilibrium. In a pipeline this might be easily represented by increased or decreased demand for product; for GPS satellites this may be a result of satellites lasting

longer or shorter than expected. By setting the objective at 27, the hope is that even in the event of exogenous shock, the capability of 24 will be maintained.

2. It is also highly likely that a pipeline model with correction for gaps may trigger over production and a capacity greater than 27 may exist: both these conditions have occurred with the actual GPS constellation.

3. Figure 3-11 also indicates that if the outflow or the SVs Expended rate were to be lower than expected, the natural response of the system would be to slow the order rate.
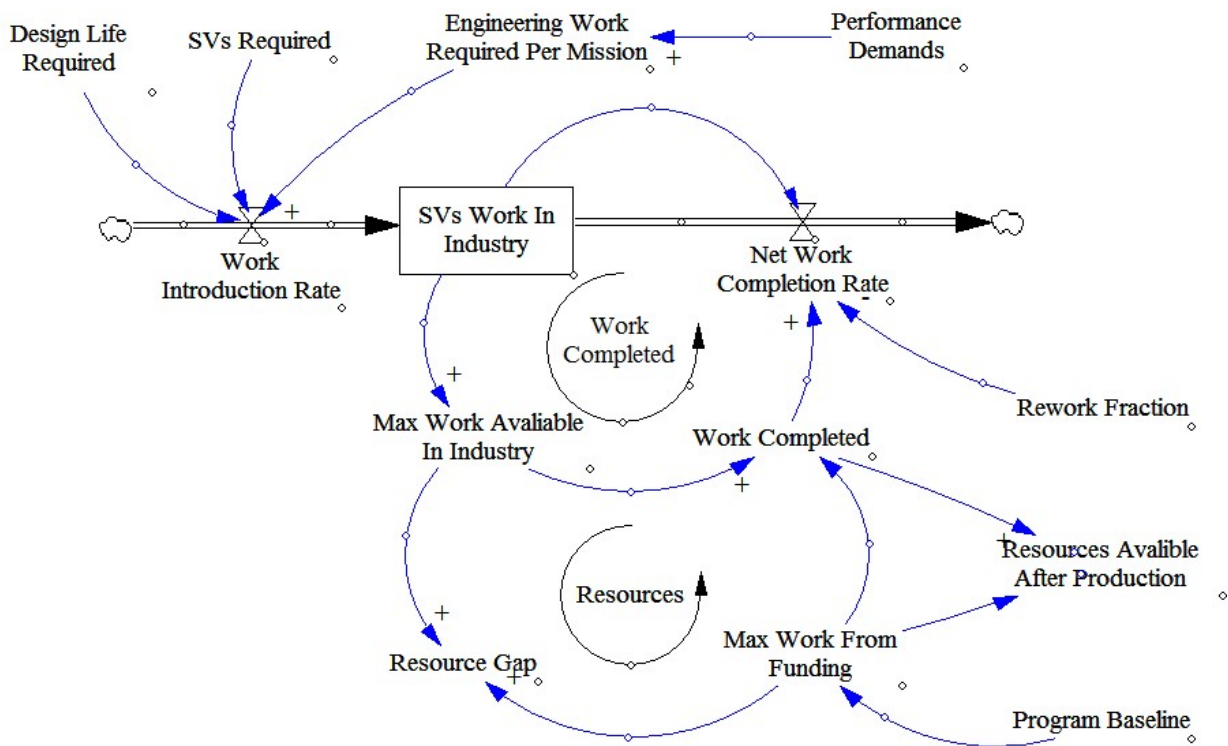
Figure 3-12: Space Vehicle (SV) Production Pipeline

To incorporate the concept of a "gap" (such that the total number of satellites desired on orbit minus the actual stock on orbit has an impact), an adjustment must be made to the pipeline model whenever a negative additional capability is ordered. Converting the generic terminology to the specific terminology of the Space Industry results in a pipeline such as that shown in Figure 3-12. A new Resources Loop has been added to track the size of the backlog of work, and in the event that more resources are available, the Resources Loop can calculate how much is left over after all tasks have been completed. It can also monitor, though not change, a gap in resources (aka an overrun in the program baseline).

Since Hines' pipeline tracks the inflow and outflow of units of widgets and the GPS pipeline tracks both the raw number of satellites and number of months of operational capability on orbit, a modification was made to "Production Starts" to handle two outflow rates. The first variable, "Satellites," is a discrete value representing whole satellites. If constellation strength is not maintained, then the performance threshold is violated. The second variable, "Months of Operational Capability Remaining," is a continuous value which must be included as it informs the "Replacement Starts" or "Satellite Request" variable when the order for new satellites must be

made such that the on-orbit capability threshold of 24 is not violated. Consider the example of Satellite with a design life of 15 years. If we assume the "satellite production time" to be five years, then a new satellite must be ordered when this Satellite has five years of design life remaining. If the pipeline tracks only the number of satellites on orbit, it will not act to order a replacement for the Satellite until the Satellite reaches the end of its design life. This modification is shown in Figure 3-13 where instead of one pipeline, two pipelines are shown, one tracking Satellites and the other tracking Satellite capacity in months of operational capability remaining. In this diagram for simplicity it also notes that the production time of a satellite is some fixed fraction of the design life required. In the eventual model Production time will not be a fixed constant as listed in the generic pipeline model.

This simple pipeline of Figure 3-13 does not include launch delays, or the concept of storing satellites "in the barn" as a method of buffering need; both, however, could be included with another stock and associated time factors, currently this is beyond the scope of this work.
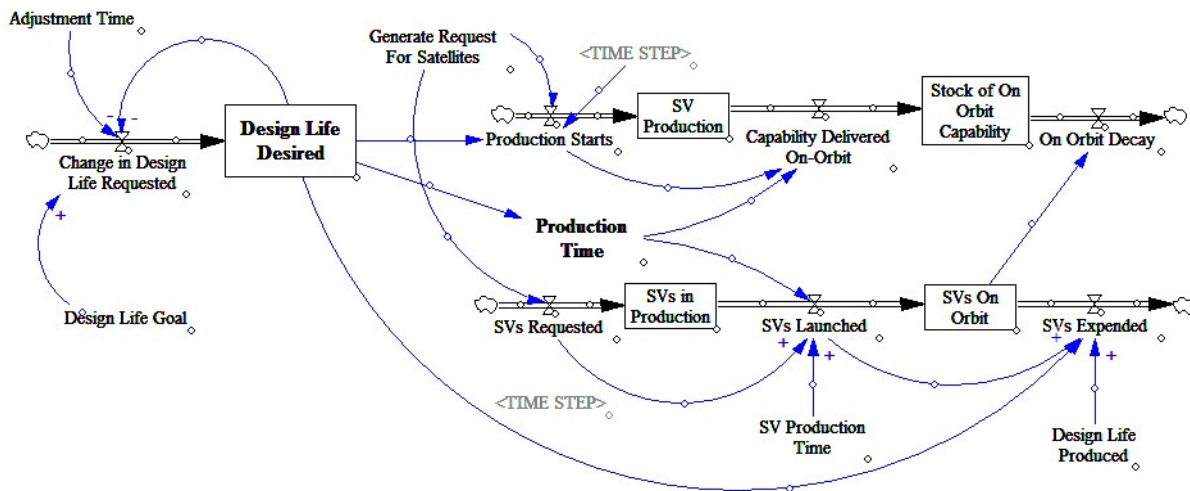
Figure 3-13: Satellite Production Pipeline Model

Figure 3-13 shows how a number of structures have been pulled together to create a pipeline in Vensim, elaborating on the basic pipeline of Figure 3-11. Pulsing the variable "Generate Request for Satellites" creates a spike in production similar to the effect of signing a contract. While this is not a perfect abstraction of what happens in the real world, both SV Production and SVs in Production are macros which represent third-order material delays, and thus provide a reasonable smoothing effect in estimating production and launch of satellites.

Time Step is used as a divisor to make the spike of appropriate "height" given the integration time (the 'dt' or time slice that represents the smallest move forward/backward in time) of the model. This allows the model to be run with fidelity as low as a year for integration time (for coarse adjustment) or as high as desired without having to change any hardcoded variables. Normally the model is run with an integration time of .125 (years). The final model combines model structures shown in Figure 3-12 and Figure 3-13 to comprise the first feedback loop in a possible SD pipeline representing GPS acquisition.

3.3 Model Formulation

Before core model loops can be constructed and tested, one additional, basic structure must be evaluated. The "Work Harder vs Work Smarter Balance" SD model, documented in Morrison's 2011 paper, may be added to the SD loop as another molecule of structure (Morrison, 2011) to further improve the pipeline structure developed above. Morrison's work explored the consequences of allocating resources between two activities: producing goods and improving processes; it is a SD representation and extension of Learning Theory. In this work, a pipeline was designed to maximize the rate of net process throughput given a production process with a certain capability, and increase the capability of the process. The model enabled examination of the system's response to a variety of external policies and noted that initially if resources are shifted from process improvement to production, then production increases. The second-order consequence demonstrated by Morrison's model was, however, that after a period of time, process degraded and overall output dropped. Morrison's model-structure functions as a control or rate-flow mechanism on Hines' pipeline's "processing" variable. For this thesis, the two models are merged. Together they form the core of the SD model developed in this chapter.

Figure 3-14 depicts a work-backlog, or a set amount of work to be completed, and an outflow representing work being completed at any given time. Work, in the generic sense, is typically referred to as widget production or some unnamed product. In this thesis work represents tasks required to build satellites. Eventually mass will be used as a proxy for work required for a satellite. The rate at which work flows out is a function of the amount of resources (denominated in FY 2010 USD) sent towards production, multiplied by the rework fraction or the amount of work that due to inefficiencies or mistakes must be re-accomplished or does not finish within the expected time period, having been given appropriate resources for the work.
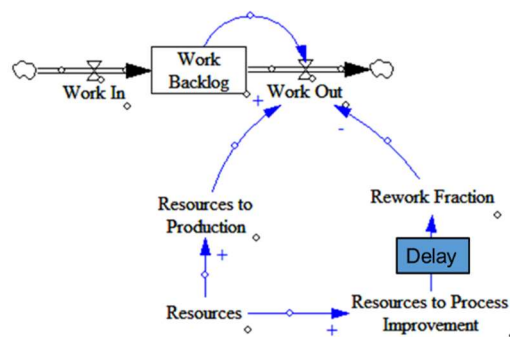
Figure 3-14: Rework Fraction Applied to Work Completed in Backlog (generic structure)

Figure 3-14 also incorporates a time delay. Based upon Morrison's work, this model structure shows that resources sent to production immediately improve work out, but resources sent to process improvement come with a time delay before they will reduce the rework fraction and increase work out. Note that the inverse is also true: taking resources from production and sending them to process improvement will immediately hurt production but there will be a time delay in the effect of increasing resources for process improvement. Indeed, Figure 14 explains a common productivity trap. Given fixed resources, a manager decides to direct all resources to complete a task. This is sometimes referred to as "firefighting." Yet with no resources directed at process improvement, there is no long term learning or process improvement. Second-order improvement

is necessary to build sustainable capability and stripping funding now "eats seed corn," but when a deadline looms the natural tendency is to focus on today's problem rather than build a better tomorrow.
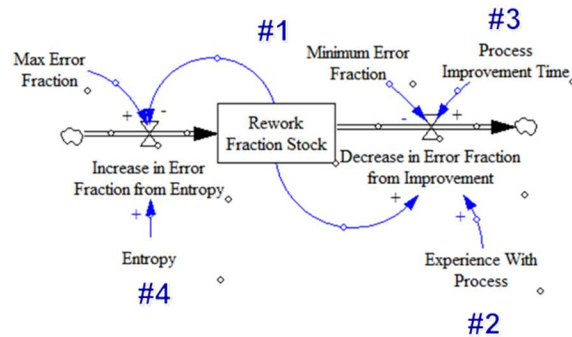
Figure 3-15: Rework Fraction Stock and Associated Variables

According to Morrison the rate at which work is completed is defined as Resources multiplied by the efficiency with which the (limited or constrained) resources are implemented based on an "error rate" or "rework fraction." Theoretically, given a set process, people have a level of familiarity with that process, and the more familiar they become the more they can achieve with the same resources. This is shown earlier in Figure 3-12 where the "Net Work Completion Rate" is the multiplicand of the Work Completed and the Rework Fraction. Now we see how the rework fraction can be computed and tied into the pipeline. Figure 3-15 notes four major variables to constructing this relationship:

1. Rework Fraction functions as flow control to Production Rate.
2. Experience translates to effectiveness with processes; has a "sticky" property.
3. Process Time Improvement is static (not causally linked).
4. Entropy or Error Injection rate is static.

The Rework Stock creates "tug of war" between one and zero (i.e., the max and min error fractions), where a zero denotes that no work ever completes and a one is the perfect "happy path" where no mistakes are ever made in production. Both are impossible states in both reality and the model.

To adapt this concept of a pipeline production and the process of producing widgets to the process of building satellites, several modifications are needed. The first modification is for this model to allow the variables Cycle Time, Process Improvement Time, and Rate of Entropy to change over time. Cycle Time or Process Improvement Time was considered an exogenous constant in Morrison's work because his model was applied to workers adapting a specific process with a known development time. Due to the shorter time horizon of his work it was also assumed that the rate at which entropy was introduced into the system could be considered to occur at a fixed rate which would remain unchanged over the time period of the investigation. In Figure 3-16 both of these constants are modified and shown as variables which change throughout. This is necessary because the time period of investigation extends over a long enough time horizon that

these two variables (Entropy and Process Cycle Time) are likely to change.
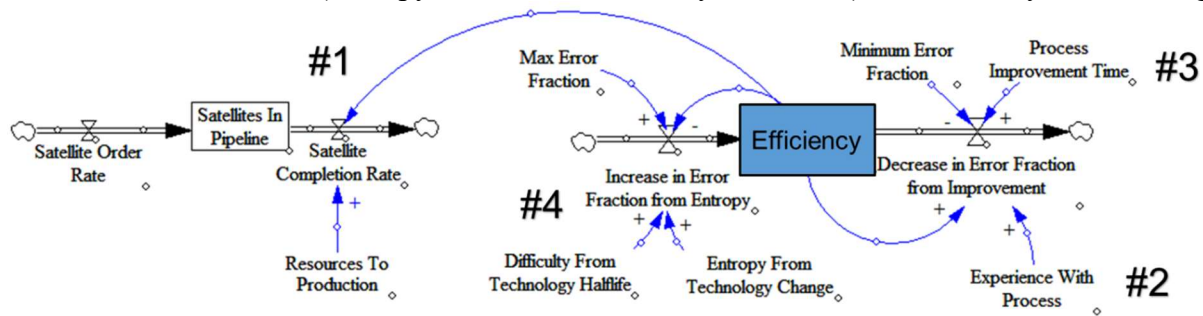
Figure 3-16: Efficiency Implementation

Thus, rework becomes "Efficiency," not just because Cycle Time and Entropy are brought into the model, but also because the work being completed is not whole satellites but rather, pieces of satellites. At any given time-step a whole satellite may not be produced, rather a fraction of one. (e.g., if the pipeline produces one satellite every six months then based on eight time steps per year each time step produces one-quarter of a satellite). In comparison, where Morrison's original work considers a single pipeline producing widgets, the GPS pipeline is now comprised of Work Breakdown Schedule (WBS) elements. The combined model will eventually use mass instead of widgets or WBS elements as it is a dynamic value which can be computed from existing models as seen in Chapter 1.

Keeping the same format, Table 3-3 compares the original four elements of Rework Fraction with Efficiency.

Table 3-3: Closing Work-Rework Loops to Evaluate Efficiency

Concept in Work-Rework	Modification in Efficiency
Rework Fraction functions as "flow" control to Production Rate	Funding can vary with increases in performance demands. NRE Funding replaces Resources to Process Improvement. This is one of the exogenous variables which will be changed and the model's response examined. It will also become an interface with the TSE model in Chapter 4.
Experience translates to effectiveness with processes; has a "sticky" property	Experience loses some "stickiness" when Switching Vendors and Changing Generations of Satellites. The actual implementation of this is depicted in the Experience with Process section in this chapter.
Process Time Improvement is static	Process time can change; experience is gained after a satellite is built. The time to produce a satellite has changed and can change over generations.
Entropy or Error Injection rate is static	Entropy changes over time and time/technology are considered major sources of entropy. This is substantially more complicated than a static entropy rate and its implementation is discussed in the Technology Gap section of this chapter.

These four concepts comprise their own causal loops, each passing through the Efficiency variable, hence making Efficiency the flow control variable which determines the rate at which resources (FY 2010 $M USD) are converted into satellites. The model has two concepts, Entropy and Experience with Process. Entropy and the rate at which entropy advances makes work more inefficient. Experience and the rate at which lessons can be learned makes work more efficient. These two concepts and their associated time constants (the time required to close half of the gap between to levels) form a balance over time in the Efficiency stock.

3.3.1   Satellite Production Costs

In Chapter 1 the equation for replication cost of multiple satellites in a block buy was listed as a Matlab script implementing the cost reduction in replication of space assets as outlined in the SMAD (Wertz, Everett, & Puschell, 2011). It is repeated here for ease of reference.

$$s = \text{replication modifier an arbitrary constant from .9 to 1}$$

$$B = 1 - (\frac{Log\left(\frac{1}{s}\right)}{\log(2)})$$

This equation becomes the constant to which the Number of satellites to be produced is raised:

$$L = (Number\ of\ satellites\ To\ produce - 1\ )\verb|^|B$$

The –1 is included to remove the Theoretical First Unit since its cost has already been accounted for in the NRE computation.

$$Cost\ of\ Aditional\ Units = First\ Production\ Unit\ Cost * L$$

In applying this script one could examine the implication for the level of the SV Construction Learning Curve when applied to purchase of a given number of satellites. However, as the SD model developed here produces satellites by consuming resources, limited by the efficiency of the system, this SD model which implements learning effects over time may be a superior method to computing the cost of production. Both calculate the same process, replication of satellites and the reduction in cost from one unit to the next based on assumptions about learning. But the SD model will replace this code with an alternate method of computing the replication cost: one based on the causal factors driving cost, rather than arbitrary constants.

3.3.2   Structures required to Draw Clustered Variables and Concepts in Model Boundary

The overall model above centers on a pipeline production where Efficiency modulates the completion of satellites based on resources provided. A causal loop is drawn in this pipeline where satellites lasting longer than expected leads to fewer satellites being ordered. A second causal loop is based on Morrison's work, stating that inefficient work completion has the potential to lead to greater rework and greater commitment of fixed resources to production as opposed to development. This is encoded as one of the model's dynamic hypotheses.

This dynamic hypothesis aligns with the design point seen in Figure 3-7: Industry Design Paradigm. In this world view, errors leading to rework may also be generated through a lack of experience due to low production numbers, a long time between technology refreshes, and long

process improvement cycle times. This is stating that while dedicating resources to process improvement is beneficial, its benefit is diminished by the number of times the process is used. For example, it does not matter how good a manual or checklist you write if it is used only once or twice a year. Experience retention will be low and production times long, and these factors even more so as cycles approach lengths equivalent to that of the average person's career length in the industry. This implies that improvement to process cannot simply come from spending money on R&D or process improvement. To investigate this dynamic system, additional causal loops must be drawn to close the loops of the four translated concepts from Table 3-3:

1. **Peanut Butter Spread:** As resources are constrained, this model makes the assumption that if insufficient funding (either from cost overrun or a desire to save money) occurs, the first "lever" pulled is to extend design life in an effort to maintain the same cost per operational year. This has the impact of reducing the amount of work sent into the pipeline; initially this takes off pressure in the form of work backlog and thus decreases the overrun. This also, however, reduces experience with process—as less work is being completed. Under a severe situation, the model also has the ability to overrun its baseline and ask congress for more money or take funding from R&D efforts and use them for production.

2. **Process Improvement Time:** In this model the production time is now linked to the process improvement time; previously this was a static constant based on assumptions about a particular pipeline. As satellites take longer to produce, the longer the cycle time to flow back lessons learned becomes longer; conceptually this now lengthens the time period for a decrease in the rework fraction. The opposite is also true: process improvement time will decrease if satellites are produced faster and lessons learned are more quickly passed to the next production.

3. **Experience:** Experience represents a "soft-system," a mental model or a human construct of something that cannot be directly measured in the real world. As SD already abstracts the world it is also able to create a "stock" for experience and create a hypothesis about how it behaves. The Experience Loop is one of the core loops in Morrison's work. He used a lookup table to translate between experience as a stock with a sticky property that increased over time, but could be translated into a value between zero and one. The implementation used an S-curve as a way to note that initially there would be little benefit, then a region where learning matters a lot, and finally a region where more experience results in little more gain, having "aged out."

4. **Entropy:** This model adds the impact of a technology and associated technology half-life on the production of assets. The logic behind this structure is that technology and experience with a technology is only good for a limited number of years. Consider the case of ~15 to 20 years. Based on current technology advancement, it is apparent that technology this old will be outdated and have almost no value to the next generation of technology. In this case external technology will be transferred into the industry, or technology will be created from scratch as opposed to improving on the last design. This is different from experience with process presented in the original work by Morrison, as the original time frame of his work would likely not experience significant impact from this type of technology obsolescence, or it would be rationalized that since the cycle time was much smaller than the technology time in the original work, technology advancement issues would be absorbed or are built into the process.

5. **Firefighting:** As previously noted, the pipeline representation of Efficiency possesses the core concept of a firefighting mode: spending resources to partially or incorrectly

complete a task leading to more future rework. This model views one aspect of firefighting behavior in the Space Industry as stripping funding from future R&D efforts or process improvements and devoting those resources to current production efforts. Morrison suggests two hypothetical/abstract/theoretical processes in which the new process could overcome firefighting through a mixture of various policies to include: reduced workload, increased resources and adaption to the new process. The model developed for this thesis removes the "new" process as no such process is being proposed. The existing process will likely remain unchanged, as it is unlikely that the existing DoD acquisition system and its relationship with contractors will change. But if core acquisition policies are not likely to change, it does not mean that other policy changes might not improve the satellite acquisition situation. It is possible that the process is not the problem, or that polices other than changing process may improve the system.

3.3.3   Exogenous Pulse-Generating Functions

Within TSE, exogenous constants are often hard to visualize, as what is required is a specific number at the time of optimization. Using Vensim as a tool to construct exogenous constants enables the modeler to program an understanding of how the variables might change over time into the model. It is much easier to understand a relative trend line than extract meaning from a specific point without any other context. Visualization of constants across time allows for a better relationship between the modeler and the data. The molder can respond to a line, as well as change the inflection or slope of that line with respect to their belief about how it could change in the future. These exogenous values can also be used to vary constants over time if the variable is believed to change over time.

3.3.3.1   Technology Gap

Figure 3-17 presents the creation of an exogenous variable, "Technology Gap," constructed by using proxy data for mass change for satellites over time as well as performance change. This is not a stock and flow structure, but a method for creating a curve for querying across time. This illustrates one strength of the SD approach: through the use of Vensim a complicated idea can be distilled into a number of structures from which meaning can be extracted. Varying these structures is similar to changing context variables in Epoch Era Analysis; but much easier to implement in Vensim than in a traditional coding language. Additionally, the resulting visual representation of the curve as shown in Figure 3-18, is easily interpreted by subject matter experts. This curve could

be compared to actual data—such as the change in bandwidth available for communications satellites, or the resolving power of optical payloads.
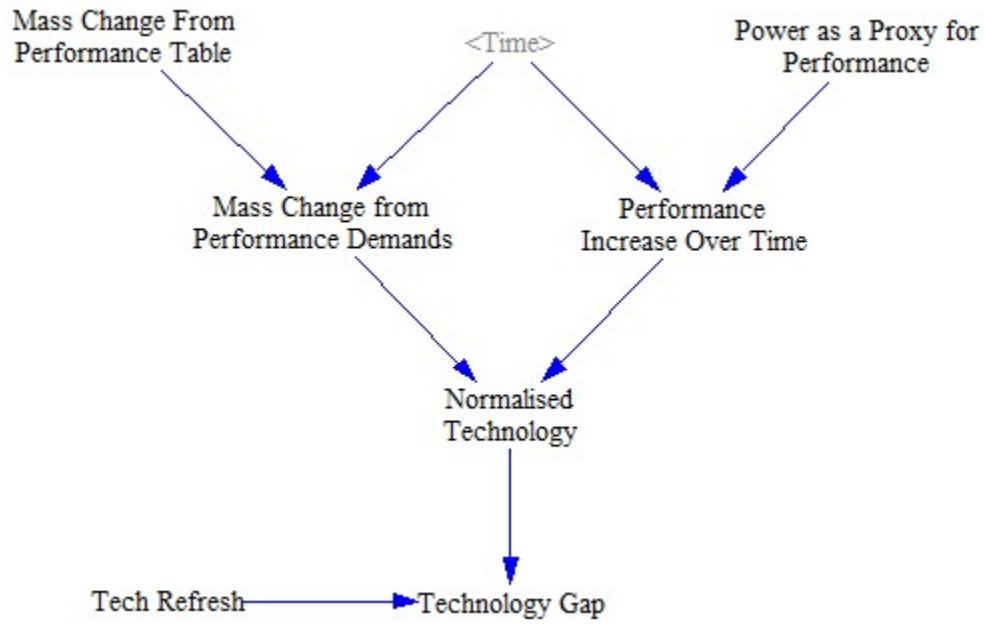
Figure 3-17: Vensim Model of Exogenous Variable: Technology Gap

Normalised Technology

Normalised Technology : Tuned Baseline with S-curve Assumption ——————
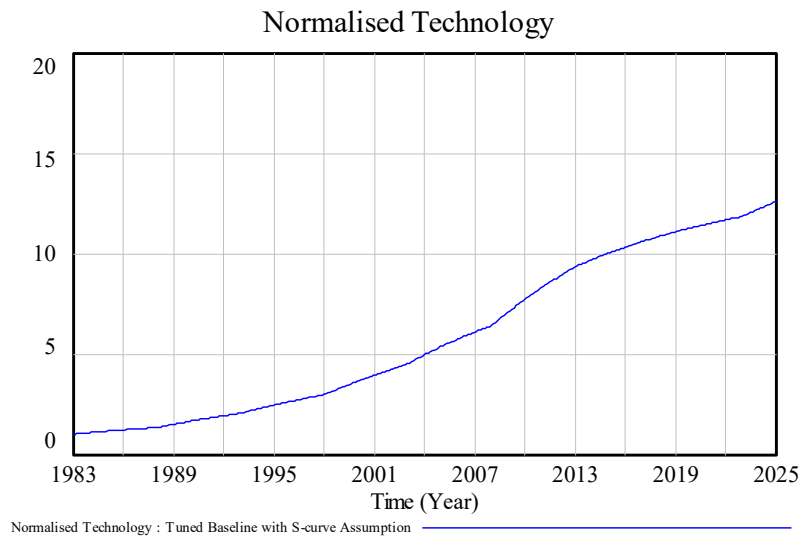
Figure 3-18: Exponential Technology Growth Smoothed into S-Curve Example

Figure 3-18 shows the growth in a proxy measure for performance: the power of communications satellites divided by the total mass of the satellite required to provide this power. These actual data, shown previously in Figure 1-2: Launch Masses of Active Geosynchronous Spacecraft over the Last two Decades (UCS, 2014) and Figure 1-3: Increases in Average Power of Geostationary Spacecraft (Jones and Spence, 2011), create a surprisingly uniform curve of increasing performance. There is a roughly nine-fold increase in performance, likely from technology changes over the last 30 years. It is also an interesting visualization as it shows the rate of increase has increased and the last doubling in performance occurred in just the last 10 years. Moving forward, performance may continue to increase at this rate, may become linear or may taper off into the top of an S-curve (as demonstrated in the figure). Each of these future scenarios may be tested and may impact model performance. Figure 3-21: NRE Pulses and Difficulty due to Age of Technology and Figure 3-19: Technology Decay below show how this structure for computing the rate of change in technology can be merged with another structure to create a meaningful representation of technology change over time.

3.3.3.2 *NRE Gap in Relation to GPS Historical and Planned NRE Investments*

Figure 3-19: Technology Decay presents the historical NRE pulses of the GPS program as well as two predicted future pulses, required for Block IV and Block V. Assuming the 15-year design life, the current Block III contract with option to buy 32 satellites, and the development time of the Block III contract, development for the Block IV must begin in 2023. If it does not, the Block IIIs must last longer than 15 years, the DoD must buy more than 32 Block IIIs, or a gap in capability will emerge around 2032.
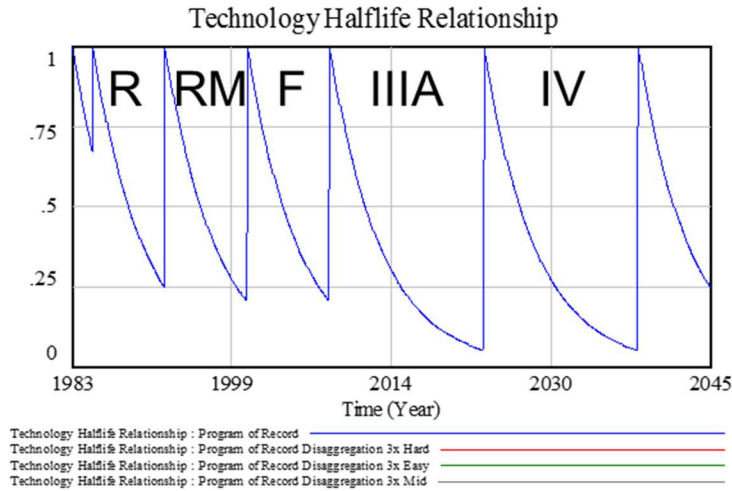
Figure 3-19: Technology Decay

Creating satellites is a process which requires writing code, modeling and simulation, physically constructing assets, space-rating hardware, and many other highly technical activities. These tasks become more difficult the older the technology and assets used: older code is harder to maintain, suppliers go out of business, and updating becomes more arduous. Regardless of task, the longer the time between generations, the harder the work becomes for the next generation. At the extreme, technology (as an abstract concept) is being re-created or new from scratch. Figure 3-20: Structure for Producing NRE Pulses and Tracking Time Since Last Technology Refresh depicts a SD structure that is capable of recording the last time an NRE pulse is requested of the model and then tracks the time that has elapsed since the last NRE pulse.
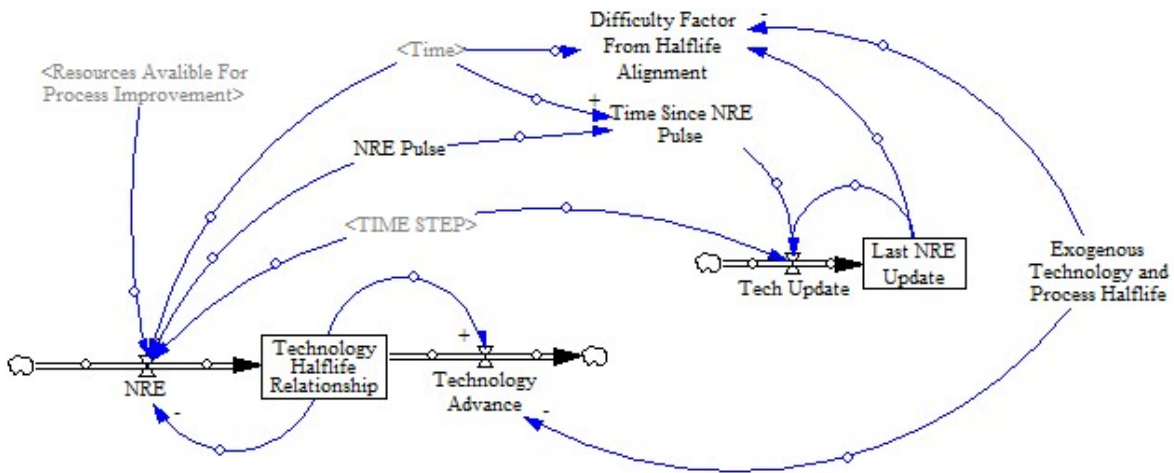
Figure 3-20: Structure for Producing NRE Pulses and Tracking Time Since Last Technology Refresh

Another way of viewing the difficulty of working with older technologies is to assume that technology outdates at a rate of 50% obsolescence per half-life of the technology. Thus, if the half-life of a technology is five years, after five years half of the technology paid for at the last NRE infusion of funding is still useful to the next generation. After about three half-lives, almost all the technology in a new development needs to be re-created none of the previous technology is

105

relevant and simultaneously working with the old technology is now three times as hard due to legacy issues. This rate of decay might look similar to that seen in Figure 3-19, marked with the actual times and names of the various GPS generations. When a function similar to Figure 3-19 is processed through the structure seen in Figure 3-20: Structure for Producing NRE Pulses and Tracking Time Since Last Technology Refresh the rustling output will be seen in Figure 3-21: NRE Pulses and Difficulty due to Age of Technology. As an exogenous constant, the model increases the entropy into the rework stock in a linear ramp, as seen in Figure 3-21 "Difficulty Factor from Half-life Alignment". This is how the model dynamically changes the difficulty associated with entropy across time based on how old the technology has become between NRE events.
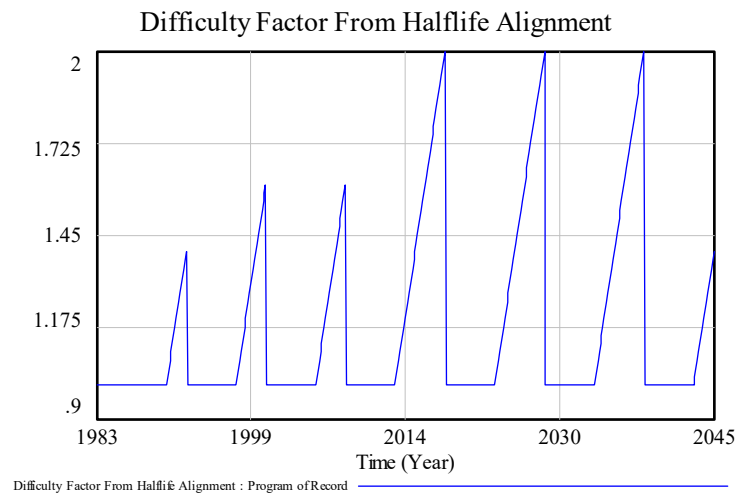
Figure 3-21: NRE Pulses and Difficulty due to Age of Technology

3.4 Model Testing—Major Loops

Having constructed a core model which represents the production of satellites in a pipeline modulated by the efficiency of the system, it is time to incorporate other concepts examined while clustering variables: learning, experience, process time for satellite production, and the impact of changing technology and resource levels. The relationships between these concepts must be determined; in the language of SD, the loops must be closed. The following causal loops, previously elaborated upon in Section 3.3.2, are currently believed to act as key driving forces in the U.S. Space Industry and are presented in Figure 3-22 below:

1. Funding or Peanut Butter Spread, responses to funding gaps
2. Process Time for completing satellites
3. Experience Gained in production of satellites
4. Firefighting behavior and the NRE Gap

Figure 3-22: Four Loop Causal Diagram

3.4.1   Peanut Butter Spread Balancing Loop

The first structure to be added to the pipeline model is the concept of "Design Life," which is also the design variable for satellites within the TSE model in Chapter 1. In the SD model, design life desired is modeled as a first-order information delay—shown in Figure 3-23. Design Life Goal is currently exogenous to the model, as depicted in Figure 3-23. Figure 3-24 presents the output if the Design Life Goal is set to 15, the Design Life Desired initially set to five, and the adjustment time to five years. The curve in Figure 3-24 shows how a first-order information delay closes the gap between the value of a stock and the desired goal. The rate at which this gap closes is based on the time constant, seen as adjustment time, where half the gap will be closed during this interval.

Figure 3-23: Design Life Desired, a First-Order Information Delay
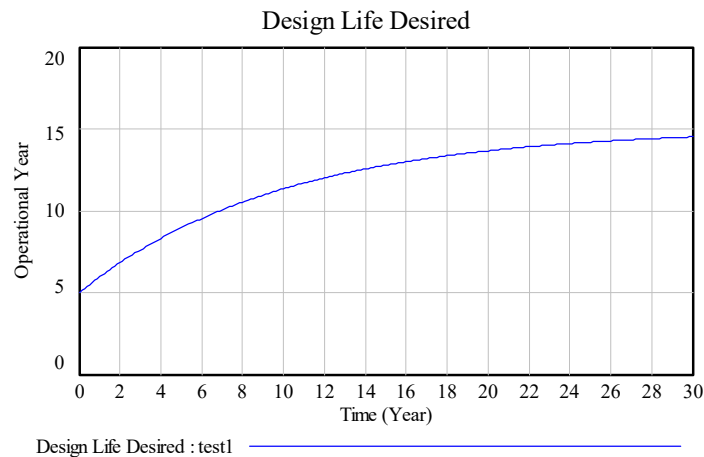
Figure 3-24: Design Life Change over 30 Years

How such an information delay may be incorporated into the GPS pipeline is shown in Figure 3-25 (and was also previously shown attached to the pipeline in Figure 3-13). The basic concept behind the Peanut Butter Spread Loop is that through change in design life, a gap in the resources required versus the resources available for satellite production can be closed. This is reasoned as:

1. An increase in the design life required for satellites will decrease the amount of work entering the industry per year (lowering the number of missions or satellites seen in the production rate variable, all else being equal).
2. A decrease in the amount of work entering the pipeline over time given a constant production rate will decrease the amount of work in the satellite pipeline, resulting in a smaller backlog.
3. A decrease in the backlog will decrease the gap between the amount of work to be done and the resources available.
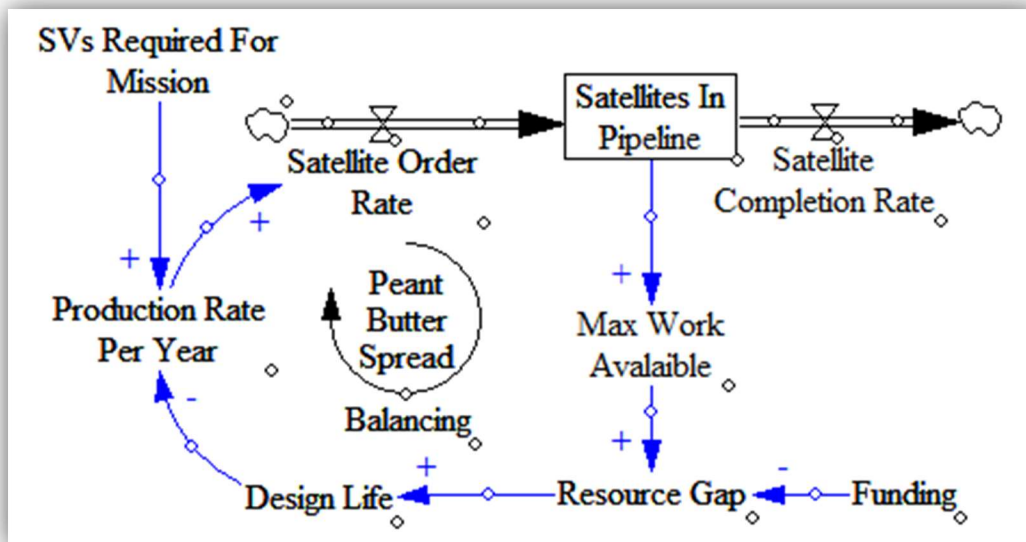
Figure 3-25: Design Life Added in Peanut Butter Spread Loop

This balancing loop is bounded by a minimum design life desired and a maximum design life possible. This loop also captures the idea of pushing work out into future years when money is not available in the current year. The backlog represents work that could in theory be completed in the current year if sufficient funding were available; if resources are not available, then the work must be completed in the future.
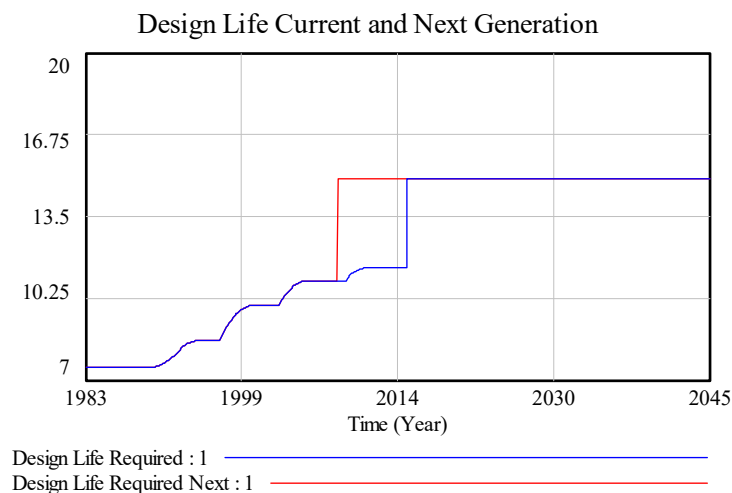
Figure 3-26: Design Life Required, Current and Next Generation

The model must also possess the ability to track desired design life as opposed to the implemented design life. It must also recognize that generally within the concept of a pipeline there are two or more programs under construction: the program being developed, and the program physically in production. Historically, these programs have possessed different design lives, as

109

seen in Figure 3-26. In Figure 3-26, the impact of the first-order information delay on generation change is made clear. The model responds to a gap in funding relative to the performance desired by increasing the design life. This loop, when simulated by itself, matches the inflection and direction of historical design lives for the GPS program.

3.4.2   Process Cycle Time Reinforcing Loop

As a pipeline can be represented by a FIFO (first-in-first-out) queue, the duration inside the queue can be approximated by the number of elements in the queue divided by the outflow rate. The SD model measures the backlog (shown in Figure 3-27) and then divides this by the average production rate shown in Figure 3-28, to compute the average production time for a GPS satellite.
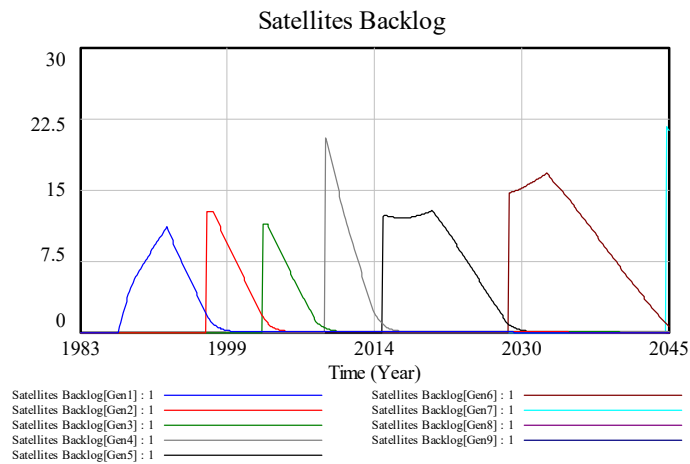
Figure 3-27: Satellite Backlog by Generation
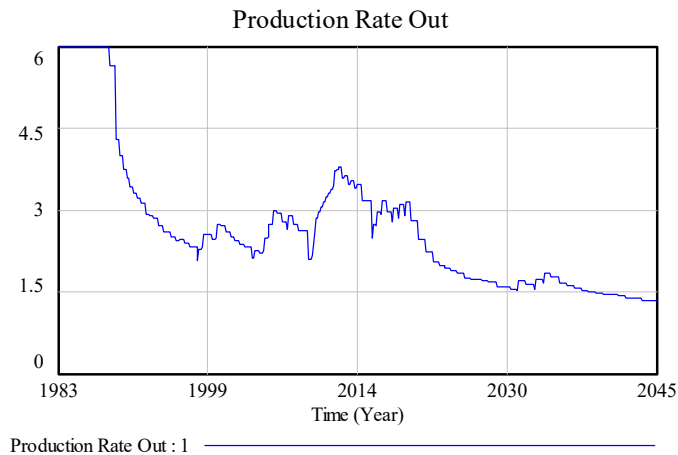
Figure 3-28: Satellite Production Rate Out

The Process Cycle Time Loop is designed to reflect the premise that learning and improvement in a process cannot occur until the process is completed. Consequently, the model must know how long work is taking. There is an implicit assumption that in satellite production the final step of integration is required before lessons learned can be flowed back into the next process. It is also reasoned that lessons learned when flowed back into satellites still in production

may produce rework. Figure 3-29 depicts the process for measuring time to compute the rate at which lessons might be learned. Underlying assumptions include:

1. The faster a satellite is produced, the faster the process time of flowing back lessons learned to the next generation.
2. The shorter the time between building satellites, the easier it is to transfer lessons learned from one satellite to the next. This allows a faster decrease in the error rate in satellite production, however, this can never be greater than the experience being generated.
3. A lower error rate or rework rate enables faster production of the next satellite; this is a reinforcing loop, faster leads to faster.
4. The loop states the opposite is also true, the longer a satellite takes to build, the longer the cycle time for the satellite production process, which leads to greater opportunity for entropy to degrade the process leading back to longer satellite production times.
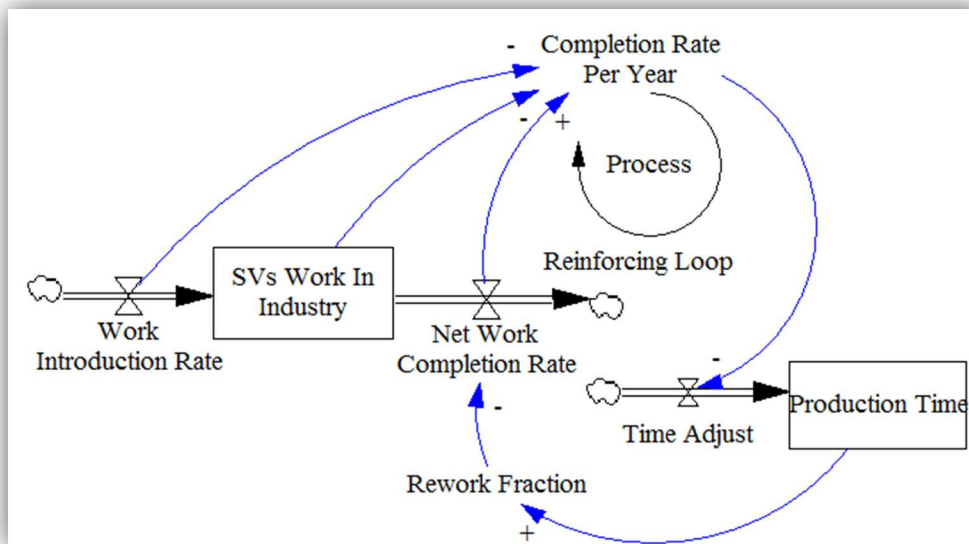
Figure 3-29: Process Cycle Time Loop

The time associated with exogenous technology advanced pulse-generating function and the associated half-life technology gap was outlined above. Both the technology half-life variable and this Process Cycle Time variable have the same dynamic unit, time. In Figure 3-16, both of these variables appear as the time constants for the inflow and the outflow of the Efficiency variable. This implementation sets up a relationship between the rate of exogenous technology advancement and the rate at which satellites are produced. As SD often views the strength of various loops with respect to their time delays, the relationship between entropy and experience is constrained by the time period over which they operate. In short:

*   Faster Satellite Completion → Lessons Learned Faster
*   Longer Development → Lessons Are Valuable for Less Time Relative to Technology Half-life

3.4.3   Experience with Process

As experience with a process is a broad concept that does not directly relate to an equation, this model implements the concept of experience through a lookup table tuned to historically observed performance. The inflow or change to Experience with Process is the raw number of satellites produced per year. This stock of experience represents the cumulative knowledge of production for the current generation of satellite. This line solely represents effectiveness of people implementing an existing process. It does not state how good the process is; it does not state the performance of the system being produced; it is agnostic to the complexity of the task, and it does not know how long the task takes or what the task is. It represents only how good people are at implementing the SV building process for the current generation.

The structure represented in Figure 3-30 was also implemented in Morrison's work as a way to represent learning and forgetting within a process. This model implements this code as a molecule of structure (*a la* (Hines, 2005)). The concept of learning with respect to satellite construction is considered to have two forms in this effort; reductions in cost and schedule when creating clones of an existing system, and reductions in cost and schedule when creating new systems. To capture the change in process time, this modeling effort must possess the ability to examine how this experience increases or decreases over time or satellite generations. This structure states that over time, experience degrades and entropy impacts learning. Experience One might view this as saying: as technology progresses, older technology is less valuable, and as people change in and out of the industry, individual skill is lost. The rate at which learning progresses or is lost relates to the half-life of the process. The half-life degradation of technology's value over time was seen in Figure 3-19. Now we might suggest that similar to technology, experience possesses a half-life and is valid for only a limited time.
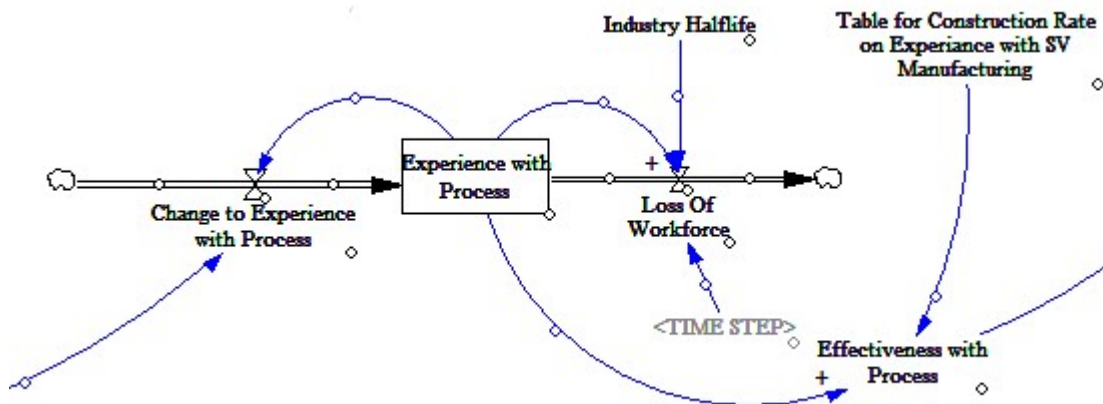
Figure 3-30: Experience with Process for GPS Program of Record

Based on the Iridium Satellite Program, a standard in the industry for excellence in cloning satellites, the model is coded such that a production rate of 52 satellites per year or one per week equates to perfect experience with process. To determine appropriate values for the GPS program in its current incarnation, a technique called "setting the model in static equilibrium" was invoked. To achieve this, the Experience Loop was disconnected from the model and a sweep was performed across an exogenous constant in place of a lookup table. By fixing the historical production funding for the GPS program, the historical production rate, and the rate of entropy,

the value of experience required to meet the requirement of 27 satellites on orbit at all times could be computed. This technique solves for what the effectiveness with process variable "should be," by using the GPS program's historical values.
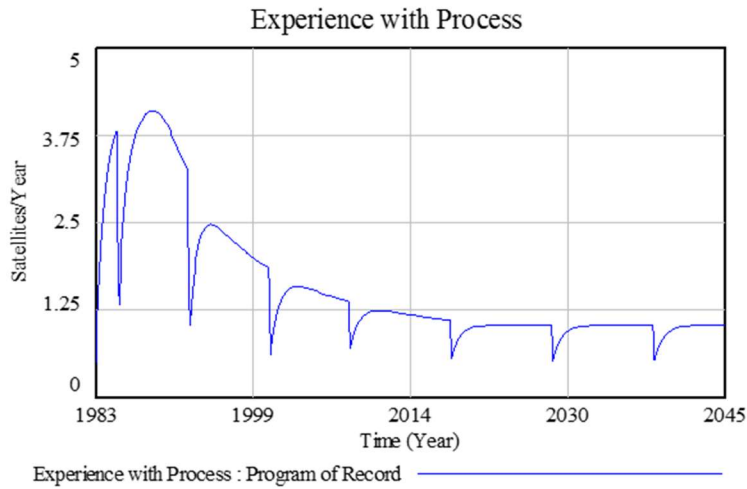
Figure 3-31: Program of Record Experience with Process

The results of the static equilibrium tuning indicate that an efficiency of 30%, given a 7.5-year design life as seen with the GPS Block IIs, based on all other historical data, and a production rate of about four satellites per year corresponds to a steady-state equilibrium. This 30% value has no direct real world meaning. The concept of Work and Re-Work ties to reality in the idea that a single object or job would fail to complete in the appropriate timeframe given the appropriate funding. This is similar to the Efficiency value here, where the additional concepts of technology and the injection of entropy across time is now included. This Efficiency value is thus a construct designed to back out a proxy metric for efficiency in turning resources into satellites. (In this respect it acts as a proxy for health as well.) To achieve a steady-state model equilibrium for the GPS Block III satellites, given a 15-year design life, or production rate of 1.6 per year, an efficiency constant of 20% is required. Figure 3-31 being converted to a value between 0 and 1 in Figure 3-32 based on the constructed curve.

113
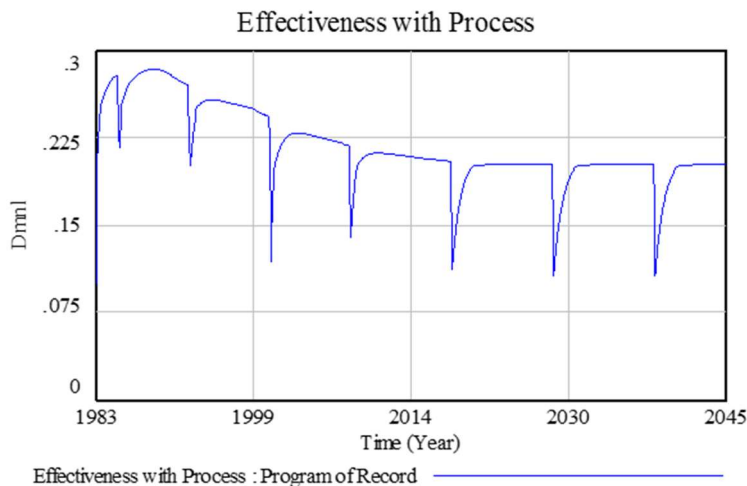
Figure 3-32: Program of Record Effectiveness with Process

While the model enforces an experience loss when the program switches generations, this does not represent a loss of technical capability, but rather a loss of experience with the process of creating the specific satellite design currently in production. In a new generation, by definition, no one has worked with the process so experience in building the new generation starts low. In Figure 3-31, the decreasing experience of the current GPS program is seen, as well as the drops associated with new generations. In Figure 3-32, the result of the experience value when sent through the lookup table is presented.

Having defined the look-up table and math used to convert the soft-system of experience into the pipeline model, the SD model now possesses the ability to implement the high-level concept that production of satellites increases experience, which leads to learning, which results in more efficient production of satellites, which as noted earlier reduces the backlog and in turn, requires fewer resources.

1. The higher the production rate (number) of satellites per year, the greater the amount of experience generated within the satellite production pipeline.
2. The greater the experience generated, the lower the error rate in the production of satellites.
3. The lower the error rate, the faster the production rate, which in turn decreases program cost overruns.
4. A decrease in overruns leaves more resources available for more missions or more satellites which in turn leads to an increase in the amount of experience in producing satellites.
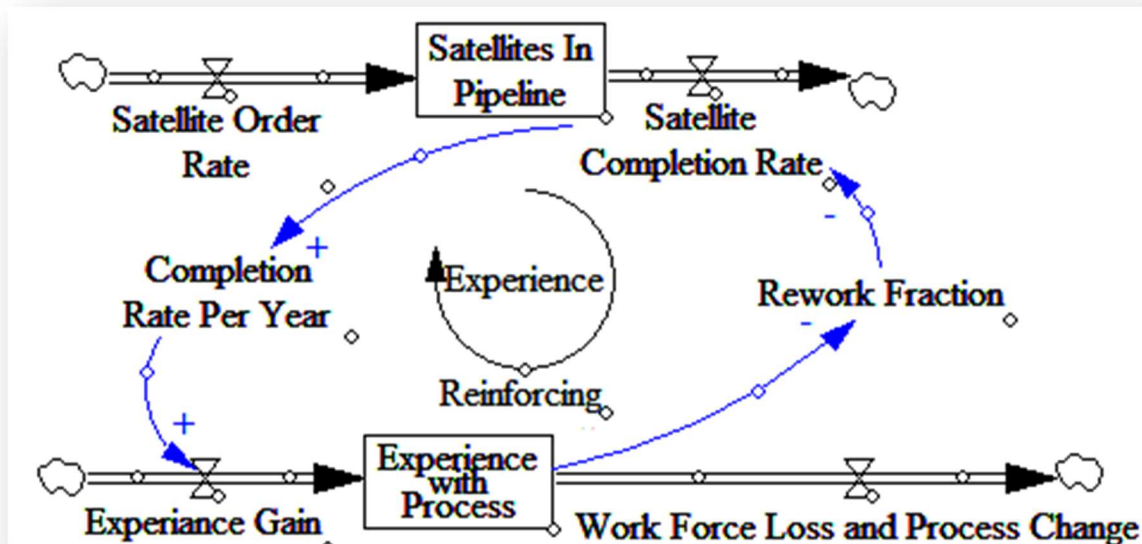
Figure 3-33: Experience with Process Loop

The model now reflects:

- More Activity → More Experience Building SVs
- More Experience → More Efficient
- More Efficient → Less Cost per SV
- Less Cost per SV→ More Resources to Development

3.4.4   Firefighting and NRE Gap Reinforcing Loop

As program overruns increase, resources for improvements are diverted to resources to production to cover the short-term gap in funding required for production of satellites. This decreases the amount of money spent on NRE to improve the next generation of satellites and also increases the duration between NRE events. This increased time between NRE events increases the entropy attributed to the age of technology associated with satellite production. The older a technology becomes, the more work is required to implement it or the more difficult it becomes to upgrade (eventually completely obsolete technology would need to be created from scratch and building anything new always requires substantial work). As every effort becomes a first-of-a-kind effort, fewer experiences and less technology transfer from one program to the next, leading to increased program cost overruns. This loop also works in the other direction, where resources spent on improving process lead to a lower rework and error rate, which eventually leads to more resources being available for process improvement as less needs to be spent on constructing physical satellites. Another consequence is the increasing size of the backlog of satellites in production, which in turn makes production harder as fixed resources are divided among more concurrent satellite productions. The Firefighting Loop displayed in Figure 3-12 contains the backlog of work in the industry (satellites in production) as seen in Figure 3-27. Here in Figure 3-34 we see the impact of the time gap between NRE events. Over the years the length of time between NRE events has grown progressively longer, and the consequence of this is presented in

Figure 3-35. The difficulty with dealing with legacy technology has been modeled with a linear function, where each half-life of time increases the entropy injection into the system. This becomes the entropy injection rate into the Efficiency stock.
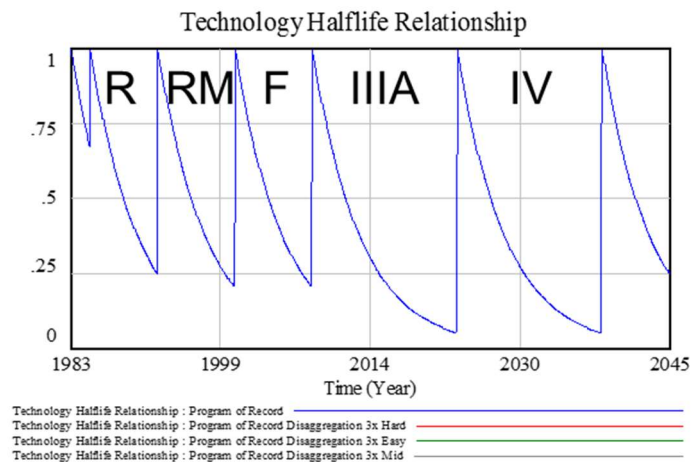
Figure 3-34: Technology Half-life Reset at Generation Update

Note: the technology spike in technology occurs when the NRE is paid. This fixes technology to the date of inception as satellites are designed with an expected capability on this date. Technology is not fixed to the date of a satellite's production.
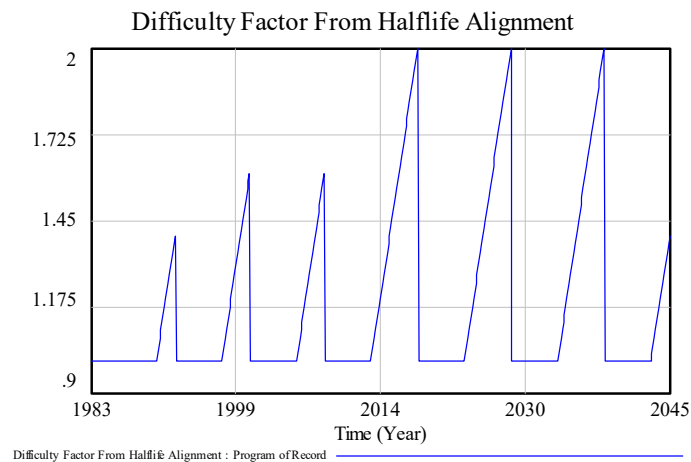
Figure 3-35: Difficulty Derived from Technology Half-life Relationship

3.4.5   A Fifth Loop: Nunn-McCurdy

In inductive analysis in Chapter 3, it is noticed that tuning of the model reveals a slight specification error in the construction of this model. While the initial model was sufficient to capture most of the reference modes, it became quite "unstable" over time in response to underfunding. If satellite acquisitions were underfunded for long period of time, the model efficiency would drop as a result of too few satellites being produced and the backlog would rise, creating an unreasonable level of firefighting. This does not match reality, where program overruns do occur, but in response additional funding is provided to complete acquisitions. The model was already designed to operate under a changing cost ceiling depending upon the performance

116

required of the system. Thus, using the "gap" variable to analyze the difference between the amount of money provided for production and the amount of money required was possible. As in the real world, additional funding, or program re-baselining cannot be achieved until after 125% of the program baseline is breached. Since this requirement is imposed in the real world by the Nunn-McCurdy Act, the same name is given to this loop. The difference in model execution with and without this loop is documented in Chapter 4.

The rising baseline in funding required for production, in Figure 3-37, is primarily ascribed to the increase funding provided due to the increased capability of each successive generation. The blips or increases/decreases around 2008 and 2028 are the consequences of firefighting behavior across time as displayed in Figure 3-36. Prior to 2008 this loop is not activated because historical cost of production for existing GPS satellites included overruns which had already occurred. The consequences of these overruns are included in the final cost of the satellites produced. GPS IIIA and future programs have theoretical but not actual costs of production. As such, from 2008 on, the model must have the capability to handle both over- and underruns.
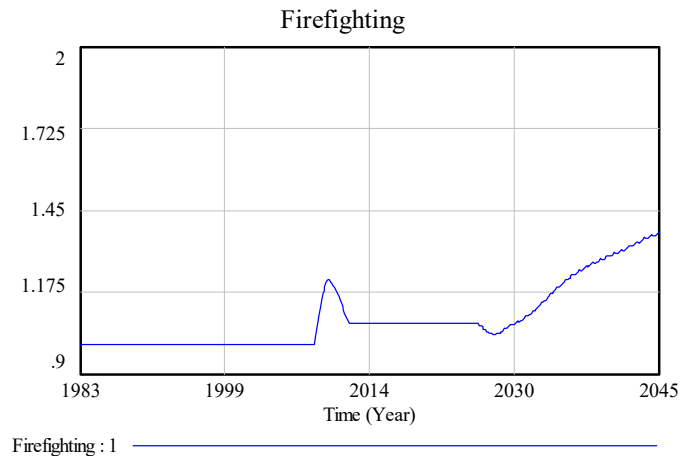
Figure 3-36: Firefighting, Resources Required over Baseline

117
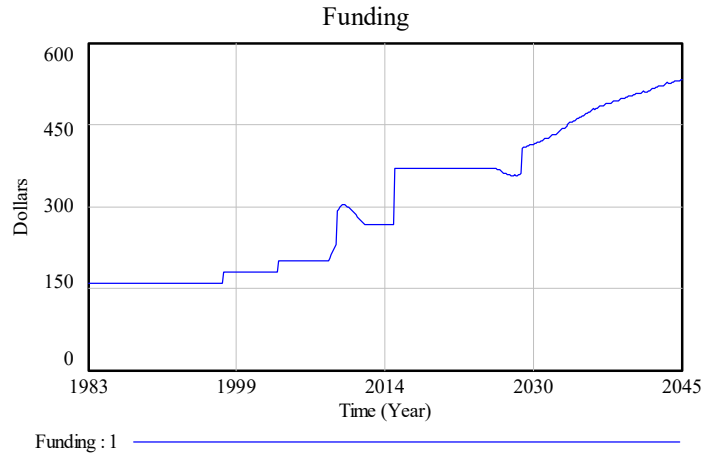
Figure 3-37: Funding Required for Production

Figure 3-38 displays a simplified pipeline as well as the interaction of resources provided compared to the work in the pipeline. The first-order information delay shown in Figure 3-39 is used in conjunction with the pipeline to measure the firefighting level and cost overrun. This relationship compares the expected amount of work that can be completed from the pipeline in the current time step, versus the amount of work that needs to be completed in a time step (one-eighth of a year) to ensure 24 satellites are maintained on orbit.
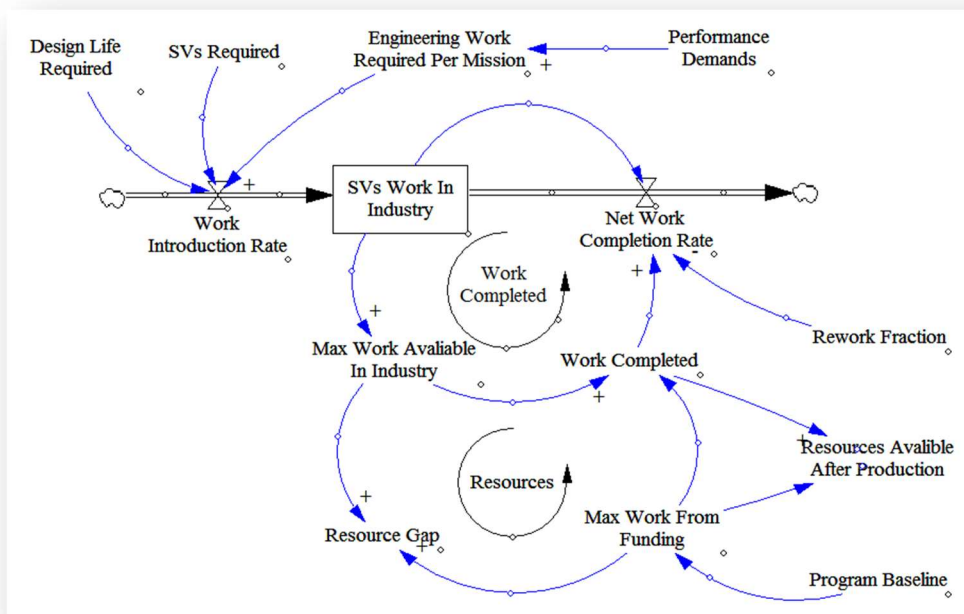
Figure 3-38: Resources Gap in Relation to Work in Industry and Program Baseline
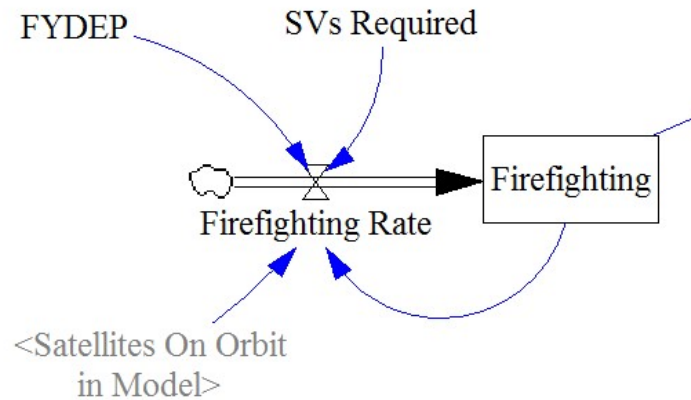
Figure 3-39: Firefighting First-Order Information Delay

3.4.6 Meta Loops

As this SD model will be merged with the TSE model in Chapter 4, a new type of loop comes into existence. This is a causal loop where the state of the GPS acquisitions pipeline influences some aspects of the satellite as modeled in the TSE model, and the output of the TSE model then influences the SD model's execution. These loops are further explored in Chapter 4. Two are noted here to make the reader aware of their existence:

1. SVs Ordered: This loop gaps outside the SD model and passes into the TSE module in the following manner: satellite production puts satellites on orbit, satellites on orbit decay, which triggers satellite procurement, which passes to the TSE module, which then places the appropriate number of satellites to be procured into Generate Request for Satellites.
2. NRE Refresh: The TSE model creates the NRE pulse, which in turn changes the entropy associated with technology, which changes the difficulty associated with producing satellites, which changes the time (year) of the next order of satellites the TSE module.

3.4.7 Causal Loops Excluded from System Boundary

A loop (with a very long time delay) also likely exists when the concept of the entire U.S. Space Industry is examined. It postulates that learning in the GPS program correlates to some degree with learning in the overall Space Industry, which leads to reductions in cost and production time, leading to a better-performing industry, which in turn brings knowledge back to the GPS program. As the time delay of such a loop is quite long and likely small in impact, it was excluded from the model.

There is also probably a loop active over a long time line that sizes rockets based on the size of space vehicles, and then space vehicles are designed to fit on rockets, increasing the size of the next generation of rockets. Due to the extremely long timeline of this loop, it and rockets have been excluded from the deductive SD model and will be treated only within the context of TSE.

Undoubtedly there are many additional powerful loops in the Space Industry currently affecting every phase of space-based assets. The use of a core architecture of a simple production line enables these loops to be included in future modeling work. For example:

- Launch Costs Force Satellite Costs: If a launch vehicle must cost less than the satellite being launched, this may force aggregation or more complicated solutions because the implied utility function looks not only at value delivered but also pure cost. This may lead to larger satellites, which in turn would force larger launch vehicles. If the satellite, on average, must be a higher multiple of the cost of the launch vehicle, this may make this an even more powerful loop. This may lead to overall higher program costs which would lead to demands for higher reliability. Combined with the attractiveness of high economies of scale associated with large, long-lasting space systems, this may contribute to the design point we see today.

- This SD model does not draw satellite launch into the picture. Even though some consider the GPS launch rate to set the schedule of USAF launch, it was not included because historical evidence relating GPS launch rate to launch vehicle cost could not be obtained. It is reasoned that the existing United Launch Alliance (ULA) contract likely possesses a larger impact on launch cost than launch rate and experience. As such implementation of any data about launch may be clouded by this large causal factor; the fixed launch contract.

- Failure Begets Failure: If a program is cancelled, the next program attempts to include all the lost performance of the last program. Since the last program failed because it was too difficult, the chance of success for the next program is even less. This concept of one program's result impacting the next program, is natively supported in the model where the Efficiency stock possesses some "stickiness." The state of the industry at the end of one program is the starting efficiency for the next program, however, it was not directly programmed as a variable; this approach is a consequence of stock-and-flow modeling.

- Utility Theory Versus Prospect Theory: People are willing to pay to reduce uncertainty. If decision-makers attempt to eliminate all risk, they encounter exponentially rising costs. It has been seen that the pain of loss is two to three times greater than the elation of success (Tversky & Kahneman, 1979) (Curley, Yates, & Abrams, 1986). If the model implements a prospect theory view of risk management, a reinforcing loop may emerge which pushes for higher reliability, which at a certain point makes space systems so expensive that none can afford to fail. This may be useful for deductively understanding convergence on the current design point. As risk and reliability was also fixed as a historical desire for 100%, this puts such analysis outside the current model boundary.

- The Impact of Forced Cost Reduction: a policy attempting to minimize cost and associated feedback mechanisms. If external policy is applied to the Space Industry as a whole, or a single program, the model will respond by increasing design life to supply performance for a longer time period. This is a short-run solution that has second-order consequences that are of interest for examination. This was deemed to be a temporary requirement of external policy, not a core model structure.

- Reliability Loop: The literature supports the concept of a desire for reliability. A detailed analysis of how this may impact perceptions is found in Putbrese's thesis (Putbrese, 2015). This SD model makes the assumption that reliability of 100% has always been desired for the GPS program and sufficient funding to achieve such has always been provided. Given this assumption, historical cost data captures this desire in this model.

3.5 Model Assumptions and Views

Having selected these loops to represent the core causal mechanisms involved in the production of satellites, some variables have been clustered (as already noted), and others have been excluded. Assumptions about variables and concepts listed above, but considered exogenous factors to this model, include:

1. Reliability has always been desired and designed to be 100%, or no failures before design life. This assumption implies that the cost models implemented are based on the expectation that the satellite will achieve its full design life on orbit and as all the satellites in the data set did this is a reasonable assumption.

2. Cloning and creation of satellites has been combined into a single pipeline; satellites are either in the generation being designed, the generation being produced, or the multiple generations on orbit. Thus, this model makes the assumption that experience in replicating satellites and experience in creating the next generation of satellites can be clustered into one experience stock. Admittedly, in manufacturing these are different skill sets and some fidelity is lost by this assumption. However, satellites are produced in very small quantities, many are unique, and even large constellations typically have changes made throughout the production run. A single pipeline model does not appear to differ greatly from reality and has been adopted for the sake of model simplicity. Regardless of whether the work is developing the next generation of satellites or cloning the existing generation of satellites, the older the technology the more prone to delays and difficult it will be.

3. Performance of GPS satellites at any given time has been designed to be the best that current technology can achieve. This model assumes that performance demands are always equal to technology available. This is based in the reality that the government typically releases a request for proposal (RFP) and contractor's reply listing what they believe they can produce. The government then bases contract specifications on the RFP results from the first solicitation as well as internal expert opinion and opinions from the Aerospace Corporation about what is feasible. This assumption allows excluding technology and capability demands from the modeling effort or at least their consideration as exogenous factors, not included in any causal loops. This assumption does not exclude reducing future requirements to be less than what could be possible in the future; this is a possible policy whose implementation will be tested.

    a. Thus, the difficulty at any point in time to produce the best satellite remains static: changes in technology and tools mean consistent difficulty for the time period across all time (1983-2045).

4. Mass can serve as a proxy for work needed to complete a satellite.

    a. Increased work from increased complexity is mitigated by better tools.

    b. This biases the model against disaggregation; there is no benefit from non-linear scaling.

    c. This assumption is tested in Chapter 5 against a non-linear assumption by enabling a reuse factor of design (NRE) costs for disaggregated architectures.

5. The model implements the concept of NRE payment or a pulse of R&D funding that is in line with the typical start of a new contract. In this model, experience with process peaks

before contract signing and error reduction is at its highest right before paying the NRE. This is consistent with the concept of starting a new production line. Logically experience with process in cloning satellites is probably at its highest for the last satellite made in a block. This pulse feature could also claim to capture the real-world impact of switching contractors: both the positive from the NRE boost and the negative of experience loss in transfer, when the old program is shutting down. Shown below in Figure 3-30: Experience with Process for GPS Program of Record, every time an NRE is paid it takes several years to bring experience with the new generation to the level of the previous. A mathematical assumption in the model is that every technology half-life linearly increases the difficulty of dealing with old technology by a factor of one. There does not appear to be literature addressing this issue, so a reasonable assumption is to implement a linear function (e.g., one half-life of time is difficulty factor one, a half-life of 2.63 equals a difficulty factor of 2.63). Initial analysis indicates that assuming a linear relationship generates results that do not differ substantially from those of square root or quadratic functions.

a. There is also a technical problem in implementing other than linear functions based on current model structures. Due to the model triggering new acquisitions at different time periods it is impossible for a direct comparison to either a square root or a x^2 function. The reason for this is that the time of a new acquisition is unknown and is triggered by the desire to maintain capability versus design life. This provides no opportunity for the model to scale the respective functions and consequently, in this model as currently designed can only implement a linear function to serve the purpose and achieve direct comparison between different architecture designs.

6. This model operates with the assumption that contractors can be considered a production arm of the Space and Missile Systems Center (SMC), one organization responsible for government acquisition of space assets. This is not literally true; however, the concept of a military-industrial complex means that this assumption is not without merit. If preferred, "profit" from contractors could be viewed as drag or loss.

a. The model can also implement a "loss constant," to represent this inefficiency as SMC, the contractor, and the Aerospace Corporation form the trinity of satellite production.

b. It is assumed that in a consolidated industry, systems construction knowledge lies with either Boeing or Lockheed Martin and the Aerospace Corporation. Thus, half of one third would represent about a 17% loss due to inefficiency in the process due to switching vendors.

c. Arguments could be made that loss is greater, because knowledge in SMC and Aerospace does not contribute to efficiency with process inside the contractor facility.

d. Conversely, one might argue that employees transfer among companies and many subcontractors who physically produce assets are employed by major system integrators. Specific technologies are usually handled by a subcontractor and the large contractors serve as system integrators, hence, regardless of the large contractor selected for the role of integration, the best industry knowledge for a specific capability will always be available (e.g., atomic clocks for space use are made by one contractor).

e. After model tuning this constant was removed from the model as it appeared unnecessary. Given current operations, each GPS generation is so far apart in time that almost no learning is occurring across generations. Thus, switching contractors is irrelevant, as even staying with the same contractor means no learning is likely to transfer. This does, however, pose a threat to validity for future scenarios where learning exerts large positive effects across generations. At some unknown point the model must consider re-introducing this assumption. This is heavily intertwined with assumption number 2 and the model's pipeline structure and tracking of experience in a single variable.

7. The model views work added to the industry as an "even" process per year. One could also view this as a pulse every time a satellite is requested, or as a large pulse when a contract of satellites is added (e.g., the model could pulse eight satellites every five years for GPS). To do this, a minor change to the mechanism for measuring the size of backlog is needed to assure that at the time a large contract is input into the model it does not interpret this as a giant backlog that has suddenly appeared.

   a. The model does not possess the ability to force a specific number of satellites to be built. The feedback loop from the pipeline attempts to keep an inflow sufficient such that, based on expected design life, no fewer than 27 should ever be on orbit. Still, as buffering and time delays separate ordering and production, the system is prone to oscillatory behavior.

   b. This enables the "what if a satellite lasts longer than expected to operate" question to be examined.

   c. It appears this creates a bias towards the industry being in a "better" position as extra IIF satellites are believed to have been produced. As the tuning in Chapter 3 is close to the reference modes even with this bias introduced, no correction to this was proposed, as it would require additional structures which would add confusion when testing the dynamic hypothesis.

3.5.1 Exogenous Constants

Within the model some parameters are encoded for tuning and examination of the model's response to exogenous shock or change in context. The major control variables are:

- Technology Half-life is hardcoded to five years. This is an important constant since fewer than three years leads to the buildup of an unlimited backlog; greater than seven years and the model views satellite construction as a trivial problem and predicts the industry should be much healthier than it is. This variable deserves substantial sensitivity analysis and in model tuning (Chapter 4) is heavy examined. Assumptions about technology change in the future can also be analyzed through changing this variable dynamically over the future timeframe.

- Industry Half-life is hardcoded to 10 years. Until this falls below five it has little impact on the state of the model. This represents how long the average employee is in the industry and represents a loss in human knowledge from people leaving. If production time of a satellite approaches this constant, the model notes that programs take as long as people might stay in the industry. As production time approaches this constant, the rework fraction

will represent poor performance in the industry—work is being completed by people with little experience.

- FYDEP is coded to five years and given the name, Five Year Defense Plan. This is the update time for the Peanut Butter Spread Loop. This value was also used initially for the Firefighting time constant. Tuning found that with the value of five this structure was too "weak" or unable to balance as it was intended to do. For Firefighting, a value of two provides the desired performance and a better fit to the data.
- Design Life Cap: enables setting a maximum design life for satellites as a policy implementation.
- Program Baseline: Sets the funding profile or resources for production. This can be changed to examine policy associated with additions or reductions in funding. This has been set at $192M FY2010 dollars as this is the cost to produce 1.5 GPS III satellites, which is the average rate of satellite production over the history of the program.
- Disaggregation Policy is set as one. Varying this implies splitting the GPS program into several satellites of equivalent capability as one GPS satellite. The policy is hardcoded to go into effect in 2008, as a policy in place of the Block III historical purchase.
- Enable Nunn-McCurdy: If this is set to one, then Nunn-McCurdy Loop is allowed to increase the program baseline, if set to zero, the loop is turned off.
- Nunn-McCurdy Level: If this is set to one, when the program exceeds 1.25x its baseline the program, it will be able to raise funding to the level of 1.25x but no more. Higher values enable testing of policy which, in the event of an overrun, additional funding beyond just the overrun is provided. The idea here is to combat the idea that failure begets failure and counter firefighting behavior. If the system is "broken" and only the money required to fix the immediate problem is provided, then the underlying problem is never addressed and more money is spent just on production. If, however, additional funds are provided, the extra money is presumed spent to correct underlying problems in production—thereby improving the process. In Chapter 3 this impact is seen to possess the potential to impact the magnitude of the overrun, delays in production, and the cascading impact on the next program.

3.6 Deductive Model Outputs

The full model, constructed from the relationships discussed throughout this chapter, appears in Figure 3-40. Unlike previous figures that depicted potential relationships, this represents actual executable code and is the front end of the Vensim model implemented in this work. To fit this on a single page, some structures have been hidden, most notably the "accounting structures" which track the units of "months of operational capability" and the exogenous pulse functions.
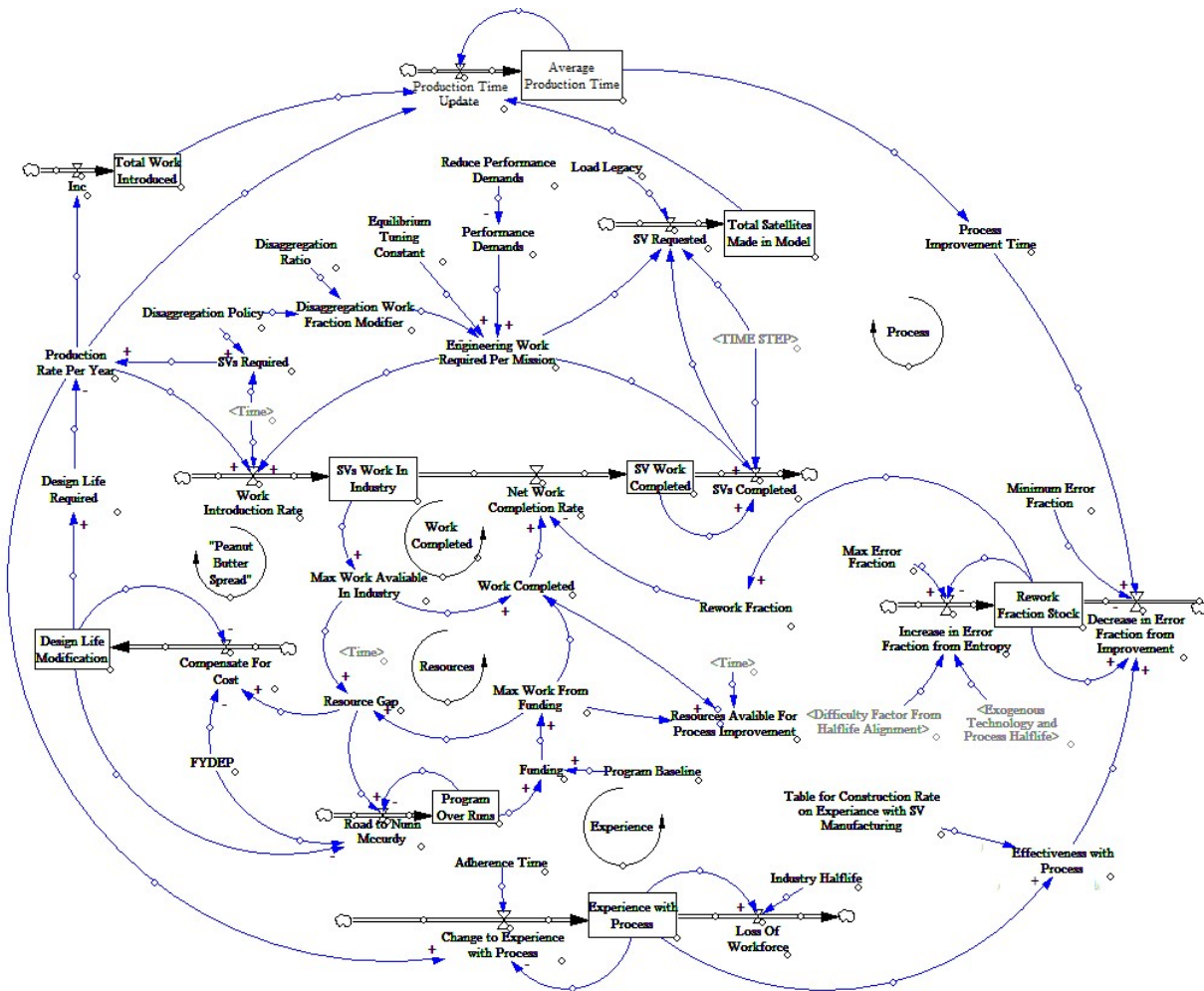
Figure 3-40: Vensim GPS Production Model

3.6.1 Model Representation of the Current GPS Block III Deployment Plan

At this point the model cannot be considered verified or validated. In order to accomplish this, it is essential to test the model's sensitivity to change. Examining the outputs of the model in response to change will help to ensure the basic functionality and feasibility of this approach. Simulating the deductive model, as well as varying exogenous constants, will show how time constants change the strength of various loops relative to each other. While the individual loops are designed to match trend and inflection, there is no guarantee that they will work together.

In model construction, different implementations were iteratively tested and direction of relationships examined. The hardest to develop was the Nunn-McCurdy Loop which seeks to approximate actual human behavior with respect to cost overruns. Predicting the circumstances under which people would declare a cost overrun and how to approximate the behavior of re-baselining was not immediately obvious. The evolution of the model, and the value of the model is only known when all the loops are simulated together.

Figure 3-41 presents the model's abstraction of the current plan for procuring the GPS constellation. It represents block buys of eight satellites ordered in advance of the decay of

satellites on orbit. The first 10 years of the model tune it by loading the GPS Block II satellites and placing them on orbit. The blue line represents the number of satellites on orbit and the black line represents the average number of satellites in construction inside the pipeline. The model does not tune with data before the year 2000. While it appears that the model places more than 24 satellites on orbit, this is not a shortcoming. Most of the time the extra satellites are very near the end of their design life, and new satellites must be procured with a small buffer of time such that they can complete Launch and Early Orbit (L&EO, not to be confused with LEO, Low Earth Orbit) procedure before the old satellites are decommissioned. In the real world this is not a smooth operation, and the SD model clearly shows the difficulty of phasing acquisitions and launches with perfect efficiency.

The model currently does not examine what happens if a satellite lasts beyond its planned design life. In initial analyses the simplest picture of model execution is selected to determine if a model functions logically. To examine the effect of life beyond planned design requires changing the outflow structure from a pipeline delay to a delay of order other than infinite. Due to the design of Vensim, this requires a change in only a single line of code, so this issue can easily be examined later.
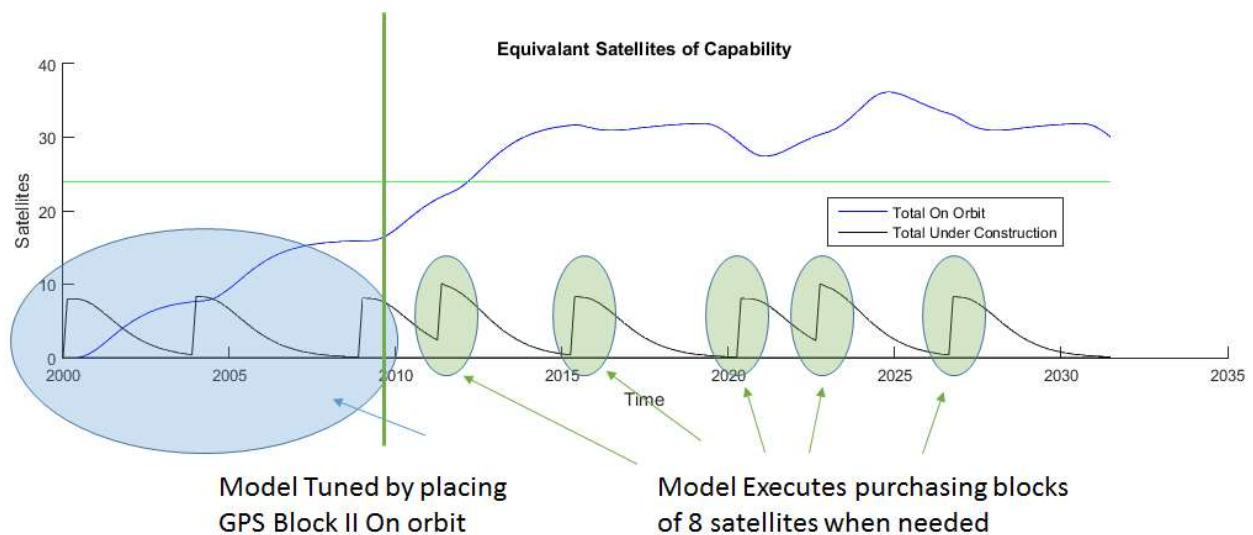
Figure 3-41: Model Representation of Satellite Capability Level, Procuring and Launching GPS Satellites Under GPS BATNA

A slightly different way to visualize procuring and launching satellites is in terms of operational years of capability. (Refer to Figure 3-42.) This visualization is useful for several reasons. It shows the amount of capability on orbit. It also shows a proxy metric for the amount of activity or level of production in the industry. And, it serves to indicate when a satellite on orbit is about to expire, based on the stock level stored in the SD model. For example, a satellite that lasts 10 years would have 120 months of operational capability whereas one designed to last five years would last for only 60 months. More years of capability on orbit would indicate a longer time before replenishment is needed, but also represents more that can be lost at any given time. Richard's survivability metric suggests thinking of this in terms of "Time-Weighted Utility Lost" (Richards M. G., 2007). One might infer that an industry producing 24 months of capability per

year (the average under the current GPS procurement plan in Figure 3-42), would have a different difficulty ramping up production (in case of a catastrophic loss event or some other urgent need) than one producing 72 months of capability per year (which is required to implement GPS capability using Galileo's approach [3x Disaggregation]). As this SD model possesses a stock of capability and an outflow of capability, it is possible that this model represents a new way to test the concept of a time-based utility loss function. In theory, the outflow could be "hit" with an exogenous spike and satellites could be taken out of service prematurely. The model would then need to respond by replacing these satellites; and the model would be able to track the time and the cost before capability could be restored. This response time could be compared against a pipeline producing 72 months of capability per year. Replenishment time is a large factor in assessing the value of a space system; positive value can be ascribed to a system that can recover faster. In Figure 3-42 the switch from black to red indicates the switch from Block II to Block III designs, and the axis has been changed from "Satellites" in Figure 3-41 to "Months of Capability on Orbit."
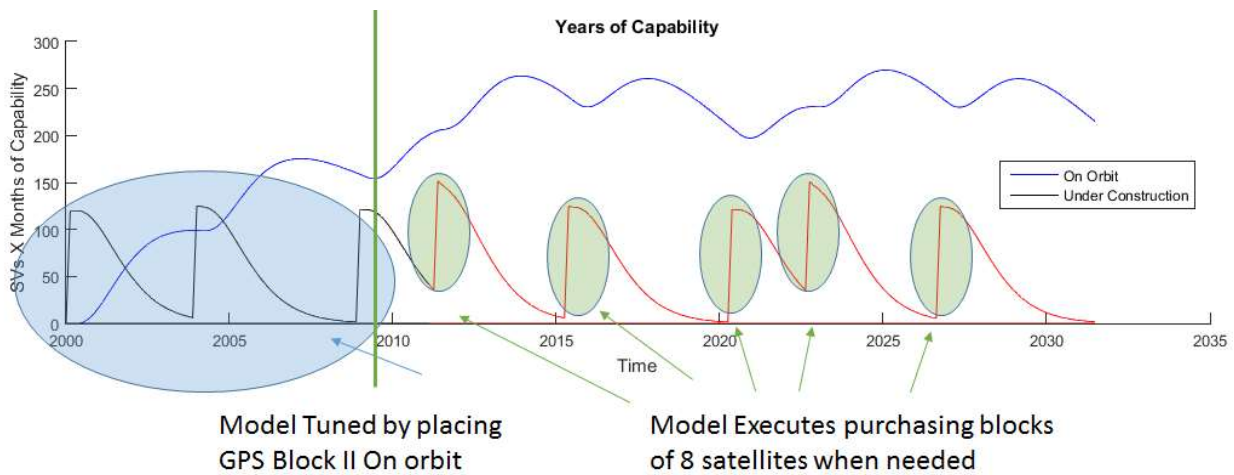
Figure 3-42: Model Representation of Capability as Measured in Years for GPS Satellites Under GPS BATNA

In Figure 3-43, the actual time of satellite launches is recorded in pulses. Even though the SD model tracks the average outflow, it also buffers completion until sufficient work is completed such that a whole satellite is ready for launch. This is accomplished through subscripts in Vensim, where the first subscript represents the Block II-A satellites and the fifth then equates to the GPS III A. (Implementation of subscripts is expanded upon in the Appendix F Implementation of Subscripts in Vensim.) Subscripts allow for a single variable to be split into subcomponents where an individual generation's data or the sum data of all generations overlapped can be viewed. Above in Figure 3-41 and Figure 3-42 the sum of all outputs is presented, here in Figure 3-43: Individual Satellite Launches the individual generations are called out.
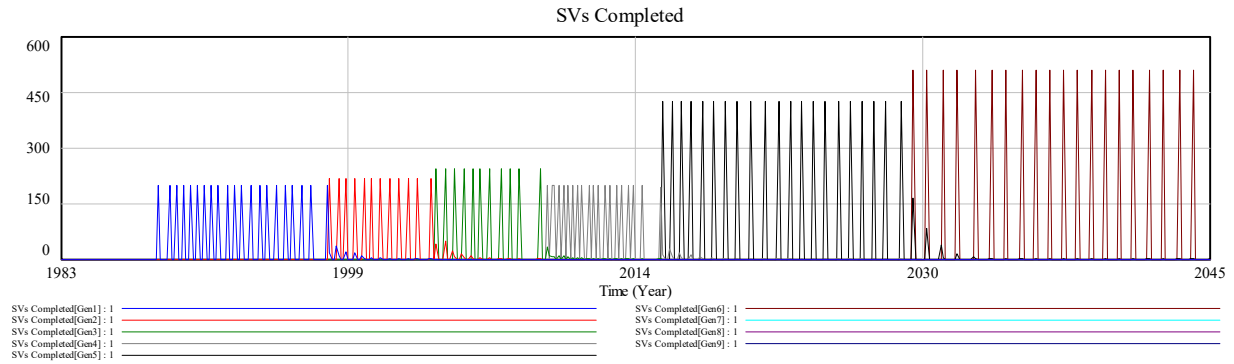
Figure 3-43: Individual Satellite Launches

3.7 Reference Modes and Model Validation

To begin validation of the model, the outputs of the model must be compared against the historical data of GPS programs. The variables of Design Life, Number of Satellites on Orbit, and Number of Satellites Produced are a good place to start to visually inspect the model for any needed high-level, human correction. Due to the consolidation of production time for new satellites and the activity of cloning satellites, the variable "Production Time" no longer tracks the real-world values. The value of this variable, however, should always be greater than the time required to clone a satellite and less than the time to produce the Theoretical First Unit; this is the nature of SD in clustering variables.

When examining reference modes for the production of GPS satellites, one of the difficulties is that the GPS Block IIs (A, R and M) all were designed with 7.5-year design lives, but with one major exception all lasted 15 years or more. As a result, the production run of 33 Block IIF satellites was reduced to 12. (The reduction was also desirable due to technical problems and cost overruns (GlobalSecurity.Org, 2011)). If we look at the reference mode based solely upon launching GPS satellites given their original design lives, it looks like the "Baseline" in Figure 3-44. As a matter of performance, the GPS constellation requires a minimum of 24 satellites, however, the average has been 30+ due to satellites lasting beyond their planned design lives. This can be seen in Figure 3-44 in the line "2x Design Life". The current Block III plan with a 15-year design life has been input beyond 2016.
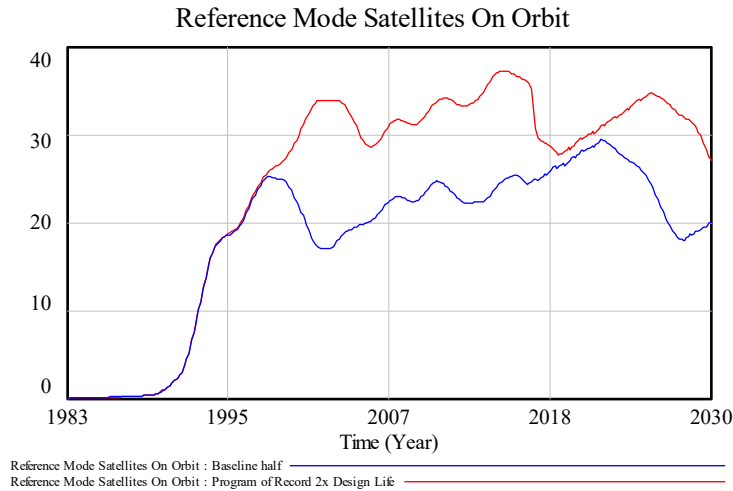
Figure 3-44: Satellites on Orbit Based on Design Life and Double Design Life

In Figure 3-45, historical requests for change in design life are compared with the model's prediction of the design life required over time. The model also predicts that in the next generation a design life of 18 years will be required to minimize cost per operational day. Beyond this generation, it is likely additional design life will be requested if technology can provide it. The SD model closely approximates the number of satellites needed to meet the operational requirement, as well as the total number of satellites produced (Figure 3-46 and Figure 3-47). It is interesting to see that the current plan indicates that fewer than the required number of satellites would be on orbit by 2025 if the Block III satellites and the Block IIF satellites do not last beyond their design lives. It is also interesting that the model is able to keep about 18 or only 75% of the required satellites on orbit given no additional increase in funding or no additional service life on orbit. While further examined below, the model's failure to meet the operational requirement without additional funding or cost overruns is primarily due to the long development times and increasingly old technology by 2023. For now, we know that from an "eyeball" standpoint the model can keep about the same number of satellites on orbit as historically occurred.
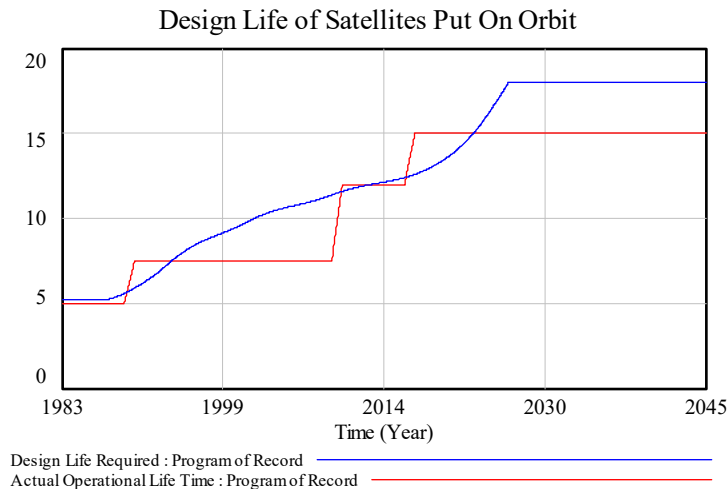
Figure 3-45: Design Life of GPS Satellites, Reference Mode vs. Model Output

On Orbit

Reference Mode Satellites On Orbit : Program of Record
Satellites On Orbit in Model : Program of Record
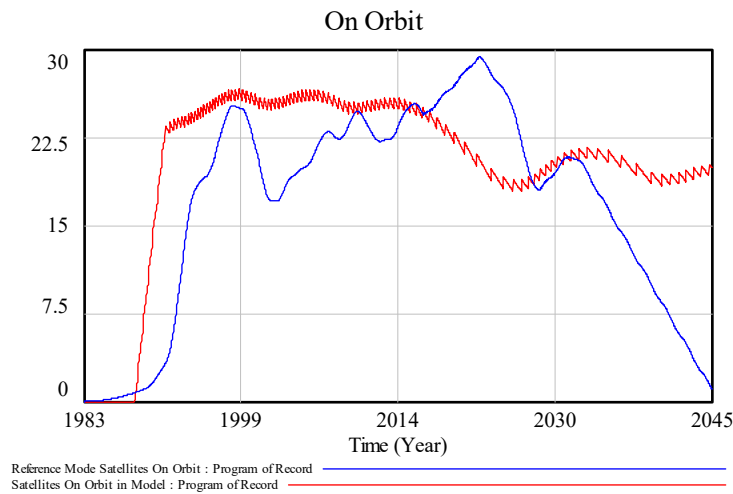
Figure 3-46: Number of GPS Satellites on Orbit, Reference Mode vs. Model Output

Number of Satellites Produced

Reference Mode Total Launched : Program of Record
Total Satellites Made in Model : Program of Record
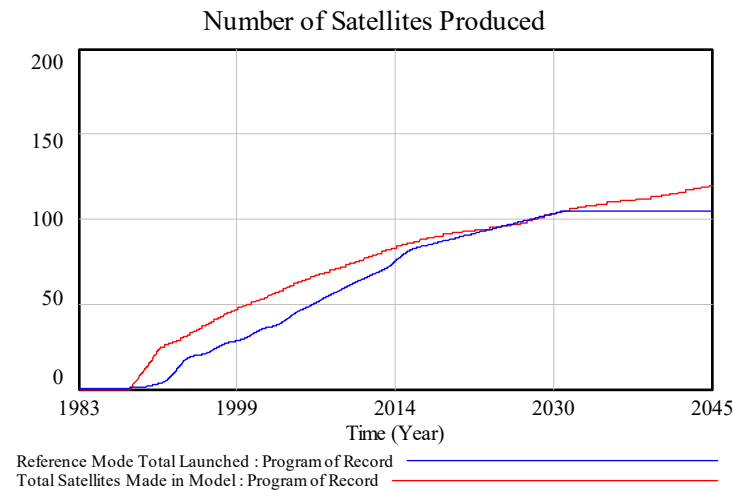
Figure 3-47: Number of GPS Satellites Produced: Reference Mode vs. Model Output

3.7.1   Changes to Efficiency

One possible representation of learning effects can be a learning curve and its progression over time. Heuristically, the work by Morrison discussed in this chapter and the associated structure in Figure 3-15: Rework Fraction Stock and Associated Variables and its change to efficiency presented in Figure 3-16: Efficiency Implementation, forms a structure which tracks learning over time. Figure 3-48 records the efficiency of the system in turning resources into satellites. This may also be understood as the impact of learning and experience on the process (building GPS satellites) examined within the model. This serves as one possible proxy for the "health" of the industrial base, where healthier is defined as the ability to turn resources into satellites faster and less expensively, relative to the speed and cost historically. This implementation of a learning curve in a SD model also stores learning (or forgetting) within the specific program under examination, in this case GPS. This structure also contains the sticky aspect

of learning, where one program inherits some of the virtues and/or sins of the last, as the efficiency of one program starts where the last left off.

Efficiency

Efficiency : GPS BATNA
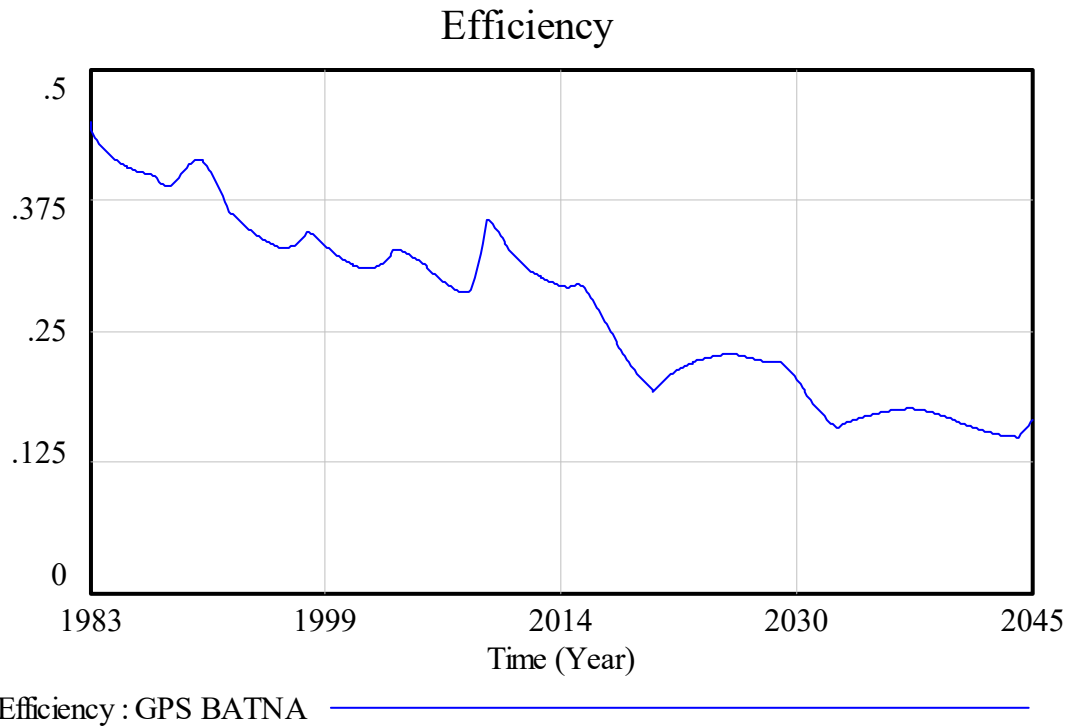
Figure 3-48: Model Representation of Learning Curve for GPS Satellites and Linked Industry Effects Under Current Plan

3.8 *Evaluating the Policy of Disaggregation*

The next sequence of graphs present model outputs from the 3x Disaggregation payload alignment option from the Design Vector in Chapter 1. Additional investments of NRE are made in this future, as in the current planned GPS future, at the second and fourth block buys with the intent to keep the satellites up-to-date with current technology—rather than staying with clones as was displayed in Figure 3-41. (This is implementing a 1 in the Design Vector in Chapter 1.) Figure 3-49 shows the model's representation of this future, and it can be seen that there are now three lines where in Figure 3-41 there was only one. This is making use of the subscript capability in Vensim to implement three production pipelines. Inside the TSE code each of these satellites is designed independently and sized for the specific payloads desired. In this case, the old civilian signals have been put on one bus, the new civilian signals have been put on a second bus, and all the military hardware has been placed on a third bus.
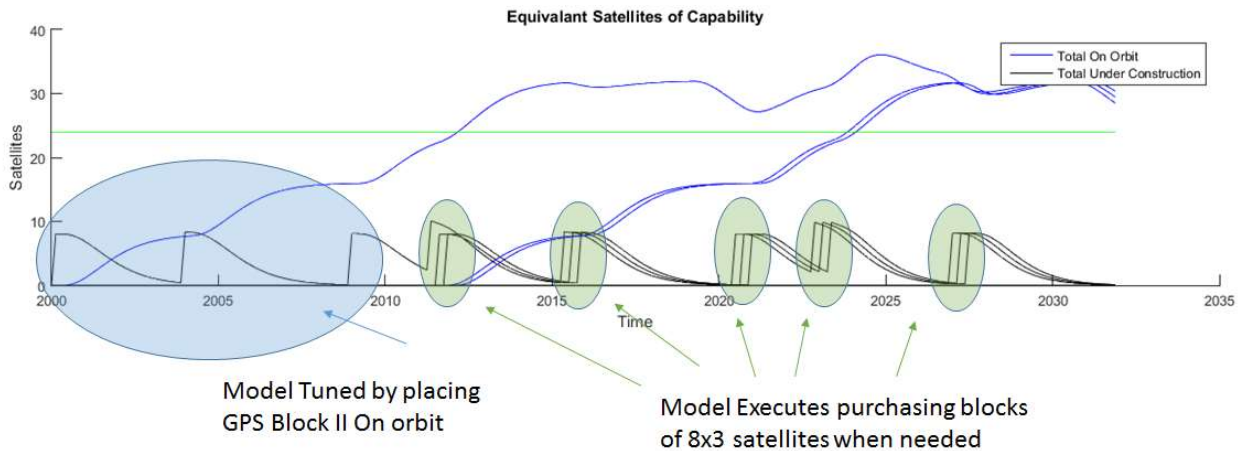
Figure 3-49: Model Representation of Satellite Capability Level, Procuring and Launching GPS Satellites Under 3x Disaggregation

Figure 3-50, similar to Figure 3-42, examines years of capability under production and on orbit. This can be useful for examining activity levels given disaggregation of systems. If GPS is broken into three component systems, the three components normalize to one equivalent capability, but the raw number of satellites and their respective years of capability is larger by a factor of three. The construction activity in a block buy of eight is now a total of 24 satellites. Given the proper conditions, e.g., the same bus, this is a large shift in activity level. This illustration is also useful for analyzing the smoothness of the associated production pipeline. This is of considerable interest since one complaint about the Space Industry is that it needs to establish a smoother pipeline and become less of an industry of "fits and starts."
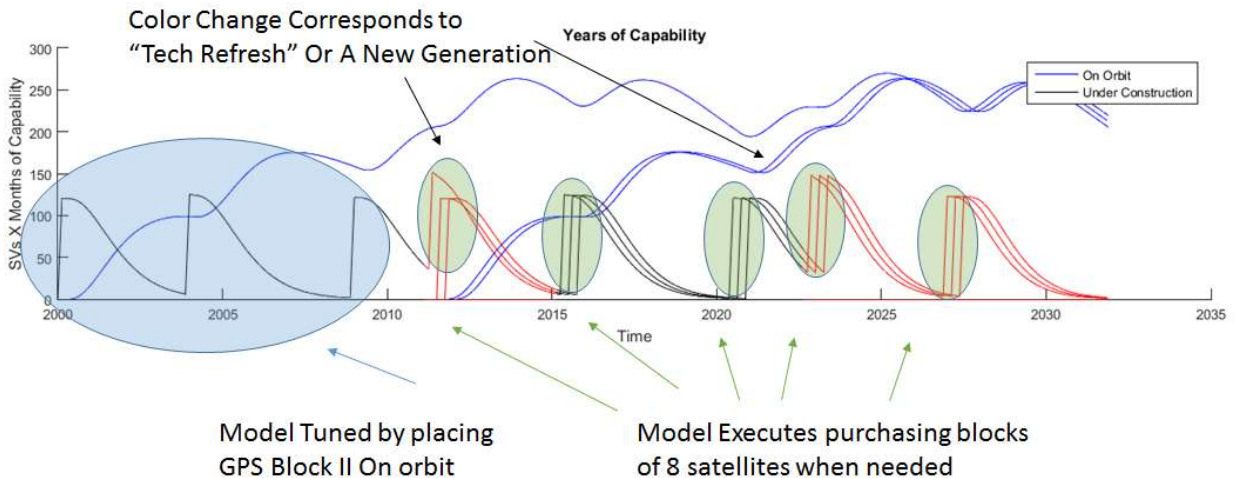
Figure 3-50: Model Representation of Capability as Measured in Years for GPS Satellites Under 3x Disaggregation

In this particular example of disaggregation, the NRE cost or tech refresh cost is paid not only for the first set of satellites, but also for the second and fourth block buys. This is shown in Figure

3-50 by the color change between red and black. In Figure 3-52 it is associated with the resetting of the tech-gap curve to zero at the times corresponding to acquisitions 1, 2 and 4.

3.8.1   Program Starts and Technology Advancement

In the process of its design, a new satellite typically brings together the latest technologies. This might include: software, guidance, batteries, solar cells, systems engineering, testing, etc. These NRE costs produce a technology refresh relative to a particular capability. Some technologies progress outside of an individual satellite program and outside of the Space Industry. This exogenous advancement will also have an impact on new satellites. Figure 3-51 shows the relationship between advancements in technology as well as the concept of technology refresh relative to the exogenous Technology Gap. The dip in 2011 represents the technology refresh associated with the GPS Block III contract and NRE as executed and displayed in Figure 3-41.

Figure 3-51: Model Representation of Technology Gap for GPS Satellites Under GPS BATNA
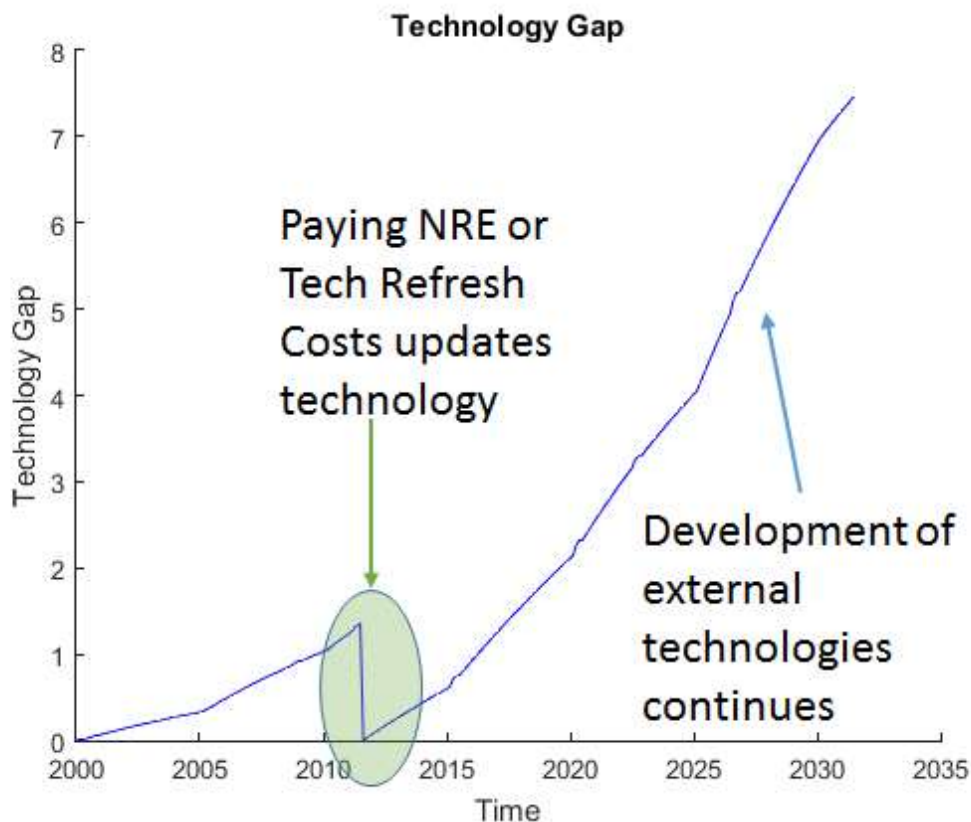
Having outlined a future scenario where more technology refresh or NRE events are scheduled (see Figure 3-49), the number of times that technology is to be re-baselined or aligned with the current technology of the day increases. Figure 3-52, which presents a future under a possible policy of disaggregation, contains two more events where NRE resets the exogenous technology curve to zero. As explained in the section on the Technology Gap producing function, this behavior mode changes the amount of entropy injected into the model.
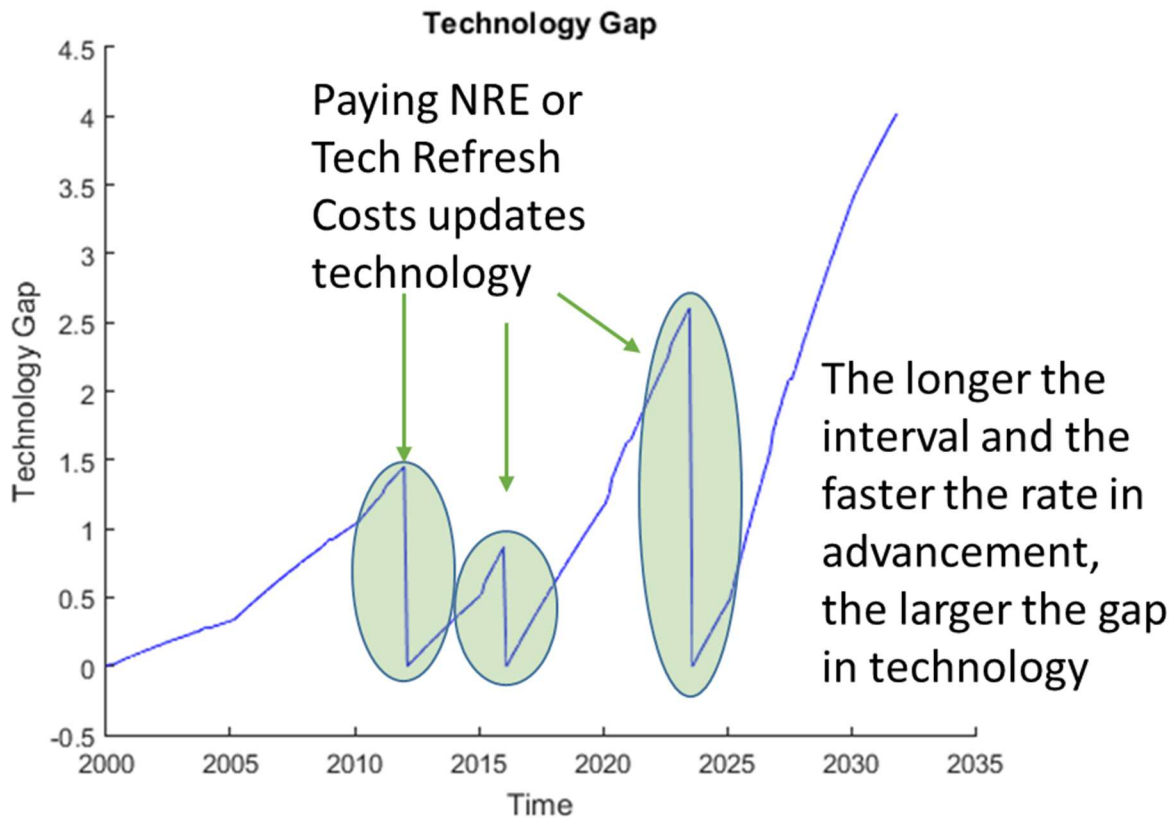
Figure 3-52: Model Representation of Technology Gap for GPS Satellites Under Disaggregation to Three Satellites

3.8.2 Deductive Bounding of Model Outputs

In Chapter 4 there are several tables listing different policies which this model can examine. In this section, the policy of disaggregation and its impact on the rework rate in the production of GPS satellites across time is examined as an intermediary step to check the sensitivity of the model to changes in exogenous variables. This work serves to bound potential outputs of the model. To gain an initial understanding of the impact of disaggregation on production, assumptions about additional work under the new policy are tested across a range of values. This examination requires fixing some dynamic relationships such that:

- The performance of the satellite architecture is equivalent to each other and to the baseline program.
- When capability changes in future generations it changes at the same time.
- It is assumed that three disaggregated satellites could be fit onto one launch vehicle and it is acceptable to delay launch until all 3 vehicles are ready.
- The order rate is fixed and constant and the pipeline feedback loop is disabled (to remove oscillatory effects).
- The Nunn-McCurdy Loop is turned off; but the gap is still tracked in the firefighting stock and Program Over/Underruns, but the model cannot "re-baseline" itself.

These assumptions are not in line with the basic assumption and context vector laid out in Chapter 1, and will not hold up under scrutiny as we examine more detailed results available from performance models.

In Chapter 4, mass will be used as a proxy for work required to produce each satellite, instead of a unit-less variable (widgets), as in the generic SD pipeline model. When comparing against disaggregated approaches, this mass is the sum total of all dry mass as generated by the mass models in Chapter 1. For now, we will use a tuning parameter to see how the model behaves in response to changes in work. In initial model testing it is very important to test these corner cases. Testing is also valuable to see if any tipping points exist; one of the goals in Morrison's work was to find a possible region where process efficiency became so good it became robust against exogenous shocks. In this work we are seeking regions where efficiency becomes good and then becomes robust to exogenous shocks, or a set of policies that result in lower costs than the GPS BATNA. Saturation of a model can occur if an exogenous variable forces a loop to dominate model performance or produce illogical results and this must be checked for in model creation.

To examine the model's sensitivity to changes in work levels while fixing resources provided, we select three levels. This is required because at this point the SD model has no ability to select appropriate values for mass or the amount of work required to produce a satellite. It does know the mass of each of the GPS III satellites if disaggregated, but we can reasonably bound the inputs:

- **Hard:** It is assumed that disaggregating one GPS satellite into three GPS satellites equates to tripling the amount of work required to field the constellation. This serves as an upper bound as it is highly unlikely that three smaller satellites with less performance could ever cost more than three large satellites each with the capability of those three smaller satellites. This is similar to tripling the work while providing no additional resources.
- **Midlevel:** It is assumed that building three smaller satellites is twice the work of one large satellite. This is a middle-of-the-road assumption and may be a reasonable place to start analysis. This might be assumed if the software for every satellite had some reuse rate and the physically smaller satellites made fabrication easier. This is the same as doubling the work while providing no additional resources, but getting triple the gains in experience.
- **Easy:** It is assumed that building three disaggregated satellites requires the same amount of work as one traditional GPS satellite. This acts as a lower bound, because it is unlikely that designing three smaller satellites would ever be easier than designing and fielding one large satellite. This assumption does not preclude these three satellites from becoming cheaper or easier in the long run, it simply states that we would get three times the experience for no change in the amount of work required. This would give triple experience for free: an unreasonable assumption as there would likely be some overhead growth from disaggregation.

In Figure 3-53: Effectiveness with Process all three levels of difficulty are associated with a rise in the industry's effectiveness with building satellites relative to the baseline program. Both the Mid and Hard levels eventually lose some of that effectiveness over time.

Effectiveness with Process
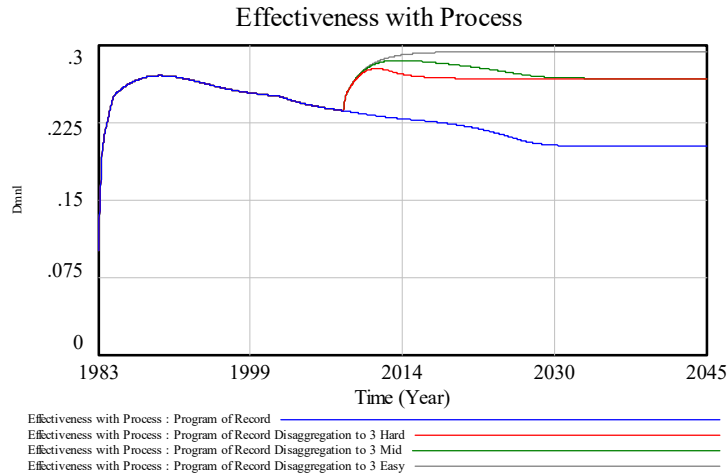
Figure 3-53: Effectiveness with Process

This is due to the decreasing production rate, as seen in

Figure 3-55: Production Rate per Year. As more work is added to the industry due to the increased number of satellites being built, the Peanut Butter Spread Loop extends design life as a way to reduce the work required to deal with backlogs in the industry. (See Figure 3-58.) While the gains in effectiveness are not substantial—tripling the number of satellites is not enough to move very far on the effectiveness curve (it is about the same production rate achieved in 1988)—even with midlevel difficulty eventually there is enough experience that, all other things being equal, the industry is able to gain some experience and increase its efficiency. (See

Figure 3-56: Rework Fraction.)

Process Improvement Time
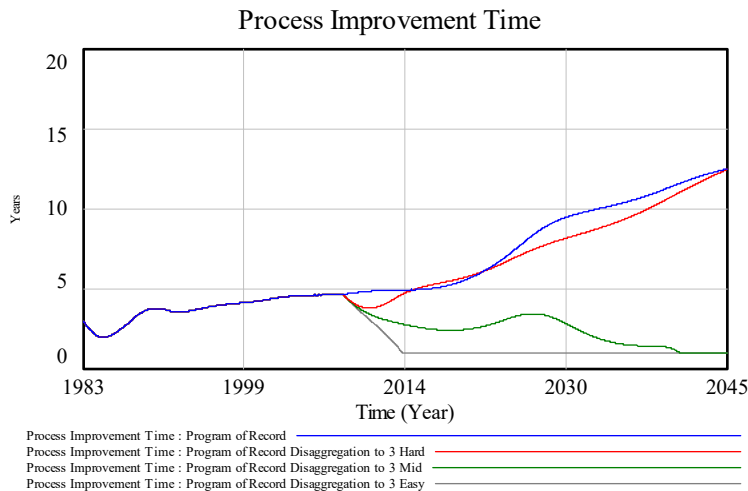
Figure 3-54: Process Improvement Time

The increase in efficiency, while assisted by more production, primarily comes from the decrease in process improvement time. In the program of record process improvement time is working against the industry, as longer procurement times lead to a greater increase in the rework fraction, leading to bigger backlogs and in turn greater increase in the error fraction. In the midlevel

136

and easy cases the impact of building smaller units more quickly is enough to get inside the technology half-life and human half-life times. Under these two instances, the loop works for the industry; though it requires over two decades in the midlevel case before this loop is able to pull process improvement time down to highly efficient levels. This is a key insight: a good policy needs to make the process improvement loop work for the industry.
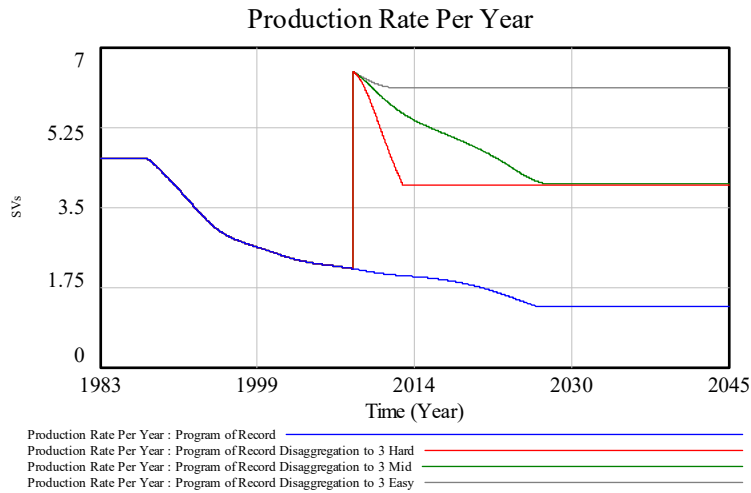
Figure 3-55: Production Rate per Year

Since it is unlikely that any policy will enable production to approach the levels required to gain substantial experience with process, it may be effective to focus on policy that grants some more experience but more importantly shortens the time between experiences for people. This evaluation also points out a potential difficulty in implementing this policy: as initially disaggregation will add an increased spike of work for the industry if either an increase in resources or a decrease in requirements does not accompany this policy implementation, it is possible it could exacerbate the existing work backlog problem as occurs in the "Hard" case.

Efficiency

Efficiency : GPS Full Disaggregation ————
Efficiency : GPS 3x Disaggregation ————
Efficiency : GPS BATNA ————
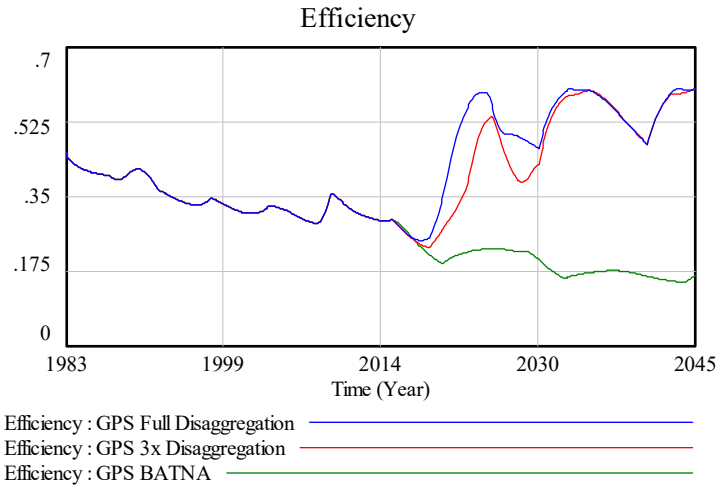
Figure 3-56: Rework Fraction

In Figure 3-57: Work Backlog in Industry the impact of tripling the work with providing no further resources is clearly seen on the red line where the backlog continues to grow. The model is stating that this growing backlog increases firefighting behavior and in-turn forces up production time. To compensate for long development times, as is seen in Figure 3-58, design life goes up. This is in line with Wertz's belief about the loop in which the Space Industry is stuck. The Midlevel and Easy assumption sets do not force an increase in design life, as relatively quickly (within a decade or two) both of them halt overruns and slowly decrease the backlog. That said, it is important to remember that these are not actual results but interpretations of a tuning parameter. Nonetheless, this is an indication that the model is capable of examining such regions of performance.

SVs Work In Industry

SVs Work In Industry : Program of Record ————
SVs Work In Industry : Program of Record Disaggregation to 3 Hard ————
SVs Work In Industry : Program of Record Disaggregation to 3 Mid ————
SVs Work In Industry : Program of Record Disaggregation to 3 Easy ————
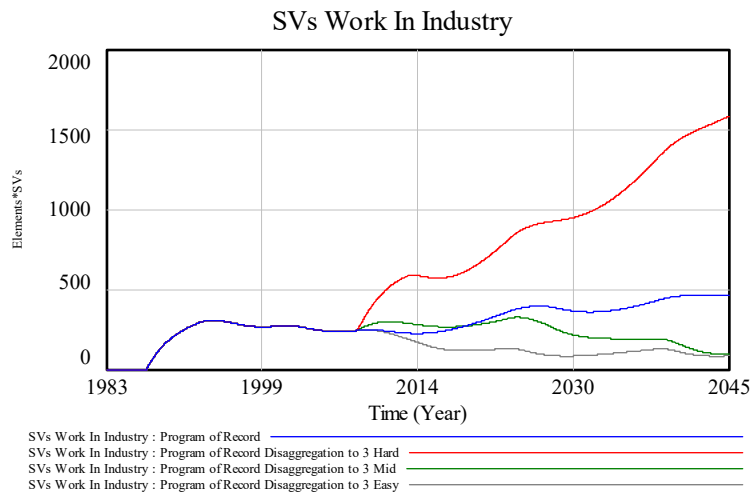
Figure 3-57: Work Backlog in Industry

Figure 3-60 shows the number of satellites on orbit assuming static funding. As previously noted, in the program of record (GPS BATNA) a minimum of 24 satellites are required to meet the performance requirement. In each of the disaggregated cases 72 satellites are required to meet

138

the same performance threshold. We see in Figure 3-60 that under the hard condition it is impossible without additional funding to meet the performance requirement of 72 satellites. Even under the Midlevel difficulty case the fielding of the needed 72 satellites is delayed, as learning effects do not immediately compensate for increased work.
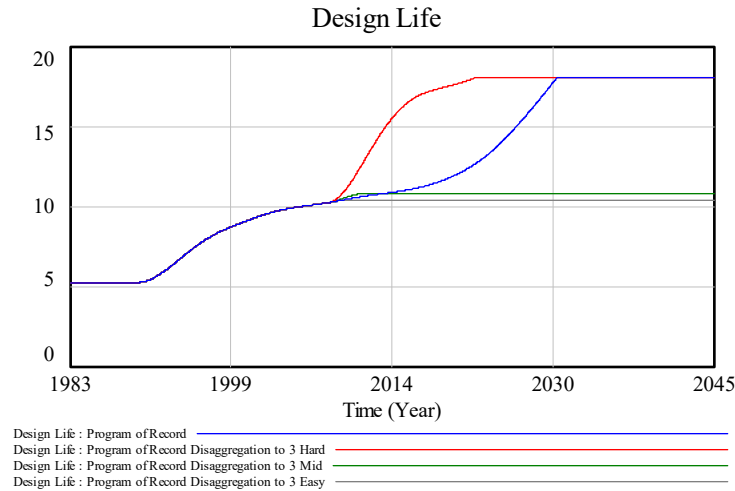
Design Life

Figure 3-58: Design Life

Figure 3-59 displays the relative funding increase likely required or program overruns beyond the baseline that may occur. It also indicates that the current program of record (GPS BATNA model representation) may experience overruns beyond the funding baseline by 2030. By 2023 it will be very difficult to create the technology required for the Block IV design as no R&D efforts will have been completed since 2008. At this point the government will be faced with a decision, clone more Block III satellites with a new contract, or start from scratch and create new technology. As creating new technology will be tantamount to starting from scratch, low efficiency is a reasonable expectation—consistent with the declining green line observed previously in

Figure 3-56: Rework Fraction. From a decision-maker's vantage point, it may seem beneficial to order more clones and "keep the pipeline open" as opposed to develop a new design. This, however, will only push the problem further down the road.
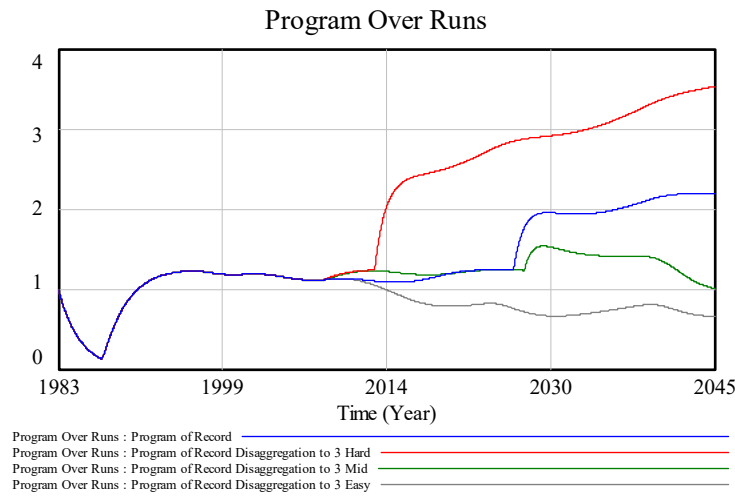
Program Over Runs

Figure 3-59: Program Overruns

Satellites On Orbit in Model
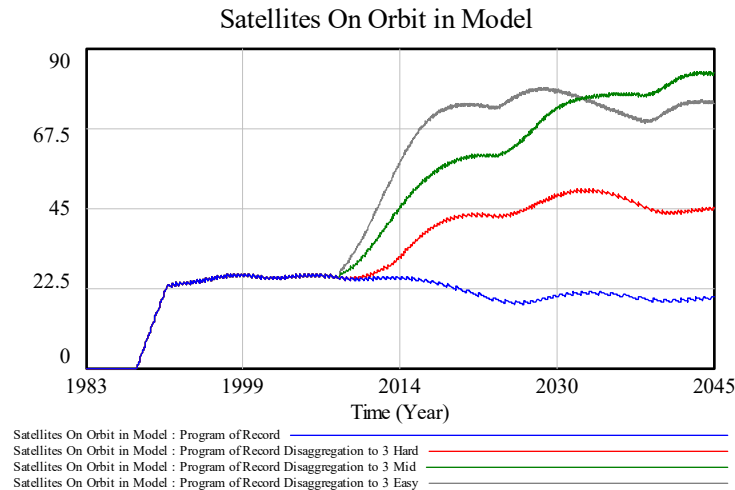
Figure 3-60: Satellites on Orbit vs. Performance Requirement

3.8.3   Efficiency under Disaggregation

Figure 3-61 displays the theoretical result of disaggregating the GPS system into three satellites. Some gains are made in efficiency, however, it remains to be seen if this equates to cost savings over any time horizon. The eventual goal of a policy would be to create a state where a virtuous cycle has emerged and the three reinforcing loops work for the industry and not against it. At this point production quantity and smaller satellites are only propping up efficiency; a virtuous cycle has not been yet been created and many more policies need to be tested. As the exogenous space industry was set to produce the equivalent of 18 satellites per year or 1.5 per month, we now see that GPS has become larger in terms of physical quantity of satellites being produced and some interplay and iterative gains between the GPS program and the industry as a

140

whole does develop. The overall industry learning curve is depressed more than just the sum average of adding the GPS component and the trend-line representing the industry. These results indicate that the model is capturing the concept of GPS being part of the overall industry's performance. It is no surprise that artificially inflating production by a factor of three does not cure every problem; but disaggregation could produce a non-linear effect when equating production levels and experience.
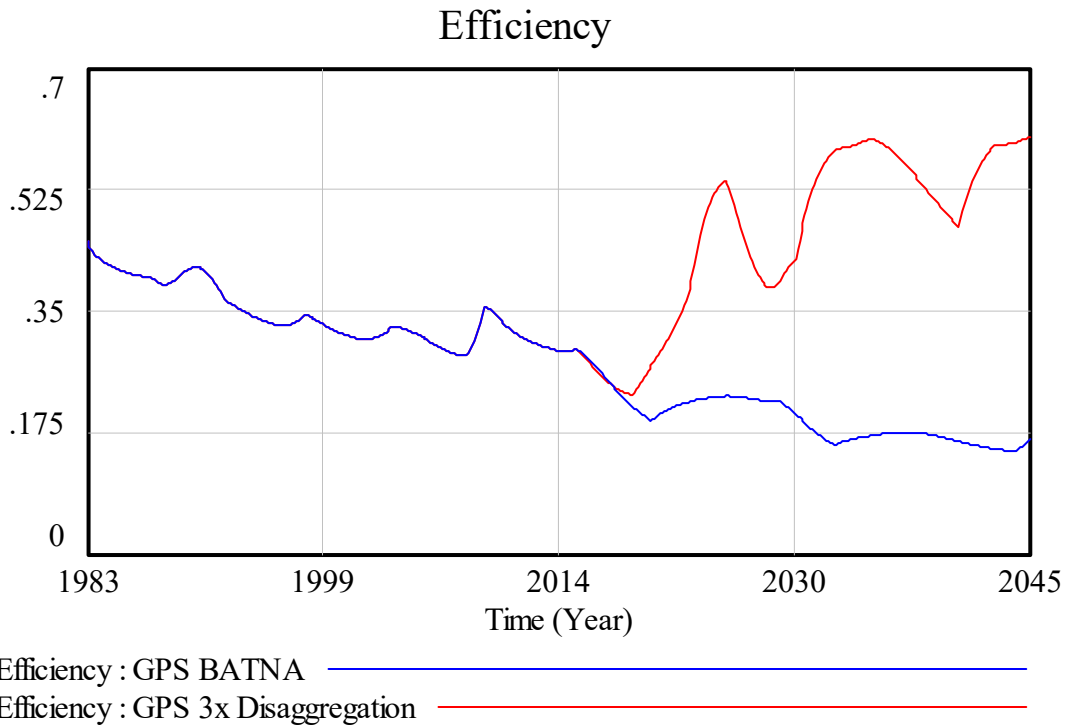
Figure 3-61: Model Representation of Efficiency as a Proxy for Learning Effects in GPS Satellite Production

3.8.4   Disaggregation Under Exceptional Performance

It has been argued that building smaller satellites might be easier than constructing large satellites because the process would be less complex. This argument is also derived from the logic that complexity increases in a greater than linear fashion as more sensors or mass are added to a satellite. If complexity indeed rises at a rate greater than linear, then it is logical that it should decrease in the same fashion. Three disaggregated satellites should possess a production difficulty less than the single large satellite whose capability they are replacing. For this reason, the model possesses the ability to test the assumption of the relationship between mass and complexity of a satellite. For example, if building three smaller satellites required only half the work of building one large satellite, then a modification variable (exogenous constant) can be inserted. In fact, it was found in tuning, and variable sweeps, that the model did not tune well with such an assumption. Consequently, all future work assumes a linear relationship between mass and complexity. In the event that data become available to corroborate a different pattern of behavior in disaggregated construction, the model should be re-tuned and re-run with that data included.

3.9 Initial Observations of Causal Loop Interactions

Overall, using this system of bounding the model outputs demonstrates that the model is able to capture response to a wide range of responses without saturating and that it encapsulates reasonable responses to exogenous shocks. Based on initial causal-loop diagraming and simulation, it appears that this system of three reinforcing loops and two balancing loops is prone to tipping (where a small incremental change in one variable leads to large, typically non-linear, changes in other variables). More specifically, the tipping is caused by work not completing in the time required. This delays not only the work but, because resources are fixed, the next work which should have been started. Less work completed leads to less experience. Longer production times also lead to longer cycle times, implying that as technology (both exogenous and industry-driven) relevant to satellite design increases, experience with implementing this technology is valuable for less time. By the time experience with technology or process can be flowed back to the next production, that technology or process may already be out of date.

Once these three reinforcing loops work against the pipeline there is nothing to reign them in. Even worse, while early "success" or satellites with longer than expected design life in the GPS constellation appeared advantageous to the government, in the long run this leads to fewer satellites being ordered. This fuels the other three reinforcing loops toward ever- longer time cycles. The rising cost of satellites increases the demand for longer design life which further propagates the three loops forward and the balancing loop fails to balance the whole model, managing only to keep it under the cost ceiling. With the addition of the Nunn-McCurdy Loop a second balancing loop is included, which ensures that performance requirements (24 satellites on orbit) are met. But this cannot reverse trends, and the next exogenous shock to the system only pushes efficiency lower and costs even higher. Based on this model there is no expectation that the industry will ever perform better than it currently is; either the industry is already in equilibrium or in a slow "erosion."

Some final observations about the time constants between different loops speak to the relative power of these loops under current operations:

- Increased production alone is not likely to help at the current design point. The Production Cycle Time is too long. Any experience from production cannot be captured relative to the forces of entropy.
  - ♦ Cycle time must be brought in line with, or below the technology advancement rate; this is the tipping point at which experience with technology becomes valuable. If satellites are produced faster than the technology expires, people can become familiar with both the processes of replicating satellites and constructing the next generation.
  - ♦ It appears logical that once you can't get "inside" the Technology Loop (approximately five years) to push apart NRE intervals to as far apart as possible. The reason for this is minimizing cost associated with NRE events, as over 50% the technology must be updated anyway longer intervals between NRE events minimizes NRE cost (however this can increase replication costs, but while replication is in low volume this is still a minimization of overall cost).
  - ♦ One might also conclude that such cycle times would reduce requirements creep on capability. With closely planned generations not every capability upgrade need be delivered on the next design.

- Saleh noted that savings were maximized at a design life of around eight years. This work does not disagree with this but suggests that the nature of the GPS pipeline pushes desire for design life beyond eight years seeking further cost reductions.
- The SD literature often examines work-reduction policies as a general class. It is reasoned that decreasing requirements on a system for a short duration are good as a strategy for clearing the backlog, allowing management and staff to take a "breather," reduce overall firefighting behavior in the organization and gain familiarity with new process. This is typically only good as a temporary measure and when used to combat firefighting behavior a decision must be made about when to "ramp" production back up.
  - This relates to an observation about the satellite industry—they are having a hard time producing satellites.
  - A natural response would then be to extend design life as the work reduction policy; it will save money and reduce strain on industry (first order, short run). Since the system (Government, Aerospace, and Contractors) cannot reduce work in another fashion like a factory could, this is the heuristic equivalent.
  - The result however is that Industry gains less experience and is not able to ramp production back up (second order result). Instead even less is asked of the industry and even more "work" is taken away.
- "Failure Begets Failure"—one program struggles, the next inherits its problems; we order something more difficult to compensate for the previous failure and cover the capability/performance gap. This is not directly coded into the model, however, generation over generation, production time in the model increases dynamically. In each generation the size of the backlog of work is larger than in the previous, and not just because satellites are larger and designed to last longer. This emergent behavior represents the concept of cascading failure, where the larger the backlog the harder it becomes to complete work over time.
  - This result refutes the concept of "day-for-day slip" in program management; it suggests that if a program loses a day, more than a day in just that program is lost. Failure to capture experience and a loss of the time value of technology occurs which impacts the next program as well. While a loss of one day is probably not a large impact, a delay of two years is substantial especially under the assertion that technology for space assets has had a half-life of around 4.5 years over the last three decades.

4 Inductively Tuning the GPS Pipeline System Dynamics Model

This chapter takes the deductive SD model developed in Chapter 2 and inductively tunes it, i.e., attempts to improve the fit of the SD model to observed data by using reference modes based on historically observed data. This chapter also measures the usefulness of this SD model and its predictive power through statistical tools.

As SD derives from control theory, the act of tuning a SD model may be considered similar to choosing the values of capacitors, inductors and resistors in tuning a Resistor, Inductor and Capacitor (RLC) circuit. A stock and flow in SD is tantamount to a Laplace transform representing the stock, and a signal input representing the flow (Mehmet & Yasarcan, 2015). The model is constructed by selecting known inputs and outputs (reference modes) and then viewing the model as a "black-box" to translate known inputs into known outputs. Thus, a properly tuned SD model, when sent a different input, should apply the same transform on this input and the resulting response of the system should be valid over a range of inputs. This underlying premise is important to establish the validity of this approach and also implies that there is a region for which this model is useful, as well as a region of "saturation" above and below input thresholds where the model gives incorrect results.

This tuning encodes the model with a balance between stability and performance of the system under examination, in this example the production pipeline of GPS satellites. The more stable the model the less reactive it is to exogenous shock. Yet, a stable model is likely to be slow to change even in the face of a needed change. Stability typically sacrifices performance, measured as time needed to react. As with many other large bureaucracies, the satellite acquisition pipeline is likely to be very stable and slow to change. Change is likely to require many years to propagate throughout the acquisition system and this should be reflected in the model. (As seen in Chapter 2, many of the potential time tuning variables are listed in years.) As the goal of this modeling effort is to simulate acquisition of satellites over time, the historical times associated with procurement and change are encoded within it. These historical time constants enable the model to react to a change of exogenous inputs, and react in a similar manner to new inputs with respect to time. Thus, the model provides a test-bed for conducting experiments, where the independent variables are the exogenous inputs and the dependent variables are the stock levels inside the model. As no real-world experiment is possible without large amounts of capital, this is a workable and cost-effective way to learn about the system.

4.1 Tuning Method

Vensim natively supports sensitivity analysis and several forms of model tuning to assist modelers in validating their designs. As with regression models, SD models' prediction power can be measured by a variety of standard statistical tools as described by Lane and Olivier based upon the original work by Sterman in the 1980s (Olivier, 1995). These include R squared, Mean Average Percent Error (MAPE) and Root Mean Squared Error (RMSE). Since the ultimate goal of this research required interfacing Vensim with external applications, the decision was made to perform all tuning externally (by using Matlab to externally send command strings), as opposed to using Vensim's built-in statistical package. This has the additional benefit of offering more control and insight into the tuning process. This work offers a robust and easily repeatable process for tuning any SD model to reference modes. Interfacing with Vensim is accomplished through "Command"

scripts loaded through the standard Vensim Dynamic Link Library; commands are available online (Ventana Systems Inc, 2015). The method and technical process is described in further detail throughout this chapter.

4.2 Reference Modes Selected

The following five variables have been selected to tune the deductive SD model constructed in Chapter 2. Each of these variables was selected because they represent underlying behavior of the industry desired to be investigated. The major causal loops in the model are linked to at least one of these tuning variables and together they form a picture of how the system evolves over time. While no single metric of health (nor any data) for the pipeline is available, the model will be able to solve for the Efficiency metric based on these variables:

- **Unit Cost**: Production cost of the last space vehicle produced.
- **Design Life**: How long satellites are designed to last.
- **Total Number of Satellites Produced**: Quantity is summed across time.
- **Production Rate per Year**: Space vehicles completed each year. Note: this is not the number of space vehicles ordered each year. Ordered is the input to the pipeline, this is the output.
- **Space Vehicles on Orbit**: The number of GPS satellites on orbit at a point in time.

Two other parameters indirectly used in tuning are:

- **Number of Satellites Produced per Generation**: In Chapter 2, the model's production rate was defined not as a specific number, but rather as the number requested to meet the goal of maintaining a capability of 27 satellites on orbit.
  - ♦ The Number of Satellites Produced in a Generation is not included directly in the tuning, however, as each satellite possesses a cost it is likely that the number of satellites produced in the model should closely match the reference mode for Unit Cost and Total Number of Satellites Produced. This output is examined more closely in the Additional Variable Outputs section.
- **Date of First Flight Unit Produced**: In acquisition, there is a time lag between the first NRE payment and when the first flight unit is produced; this time delay is included in the model. For example, GPS IIF NRE was paid in 2000 (original contract signed 1996) and the first launch was in 2010. The NRE was paid for the Block IIIA in 2008 and the first flight is now scheduled for 2017 (originally scheduled 2014). The model must dynamically compute the time lag between the NRE payment and the launch (i.e., the amount of time required to go through the pipeline).
  - ♦ The change between one generation of satellites and the next is triggered by an external pulse of NRE. This ends the ordering of the current generation of satellites and begins the construction of the next generation. The production time between the NRE pulse and the first flight unit of the new generation being launched into orbit is not a time that is directly tuned against. Any statistical measure of fit will show a large deviation for a tuning in which the reference modes do not change to the levels of the new generation at the right time (one-eighth of a year). As such, the tuning of when generations change is also implicitly encoded into this tuning.

4.3 Parameter Sweep

Based on the model created in Chapter 2, a sweep across potential tuning parameters was performed as the method for tuning the model. It is possible that such a model could also have been linked to an optimization or goal-seeking routine. Vensim natively supports functionality to minimize, maximize or target a single variable inside the model. Vensim also enables importing of multiple external reference modes, typically in the form of comma separated values (CVS), and then attempting to fit such data in a pairwise comparison between each reference mode and its associated model variable. These methods were attempted but without success. As such a parameter sweep across a logical region of interest was selected as the tuning method. As each parameter sweep took approximate .25 seconds to complete this was a slightly slower tuning method. Nonetheless, over the course of an eight hour tuning run this enabled a coarse evaluation of a large region of interest. Due to the large combination of potential variables, in the beginning coarse runs were performed to hone in on potential sets of variables. After several potential candidate sets of tuning solutions were identified, a fine analysis of the potential tuning regions was conducted. This resulted in identifying the model with the best statistical fit to the reference modes of actual data. The following variables were operated as tuning parameters:

1. **Equilibrium Tuning Constant [between .01 and .025; changes by .001]:** This variable, as noted in Chapter 2, was placed in the model as a way to convert dollars to kgs of satellite mass. Since the cost and mass of four generations of satellites is known, this variable is introduced into the model as a static constant which reconciles the two units into a linear function. This relies upon the previously stated assumption that complexity of design is linear against time, such that there is an equivalence of difficulty in managing complexity due to the available tools of the day.

2. **Maximum Efficiency Value [between 1 and .85; changes by .01]:** This is the highest possible value of the Efficiency function constructed in Chapter 2. Initial work fixed this value at one, however, reducing the "pull-up" of this value can impact tuning—making satellite construction easier as the gap between the current efficiency level and the value is smaller.

3. **Minimum Efficiency Value [between 0 and .15; changes by .01]:** This is the lowest possible value of the Efficiency function constructed in Chapter 2. Initial work fixed this value at one, however, reducing the "pull-down" of this value can impact tuning—making satellite construction harder.

4. **Design Life Update Time [between .125 and 2; changes by .125**]: This represents the time taken by the Space Industry to change the requirement of design life based on the size of a funding shortfall or gap between the funding provided and the desired cost per operational year of the system to be fielded and the size of the work backlog currently in the Industry.

5. **Nunn-McCurdy Update Time [between .125 and 2; changes by .125]:** This represents the time required to close a funding gap once it appears. This represents the real-world reaction time to detecting a problem, having the problem become so bad that a cost overrun must be addressed (the problem must exceed 125% of the theoretical baseline) and the time necessary to authorize new funding (program is re-baselined).

6. **Nunn-McCurdy Magnitude Allowed: [between 1 and 5; changes by 1] (Inputting a 0 turns off this loop):** Once a Nunn-McCurdy breach has been detected, this represents the amount of additional funding authorized until the inflow and outflow rates stabilize. A one

represents funding equal to the overrun, values greater than one represent multiples which would allow the system to recover faster; this is a way of approximating the activity known as "re-baselining."

7. **Technology Half-Life:** Two methods were tested as potential tuning values:
   a. Between 3 and 8 changes by .5 years. A static time constant.
   b. A dynamic variable alternative to a static time constant is proposed in Figure 4-1:
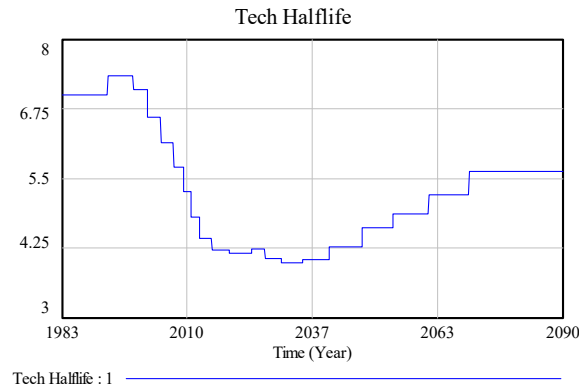
Figure 4-1: Technology Half-life Time to Double Capability

    i. As constructed (see Chapter 2) this model possesses the ability to implement a technology half-life curve to represent a change in technology over time. Figure 4-1 shows the time required for a doubling in performance. Between 1988 and 2008 technology half-life sped up, indicating a faster rate of technology advancement, which would translate into a more difficult environment within which to develop (the entropy injection should logically be larger in the Efficiency function). Data from 2015 to 2070 is constructed by extrapolating the historical data to an S-curve, which over time slows the technology advancement. This represents a world view wherein the fastest rate of technology advancement is achieved by 2010, implying the technology is now in the middle of the S-curve. Between 2015 and 2040 a relatively similarly growth rate will be achieved. After 2040 the growth rate will slow as the S-curve reaches the maximum potential of the technology. This would be a future reality where providing GPS signals to the earth's surface is no longer a challenge but a commonplace activity by 2090.

    ii. **Tech Half-life Error Factor: [between .8 and 1.2; changes by .1].** The time to double capability curve may possess error. To accommodate this, the Tech Half-life curve was tested to plus or minus 20% and the computed value multiplied against the Tech Half-life value, resulting in a time to double change.

    iii. **Tech Half-life [S-Curve, Linear, and Continued Exponential]:** If such a curve is used in place of a static constant, model results/predictions will change based on the context assumptions about future technology growth rates.

    iv. One very interesting observation emerging from this plot is the rapid advancement from 1990 to 2010. This plot implies that for satellite technology, capability doubled from once every seven years in 1990 to once every four years in 2012.

8. **Effect of Acquisition System [between 0 and 1; changes vary].** A zero represents that no learning was possible and a one represents that the DoD acquisition system imposed no additional loss on the translation of experience into satellite construction efficiency.

a. This variable was added as a way to test the experience values being produced to see if another loop dealing with the experience might be required. Experience, as noted in Chapter 2, is translated to experience with process and the results of this conversion impacts the pipeline's performance. As there is a logical argument that switching contractors may have a larger impact across generations than currently modeled. Such a factor could increase experience loss across generations and enable further tuning.
b. Ultimately, this variable was not required for tuning, however, this is does not mean that the DoD acquisition system does not suffer loss of experience when switching contractors. It is rather that the model already includes the loss sufficiently in the lookup table (experience to experience with process) as well as the experience lost across generations (outflow on the experience stock).
c. This variable was also useful for turning off the Experience Loop and then setting all other loops into static equilibrium when computing the lookup table for the experience to experience with process conversion.

4.4 Parameter Sweep Vector

Consistent with the tuning parameters listed above, tuning the model includes a parameter vector of the form:

[Equilibrium Tuning Constant, Maximum Efficiency Value, Minimum Efficiency Value, Design Life Update Time, Nunn-McCurdy Update Time, Nunn-McCurdy Magnitude, Technology Half-life, Effect of Acquisition System]

One example would be:

[.15,.9,.01,1,1,1,4.5,1]

Each of the variables is swept over the range specified in the Parameter Sweep section. For tuning in specific regions, variables can be fixed at a given point. This is identical to how the TSE algorithm creates a design vector.

4.5 Parameter Sweep Execution Sequence

To perform tuning, a Matlab script operated in the following sequence, communicating with Vensim as appropriate:

1. Create tuning vector
2. Load SD GPS pipeline model
    a. Initialize model
    b. Pre-allocate memory for pointers to Vensim; very important as memory demands will be large.
3. Load tuning parameters based on position in parameter sweep
4. Execute model over first tuning point
5. Compute R-squared (R^2), RMSE and MAPE for run in Matlab memory
    a. Compute values based on 1988 to 2008 values
    b. Compute values based on 2008 to 2015 hold-back data
    c. Store all values to memory

6. Save resulting Command Script (a Vensim file that allows replication of the model run)
7. Repeat Steps 2 through 5 until parameter sweep of all tuning variables is complete (thousands of possible permutations, it takes ~.1 seconds per execution and the slowest part is memory read)
8. Normalize the results between 0 and 1 for all five reference modes.
9. Using an even-weighted sum, average all five reference modes to compute the best fit for each of the three error values:
   a. R^2
   b. MAPE
   c. RMSE
10. Report the best fit as the design vector with the lowest normalized score.
11. Run Command Script of best fit result, and graphically display results.

Due to the type of data present in the reference modes it was decided that MAPE would be used to calibrate the model—it was the least impacted by outlying data points (unit cost and design life have the largest relative gains). The MAPE tuning also produced the best fit of all tunings for the hold-back data. An even-weighted sum of R^2, MAPE and RMSE could have been used, however, the large changes in cost and design life as well as the number of satellites on orbit over-weighted the GPS IIF program, as its values are larger than the other three generations.

4.6 Additional Considerations in Tuning

4.6.1 Generation-Specific Tuning

It is possible that a specific generation of previous GPS satellites (IIA, IIR, IIR-M, IIF, IIIA) might have needed a difficulty factor adjustment in addition to the Equilibrium Tuning Constant. This would set a different value for the Equilibrium Tuning Constant for each generation. Such an individual tuning would pose a threat to validity, as the model would then have to create an assumption about what this value is for future generations. This variable would have to be multiplied against the specific program's mass value as a means for making the program more or less difficult.

It was initially reasoned that such a difficulty factor adjustment value might be required for the IIF program, as its mass was less than that of the IIR-Ms. Existing models would suggest that due to its lighter mass, the IIF should have cost less than the IIIR-Ms with mass alone as a proxy. Nonetheless, this was not the case, the model having simultaneously tuned a decrease in the efficiency in satellite production ("erosion"), producing a higher cost for IIF due to lower efficiency with no additional tuning required. Thus, this difficulty adjustment was excluded from all future tuning, but could be used to test assumptions about future generations for "what if?" questions.

4.6.2 Potential Exogenous Constants Not Changed

The time delay for the Process Cycle Time could also be a potential tuning parameter. The decision was made to place no smoothing or time delay on this loop. Thus, the Process Loop, or the speed at which experience can be captured, is always equal to the speed at which satellites are being produced. Additionally, experience is only useful after a satellite has been completed. One

might also say that this operationalization is tantamount to the belief that the difficult part of satellite construction is in integration, not the fabrication of individual parts.

Average Entropy Time (Human Learning/Forgetting) has been set at five years to represent that for any given individual, the half-life of technical knowledge is about five years. That is to say, after 15 years, 95% of a person's technical knowledge will have degraded if they are not retrained or have not learned new techniques. The postulation sets the average rate of human competency loss for the system, which theoretically arises from people retiring, new people arriving, and other inefficiencies in switching processes.

Production Time relative to other endogenous factors (e.g., Design Life): the model does not assume that within the Space Industry there is a base time required to produce a satellite plus an additional time based upon how long it is designed to last. In actual GPS production there has been a static constant where the time spent in thermal vacuum testing was a percentage of design life. This modeling assumption, that a large percentage of design life be spent in testing, deviates from current test practices in the Space Industry. Implementing such a flat scaling would, however, preclude examination of large changes in production (i.e., forcing a minimum 18-month production time because it was the fastest ever achieved would be illogical). Production of large satellites in a short time period is a realistic possibility when examining different architectures and implementation strategies, as such, the model must be able to predict the existence of such a scenario.

4.7 Model Tuning and Results

Data from 1983 through the first six weeks of 2008 were used to inductively tune the SD model. Data from the rest of 2008 to January 1, 2015 were held back and used to validate the predictive power of the model. Data from 1983 through the first six weeks of 2008 are actual values obtained from the GPS Block IIA, IIR, IIR-M and IIF programs. Data held back from 2008 to 2015 are from the end of the production run for IIF and the initial acquisition of the IIIA system. Data were obtained online from various sources (these are listed in Chapter 2). The model-tuning algorithm does not use the hold-back data for tuning. If the predictions for 2008-2015 produced by the SD model, did not match the observed reference modes, then additional work would be required to refine the model.

The figures in this section present key data for understanding the evolution of GPS acquisitions over several generations. The historical values (reference modes) are represented by green lines, and the model estimates are in blue. Beyond 2015, the green line shows an extrapolation of current acquisition plans based on published documents and then run through a small additional SD pipeline model instructed to track launches based on rate and requirement. If the green line, representing actual data is incorrect (1988 to 2008) it is not a threat to the validity of the method but is a threat to the validity of the eventual results. If better tuning data become available or tuning data for a variable not listed become available, the model should be re-tuned for a best fit encompassing the new data. Also, if a new causal loop is added, re-tuning is required.

In each of these figures the R^2, MAPE and RMSE are presented for the tuning data (1988-2008). On these same subplots, the MAPE and RMSE are also shown for the modeled data (2008 to 2015). As discussed above, the model is tuned specifically for the MAPE as for this type of data

R^2 and associated RMSE values may be over-influenced by the higher values associated with the IIF and IIIA Blocks.

4.7.1   Unit Cost

Unit Cost represents the replication cost per satellite coming off the production line at a specific point in time. This is one of the primary outputs of the SD model designed to operate in conjunction with other cost-modeling techniques to obtain a more precise measure of replication cost. Figure 4-2 reveals that the SD model is precise in estimating the unit cost across historical values with an R^2 of .85 for the region from1988 to 2008. The MAPE and RMSE are also very good between 2008 and 2015: capturing the rise of the IIF in replication cost and the IIIA predicted replication cost on the hold-back data.

The SD model estimates GPS IIIA clones will cost closer to $250M than the projected $224M. Also seen in Figure 4-2 is the model's ability to predict the launch time of the first unit of the next generation. As the rise times align with the historical first production unit times, this indicates that the SD model possesses a degree of precision in "understanding" how long a new generation of satellites must remain in development before the first flight unit can be produced. Confidence in the SD model is furthered by its ability to detect the substantial rise in production cost (tuned to $112M for IIF but jumping to $224M for the IIIA in 2015), without any information other than a predicted dry mass of 3,680 kg. The cost estimate will improve when merged with the more precise information available from the TSE model. At this point, we have reached the limits of precision for cost modeling in SD.
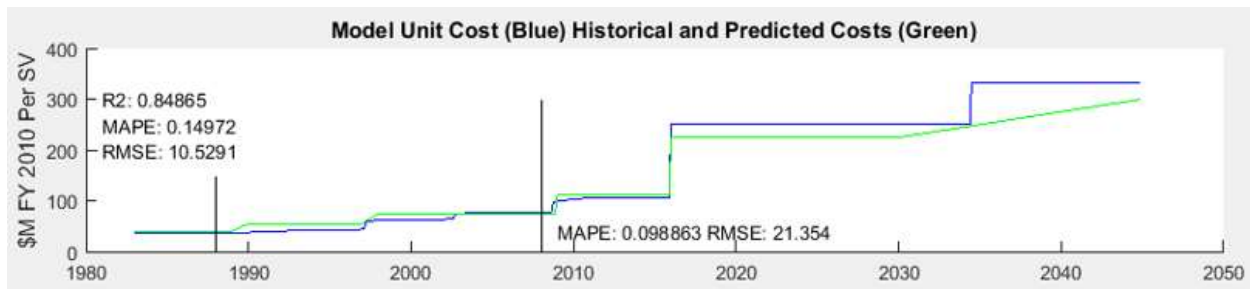
Figure 4-2: Model Tuning Unit Cost, Tuning 1988 to 2008, Hold-Back 2008 to 2016, Estimated 2016 and Beyond

4.7.2   Design Life

Design Life in Figure 4-3 shows how long each satellite is expected to last on orbit to maintain the required constellation of 27 satellites. The R^2 value for Design Life is low because the model attempts to find a value that matches this reference mode, as well as the number of satellites on orbit (seen below in Figure 4-6: Model Tuning: Space Vehicles on Orbit.) The historical design life of GPS satellites at their time of launch is shown by the green line; the additional grey line represents how long those satellites were kept (and planned to be kept) in operational service, and the blue line shows the model's prediction for how long satellites must last to meet cost and performance constraints. At the time of writing this thesis, the lives of the IIR and IIR-Ms on orbit have been extended yet again to 15 and 20 years average operational life. This extension to almost twice their initial design lives is a way to compensate for the production of only 12 IIFs and delays in the IIIA program. This retroactive process was not modeled in the SD model, and the result is that the SD model assumes that more IIFs would be produced to keep 27 satellites on orbit at all

times. This is seen and discussed below in Figure 4-7 and Table 4-1. For now, it is noted that the modeled results (blue line) correctly detect the time of the change in generations (2008 and 2015) and fall between the initially planned (green line) and extended design life (grey line). Beyond 2028 there are no projections about how long GPS systems will be expected to last, hence a linear extrapolation to 20 years is displayed via the green line. The model believes (computed from the Peanut Butter Spread Loop) that in 2035 with the start of the Block IV generation a design life of ~20 years (specifically, 19.73) will be desired.
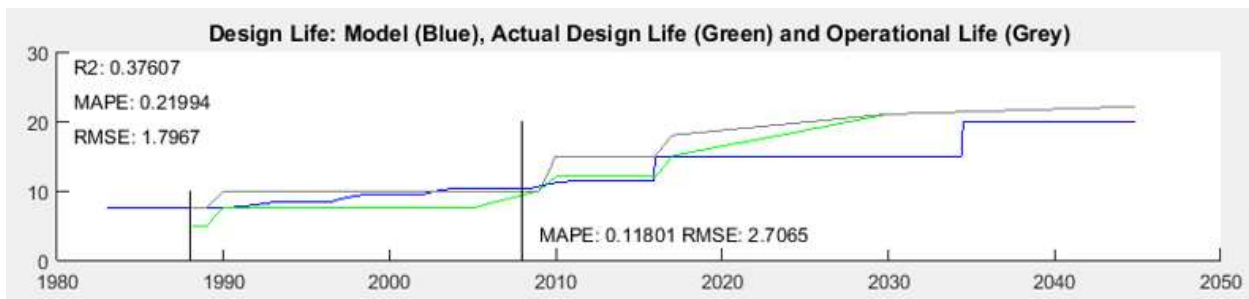
Figure 4-3: Model Tuning Design Life

4.7.3   Total Number of Satellites Produced

Total Number of Satellites Produced records the total number of satellites required over the period of examination. While these data can be broken into individual generations, as in Figure 4-7: Model Tuning Satellite Launches, for now they are viewed as a total sum. Note that the model (blue line) predicts that with static funding, after 2008, fewer satellites will be produced than the number forecasted (green line). The SD model perceives a gap forming between the resources required and the resources provided. This is a logical development based on the design life data seen in Figure 4-3. There, the SD model over-estimates the design life produced (the blue line is above the green line). This over estimate of design life lowers the number of satellites that would be required relative to the historical design life of the reference modes. The R^2 and other statistical measures are nearly perfect for the tuning period. Yet, as the variance is small for many of the tuning runs, this variable has little impact on the overall tuning.
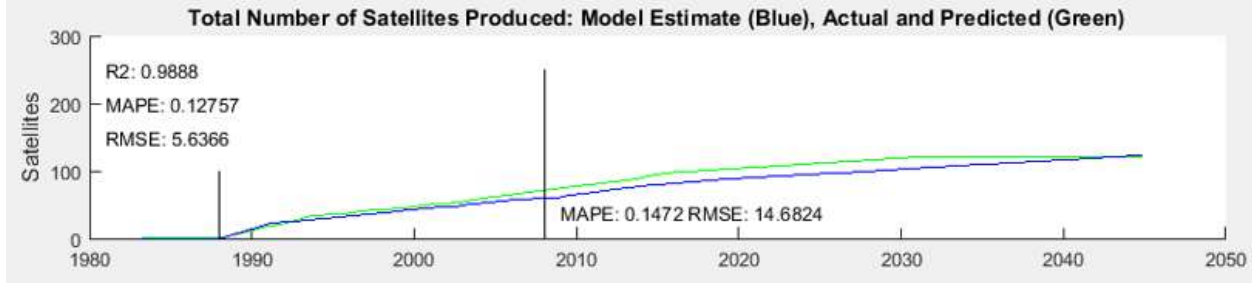
Figure 4-4: Model Tuning Total Number of Satellites Produced

4.7.4 Production Rate per Year (Out)

Production Rate per Year (Out) (Figure 4-5: Model Tuning Production Rate per Year (Out)) shows the rate at which satellites are produced. The statistical fit for this variable is more modest due to the oscillatory nature of the reference mode; however, it captures the average perfectly. This variable can be compared to the rate at which satellites are ordered, and the time a satellite spends in the pipeline being produced. The order rate is not shown as it cannot be easily compared to historical data, whereas there is no debate about when a launch occurs. The order rate or Production Rate Per Year (In) was not used as a tuning parameter as the model calculates the order rate based upon the number of satellites in the constellation (27) divided by the design life (e.g., 10 years). As such orders would, on average, be 2.7 space vehicles per year. DoD purchases occur in blocks and receive funding authorizations within individual fiscal years, but in an attempt to create a pipeline this is an acceptable abstraction. The exact data concerning when satellites were ordered (contract funding loads) and in what quantity (dealing with long lead-time items) are nearly impossible to acquire. Furthermore, this process is too complicated to model and not well suited to a SD model. The oscillatory nature of this process can be seen in Figure 4-5: Model Tuning Production Rate per Year (Out) where actual production (green line) spikes in some years where a lot of launches occur, and wains in others. As the end result of the DoD acquisition is an attempt to make a pipeline, a pipeline does effectively model the end result (average number per year). Clearly, a small uncaptured oscillatory causal structure exists beneath the larger pipeline structure modeled. As the method of computing the order rate based on this design versus reality has large discrepancies and the data which could be trusted were hard to obtain for this variable, implanting such an additional reference mode could have an adverse effect in tuning. Specifically, attempting to match the smaller oscillator effect seen would be hard to match, as there is no causal structure currently programed in the model which could represent such variability.

153
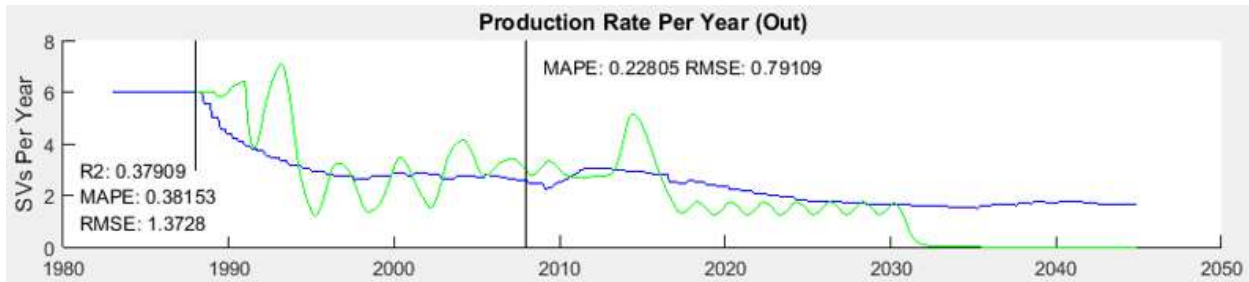
Figure 4-5: Model Tuning Production Rate per Year (Out)

4.7.5   Space Vehicles on Orbit

Figure 4-6 has a red line to represent the minimum requirement of 24 GPS satellites on orbit at a time. While the SD model predicts times when satellites on orbit fall below the critical 24 line (the blue line crosses below the red), this did not happen in real life. This would have happened in reality if the satellites launched had lasted only their originally-planned design lives (as noted by the green line). In terms of setting policies, predicting sub-optimal performance and a tuning closer to planned design life (the green line) is preferable to tuning to achieved operational life (the grey line). This is because **one should not design a system and then rely upon it to exceed its design specification as a means of meeting a performance threshold.** The model could be tuned to match achieved operational life (the grey line), but that would imply that we want the model to design future systems that also rely upon exceeding design life as the normal order-of-business. From a policy perspective, this would be a poor decision. Thus, as developed, the SD model incorrectly predicts that historically 24 satellites were not always kept on orbit. The model is, however, more properly tuned to meet performance requirements than it would be if it accurately tracked number on orbit. For this reason, the discrepancy from 2000-2010, is accepted in the tuning.
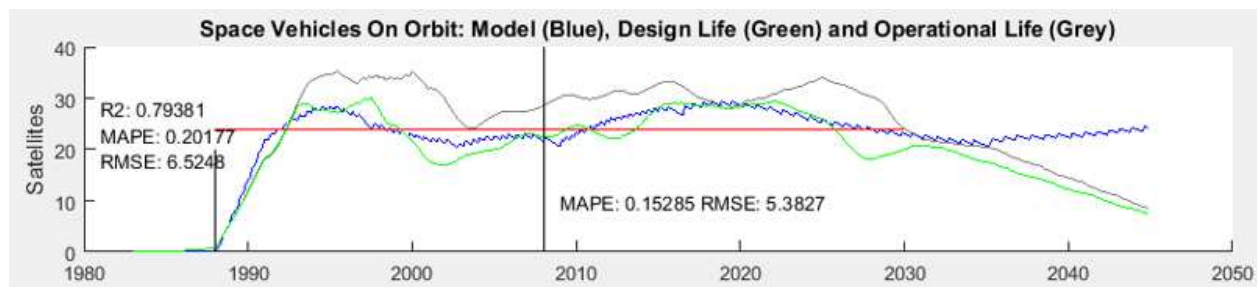
Figure 4-6: Model Tuning: Space Vehicles on Orbit

4.7.6   Specification Error Fix: Nunn-McCurdy

As noted in Chapter 2, validation of the model required the addition of a supplementary structure. This loop was implemented to assist with execution under the condition that work is added faster than it can be completed and firefighting becomes so severe that the model is "saturated" or falls into a region of such low efficiency that work slows to below the level where 24 satellites can remain on orbit without additional funding. It was observed that the initial SD

model was too sensitive to overruns snowballing into large backlogs. The model ordered more and more satellites to compensate for the shortfall of capability on orbit further exacerbating the firefighting and pushing the Efficiency variable to very low levels. This behavior did not match what would be expected to occur. Upfront cost estimates for government acquisition rarely match actual costs, and the eventual result is more funding being provided by the government. (This is not to state this is acceptable, but to explain that the model is attempting to capture reality.) Consequently, the Nunn-McCurdy Loop was added to the SD model to allow a program to be re-baselined and additional funding to be provided.

Figure 4-7: Model Tuning: Satellite Launches displays the model's prediction about the precise number of satellites required in each generation (IIA is Blue, IIR is Orange, IIR-M is Yellow, and IIF is purple). Looking at the Block IIIA satellites (seen in green pulses), it appears that these satellites are produced at a small cost overrun until 2035. The model predicts, however, a second-order consequence of this overrun such that the theoretical Block IV program (seen in teal), if started in 2023 would not launch its first satellite until 2035, and continuing this trend, by the fifth generation of GPS satellites the program would be completely unable to deliver capability.
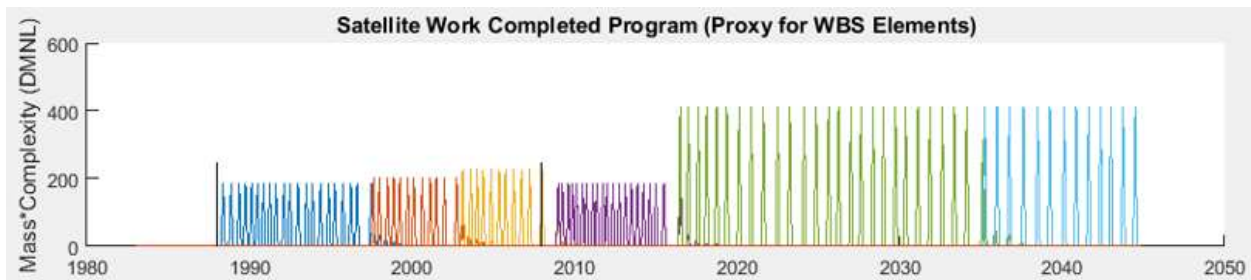
Figure 4-7: Model Tuning Satellite Launches

The addition of the Nunn-McCurdy Loop enables the model to change the funding level when the funding required exceeds 125% of the baseline. The change to the model's performance is shown in Figure 4-8: Satellite Launches with Nunn-McCurdy Loop Added where the GPS IIIA program now completes in 2028, as opposed to 2035. This is much more in line with expectations for this program and also enables the model to keep the required number of satellites on orbit—as seen in Figure 4-9: Satellite Launches with Nunn-McCurdy Loop Added. It is interesting to note that the model also activated this loop for the IIF program, believing that the IIF program would also overrun due to poor performance.

Figure 4-8 is also extended to four subsequent generations (until 2070) to examine the model's ability to reach an equilibrium if nothing changes after Block IV (i.e., Block V (red) and Block VI (blue) are identical to the Block IV (teal) requirements). In Figure 4-8, Satellites Completed/Launched is shown as individual generations, where IIA is blue, IIR is red, IIR-M is yellow, IIF is purple, IIIA is green and IV is blue. The black spikes in Figure 4-8 indicate NRE events and the time between the NRE and the first production unit being launched can be calculated. This enables verification that the model is stable, which is now seen. If the interval between satellite launches were to increase, or the model failed to keep 24 satellites on orbit after reaching equilibrium, questions about the model's stability would arise, but this does not occur. (This was a problem in Figure 4-7 where the interval kept increasing.)
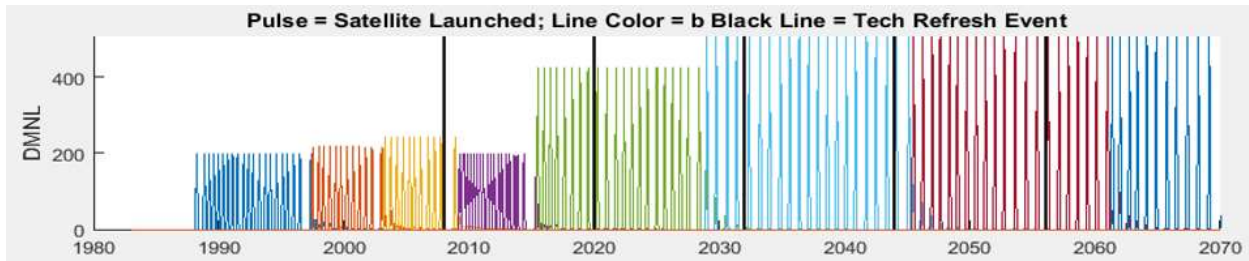
Figure 4-8: Satellite Launches with Nunn-McCurdy Loop Added

With the addition of the Nunn-McCurdy Loop, Figure 4-9 replaces Figure 4-6 and we can see that the model now predicts that in the future 24 GPS satellites will be kept on orbit (the blue line stays above the red beyond 2008 whereas previously it did not). The historical region of 1988 to 2008 is unchanged.
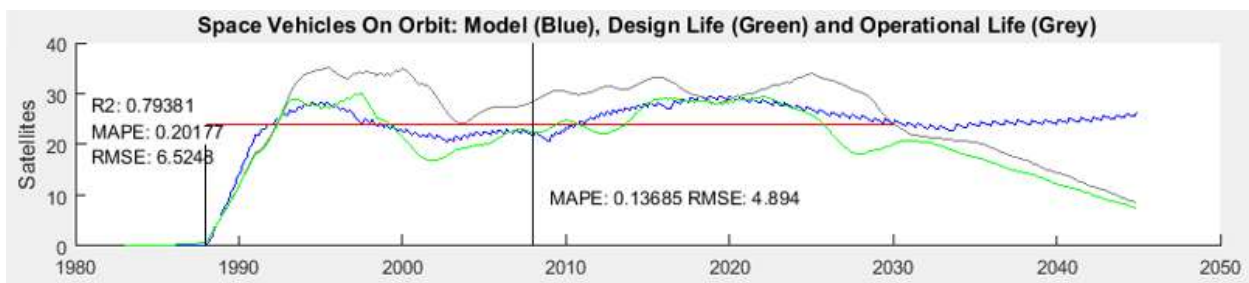
Figure 4-9: Space Vehicles on Orbit with Nunn-McCurdy Loop Added

In Figure 4-10: Unit Cost with Nunn-McCurdy Loop Added the bumps upwards (blue line) indicate the overrun expected per year. The area under the curve for a generation represents the entire replication cost for that time period. This is in contrast to the blue reference mode and Figure 4-2: Model Tuning Unit Cost where the line was static for the period.
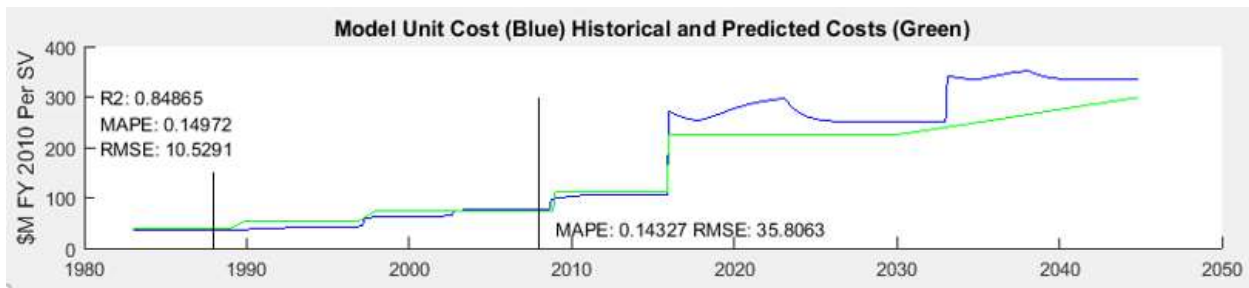
Figure 4-10: Unit Cost with Nunn-McCurdy Loop Added

4.7.7   Additional Variable Outputs

While not checked against the statistical power directly, the results of this now tuned model's production numbers should be compared against the historical number of satellites produced in each generation. Table 4-1: Production Time and Number of GPS Satellites by Generation displays the actual number of satellites built per generation against the model's prediction of how many satellites are required. Based on previous discussion (i.e., the projected overruns seen in Figure 4-4: Model Tuning Total Number of Satellites Produced), it is no surprise that the model produces a few more satellites than were produced in real life.

156

Table 4-1: Production Time and Number of GPS Satellites by Generation

GPS Generation	Years (Actual)	Years (Model)	Number (Actual)	Number (Model)
IIA	1991-1997	1989-1996	19	23
IIR	1997-2004	1997-2004	13	14
IIR-M	2005-2009	2003-2007	8	9
II-F	2010-2016	2007-2015	12	18

The model in this tuning routine, produces exactly 27 satellites for the Block III generation as a NRE pulse is sent to the model as soon as the 24th satellite is ordered. For examination, exactly 27 satellites are also requested for the Block IV generation. Figure 4-11 displays a pulse at the time that the model computes a satellite launch will occur. The previous
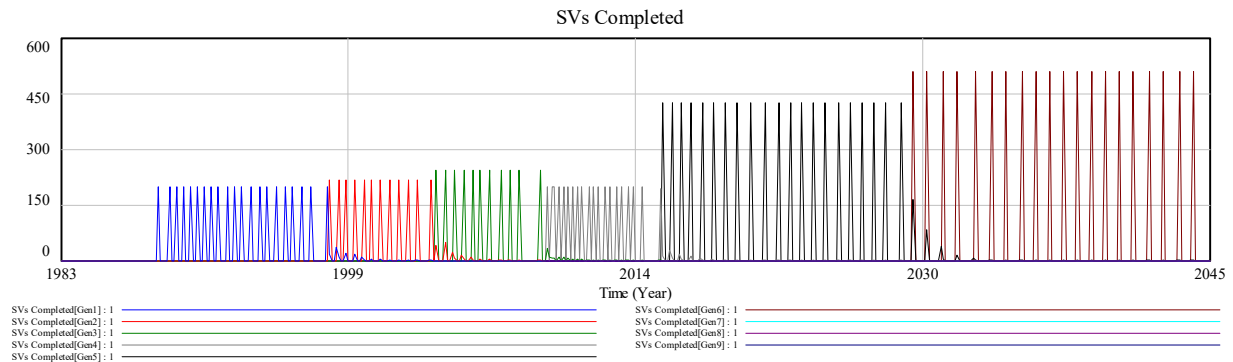
Figure 4-11: Model Tuning, Historical, Holdback, and Projected Satellites Completed

The Efficiency Metric outlined in Chapter 2, is shown here in Figure 4-12: Efficiency Metric as Reported in Model Tuning. Recall that this metric functions as a flow rate for how efficiently money is converted into satellites. The efficiency being discussed here is not efficiency in the general sense of the term, it is efficiency in implementing available experience within a generation of satellites to reduce cost versus the entropy injected by technological advancement. According to Figure 4-12, this efficiency has been decreasing over each generation. Performance, as measured by satellite ability to deliver GPS signals has increased, but the efficiency of the system producing these satellites has not.

The model finds the primary reasons for this decrease in ability to produce satellites in the increasing time between generations, the increasing development time of individual satellites, the decreasing quantity of satellites being ordered, and the increasing rate of technology advancement. One might also reason that the time delay between when a program starts to overrun its baseline and the time before the government grants more funding matters, as it allows firefighting behavior to increase and further decrease efficiency. Another way of stating this is that the faster you can stop a problem, the less amount of time its lingering effects will impact the program as a whole; eventually problems with increasing severity will cause cascading impacts.
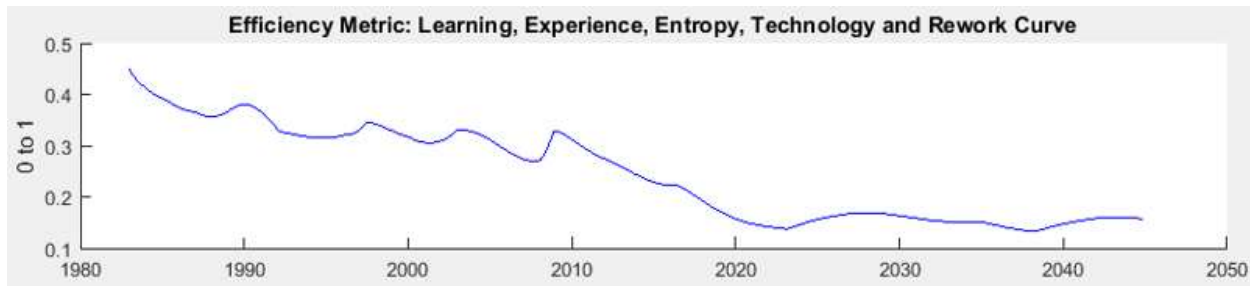
Figure 4-12: Efficiency Metric as Reported in Model Tuning

4.7.8 Tuning Results

The parameter sweep and comparison against the best statistical fit resulted in the tuning variables selecting the following values (listed with appropriate units):

1. Equilibrium Tuning Constant: .015 (Dimensionless)
2. Maximum Efficiency Value: .9 (Dimensionless)
3. Minimum Efficiency Value: .01 (Dimensionless)
4. Design Life Update Time: 1.5 (years)
   a. This time was a substantial change from the 5 years initially expected based on FYDEP time.
5. Nunn-McCurdy Update Time: 1 (year)
6. Nunn-McCurdy Magnitude: 1 (Dimensionless)
   a. Technically relative magnitude. e.g., if overrun occurs, 1 enables additional 25% funding which is just the magnitude of the over-run.
   b. A 2 indicates 50% funding applied, 25% to fix the overrun and 25% more to combat firefighting and get ahead of the problem to combat future overruns.
7. Technology Half-life: 4.5 (years)
8. Effect of Acquisition System: 1 (Dimensionless)

As the model achieved a good statistical fit without needing an exogenous constant, it was concluded that another possible loop, one representing the impact of the DoD acquisition system, was not needed to capture and model the reference modes selected.

4.7.9 Variables Not Included in Tuning

The concept of Production Funding per Year could have been used in place of Unit Cost, however, both should not be used as it would have been redundant tuning. In this model Satellites Ordered per Year multiplied against Unit Cost equals Production Funding per Year. Both Production Rate and Unit Cost are already variables being tuned against so Production Funding Per year was excluded from tuning.

Time between satellite launches is the inverse of Production Rate per Year (1/Production Rate per Year (out)), so it was not used as a reference mode for the same reason Production Funding per Year was not used; its value is already represented in another of the tuning variables.

The variable of Production Time per Satellite was also not used for tuning, for two reasons. First, Estimated Production Time per Satellite is an abstract variable capturing both the average

time to produce a satellite in replication and the time required to create the next generation of satellites. As such, it cannot be compared to actual production values since it will overestimate production values and underestimate research and development time. Second, the variable of Production Time in the model is not a pure representation of satellite production time as it is defined as a measure of the size of the pipeline divided by the rate out (e.g., 10 satellites / two satellites per year = five years). This method of measurement may not accurately reflect real-world production time since it represents a smoothed average over time. For simplicity in the model, Production Time for each generation is encoded as an information delay, hence initial values after a generation change are inaccurate at the beginning of a production run and remain so until the model reaches a temporary equilibrium for that specific generation. This can be seen in Figure 4-13: Production Time per Satellite, where the production time is not a straight shot up (theoretically it should be a discrete gap up) to the maximum time, but rather rises and falls. It is possible that future work could improve on this mechanism, splitting it into two values and additionally working on associated information delay structures to create what would amount to a faster rise time. Yet, if this structure is improved upon or changed it must be with consideration for satellite designs which may be produced very quickly.
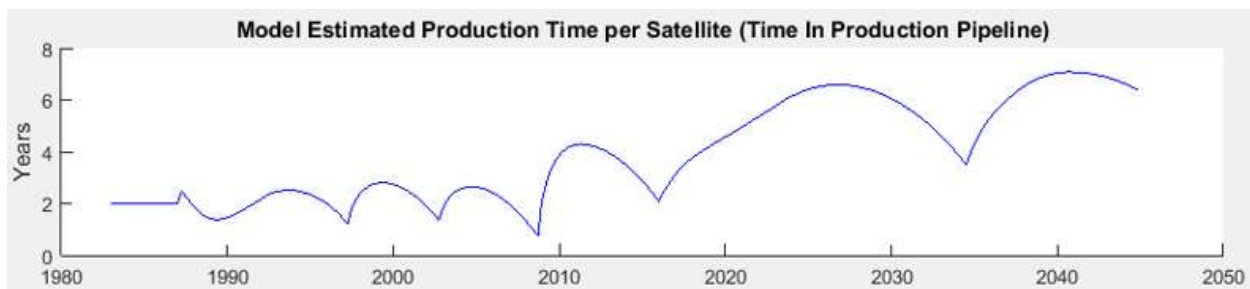
Figure 4-13: Production Time per Satellite

4.7.10   Possible Biases from Tuning:

This model was developed with the goal of testing possible policy changes. Consequently, the decision was made that any bias encoded in the simulation should favor current implementation. Now that the model has been tuned to actual historical data, several biases matching the current implementation of GPS acquisitions, emerge.

1. The model tuning incorrectly attributes more IIF satellites to the historical GPS BATNA than were produced. In reality only 12 were made and the IIRs and IIR-Ms were extended to 15 to 20 years of service life on orbit to cover the shortfall created by these missing satellites. This potentially places the Efficiency Metric in a higher position than it should be as the model transfers into the IIIA production. The reason is that approximately eight more satellites of experience were reaped in the model of IIF production than in real life. This is, however, in line with the stated goal of maintaining a bias towards the current implementation.

2. The model estimates Unit Cost for the IIIAs to be closer to $250M a clone than the reported $224M estimate, however, the $224M number is itself an estimate and the actual data are not yet available. (Keep in mind that this value is a model of mass-to-cost based on efficiency and resources provided.) The weakness of this particular variable in SD modeling is one of the reasons SD alone cannot fully explore the consequences of possible policy changes. This value will be replaced with one enhanced by TSE work later as a

159

merged model is developed. As noted in Chapter 1, the value computed in the SD model when linked with the TSE model for the GPS BATNA will be $213M, again biasing the findings toward the current implementation, since the actual GPS IIIA cost will be higher, at $224M.

4.7.11   Two Alternative Tuning Regions

One additional set of calibration values was also possible with a higher Equilibrium Tuning Constant value (.028 as opposed to .0145) and Maximum Efficiency Value (1 as opposed to .9). This region appeared to have as good statistical power, however, it was deemed the inferior of the two even though it enabled as it trivialized the impact of technology maturation requiring a technology half-life of 7.5 years (as opposed to 4.5 years). Eliminating the injection of entropy with respect to technology likely found an acceptable in tuning against the BATNA, as it has been noted that the current implementation of GPS satellites currently operates in the region of replacing much of the technology generation over generation. Based on the work on estimating technology half-life (and time to double performance) seen in Figure 4-1, a value closer to 4.5 was superior, and this secondary tuning region was the same as turning off the Entropy Loop thus (inappropriately) recasting the problem without entropy but substituting a higher default "hardness" in building satellites. This would also weaken the models ability to examine changes in architecture as changing time between NRE pulses could no longer be examined.

Another tuning region was also possible, utilizing the external technology half-life curve instead of a fixed constant. This required a lower equilibrium tuning constant (.011). This curve, seen in Figure 4-1, offers an attractive tuning point as it offers a potential causal explanation for the difficulty with the IIF program. The curve indicates that time to double performance was becoming shorter (decreased from seven years to four over the span of 20 years). This curve is able to tune the model for the four generations of reference modes (IIA, IIR, IIR-M and IIF); however, the additional difficulty caused by increased entropy generation due to faster technology maturation saturates or breaks the predictive power of the model during the IIIA generation. No tuning which could match the historical reference modes placed the IIIA generation in a position where the program would execute in a reasonable amount of time. This left the model with very poor predictive capability for the hold-back time period. With the inclusion of the Firefighting Loop, the model was able to stabilize, however, it predicted overruns on the order of 200% or a per satellite cost above $450M per clone. This tuning also cascaded such that the Block IV program was left at such a low efficiency level that no satellites were ever produced, leading to an infinite backlog. Consequently, this tuning region was dropped in favor of using a constant 4.5 years. It is possible that more work on equating difficulty from the technology half-life time may yield better results, however, as a simple fixed constant was capable of tuning the model, this tuning region was not further investigated.

4.8 Experience to Experience with Process Look-up Table

The soft-system experience and its translation to the Efficiency Metric are, as noted in Chapter 2, achieved through a lookup table derived from some historical data points and use of the technique of static equilibrium. As this technique and generated look-up table influence the tuning of the model in this chapter, a simple change to the look-up table will not accomplish a sensitivity analysis. If one wishes to check the look-up table against a margin of error, it is insufficient to

change the values in the look-up table and then execute the model. A fourth step must be added before the model is re-tuned:

1. Change values in look-up table
2. Retune model
3. Execute model
4. Compare R^2, MAPE, and RMSE to initial results

One must re-run the tuning algorithm after varying the look-up table because the model is tuned with respect to the table. If the values in the table are changed alone without a retuning, this would be invalid and not a true test of the impact of this variable on model results, as the model would then be out of tune with respect to the historical data. The act of tuning "bakes-in" the performance of the look-up table. While this makes sensitivity testing much harder, it makes the model somewhat robust to errors in the look-up table because the act of tuning itself sets other constants within the model to match the look-up table and historical reference modes. Varying the look-up table with another set of values could be performed if the experience with Process Loop was found to be the limiting loop in obtaining a successful tune.

4.9 Saturation Regions

A large threat to validity based on this tuning, is an exogenous shock so large that it forces the model (most likely a single loop) into a region of saturation for which it cannot produce valid results. To protect against this, outputs must be checked. Two key regions of saturation exist based on model construction. If production exceeds 52 satellites per week, the model is unable to grant more experience beyond this point. This region likely will never be reached as no architectural designs (driven by policy questions) in the work request this high a production rate. The second region occurs when Production Time drops below .125 years. This exceptionally good production time and the current model implementation would provide slower gains in experience than might theoretically be possible if satellites are produced in a time shorter than one-eighth of a year.

These regions of saturation could be expanded, however, this would be purely speculative as no data for tuning are available at these points. In the real world, if performance for GPS acquisition ever approached these regions of saturation it would imply extremely good performance and such a condition is worth an independent investigation as to how it could come about. It should also be noted it will take over a decade, even under the most optimal of conditions, to even come close to these saturation regions. Hence there is plenty of time to gather data and use it to improve and re-execute the model.

An example of very large production numbers of small satellites and the reduction in production time can be seen in Figure 4-14: Estimated Production Time, GPS BATNA vs. 7x Disaggregation. Here the GPS BATNA is shown by a blue line, and the alternate constellation architecture is presented by a red line. At the very end of these production runs the alternate constellation approaches a production time of .125 years. The result is that at the very end of these runs performance might be slightly better than modeled, as the Process Cycle Time Loop is running at only .125 and it should be slightly faster. The amount of this error is well below other errors in this and other cost models. To alert a model user to such saturation conditions, the model is set to flag runs where this occurs.
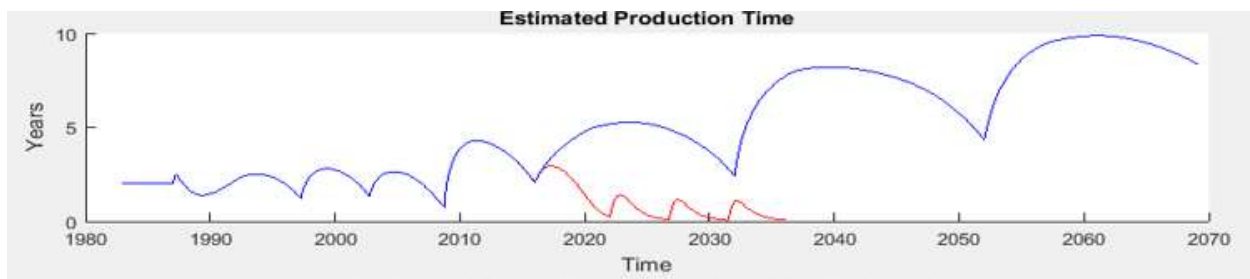
Figure 4-14: Estimated Production Time, GPS BATNA vs. 7x Disaggregation

4.10 Best Alternative to a Negotiated Agreement (BATNA)

For the remainder of this work the GPS Block IIIA and follow-on programs (Block IV, V and even a potential VI) which repeat the existing acquisition strategy will be referred to as the BATNA *a la* Fisher and Ury and as previously defined (Ury & Fisher, 1981) It is important to note that this work now references not the BATNA as defined by the real world data, but the BATNA as represented by the model. This ensures that any model error present is present in the BATNA as well as any alternative architectures. This is superior to comparing model outputs against the real world BATNA projections because the real world projections also possess their own errors. As the desire for GPS capability is unlikely to disappear within this timeframe, the work assumes that absent a reason to change from the current path, the future will repeat the same historical design pattern: larger, longer-lasting, more expensive, higher performance and highly aggregated spacecraft. Thus, any proposed change must be a negotiated agreement to the existing Best Alternative, the current GPS acquisition plan as computed by the model. In Figure 4-15: Composite View of Program of Record (BATNA) an overview of all the variables used for tuning can be seen. The green line represents the actual historical reference modes, and the blue line represents the SD model outputs. In later figures the green line will not be shown and the blue line will become the standard against which all proposed changes are measured. As with all tuning 1988 to 2008 was used for matching historical reference modes, 2008-2016 was used as a hold back period and compared to the model estimation.

It is interesting to see that when the model is asked when to pay the NRE in preparation for GPS IV, it believes it must be paid in 2020 to 2021 to enable a first production unit of the GPS IV in 2029—the year it is required if 24 Block IIIs are ordered. It is also interesting to see how the model interprets the need for production funding to be non-linear. The model detects overrun conditions (seen in the IIF program), as well as times when performance becomes good enough to lower costs (2025-2030). Based on this perspective, it appears that the USAF will either have to expect the Block III generation to last substantially longer than the planned 15-year design life or need to order more than 24 Block III satellites, as it seems unlikely that a development contract for a Block IV generation could be signed by 2020.
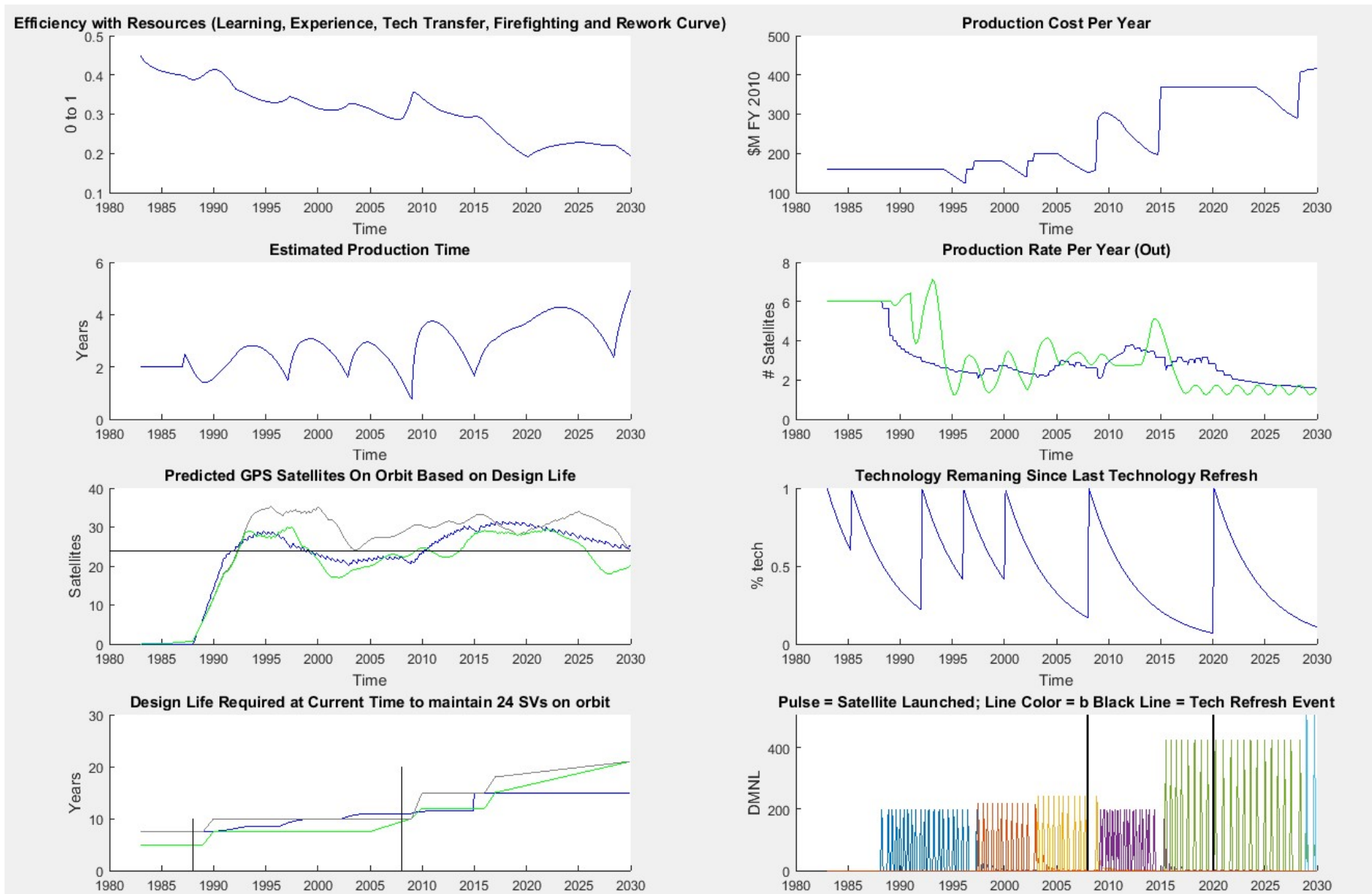
Figure 4-15: Composite View of Program of Record (BATNA)

4.11 Discussion

The goal of this effort was to determine if the production of satellites could be abstracted into a SD model. Based on this effort it does appear that such a model can be constructed and possesses statistical validity in matching reference modes. This implies that this model might produce useful insights into the procurement of GPS satellites. The goodness of fit when using the MAPE is acceptable in not only the tuning period (1988-2008) but also for the hold back data (2008-2015) for all five reference modes:

1. MAPE for Unit Cost: Tuning 14%, Hold-Back 10%
2. MAPE for Design Life: Tuning 21%, Hold-Back 12%
3. MAPE for Total Number of Satellites Produced 13%, Hold-Back 15%
4. MAPE for Production Rate per Year (Out) 38%, Hold-Back, 22%
5. MAPE for Space Vehicles on Orbit: Tuning 20%, Hold-Back 15%

The Production Rate per Year (Out) has the worst fit, but this is unsurprising due to the large oscillations in the initial IIA constellation launch; the model more closely aligns with reality as time moves on and is a much better fit in the hold back period. Most importantly the fit of these variables is better than the error associated with the USCM8 cost model; the cost model used in Chapter 2 and often implemented in government cost modeling exercises (NASA, 2010). In USCM8 the lowest error of any cost model is 23% and the highest error is 39% (as can be seen in Table 11-9 of the SMAD). Thus, this SD model when used for predictive modeling performs no worse than and often performs better than existing cost modeling practices when approximating satellite cost based on weight.

To achieve this fit, the model implemented the artificial Efficiency variable as a flow control on the GPS satellite pipeline. The Efficiency variable by itself cannot be compared for "goodness" from one program to the next as a direct proxy for health. In conjunction with the model, however, it does enable direct comparison of the replication cost of satellites at a fixed performance level.

The model as tuned indicates that that the GPS Block IV, awarded (theoretically) in 2023 and first tested in 2028, will likely have a very hard time being fielded. It would appear that under the current trajectory, the difficulty of designing and manufacturing such a system will require 125% to 150% of the baseline to place 24 satellites successfully on orbit. This may seem like a strong conclusion, but his has happened with other satellite programs. One might consider the SBIRS high program, started in 1992, first Nunn-McCurdy in 2001, third Nunn-McCurdy in 2005 and launch in 2012 a decade late. If GPS chooses to clone technology from 2008 until 2023, the next effort will again have to start from scratch based on the model's opinion of technology decay over time. In other words, the industry will not have any ability to transfer lessons learned and likely will experience the same overruns seen on the Block IIFs and the Block IIIs. This model indicates that the proverbial "deck" is stacked against such a technology acquisition approach as long lasted systems relative to exogenous technology development and human learning cycle times place each follow effort unable to capitalize on the experience of previous work. That does not mean that long lasting systems are bad, in fact the model indicates that maximization of utility through long lasting systems is preferable and is currently protecting against overruns by keeping production rate in line with the current industry capability. What the model suggests is that production time and by proxy the rate of experience from one generation to the next must be brought into line with both the technology growth curve and the human ability to retain knowledge and become familiar with

a process. Now with a tuned SD model integrated with TSE, such questions of policy can be examined.

5 Mixed Model, Merging System Dynamics with Trade Space Exploration Techniques

The questions asked in this thesis about satellite systems (specifically acquisition of GPS and SWX) concern three dimensions: Cost, Performance and Time. (This problem is usually phrased in program management as Cost, Schedule, and Performance.) In this thesis, existing cost and physics models are implemented to handle the first two dimensions through the TSE model. The SD model was introduced as a way to handle the dimension of time. As developed, the SD model also includes the first dimension, Cost. While many connections are made between these models (the full list is in Appendix H Interfaces from SD to TSE and TSE to SD), it is through the variable Cost that these two models are first merged.

While Vensim offers connectivity to external models through the Dynamic Link Library, the literature on merging SD models with other modeling techniques is sparse. This is to be expected for two reasons. First, tools and the needed computational systems to make SD modeling accessible to the average modeler have become available in only the last few years. Second, and more importantly, SD functions as a high-level abstraction combining multiple variables and concepts. This modeling inherently possesses a large degree of error and unlike many other modeling approaches does not necessarily become more useful or more accurate by including additional parameters or loops. As the value of a SD model is more anchored in explaining the impact of time and comparing the relative strengths of differing causal loops than obtaining the exact answer, adding high precision models to a highly abstract model is somewhat counterintuitive, as the fidelity of a model is typically only as accurate as the component with the lowest fidelity. This is similar to stating that in any mathematical equation the precision of a calculation possesses only as many significant figures as the variable with the fewest significant figures. Thus, adding a precise physics model to an abstract SD model at first glance may seem to provide little value, as it is unclear how the addition will enhance the value of the SD model or how the SD model won't compromise the results of the more precise work. In Chapter 4, however, it was shown that for the reference modes considered, the error associated with the tuned SD model is equal to or less than the error of existing cost models. Thus, adding this SD model to the TSE work becomes viable. Most importantly, the implementation of additional cost and physics models assists in validation of the tokenization approach implemented in the SD model. In this chapter the mechanism for this how this arrangement and the added value of such an arrangement is explored.

It is reiterated here that this merging of models creates three viewpoints for the modeling of satellite design and acquisitions:

1. The perspective of TSE, discussed in Chapter 2, where point in time assumptions are required for calculations.
2. The perspective of SD discussed in Chapter 3 and 4, where exogenous pulses are required to effect change and move a system out of equilibrium.
3. The view from a control module coordinating the two models and associated systems, which will be discussed here in Chapter 5.

5.1 On Merging SD with External Models

The perspective of adding a high fidelity model to SD is in line with the third viewpoint, and some work from this perspective has been conducted. Researchers from the University of Western Ontario made use of a SD model to evaluate the hydrologic cycle and potential impact of policy on water availability (Akhtar, Simonovic, Wibe, MacGee, & Davies, 2011). This research used an advanced physics model to validate, update and inform their SD model at every step of execution. Vensim does not natively support every function required for full implementation of their model, consequently, these researchers allowed Vensim to query Matlab for external functions such as the hydrological cycle, global water use and water quality. This allowed the inclusion of physics-based models into a SD model. For this work the researchers were also required to create a simple control module that enabled the different tools to work together: in all existing SD modeling tools, external interfaces are command line only and do not possess "point-and-click" or a simple graphical user interface to embed external models. Their work did not explicitly identify a control module but rather viewed it as a hand-off between the two models which was controlled by the user. Thus, in execution only one evaluation was performed per model execution.

Regardless of the efficiency of the processing, the inclusion of a high-fidelity physics model of the water cycle enhanced the SD work and its credibility, as the results were built upon existing water models but the combination enabled policy testing. A SD model targeting water use policy without inclusion of the physics of the water cycle would not be detailed enough to trust (the tokenization of water in an SD stock would be insufficient). This is one example where adding a high-fidelity model to an abstract one improved the results. Instead of forcing the modeler to trust the abstract concepts of "water" and "quality" possessed in stocks and flows, clear predefined performance criteria in the existing physics models could validate the tokenization in the SD model against the existing knowledge base.

Heuristically this is similar to a problem in modeling GPS satellite coverage. GPS satellites must be able to deliver a specific level of energy to the earth's surface and deliver it globally. Creating and simulating such performance is already a solved problem (see Chapter 2), and these physics models are already available. If, however, a stock in a SD model that contained 24 satellites (represented by 24 tokens in a stock) was changed to 48 satellites (now 48 tokens), there would be no way to compare the performance of the respective constellations. It is not enough to use tokenization and claim a GPS satellite or set of satellites meets this performance requirement. Physics models must be employed in conjunction with the SD model to ensure that the tokens representing satellites deliver the required performance.

Beyond the problem of token validation, a tool such as Vensim does not possess the native functionality to model discrete changes accurately. For example, the mass change in 48 satellites instead of 24 or a design life 15 rather than 7.5 years is not well defined by a single ratio. The equations discussed in Chapter 2 become unwieldly to implement in existing SD modeling tools (though, given enough time they technically could be encoded, as Vensim is Turing complete). A native SD model would not be able to "understand" these changes, as that is not the purpose of this method and set of tools. This is not a failure or a shortcoming of SD nor of the existing tools, they simply insufficient for the problem at hand. This is why this modeling effort must implement cost and physics models to compute changes associated with different policies or implementations in the GPS satellite production pipeline.

Figure 5-1: Wertz Loop Enhanced with Physics and Cost Models depicts where external Physics and Cost Models might be inserted into the Wertz Loop, previously used in construction of the SD model, to enhance the modeling of the Space Industry. A Physics Model replaces a SD structure or rather, instead of performing a single calculation, invokes an external function and accepts the return as the new value for the variable. From perspective two that of the SD model, the purple boxes are external functions accepting an input and delivering a predetermined return. This has the advantage of handling non-continuous functions not well modeled by stocks and flows or too complicated for look-up tables. Properly implemented, a Physics Model can solve issues associated with validation as the external physics model computes the required satellite size based on reliability and capability demands. Executed simultaneously, regression based cost models can be used to compute the component cost of each demand imposed by the associated physics models and performance thresholds. These models are the same as used in Tradespace Exploration, and the flow sequence as depicted in causal loop diagraming is the same flow sequence executed in a TSE model. The difference is that a TSE model returns many designs across a range of inputs and an SD model invoking cost and performance models only request a single return.
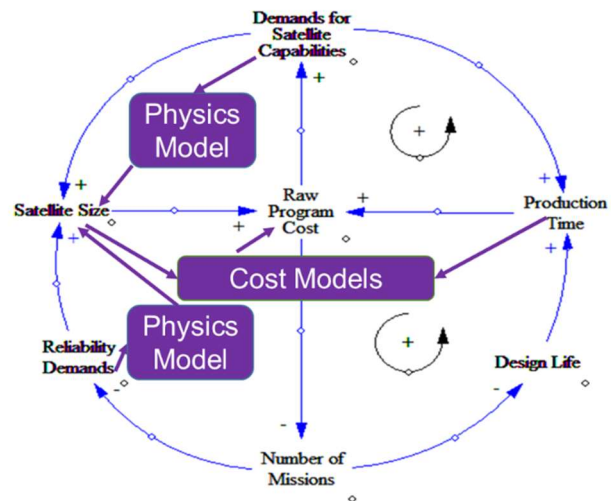
Figure 5-1: Wertz Loop Enhanced with Physics and Cost Models

One potential consequence of this implementation is <u>myopic decision making:</u> the best solution at every time point may not lead to the best overall solution. If this model were to be implemented, it would solve one of the limitations of current inductive SD models: the mass of the satellites would be precise and the performance of the systems for either coverage or reliability would likely be sufficient. However: as one optimization is considered, as local minima/maxima are hard to overcome and as the SD model has been tuned on historical behavior, it should be no surprise that this model would lead to future solutions looking much like past solutions. This would indeed be valuable for predicting the current outcome of continuing on the current path, which is highly valuable, but would not meet the research goal of evaluating systems which are different from those currently in operation.

5.2 Implementation and Execution Sequence

The technique of creating a design vector and computing across a range of possible inputs at a discrete point in time will be implemented in order to overcome the limitations of potentially

myopic decision making. As noted earlier, construction of a merged model makes use of two primary programs: Matlab (Mathworks, 2015) and Vensim (Ventana Systems Inc, 2015) TSE, comprised of physics and cost models, is implemented in Matlab. Vensim DSS is delivered with a Dynamic Link Library (DLL) which enables external commands to be sent to Vensim. For this effort, wrappers were written in Matlab to pass the commands to be executed on the Vensim model during execution, and SD functionality was implemented in Vensim.
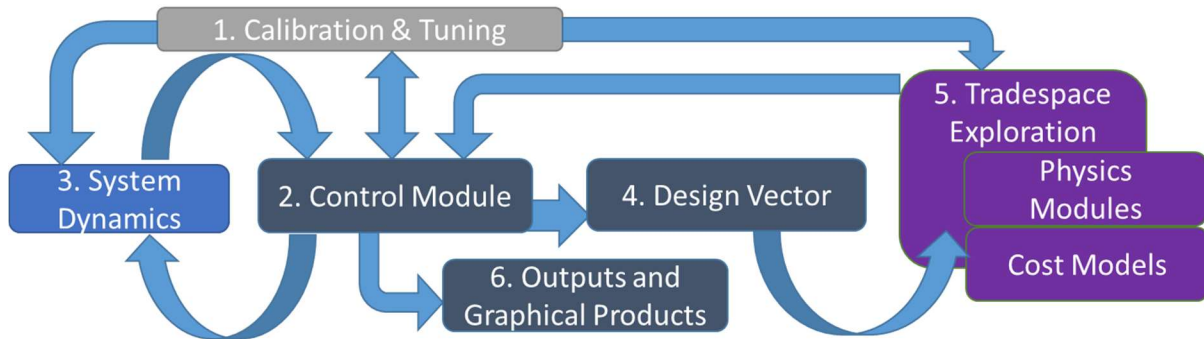
Figure 5-2: Execution Flow Control

The Control Module has the ability to carry current suboptimal implementations forward or carry a select set based on rules (this is noted in Figure 5-3: Execution Flow Control Markup by the green arrow). In point-optimization the "best" solution at a given time is selected for implementation. In this modeling approach it is as if we select a sub-optimal (non-Pareto front) point, and consider a reality where this decision was implemented. This carries the impact of selecting a suboptimal decision into the future enabling examination of its impact across multiple acquisitions. This comes at a high computational cost and is examined in the Memory Tree section of this chapter. In this design, unlike the work performed at the University of Western Ontario on the hydrologic cycle, updates from the TSE model are not needed at every time step in the SD model. It is not logical for every 'dt' or time slice of the SD model to re-run the physics and cost models when really all that is required is the actual cost or mass when the design is fixed. The Control Module must invoke the TSE module only when it detects that a new block of satellites is to be procured. Also, unlike other work, at the time the cost and performance models are invoked, more than one solution is returned to the SD model.
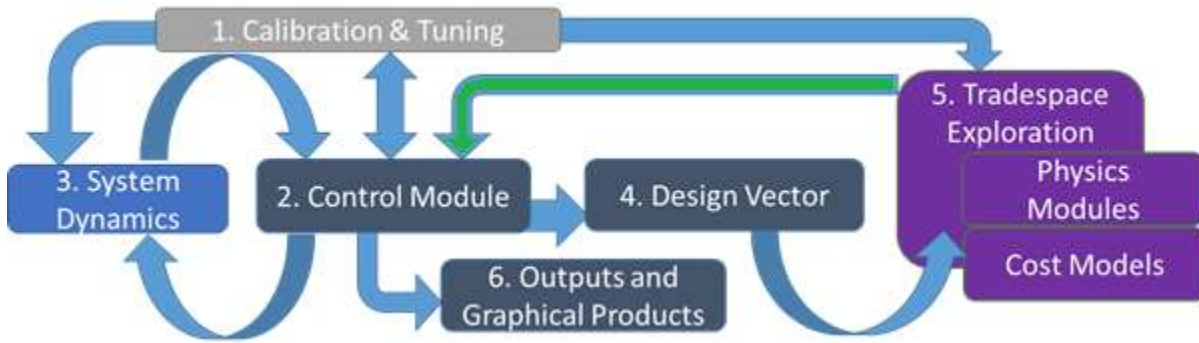
Figure 5-3: Execution Flow Control Markup

The merged-model is written such that the Control Module handles execution flow, storage of data, and invocation of the SD and TSE models. The Control Module monitors the System Dynamics model looking for the signal to begin a new acquisition. Upon detecting the need, the control module sends the "state of the world" to the TSE module. The TSE module then constructs candidate architectures based on the analysis defined in the design vector. This concludes with the control module populating new instantiations (one instantiation of the model for every design point "carried forward") of the SD model. This can be visualized in Figure 5-4 below with a memory tree, similar to the one constructed by the control module. The complete sequence of events results in an execution presented below in Figure 5-7 and is documented in Appendix I Control Module Execution Sequence.

5.2.1   Memory Tree

The model is coded such that the Control Module handles execution flow, storage of data, and invocation of the SD and TSE models; this is the third perspective discussed in this chapter. Execution forms an ever-expanding tree which is based upon the Design Vector, and is visually represented in Figure 5-4. In the hand off between the two models neither is aware of the existence of the other; they influence each other only through exogenous constants.
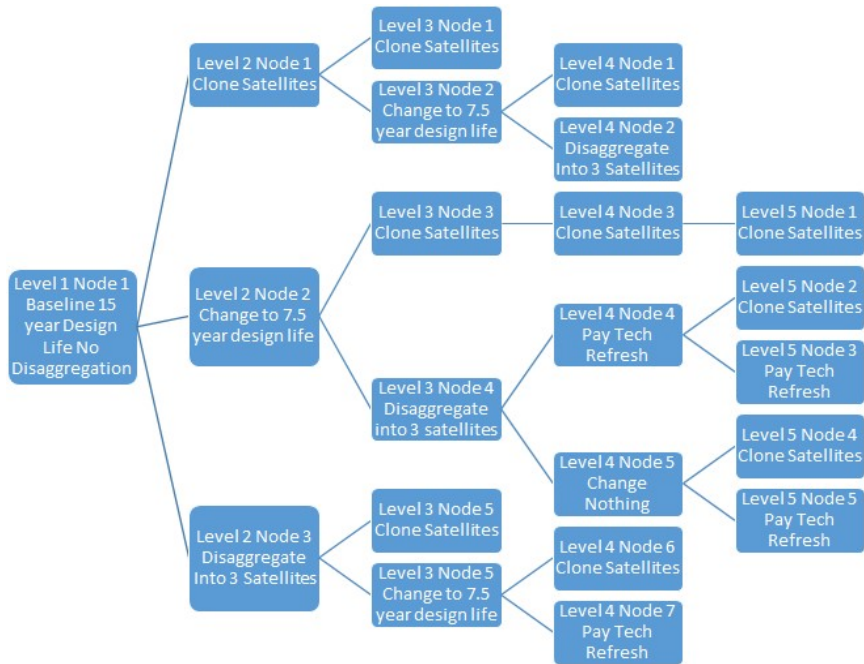
Figure 5-4: Simple Memory Tree of Future Acquisition Decisions

To simplify Figure 5-4 this Memory Tree illustration does not include a full factorial expansion of all variables at all nodes. For example, the node Level 2 Node 4, which represents disaggregation and a design life to 7.5 years, is not included. In actual execution of the code, however, these nodes would be present. This creates 2^n possible implementations where n is the number of design parameters to change in TSE assuming a full factorial expansion. The tree in Figure 5-4 is the result of a design vector that, recalling from Chapter 2, contained:

{Design Life, Payload Alignment, Number of Satellites to Be Produced, NRE Update}

{[15, 7.5], [BATNA, 3x Disaggregation], [8], [0,1]}

This design vector would create the following design space at Level 2 in Figure 5-4.

1. {15, BATNA, 8, 0} shown as Level 2 Node 1.
2. {7.5, BATNA, 8, 1} shown as Level 2 Node 2.
3. {15, Disaggregate 3, 24, 1} shown as Level 2 Node 3.
4. {7.5, Disaggregate 3, 24, 1} not shown but would exist as Level 2 Node 4.
5. {15, BATNA, 8, 1} not shown but would exist as Level 2 Node 5. The difference between this node and Node 1 is this is a technology refresh event, or how the model updates technology to combat entropy. In Node 1 technology would not be refreshed and technology would continue to age, but no technology update would be paid.

As there were three choices, the Design Vector created 2^3 or eight possible designs. Three of these designs, however, were eliminated in accord with the tree-pruning rules discussed above which eliminate impossible situations. These included:

6. {7.5, BATNA, 8, 0} pruned because Clone and Modification are incompatible without NRE payment.

171

7. {15, Disaggregate 3, 24, 0} Clone, Design Life 15, No Disaggregation} pruned because Disaggregation and Modification are incompatible without NRE payment.
8. {7.5, Disaggregate 3, 24, 0} pruned because Disaggregation and Modification are incompatible without NRE payment.

For this reason, the size of the design space is never larger than $2^{(n-1)} + 1$, however, it becomes even smaller in implementation as once a design is disaggregated, it is never aggregated and after performance is added, it is never subtracted. These additional logical rules keep the design space smaller than this upper bound.

5.2.2   Time Complexity

While this tree-building sequence could have been implemented as a "pre-order" tree-walk using a recursive algorithm for debugging, concerns about the memory required, and ease of code parallelization lead to a "level-order" implementation. Figure 5-5 graphically depicts this level-order execution and shows the sequence in which the values for each node are computed. In this arrangement each successive node only depends on information from the previous node. As such, all nodes can be split into their own separate process (thread or core), with no dependency on any other node. This enables parallelization of this problem to multiple cores as a way to overcome the time complexity associated with the computations. Without this, time complexity is clearly exponential:

1. Without any tree-pruning or rules across generations, the time complexity for each node would be 2^n where n is the size of the Design Vector in the TSE computation. Problem is exponential time hard $2^{\text{poly}(n)}$
2. Tree depth is limited to five (i.e., four generations since the first node is the state of GPS satellites in 2008)
3. Without pruning, each node would have 2^n nodes after it, yielding $5 \cdot 2^n$ time complexity for a run as an upper bound. With pruning the time complexity has an upper bound of $5^{(2^{(n-1)}+1)}$. In practice it is even lower than this.
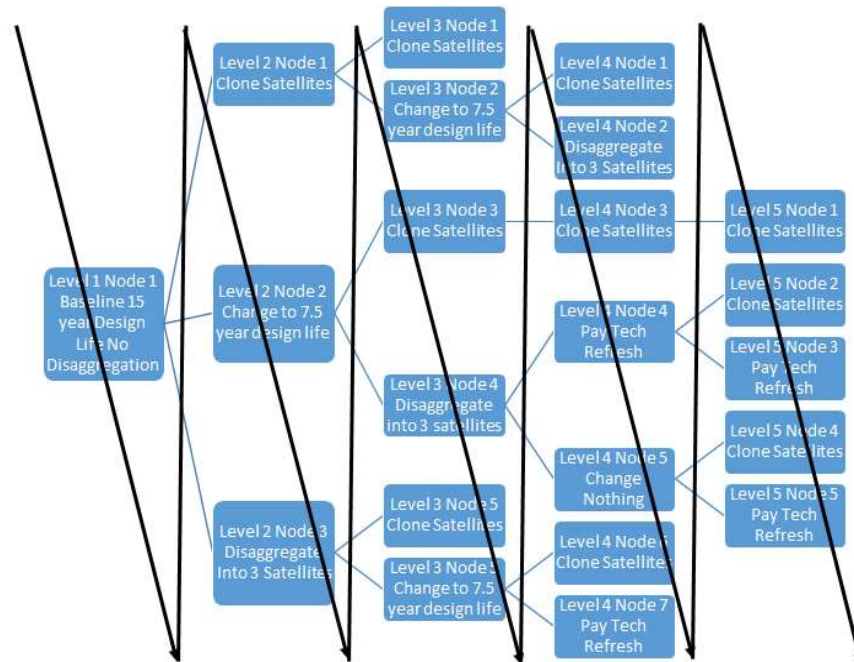
Figure 5-5: Level Order Execution

For implementation, usability and future improvements it is important to understand which elements of the code take the longest to run:

1. The longest time to execute is required by the orbital propagator and coverage physics module.
   a. Each set of 24 satellites to be examined for a 24-hour period requires ~30 seconds of time on a single core of a mid-end desktop processor.
   b. Thus, the largest constellation tested (*c.f.* Chapter 5) contains 7x24 satellites, or a total of 168 satellites. This would imply that a little over 400 such constellations could be simulated per day per processor core.
   c. A future improvement would move such computations to specialized hardware such as graphics cards which are specifically designed for large arrays of floating point computations in parallel mathematics.
2. The second-longest time to execute is required by the knapsack problem of fitting payloads onto buses and satellites onto rockets.
   a. This has been optimized using dynamic programing as discussed in Chapter 1.
   b. The execution time even for the largest constellation is less than one second.
   c. In conjunction with dynamic programing, the problem is reduced to common elements. For example, if there are 72 satellites to be placed on an assortment of rockets, not all 72 satellites need to be examined if there are only three types of satellite. Only all possible combinations of those three satellites, up to the largest number that can fit on one rocket, need to be examined, and the optimal solution propagated across all launch vehicles.
3. The third-longest time to execute is needed by the SD model, which requires an execution time of ~.25 seconds.

173

a. Due to the level-order execution, an additional small time complexity is added over a recursive tree walk. It requires an additional linear '$O(n)$' time complexity, where n is the number of nodes in the Memory Tree.

b. This time penalty enables the code to execute in parallel and each node to be self-sufficient in memory. A recursive approach is not as easily parallelizable as memory becomes difficult to unpack and reintegrate after execution.

4. The remaining physics and cost models execute in less than one-fourth of a second.

With such a high time complexity, a full-factorial expansion of all design vector points at fine resolution is not possible. Nonetheless, a coarse analysis is still possible and useful to gain insight into the research questions posed in this thesis. It is also useful to re-align this tree and plot it not with respect to tree depth but with respect to time. Using the same run displayed in Figure 3-42: Model Representation of Capability as Measured in Years for GPS Satellites Under GPS BATNA where eight satellites are ordered every five years, leading to a potential to change every five years, Figure 5-4 would change as shown in Figure 5-6.
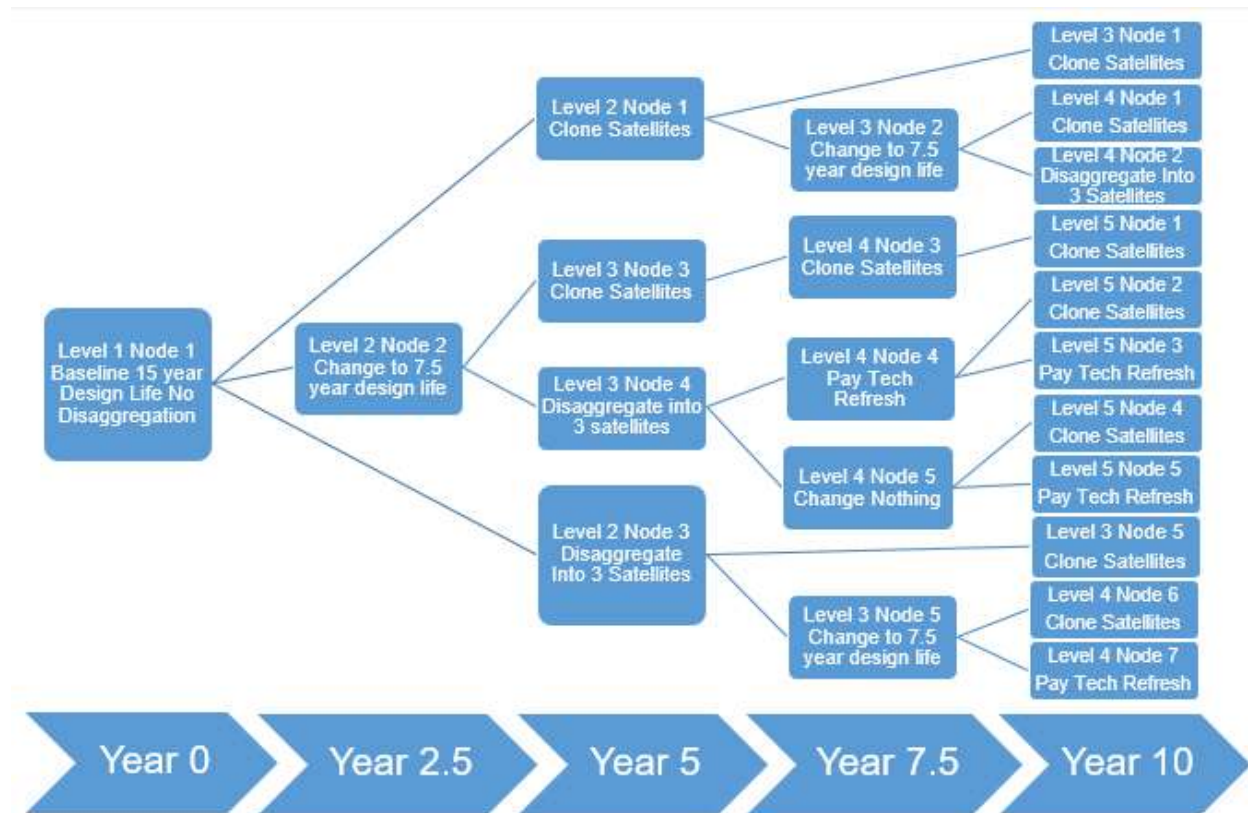
Figure 5-6: Execution Plotted Against Time

At the end of execution, the terminal nodes in each tree possess different possible futures based on the initial context variables set in the TSE model and the SD model. As one of the design elements that changes is time of procurement and it is based upon the design life of the satellites being produced, nodes with implementations that last longer require fewer nodes in the same time period (in the memory tree), as fewer satellite acquisitions are required. Each pathway ends after

174

four generations of satellites but some will require more years. In this work the decision was made to limit tree depth to five, which represents four generations. The reason for setting a tree depth of five, or four generations, is that only four generations of tuning data are available. The validity of any extrapolation beyond four future generations might be questionable. Additionally, the exponential nature of this computation for a fifth generation would require weeks of computational time, while four generations can be computed in a day or less. As the code is amenable to parallelization this would not be a problem in practice, but for development purposes proves prohibitive.

The combined model was initially designed to limit the depth of work to the year 2045, however, apples-to-apples comparison at a specific time point is not a good idea because satellites are purchased in blocks. Below this cross-comparison between tree branches is examined in greater detail and results are compared using the variable of cost per operational year to achieve an apples-to-apples comparison.

5.3 Visualizing Outputs

The following figures have been constructed to help explain and visualize model execution and outputs. These graphics do not depict the output of tuned model runs. The actual GPS Program of Record as simulated and predicted is in Results GPS Program of Record or BATNA (first displayed in Chapter 3 Figure 3-42: Model Representation of Capability as Measured in Years for GPS Satellites Under GPS BATNA and the results are interpreted below in the section: Results GPS Program of Record. These figures are for illustration of the tools and techniques implemented in this chapter to merge the SD and TSE models.

Figure 5-7 presents the two variables (Satellites on Orbit and Satellites in Production) as an abstraction for the current plan for procuring the GPS constellation. It also imbeds Figure 5-2 to show how the Control Module changes between the SD and TSE models. It presents block buys of eight satellites ordered in advance of the decay of satellites on orbit. As noted above, the GPS Block IIR through IIF satellite data are loaded during calibration and tuning, shown by the blue oval over 2000-2008. (Data from 1998-2008 are technically loaded, the graph has been slightly shortened to fit on the page.) This model tuning, represented in the oval, corresponds to Level 1 Node 1 in the Memory Tree. The merged model shifts control from the SD module to the TSE module when Satellites on Orbit need to be replenished and a new acquisition is required.
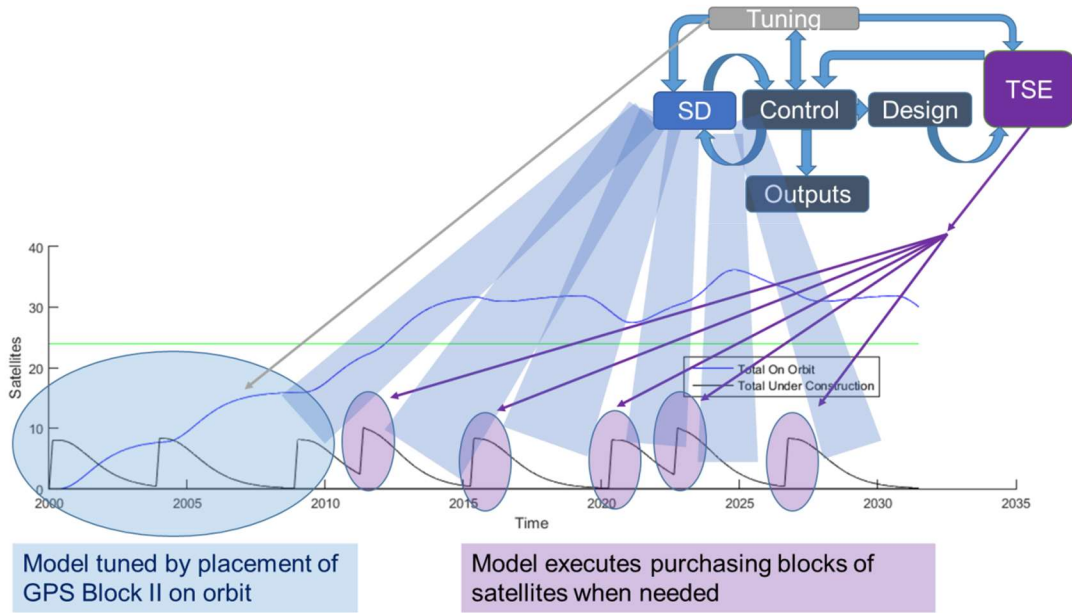
Figure 5-7: Program of Record Equivalent Satellites of Capability

While it appears that the merged model places more than 24 satellites on orbit most of the time (see the blue line), the "extra" satellites are very near the end of their design life and new satellites must be procured with a small buffer such that they can replace existing assets before the old satellites are decommissioned. In the real world this is not a smooth operation, and the SD model clearly shows the difficulty of phasing acquisition and launches with perfect efficiency. Identical to the Memory Tree (see Figure 5-4), Figure 5-8 depicts the nodes that each acquisition decision (seen in the purple ovals in Figure 5-7) would occupy in the theoretical tree produced in executing this merged model.
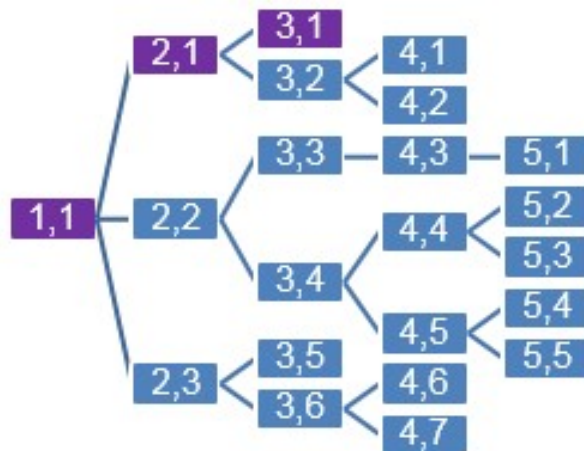
Figure 5-8: Tree Nodes Used by Model Representation of Procuring and Launching GPS Satellites Under BATNA

If GPS is disaggregated into three satellites that deliver capability equivalent to the current constellation, but the raw number of satellites and their respective years of capability are larger by a factor of three, then this decision would be a different implementation than the existing GPS plan and as such it would occupy a different chain on the Memory Tree.

Figure 5-9 depicts the tree nodes that would represent the decision to disaggregate while changing no other design variables.
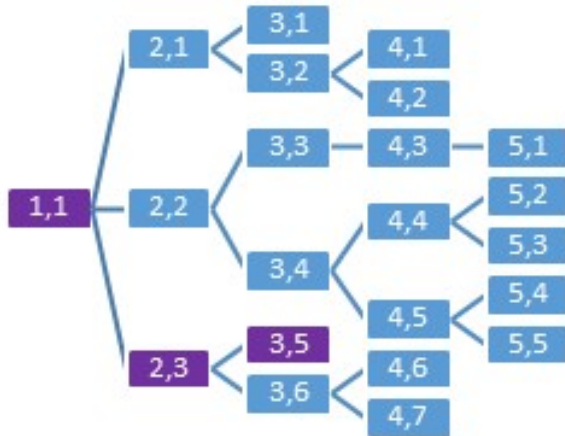
Figure 5-9: Tree Nodes Used by Model Representation of Procuring and Launching GPS Satellites Under 3x Disaggregation

The number of satellites required in a block buy is no longer eight but rather 3 x 8 for a total of 24 satellites. Figure 5-10 illustrates execution of the major loop (outlined above in Steps 3-7 of the control module's execution) which produces acquisition decisions across time and where they are recorded in the Memory Tree. Figure 5-10 embeds

Figure 5-9 to show how the Memory Tree is connected to execution across time for the acquisition of the disaggregated constellation.
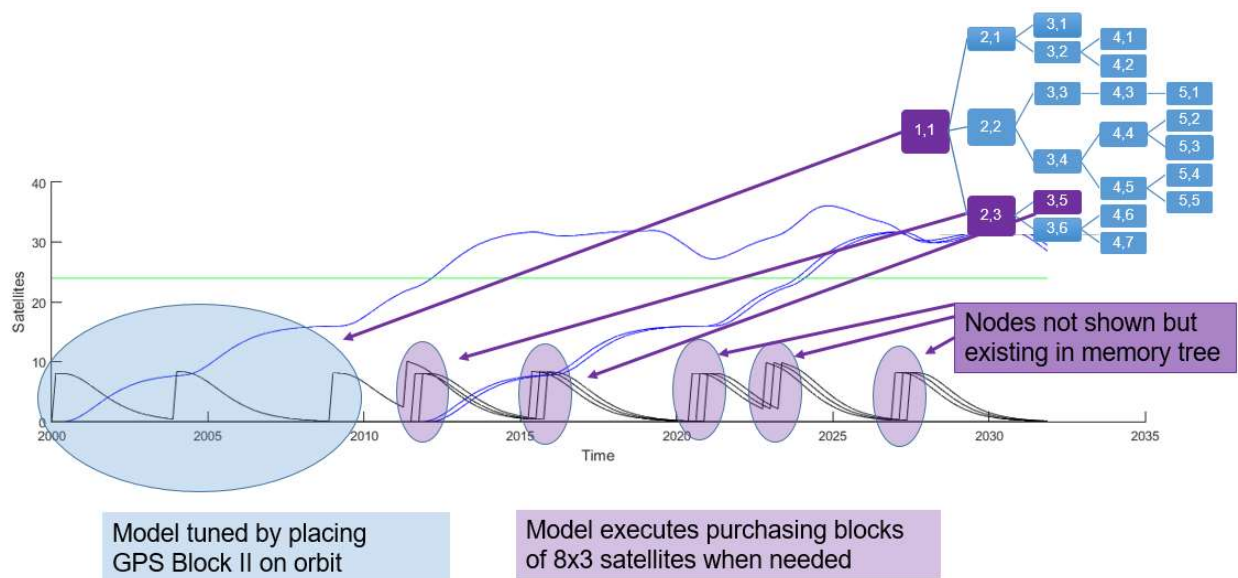
Figure 5-10: Model Representation of Procuring and Launching GPS Satellites Under Disaggregation to Three Satellites

Figure 5-7 presents the possible futures associated with the GPS system as planned (BATNA). Figure 5-10 shows a Design Vector where the choice has been made to disaggregate GPS into three smaller satellites. Recall that inside the TSE code, each of these satellites is designed independently and sized for the specific payloads desired, and each of these is validated against the physics models to ensure satellite performance is met. This enables the SD model's tokens, which now represents a purchase of 24 satellites (rather than the original eight) to demonstrate that the changed implementation achieves the performance required. In this case, the old civilian signals have been put on one bus, the new civilian signals have been put on a second bus, and all military hardware has been placed on a third bus (as described in Chapter 1). The time lag for a disaggregated system starting in 2008 to reach operational strength is shown by the blue double lines. They do not cross the green threshold of 24 satellites on orbit until 2024. Between 2008 and 2024 the constellation would be a mixture of existing satellites and the new disaggregated constellation. Figure 5-10 results imply that analysis of time lags associated with deployment schedules is possible with this merged model.

5.4 Linkages and Interface between System Dynamics and Trade Space Exploration Models

By convention, in SD and associated simulated models, a loop is not complete without a stock. Two variables cannot form a loop but one stock and a flow and a variable can. This is because a variable is not a store of memory but only an instantaneous calculation and without a stock of memory no computation across time would be possible. This is important to note in the context of the third viewpoint in this model. In construction of the SD model it was noted that a type of loop exists that passes through linked TSE modules. As some exogenous variables are now linked through the control module, loops exist that are not visible from the second view (that of the SD model) alone; the control module also possesses memory, specifically the memory tree outline

above. These loops exist as the output of the SD model represented in Vensim changes an input, thus closing the loop even though from the second perspective (the SD model) the variable is an exogenous input.

The SD model stores variables which function as context variables for the TSE model. In turn the decisions made in the TSE model change the context stocks over time, through exogenous constants from the perspective of the TSE model. The variables that pass information from the SD model to the TSE model and from the TSE model to the SD model are listed in the Appendix H Interfaces from SD to TSE and TSE to SD. As noted in Chapter 1, the cost and performance models independently compute cost and performance measures of the constellation under consideration. The information about production cost is sent to the SD model and serves as the program baseline but does not see all the associated metrics. While the SD data does not see all the information, the raw computations are stored in the Memory Tree by the Control Module for later processing and evaluation.

5.4.1   SD Loops that Pass Through TSE

The trigger for new procurement (acquisition) activity occurs when the satellites on orbit decay in the SD model to a level at which procurement must begin to avoid a capability gap emerging in the future. This detection triggers satellite procurement in the TSE, this now forms what could be considered the primary causal TSE Loop. The return of the TSE model to the SD model creates the following loops by changing exogenous constants in the SD model:

1. The "Number of Satellites to Be Produced" adds satellites to the pipeline. It is an exogenous constant which then changes the level of satellites being produced in the pipeline. This has the impact of causally changing the next time a TSE event must occur. The number of satellites designed for production by the TSE module determines the time (year) that the next acquisition must begin.
2. The act of starting a new acquisition also changes the program baseline, or the amount of funding made available for production each year. This impacts the Firefighting Loop as well as the production rate of satellites as the resources to production level is now changed.
3. The time of the procurement, while not changed by the TSE model in the current generation, determines when the NRE event (technology refresh) will occur for the next generation. This sets the relative amount of technology that will degrade between generations. This changes the amount of entropy being injected into the efficiency based on the relationship with the half-life structure (model), which impacts all major loops through the Efficiency variable throughout the production of this generation.
4. The disaggregation level of the architecture works more like an exogenous policy change than a pure causal loop. As this changes the experience with the process loop and the model's representation of learning effects on the generation and subsequent generations. Over two generations this can have significant causal ramifications for the time at which the generation completes production and the next begins.
   a. Experience with process is changed by producing more satellites, which then changes the Efficiency, which in turn changes the cost of satellite production which over time. Through the Efficiency variable the impact of this change will impact the performance of all other loops.

b. This policy also changes the mass of satellites, and smaller satellites can be produced faster than large ones, all else being equal. This policy closes a loop with the Process Cycle Time Loop due to the change in mass.

5. Resources to Production versus Resources to Improvement (NRE): To tie the model to the DoDs acquisition system, resources for production are defined as 6500 money in the government. In the model this is referred to as the program baseline. Resources for process improvement can be thought of as 6400 money also denoted as NRE in the model. While DoD regulations restrict the usage of 6500 for 6400 work or vice versa, the model does allow for the interchange of such funds as funding levels do legally change over time (years). In this model, the R&D pipeline is viewed as a critical component of the process and process improvement. This is because unlike other industries, the government is the largest player in the Space Industry and as such must still subsidize research and development activities. (This is similar to second-order improvements in Morrison's paper (Morrison, 2011)) This changes the amount of entropy injected into the model: the longer the time between 6400 efforts, the greater the rework rate. The actual implementation of such money shift is not accomplished in the SD model. It is accomplished through working under a cost ceiling such that TSE, launch, operations and production costs must all come in under the ceiling as proscribed by DoD guidance (Office of the Under Secretary of Defense, November 2012).

a. This is more complicated than the other loops because it is a discrete value that the TSE produces when some money is spent on NRE and the amount of money required for production is then computed over time in the SD model.

b. This loop comes into focus retroactively if a cost ceiling is imposed under which total acquisition cost must be achieved (either for a time period or the entire length of model execution).

5.5 Predictive Model

Having merged these two models and methods into a single executable model, the first run of interest is the BATNA as described in Chapter 4. Instead of an external "Command Script" feeding the SD model (as was seen in the previous chapter), the continual interplay as described in this chapter becomes active. With a tuned SD and TSE model the outputs will represent the model's prediction for the future if nothing is changed and we continue on the current path. In addition, we now are assured that the constellation of satellites does indeed meet the requirements of performance and in this section we will list all the associated parameters of each generation in the Appendix. In future examination this will be limited to a high-level view and meaningful results and comparisons discussed subsequently.

5.5.1 Results GPS Program of Record

The following variables are identical to the ones seen in Chapter 4. The model still uses the same calibration files developed in Chapter 3, which encode the historical data and time concepts related to the GPS acquisition pipeline from 1988 to 2008. As the model is now working with the physics and more accurate cost models, its performance beyond the Block IV acquisition decisions are slightly different than the SD model alone. This does not invalidate the tuning, as the TSE results from the GPS Block III results were placed into the calibration file for the Block III acquisition decision for the SD model tuning. (Recall that the NRE pulse for the Block III was as

implemented in 2008). This means that the results of the merged TSE & SD results are already included in the RMSE and MAPE calculations previously shown.

The run depicted is the actual run stored in Node 1 Level 1 (Figure 5-8: Tree Nodes Used by Model Representation of Procuring and Launching GPS Satellites Under BATNA) all the way through Node 1 Level 5 of the memory tree and the actual results of this combined approach as was represented in. This run depicts four future generations of GPS satellites. The graphs below implement all previously documented assumptions. Two clearly seen assumptions in the graphs below are capping design life at 15 years and fixing the time interval of all future NRE events at 15 years. As this model now represents the GPS BATNA as understood by the combined model, it now possesses the full predictive capability delivered by this approach. From the perspective of future Satellite (not pipeline) performance, the following plots include a future where all planned GPS updates are included in the Block III and Block IV generations. To better understand the model satellite performance for this, the execution sequence fixes performance for Block V and Block IV as equal to Block IV. Any changes in cost or satellite production performance is the impact of causal effects as computed by the causal loops, not from changes in satellite performance as requested in the Design Vector. Recalling that the Design Vector in the TSE module follows the form:

Design Vector: {Design Life, Payload Alignment, Number of Satellites to Be Produced, NRE Update}

This results in the following Design Vectors being implemented across time:

- **GPS Design Vector Block III: {15, BATNA, 24 Satellites, 1, NRE Pulse}**
- **GPS Design Vector Block IV: {15, BATNA, 24, NRE Pulse}**
- **GPS Design Vector Block V: {15, BATNA, 24, NRE Pulse}**
- **GPS Design Vector Block VI: {15, BATNA, 24, NRE Pulse}**

Figure 5-11: Estimated Production Rate per Year (Out) GPS BATNA outlines the model's prediction for the number of satellites which will be produced per year. This is not the same as the number that will be ordered each year to meet the objective requirement of 27 satellites on orbit (and threshold of 24 satellites); this is the number actually produced. While small blips appear (due to pipeline inefficiencies), the average production rate will likely be below 2 GPS satellites per year under the GPS BATNA. This would be the same as saying on average less than one satellite will be made every six months.
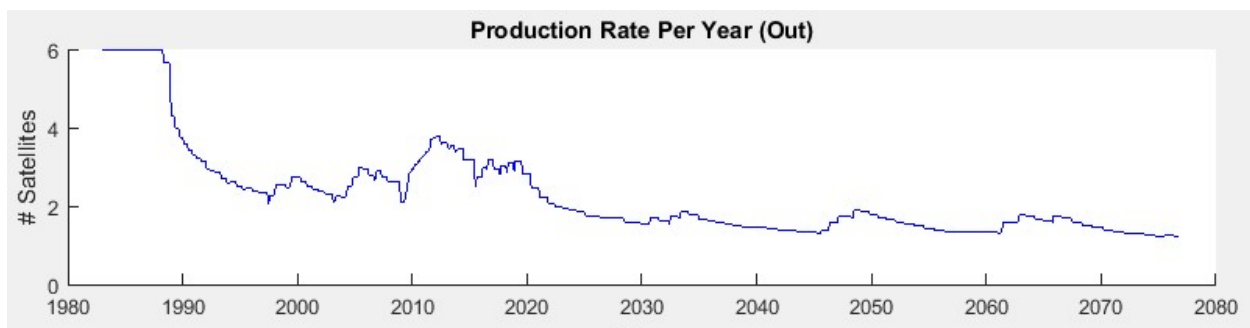
Figure 5-11: Estimated Production Rate per Year (Out) GPS BATNA

Comparing the average production rate out to the Estimated Production Time seen in Figure 5-12: Estimated Production Time GPS BATNA indicates that the backlog of satellites in the pipeline will range from 6 to 12 over the next few decades. This is calculated as a FIFO queue as documented in the SD model construction.
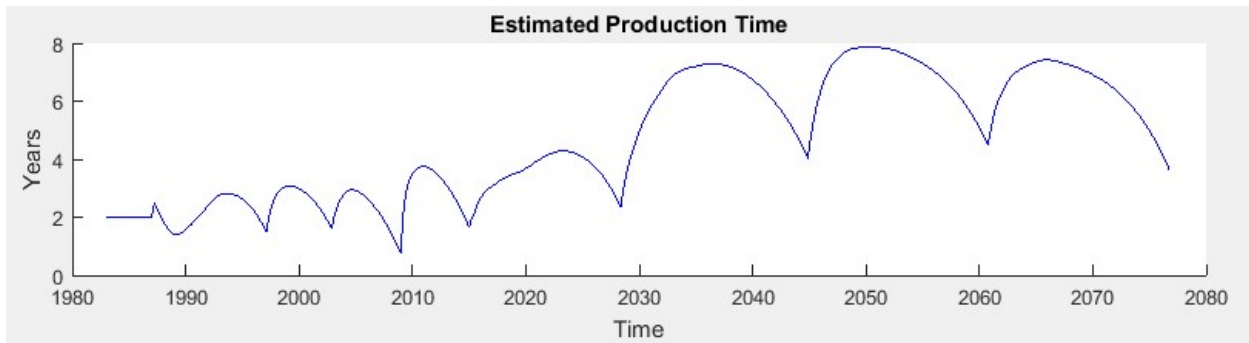
Figure 5-12: Estimated Production Time GPS BATNA

Figure 5-13: Estimated Production Cost per Year GPS BATNA plots the funding levels predicted for the GPS BATNA. In the Block IV generation additional performance above the Block III is added; as noted no more performance is added in the Block V or Block VI. Even with no further performance requests, the cost of production remains high. The model places the replication cost per year at greater than ~500M FY 2010 USD, recalling that the model does not consider inflation, nor the time value of money. The reason for no cost reduction in the face of advancing technology is from three factors. First, the time between technology refresh periods is very long, forcing people to replicate old technology implying a legacy cost. Second, the model indicates long production time of satellites, depleting the value of experience with the technology relative to its half-life. Finally, the model indicates that these long production times lead to large backlogs of work and large pipelines with slow production rates. This is an environment ripe for firefighting behavior and requirements creep. If an error in manufacturing is found, the time to flow back a fix will be long and impact every satellite in the pipeline.
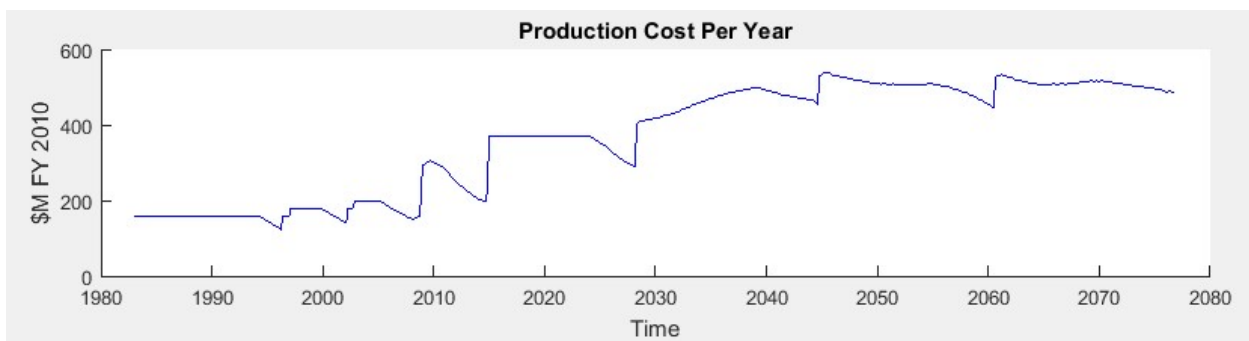
Figure 5-13: Estimated Production Cost per Year GPS BATNA

Figure 5-14: Design Life Implemented GPS BATNA tracks the historical GPS design life implemented. Per the TSE model and current plans, the Block IIIs were issued a fixed design life of 15 years. This is not the same value computed by the Peanut Butter Spread Loop, it is the one forced by the TSE model.
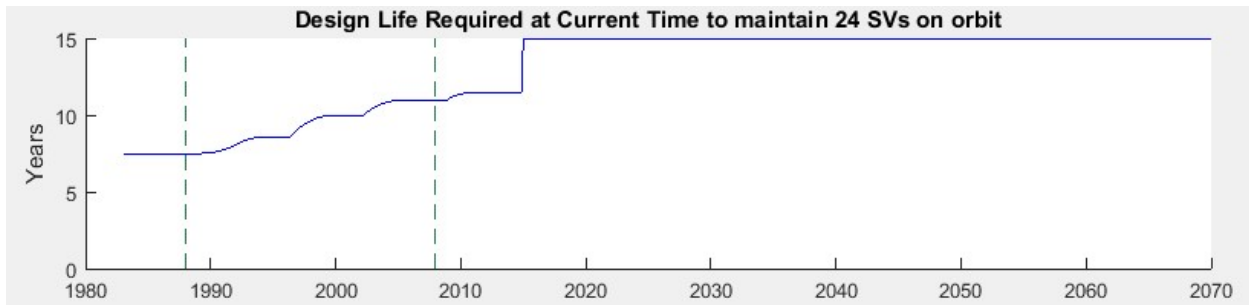
Figure 5-14: Design Life Implemented GPS BATNA

The Historical Design Life was fixed at 15 years for the BATNA. Figure 5-15: Predicted GPS Satellites on Orbit Based GPS BATNA notes that given the baseline funding provided, approximately only 20 satellites will be kept on orbit. The actual number of years of average service life required, according to the SD model is 19.21 years to maintain a constellation strength of 24. As historically GPS satellites have been expected to last longer than design life, it is likely that business will continue as usual to maintain strength. The model is, based on the time constants of the Peanut Butter Spread Loop and the Nunn-McCurdy Loop, also predicting that a small overrun will be required to maintain ~20 satellites, as seen in Figure 5-15. As the magnitude of the overrun is around 125% of the baseline, the re-baselining is slow (it takes years before new funds are added) and the status quo is maintained. The model predicts that the GPS constellation will continue to rely on expensive large long-lasting satellites and programs that struggle to complete on time and cost. The constellation will likely continue to be able to field 24-27 satellites as long as those designed for 15 years last at least 19.21, on average.
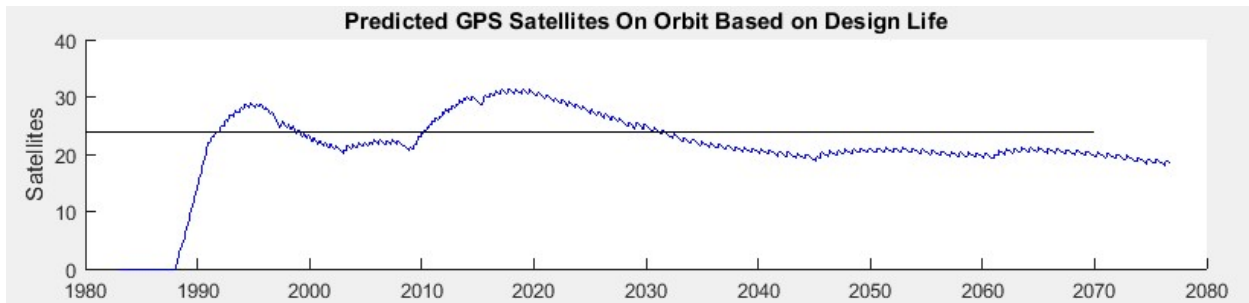
Figure 5-15: Predicted GPS Satellites on Orbit Based GPS BATNA

For the GPS BATNA the technology refresh period for each generation was approximately 15 years as the design life of 15 years implied that each generation of satellites would need to be updated if 24 satellites were built. Naturally if only 12 satellites were built this would imply an update time of ~7.5 years and a production run of 36 would push the time interval towards ~22.5 years. According to Figure 5-16: Technology Half-life Curve GPS BATNA, it can be seen that the time between technology refreshes of ~15 years against current assumptions about technology advancement put each successive generation of satellites in a situation where nearly all the technology associated with the GPS program must be refreshed. Careful observation will notice that the time gap is actually less than 15 years between NRE pulses (it appears to be more like 12-13 years for Block IV and V). The reason for the discrepancy is the longer development time, as each generation takes longer to produce, the model must back up the time of the NRE for the next generation. If each generation takes 2-3 years longer to produce than the last, then the NRE of the

183

next anticipates the longer development time and backs up the NRE to the need date. This is a different situation than was seen in the 1990s where three successive generations were updated inside 10 years.
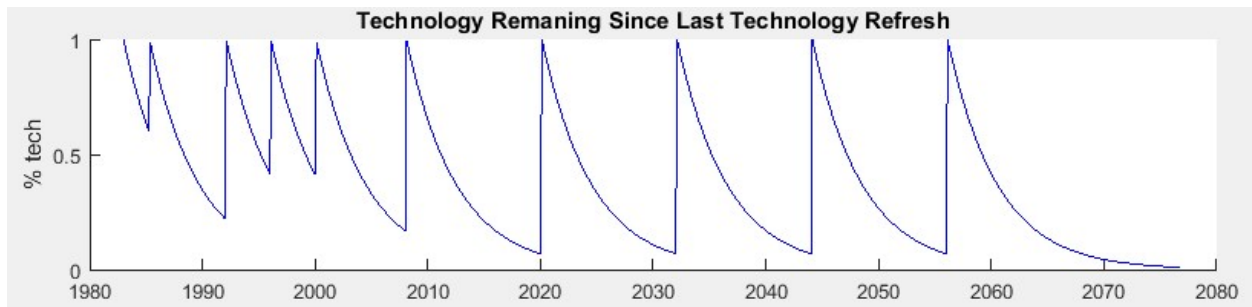
Figure 5-16: Technology Half-life Curve GPS BATNA

Figure 5-17: Satellite Launches and Tech Refreshes: BATNA displays individual satellite launches as pulses in the graph, colored by appropriate generations. Figure 5-7 also overlays NRE events, displayed as the black bars. From this plot we can extract the model view of when NRE events occur, when the first production unit is produced, and for how long the generation is produced.

- GPS Design Vector Block III (green): {15, BATNA, 24 Satellites, 1, NRE Pulse}
  - ◆ NRE Paid 2008, Theoretical First Unit Flown 2016 → 8 Years
- GPS Design Vector Block IV(teal) {15, BATNA, 24, NRE Pulse}
  - ◆ NRE Paid 2019, Theoretical First Unit Flown 2028 → 9 Years
- GPS Design Vector Block V(red): {15, BATNA, 24, NRE Pulse}
  - ◆ NRE Paid 2032, Theoretical First Unit Flow 2045 → 13 Years
- GPS Design Vector Block VI (blue: {15, BATNA, 24, NRE Pulse}
  - ◆ NRE Paid 2043, Theoretical First Unit Flow 2060 → 17 Years
- GPS Design Vector Block VII (blue: {15, BATNA, 24, NRE Pulse}
  - ◆ NRE Paid 2056, Theoretical First Unit Flow Post 2070
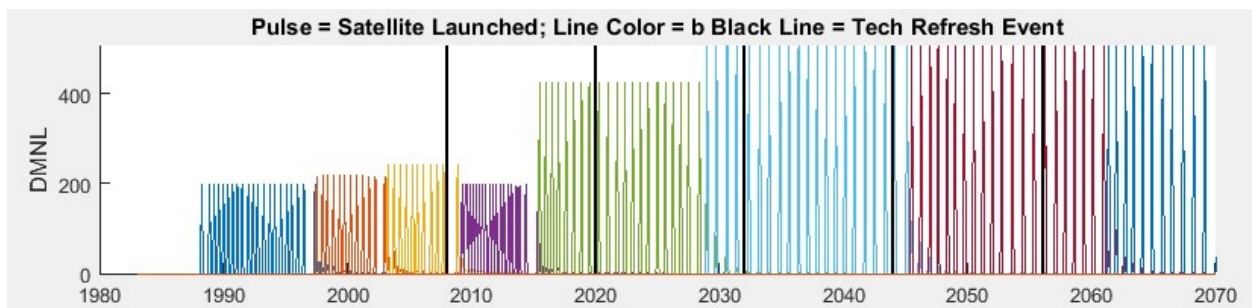
Figure 5-17: Satellite Launches and Tech Refreshes: BATNA

It is interesting to note that the model also predicts that in 2043 the NRE for the Block IV will be required 2 years before the first Block V is ever flown. This presents a serious problem as in this situation no lessons learned could be sent back to the construction (this is the final result of the NRE pulses being backed up 2-3 years each generation). Likely, in this situation decision-makers would probably choose to just delay, the model possesses no such logic to model what

184

would actually happen if presented with this situation. From this observation we can conclude that difficult decisions associated with long timelines of construction will not likely disappear in future GPS acquisitions: rather the model predicts them to be the norm.

These four data points Table 5-1 and Table 5-2 represent the four memory tree nodes associated with the GPS program of record or BATNA run. Where each computation occurs at the time of the NRE event; the green run is the computation in 2008, the teal run 2019, the red run 2032 and the blue run 2043. These generations can clearly be seen overlaid as the back bars on the satellite launches chart, Figure 5-17. As previously noted, this run includes the addition of the L4 signal, crosslinks and spot beams in the second generation (teal), however, no more upgrades are requested in the third or fourth generations. In these plots all dollar values are listed in $B FY 2010 dollars, with no inflation, time value of money or discount rate considered.

Table 5-1:BATNA: 1st and 2nd Generation Cost per Operational Year

	Variable	GPS BATNA		Variable	GPS BATNA
1	Gen #, Design Life (years)	Gen 1, 15	1	Gen #, Design Life (years)	Gen 2, 15
2	NRE This Generation	1.57e+06	2	NRE This Generation	1.96e+06
3	Cost 1st Production	2.19e+05	3	Cost 1st Production	3.33e+05
4	Replication Costs (SD)	4.80e+06	4	Replication Costs (SD)	7.68e+06
5	Launch Costs	2.67e+06	5	Launch Costs	2.67e+06
6	Ops Costs	1.46e+06	6	Ops Costs	1.45e+06
7	Cost Per Year Total	8.75e+05	7	Cost Per Year Total	1.01e+06
8	Cost Per Year Gen	8.75e+05	8	Cost Per Year Gen	1.15e+06

Table 5-2: BATNA: 3rd and 4th Generation Cost per Operational Year

	Variable	GPS BATNA		Variable	GPS BATNA
1	Gen #, Design Life (years)	Gen 3, 15	1	Gen #, Design Life (years)	Gen 4, 15
2	NRE This Generation	1.96e+06	2	NRE This Generation	1.96e+06
3	Cost 1st Production	4.24e+05	3	Cost 1st Production	4.32e+05
4	Replication Costs (SD)	8.07e+06	4	Replication Costs (SD)	8.21e+06
5	Launch Costs	2.67e+06	5	Launch Costs	2.67e+06
6	Ops Costs	1.43e+06	6	Ops Costs	1.43e+06
7	Cost Per Year Total	1.07e+06	7	Cost Per Year Total	1.10e+06
8	Cost Per Year Gen	1.18e+06	8	Cost Per Year Gen	1.19e+06

The results in Table 5-1 for Block III are identical to those produced by the TSE model as validated in that section (and those input into the command script for the SD model in model tuning). The following three generations' cost results are based upon the changing performance requested in the TSE model and the evolving state of the production pipeline.

5.6 GPS BATNA Versus Galileo Implementation (3x Disaggregation)

In Figure 5-18, two of the questions posed in this thesis begin to be evaluated:

1. Can SD techniques be merged with TSE techniques to create meaningful combined models? Further, can this arraignment create translatable results and policy recommendations?

2. How would the current GPS system change if disaggregated and constructed as Galileo-class vehicles?

Throughout this thesis the initial concept of the GPS BATNA in comparison in comparison to the equivalent capability deliver using a design point known as 3x Disaggregation or the Galileo Class Space Vehicle. Here the final results of this question are seen. With respect to the disaggregation of GPS assets into three, Galileo-class space vehicles, Figure 5-18: GPS BATNA vs. 3x Disaggregation and 15-Year Design Life indicates that if this policy were introduced in 2008, some gains in acquisition performance are possible. To unpack the model's output this comparison against the GPS BATNA specifically with Galileo-class disaggregation the model predicts the following:

- The Efficiency Metric improves over time. The Efficiency associated with Galileo-class satellites (red line) is, however, only slightly above that achieved in early GPS acquisitions. (The blue line for the BATNA is close to .4 through 1988. The Efficiency of Galileo-size satellites never rises above .5 often touching .4 through 2058.
- Initial production costs are forecast to be substantially higher than those associated with constructing the GPS BATNA. This is no surprise given that Galileo-class vehicles require the construction of three times as many satellites. It should also be noted that because the industry is currently sized to produce 24 satellites, this imposes a temporary increase in backlog. If Galileo-class satellites had been started in 2008, by 2025 (17 years later) efficiency in the industry would have reached such a level that for the first time the replication cost of Galileo-class satellites would have been cheaper than the GPS BATNA. This can be seen on the graph of production cost where for the first time in 2025 the red line representing the Galileo implementation crosses below the blue line of the GPS BATNA.
- Initially, estimated production time is nearly equivalent, but over several years production time for Galileo-class vehicles this decreases and it ends significantly lower. Generation over generation, a faster cycle time is maintained by the Galileo-class disaggregation, and this reinforcing loop is now working for the industry. One advantage of this architectural design is that the individual satellites are substantially smaller (as shown in the TSE model's initial outputs seen in Table 2-5: GPS Specifications Compared to Model Outputs). While the first few production units would still take two years to create relatively quickly, the pipeline is able to flow back lessons learned and bring production time under six months for each clone. As the design is intended to be implemented (cloned) for ~15+ years, this enables multiple back-flows of lessons learned and as the process gets faster so does the time between cycles. Further analysis as to the length of production runs and the impact of NRE spacing can now also be investigated.
    - ♦ Experience building at a faster rate; however, it is not the triple that one would expect (from building 3 times as many satellites) because experience is modeled on an S-curve. The key change is that in the face of entropy, the experience that is captured is valuable for a longer period of time against technology and process advancement. If a satellite requires six months rather than two years to build, the gained experience remains valuable in the pipeline for 18 months longer.
- The production rate for 3x disaggregated 15-year design life satellites oscillates, which would be expected as production ramps up, reaches a peak, and then slows before the next generation begins. This indicates that the model correctly captures the typical

manufacturing pattern and the difficulty in smoothing a pipeline. The level of production peaks between six and seven satellites a year with one satellite rolling off the production line approximately every two months.

- The number of satellites on orbit required is now a minimum of 72 as opposed to the 24 required of the GPS BATNA; these performance thresholds are visible on the figure. The model is trying to hit a target of 27 for the GPS BATNA, which implies 81 for the tested architecture. As previously noted, the GPS BATNA struggles to keep 24 satellites on orbit, and it is likely that the historical behavior of forcing on-orbit extensions of service life will continue. For the 3x disaggregated 15-year life approach, no such problem exists. It is able to keep more than the required number of satellites in the constellation.
  - ♦ It is reassuring to see that the model responds to reaching an equilibrium state of on-orbit capability in the third and fourth generations. The model initially overshoots the quantity required (as is common in pipelines with long lead times), however, it possesses enough stability that it does not overreact in production. After achieving the needed quantity of satellites, it does not drop below the required performance level and cost reductions are seen beyond this time.
- Technology refresh in both the GPS BATNA and Galileo-class satellites has been fixed at 15-year intervals for a direct comparison of money spent on NRE to combat advances in technology. This does not fix the dollar amounts, only the time period. As noted, NRE (technology refresh) update times will be varied and analysis of a policy variation with respect to this conducted in Chapter 6.
- The individual satellite production spike can clearly now be seen in the seventh graph on Figure 5-18. The graph also shows that in some time periods (one-eighth of a year), more than one satellite is produced. The model also reflects the difficulty of properly phasing an acquisition. Even though satellites are requested at a more or less even pace, it can be difficult to keep a more or less constant number on orbit, since early satellites may take longer to produce and later ones may be produced much more quickly, leading to a clustering of production.

The four tables at the bottom of Figure 5-18 track the costs across each of the four future generations, comparing the costs of the Galileo approach relative to the GPS BATNA. Ultimately, the model indicates that with a 3x Disaggregation and 15-year design life, some cost savings over multiple decades may be possible. The final cost per operational year computation based on the combined model is seen on line 8 in the Tables in Figure 5-18, a relative cost to the GPS BATNA. In stability the model indicates the cost per operational year to be at 80% the cost of the GPS BATNA. The difficulty in comparing two programs which operate over two different time periods is now clear. Is it fair to evaluate the GPS BATNA from 2008 to 2028 against a Galileo implementation from 2008 to 2025? For time similarity, should the run be stopped at 2025? This problem becomes even more complex when the year of NRE events starts to change: one program may produce three generations in the time another produces only two. The costs and the time over which performance is delivered will never match exactly.

To make the comparison easier, the two constellations are designed to provide equivalent performance. There is, however, a satellite performance trade implied in the shift of architectural design. The survivability of the architecture changes as it shifts to one satellite losing the associated signals to the GPS BATNA where losing one satellite loses all the signals. In this architecture the reliability of the smaller satellites is designed to be the equivalent of the existing GPS satellites,

but this must be further examined to ensure this architecture does not make the constellation "brittle". Even with these simplifications the problem of what to consider equal persists. The variable of Cost per Operational Year, however, allows a comparison. Any architectural implementation can be compared against the GPS BATNA from the perspective of cost per operational year. In this variable all associated values (NRE Costs, Launch Costs, Operations Costs, and Replication Costs) can be distilled into a single value. To compare in 2028, the cost per operational year of three years of the next Galileo implementation (which triggers a new generation in 2025) are added to the implementation when compared against the GPS BATNA (which starts a new acquisition in 2028). This avoids the problem of the NRE spike occurring at a random point in time, and smooths launch costs across the life-cycle cost of the proposed architecture. If the modeler believes that there is a difference in performance (survivability, replenishment, complexity, etc.) that is not properly captured by this model, then that can be included as part of the trade between the two architectural implementations and their associated cost per operational year.
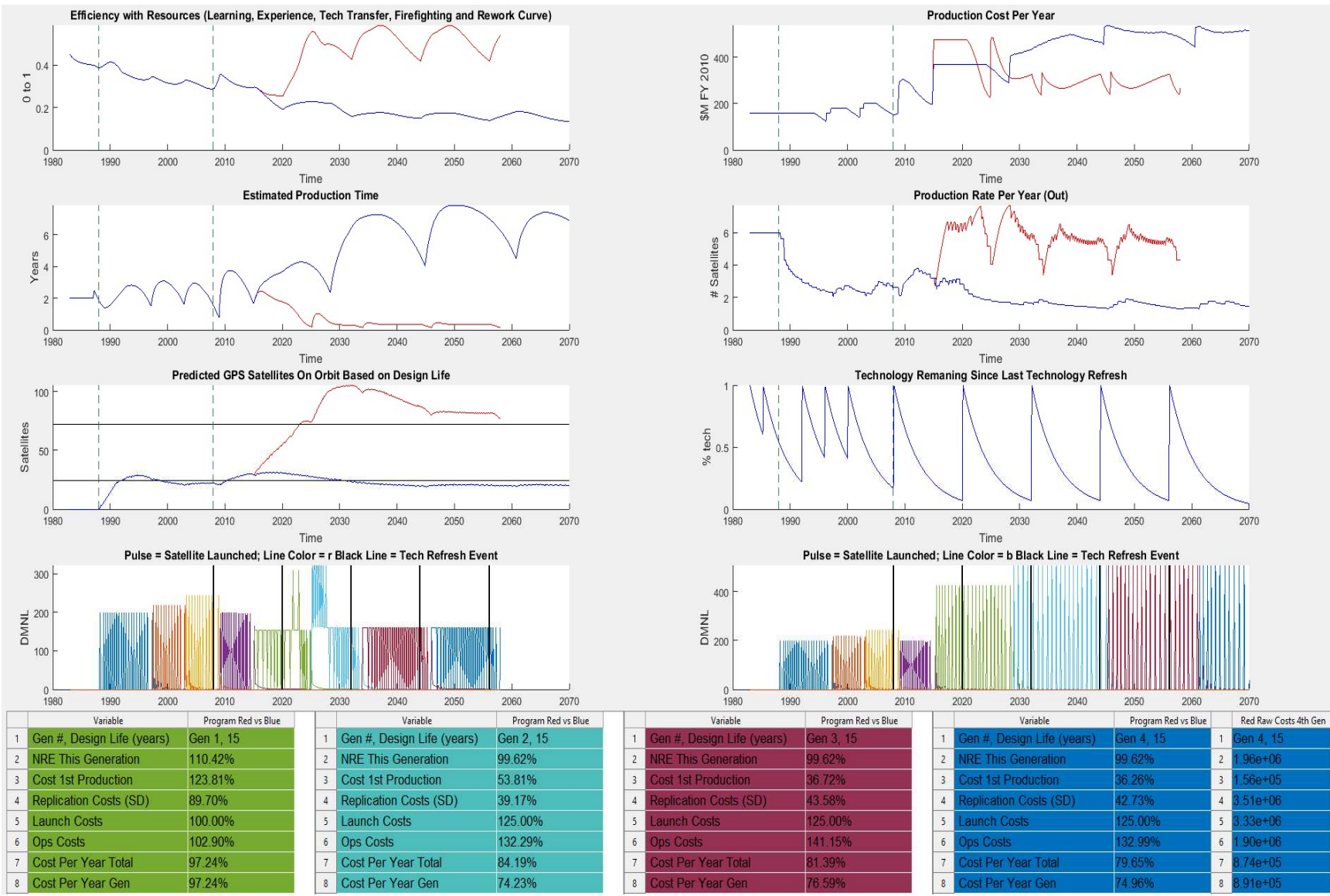
Figure 5-18: GPS BATNA vs. 3x Disaggregation and 15-Year Design Life

5.7 GPS BATNA Versus 7x Disaggregation (Corner Case)

It is typically regarded as good practice when modeling to also examine corner cases. The most extreme corner case in this initial run and policy examination would be disaggregation into five satellites, then six in the second generation and seven in the final generation; each generation adding one more signal to the constellation. Producing satellites, each with a shorter design life (10 years as opposed to 15), tests the upper limit of the model. The lower limit of the model happens to be very close to the BATNA, as no further aggregation is possible (design life realistically can be extended to 20 years and production quantity increased to 32, but the BATNA is already close to this). The model finds the actual GPS implementation in 2008 to be more cost effective at that time.

Figure 5-19 presents the results of the corner case against the GPS BATNA. Not surprisingly, the experience level achieved with production of such a large quantity of satellites is higher than that associated with either the Galileo approach or the GPS BATNA. This level of production is able to push the Efficiency Metric to .6 and keep it there with little oscillation. (The Galileo implementation was able to reach .5, but Efficiency oscillated, often dropping to .4.) While higher efficiency is achieved, total cost savings are not. Over four generations, the replication cost is brought down, but it never drops below the GPS BATNA. The corner case also possesses higher launch and operations costs. A design life of 10 years as opposed to the GPS BATNA of 15 has two direct impacts: it reduces the entropy injected from technology degradation, and increases the number of satellites that must be produced during the same time period. It should be noted that towards the end of each generation's production run, satellites are being produced at a time equal to or less than one-eighth of a year; this is the only time a saturation condition is observed in this work. This implies some additional efficiency may be present that is not reflected in the model, but this would not be sufficient to overcome the increased costs of this approach. It appears this approach would cost on the order of 140% more than the baseline of the GPS BATNA when Production, NRE, Launch and Operations costs are considered. This implementation would look radically different than current operations—one satellite would be produced every six weeks at peak production. This would be radically different concept of operations than currently experienced.
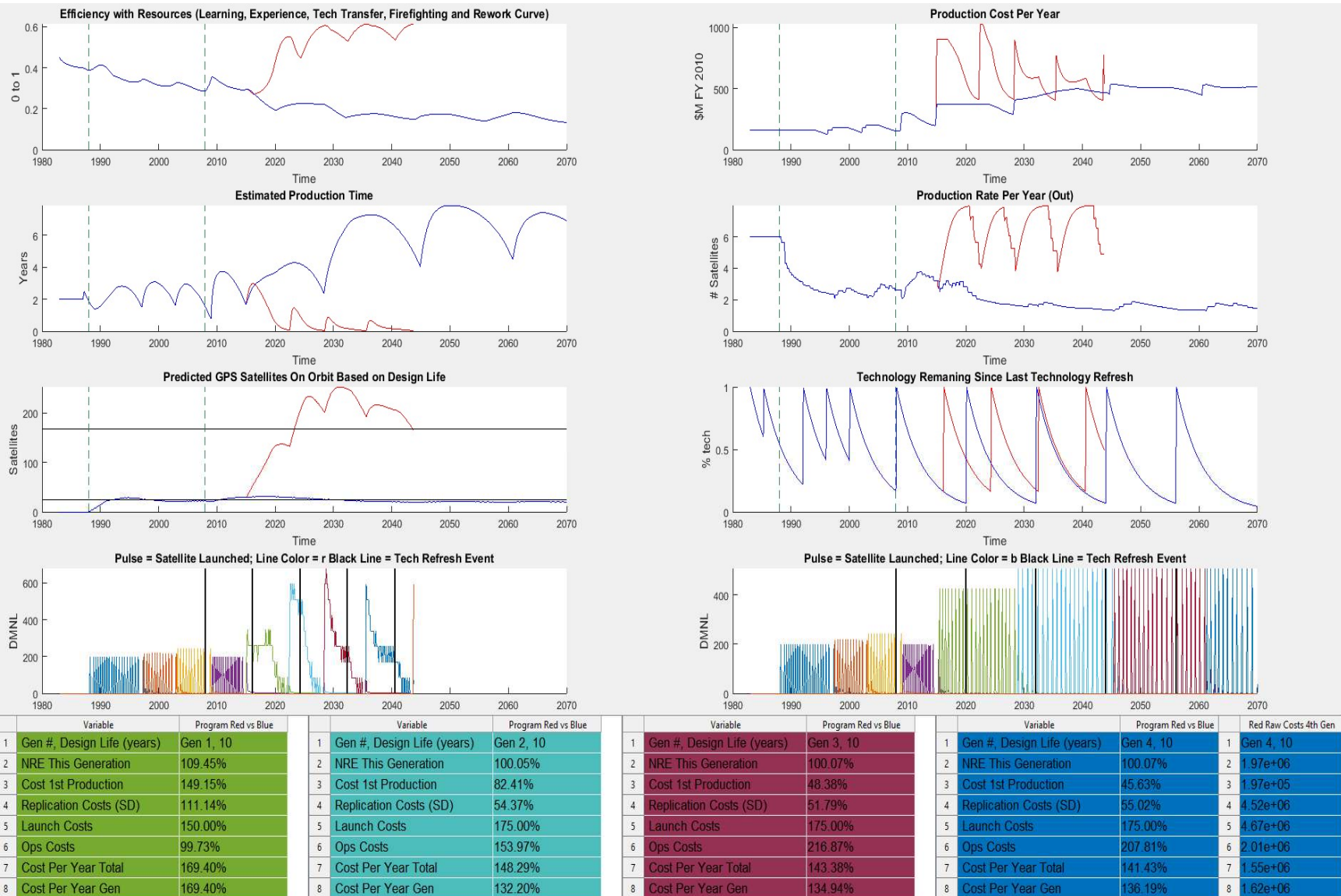
Figure 5-19: GPS BATNA Vs 7x Disaggregation and 10-Year Design Life

5.8 Impact of Policy on Cost per Operational Year

Figure 5-20 displays the model implementation of the policy of disaggregation as described in Table 6-5: Policy Test Matrix as well as varying design life (7.5, 10, 15 years) and procurement sizes (8, 16, 24, 32). While other policies are investigated in Chapter 6 here a small data run is display to examine the model output of cost per operational year over four generations of the BATNA versus the 3x Disaggregation Galileo approach. Some of these policies have the causal effect of changing the times of NRE events since NRE is impacted by how long satellites last as well as how many are cloned before a new design is implemented. As such no information about the year when these generations complete is shown, only the cost per operational year for the first and fourth generation is seen. The blue dots in the figure represent designs that are most similar to the GPS BATNA (no disaggregation, only changing procurement size 8 to 32 and design life 7.5 to 15). In 2008, the most cost-effective implementation or lowest cost per operational year designs are similar to the GPS BATNA. (The GPS BATNA as shown above is represented by the green dot.) Yet, while the exact GPS BATNA is the cheapest architecture in 2008 in the first generation, by the fourth generation it is much further from the Pareto front. It has lost ground (become 50% more expensive) as a consequence of underlying trends (less experience, longer technology maturation etc.) explored in the discussion of the GPS BATNA. Note that the cost per operational year shown on this plot is the same as the cost per operational year for the GPS BATNA in Table 5-1 and Table 5-2.
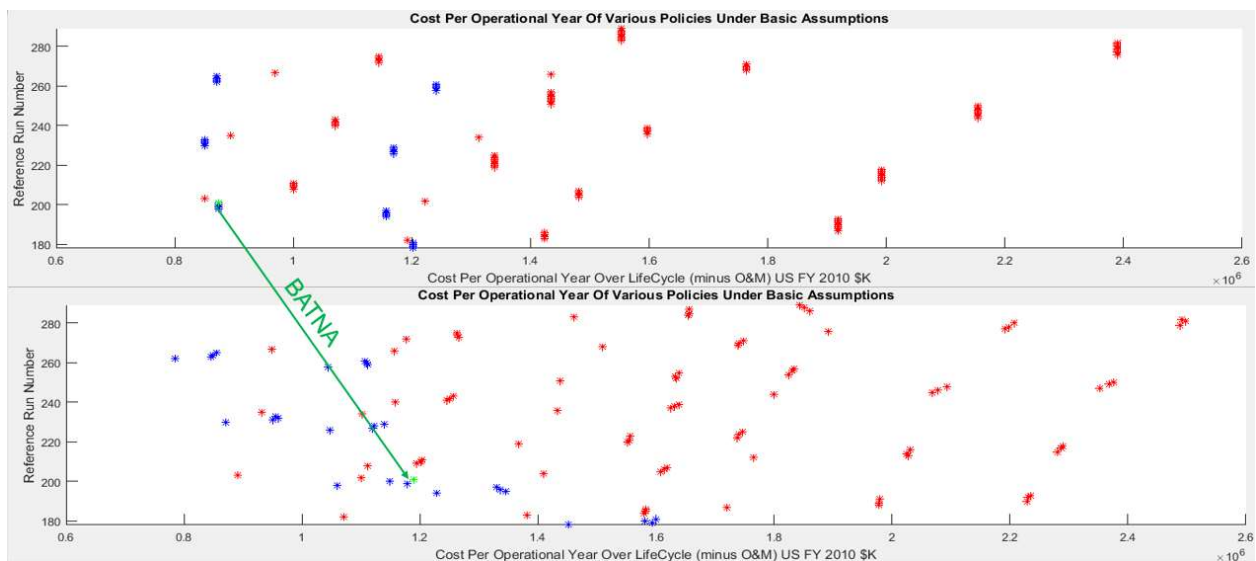
Figure 5-20: Change in Operational Cost per Year Generation 1 to Generation 4 for Various Policies

As can be seen in Figure 5-20, some disaggregated approaches seem to become viable, or cost neutral over time (shifting from the right side of the plot to the far left, indicating a drift to a more cost-effective implementation). It is worth comparing the GPS BATNA against some of those designs to see what makes them more appealing; which will be the focus of Chapter 6.

5.9 Discussion

Modeling efforts indicate that the production of GPS satellites may be prone to "tipping." One definition of tipping is "a discontinuity between current and future state of a system and introduced candidate measures of when a system tips based on changes in the probability distribution over future states." (Lamberson & Page, 2012). Detection of tipping is valuable with respect to SD and this model as knowledge about when the model tips may indicate the level to which a stock must be driven before an effect (positive or negative) occurs. From the Perspective of GPS is would be valuable for the system to tip towards fast capitalization on experience leading to a victorious cycle of learning, or capitalization on learning effects. It would be unfavorable for the system to tip into a region where production grinds to a halt as the system is overwhelmed by the task at hand. After calibration to historical GPS data, the model tips when Process Cycle Time becomes shorter than technology half-life time and it remains there for more than one Process Cycle Time while everything else remains static. Noting that the SD model always functions as an average and as such represents the probability distribution of both the Technology Half-lives and the Generation Times. The gradual small change of getting the Process Cycle Time below the technology half-life causes a reinforcing effect which leads to large changes in Production Times over a several cycles. This would be a positive situation: lessons are easily flowed back from one production to the next and people are able to capitalize on learning effects. The inverse is also true: if process improvement time is longer than the length of technology half-life, production time takes too long to capitalize on experience and learning effects and it becomes stubbornly hard to shorten. (Though the model once in this region does not tip further.) In this case, three reinforcing loops—the Experience Loop, the Process Cycle Time Loop, and the NRE Loop—are all working against the industry's production of the GPS BATNA. The Peanut Butter Spread Loop acts as a weak balancing loop and the Fire-fighting Loop possesses only enough strength to prevent problems of current overruns but not to protect against future overruns.

Modeling of a Galileo-class implementation reveals that the major reason for more cost effective acquisition is not increased strength of the Experience Loop (though it does help), but the shortening of Process Cycle Time. It is shorter cycle times that are able to offset the fast advancement of technology. Nonetheless, even if shortened, it would still likely require over 15 years to move from current conditions to a stable situation, one the model tips in favor of lower production cost, where the new normal is faster iterations (the DoD acquisition pipeline possesses a lot of inertia and the tuned model captures some of this resistance to change in its strong stability). Aside from this single tipping point, the model appears to be highly stable, where the acquisition system changes slowly and in measured response over time. Thus, the answer to the question of when do the reinforcing loops work for the industry is: when multiple generations are completed inside the technology half-life time within a single production run. A single generation would quickly spike Efficiency, but would not "catch hold" and any gains would be lost over the next acquisition. This implies that the next policy to test is the spacing of NRE events across time; should they be even or should several quick NRE events transition to longer periods?

Most worrisome are the implications of longer intervals between NRE and longer-lasting systems, which ensure that planned generation design life will be longer than the cycle times of the associated technology maturation loops. In short, GPS for the foreseeable future will be in a position of first-of-a-kind efforts, leveraging little capability from previous generations.

An additional important observation is that policies aimed at increasing experience may have the unintended consequence of decreasing Efficiency due to triggering an initial spike of work that overwhelms the industry and creates a backlog. If a disaggregated approach (or any other policy that increases the amount of work added to the pipeline) is initiated without sufficient funding to match the initial increase in work, the backlog may lead to firefighting behavior which will decrease efficiency, and in turn slow the production of satellites. This will prohibit lessons being passed from one generation to the next. The increase in the cycle time will cause this loop to further slow production; stalling the gains expected from additional experience with production.

Increasing design life does reduce pressure on an over-worked or underfunded pipeline with a finite set of resources. Decreasing requirements in the face of advancing technology can have the same impact, but then runs the risk of seeding the technological "high-ground" to another party. It is likely that policy makers are able to project future design life and commission future acquisitions with reasonable expectations about what technology can provide in the future. Thus the industry stays in a quasi-balance as long as problems can be pushed into the future where each program costs a bit more and takes a bit longer to develop. If design life cannot be extended, requirements must be sacrificed or more funding must be secured. One consequence is that simply spending more money to generate more activity will not improve industry performance. (This is the model's interpretation of why it may appear that government programs spend a lot of money and have a lot of overruns but never seem to get "healthy.") Another consequence is that with these mechanisms in place, many policies (new ideas) may show a temporary improvement, however, unless the underlying causal loops are addressed, a return to the mean is likely.

Given large production numbers, Process Cycle Time would naturally decrease—experience with production would increase and sequentially shorter production cycles would build upon themselves in a virtuous cycle. But GPS satellites have small production runs. It is hard to overcome long cycle times and what amounts to resetting to a first-of-a-kind effort. (Note also that first-of-a-kind efforts have the highest rework rate of any activity.) The impact of an inability to flow back lessons and experience is exacerbated by the speed of external technology advancement, which over the last three decades has been rapid, leading to a large percentage of satellite technology to be refreshed each generation. Under this set of conditions, the minimum cost to deliver capability pushes the time period between technologies refreshes to the longest time between refreshes possible. This gives some insight into the problem of flowing back experience from the first production unit. If it takes eight years to produce the first flight unit and then more years for the first production unit, it is not until that first production unit is complete that experience can be flowed back to the next unit in the pipeline. Due to the long lead time for producing satellites, it is likely that nearly the entire production run may be complete before lessons which could decrease production costs might be successfully flowed back to the production pipeline. This reality may better be combated by the Tick-Tock policy implementation and associated polices (evaluated in the next chapter), than by disaggregation.

5.9.1   Re-Evaluating the Model Boundary

In the introduction of the section, Elements of this Problem as Defined by System Boundary, candidates for inclusion in the model were defined. In Model Conceptualization in Chapter 3 the system boundary was again examined. The following is a reconciliation of the ultimate choices in defining the model boundary Table 5-3: The Merged Model Boundary contains hyper-links to each named section:

Table 5-3: The Merged Model Boundary

The acquisition process for space vehicles	The request for space vehicles Model Conceptualization specifically, Stock and Flow Diagrams where a pipeline generic structure is encoded to represent satellite purchases. The design and cost of space vehicles is handled in the TSE model in Construction of a TSE Model for GPS Satellites. The end result of this effort is a validation of "tokens," representing satellites which are placed in the SD pipeline. Throughout this document the delineation among satellite performance, the capability of the specific satellites under examination, and the acquisitions system's performance (ability to procure the satellites) has been outlined.
The concept of learning and the "health" or capability of the Space Industry	As the industry gains experience over time, decreases in cost and production time within generations will change. Within generations learning can also reduce the cost of each copy of a vehicle as the nth unit is produced. This concept of learning can work both within a generation of units and between generations. The Efficiency variable as implemented also works as a store of learning effects. This is seen in its construction of the Efficiency variable in Model Formulation, where the single variable of experience combines the major loops of the SD model as a proxy for health of the industry.
Policies in space architecture design	The current design point and the concept of disaggregation as related to satellite design is outlined in Payloads Placed on GPS Satellites. The impact of such architectural designs is first examined with respect to SD in Evaluating the Policy of Disaggregation. Further evaluation of such policy and its conclusions are seen in Performance economies of scale means that as a spacecraft grows larger, it becomes more capable and higher-performing. For example, a 3000 kg satellite is likely to be far more powerful and have greater service capacity than that of three 1000 kg satellites, due to the scaling up of all components. Additionally, one large spacecraft may be less expensive and require less time to produce than a constellation of smaller spacecraft with equivalent performance. This is directly seen in Model Comparison to GPS Program of Record.
Life-Cycle Costs	Non-Recurring Engineering (NRE) Costs are discussed in Theoretical First Unit, its relationship across time is discussed in the section on NRE Gap in Relation to GPS Historical and Planned NRE Investments. Cost of Launch Vehicles, Launcher Select and the impact of changes are noted in Cost of Space Vehicles. These costs are first outlined in their computation listed in First Production Unit. The adaptions to this modeling approach are then discussed in the section on Satellite Production Costs.

Technology and Performance	Changes in requirements over time is modeled in changing the design vector at each generation. This is discussed in the sections Payloads Placed on GPS Satellites, TSE Model Runs to Assess Future Capability and Results GPS Program of Record. The rate of technology change across time is also discussed in the section on Technology Gap.

5.9.2   Comparison with Epoch-Era Analysis

In Chapter 1, TSE and its composition of cost and performance models was discussed. It was noted that TSE practices incorporate multi-attribute utility theory (MAUT) to compare model outputs against a variety of performance measures. TSE and MAUT can be extended through the concept of Epoch-Era analysis. With Epoch-Era analysis, a change in context impacts the values resolved by the utility function for different design points. The key take-away being that including Epoch-Era analysis allows recognition that the performance of a system as designed may not be the performance delivered, as the future environment in which the system operates may change. Each different context arrangement, or Epoch, are assigned time periods, and the sequencing of these Epochs forms an Era. A multi-attribute utility function cannot be directly compared across contexts; comparison among designs' utility (between 0 and 1) is viable only within the individual context of the Epoch (e.g., a utility of .4 in Epoch 1 does not tell us if that design is better or worse than if in Epoch 2 it possesses a utility of .5, only the relative rankings against other designs in the epoch is valid). Nonetheless, the relative ranking of different design points can be compared to understand how different designs might fare across different contexts.

Having constructed the deterministic modeling approach of the merged model in this thesis, it is useful to compare it with Epoch-Era analysis, as they each attempt to extract similar types of knowledge about performance of systems with respect to possible future conditions. Yet, before examining the nuances of these different approaches to examining performance under uncertainty, it is important to define performance. In MAUT, performance is clearly defined by the utility function computed by the performance model(s) and normalized based on the individual weightings given to each performance metric. Utility is defined as a measure of perceived benefit under uncertainty, or how well the system meets the desire of stakeholders. (Keeney & Raiffa, 1993) While most examples of Epoch-Era analysis have focused on the performance of specific systems and implementing MAUT on them, Epoch-Era analysis can extend a model boundary to the performance of a system and the system that produces it (or a system of systems perspective), if an appropriate utility function can be produced. Thus, evaluating the performance of GPS satellites is very amenable to existing Epoch-Era analysis work.

In theory, a model that includes variables such as acquisition time and funding overruns would be able to draw the production pipeline into the model boundary (as the model in this thesis has done). The difficulty is that no existing, readily available satellite models that possess the needed metrics to compute such a system view are available. (Boeing and Lockheed likely have internal models, but the public cannot access them.) This is one of the reasons the SD model of this thesis was constructed and the Efficiency metric invented as a proxy measure/model for the satellite acquisition system over time. In modeling a system, a SD model is said to be high performance if it quickly responds to change. A modeled system is identified as stable if it responds slowly, or in small magnitude, to exogenous shock.

In this work, where a merged two-model simulation has been constructed it is important to realize that there are two concepts of performance. As just discussed, there is the performance of the SD model. Additionally, there is the performance of the GPS satellites themselves. Their performance, or ability to place signals at earth's surface, is tracked by physics models that inform the TSE modeling and typically could be well modeled in MAUT. The SD model trusts that these performance models enable it to tokenize GPS satellites and this type of performance. In the SD model, performance is measured by the ability to produce the desired GPS satellites as well as respond to changes across generations. The TSE model trusts that the SD model is able to cost and field the desired tokenized system and the SD model's performance with respect to cost and time.

This SD approach replaces the human construction and sequencing of epochs in Epoch-Era analysis with procedurally generated epochs derived from the output of the SD model. While epochs are traditionally defined by a change in context, this approach uses continuous functions rather than the discrete functions (time period) of traditional epoch construction. While this approach does not preclude using discrete functions, even if the user implements a discrete function, as developed, this approach implements epochs in a different fashion. Performance in an epoch is never tied to performance in a previous or future epoch. This is consistent with the TSE model's computation of different architectural implementations of GPS satellites as specified by the Design Vector, for which performance does not depend upon future or past designs. It is, however, inconsistent with cost and time performance in the SD model where future performance is causally linked to past performance; both for NRE and replication cost and time.

With respect to epochs, the initial state of the model (Node 1 Level 1 in the Memory Tree in Figure 5-8) is identical to constructing an epoch within Epoch-Era analysis, as this tuning function is of known length and condition. (In theory, the tuning data provided by the SD model are no different than setting the context variable for the epoch.) The approach in this work breaks from Epoch-Era analysis in the following (second) epoch, by basing the second epoch on the output of the first. In traditional Epoch-Era analysis, the modeler predetermines the world by laying out the conditions in which each epoch occurs. In this implementation, epochs are computed at run time, their length is determined by the time between need for replenishment of satellites. (As noted previously in the discussion about TSE loops, the time of acquisitions can change.) If one were to compute every single Era possible given a Tradespace Model, and if that very large set of Eras included the parameterization of every context variable, then the futures that this modeling effort produces would be a small set inside that Tradespace of all possible Eras. By using SD both to lay out an Era-style analysis, as well as parameterize the epochs, the model creates an era with as many epochs as there are time steps within the SD model. (While technically correct, this is not really a useful comparison because this is not how Epoch-Era Analysis is used and it would not be useful for this purpose).

This work is further differentiated from traditional Epoch-Era analysis as it does not implement MAUT, but rather a single utility function of cost per operational year. As previously discussed, this enables direct comparison between one time sequence and another time sequence, at the cost of fixing performance among all systems to identical levels. Use of cost per operational year is also required because of the lack of the fixed time period provided by an epoch. It would be impossible to compare designs when the time periods of execution are not exactly the same between design points. (This is also why constructing the BATNA run was critical to establishing the validity of this approach.) This approach helps to answer questions about holding performance steady while implementing changes to architectural design. Nonetheless, it is weaker when

comparing exact satellite performance than Epoch-Era analysis with respect to how that performance is delivered, as it lacks a multi-variable utility function. Instead this approach relies on the modeler to determine which performance metrics change between architectural designs, and to evaluate the change in performance between the design points, as part of the change in cost. It is possible that future work might build upon this and create a valid method of comparison across time using more than cost per operational year.

Adopting the logic of Era-style analysis, that changing the sequencing of epochs produces different eras, we can also change the time at which a context variable would change, or the sequence in which variables change, to examine performance of designs over time. All that is required is that a context variable must be changed and the simulation re-executed. These additional analyses of the effects of context change will produce almost the same number of tree nodes as the first analysis. Yet, due to the fact that an exogenous variable (change in context) will affect variables within the SD model, no two executions will possess exactly the same nodes (though the decision pathways based on the Design Vector should be identical). Due to tree pruning it is possible that some nodes may be deleted or added, and the times associated with these nodes may change.

5.9.3   Extension of Work

A common approach in executing SD models is to use sensitivity analysis or Monte Carlo simulations to test for variance in system response across exogenous input variables. From the perspective of the SD model, changing the number of satellites ordered at a point in time may fall within the region of a sensitivity analysis with a large region of examination. While the technique being used here goes far beyond sensitivity analysis, from the perspective of a SD model it will look very similar. It is possible that with future developments a tool such as Vensim would natively be able to support the type of functionality represented in Figure 5-2 and an external control module would not be required, as it would be embedded in Vensim.

This work, while deterministic, does not preclude the inclusion of some stochastic elements, specifically failure of satellites, failure of launch vehicles, and change in performance under random perturbations; however, as all calculations in this work are deterministic and this method does not seek to evaluate random events this will be left to future efforts. Still, if random events, such as premature satellite failure, or disruptions to production were introduced into the simulation, the model would respond to the perturbation and information about the time and the system's ability to cope with such a perturbation could be examined. Simple tests are possible with this model, such as removing satellites from the existing on-orbit stock. It is also possible that adding agent-based techniques, where every satellite is actually an agent, may improve this modeling technique. If each satellite in the pipeline was an agent, the model could calculate individual slots for each satellite inside an orbital constellation. The model could then also predict the need dates for the individual replacements of satellites. This could be a more effective way of modeling launch manifests in a disaggregated constellation since a more accurate count of the additional satellites required could be processed. This would have the added benefit of being able to draw launch demand and potential learning effect with launch into the model boundary. Moreover, each satellite could then be tested against its own probability laws governing orbit failure or extension of design life, as opposed to the current model which applies the same average to all satellites both in the pipeline and on orbit.

6 Policy Testing on GPS Acquisition Pipeline

Having created and validated a SD model which examines the procurement of GPS satellites over time, and having merged it with cost and performance models within the framework of a TSE model, we now implement this merged model to examine its predicted consequences for various architectural and policy changes. The goals in examining these policies are to answer the research questions of this thesis and to illuminate why some policies may work while others fail. A variety of policies were selected to answer the research questions set forth in Chapter 1. The results of these policies which emerge from the merged model are explored in the remainder of this chapter.

Remember that the current business model for GPS acquisitions and operations requires satellites to last longer on orbit than the life for which they were initially developed. While obtaining extra utility in the form of longer design life is not inherently bad, if this reality (all satellites in a constellation operating 1.5x to 2x beyond design life) is required to meet performance needs, it is a strong negative. It places the constellation in a weak or brittle position where a single failure could have substantially negative impact. This work seeks to find possible paths to eliminate this current acquisitions reality in future proposed architectures.

6.1 Comparing Programs and Architectures Across Time

A comparison of the cost effectiveness of programs and architectures across time requires a measure on which a comparison can be made. In previous chapters it was noted that the variable of cost per operational year is a potential metric for comparing the cost effectiveness of two programs. When this metric is extended to comparing programs across multiple generations, however, it can fail to provide an accurate comparison. Thus, cost per operational year is not sufficient as a measure for comparing cost effectiveness of programs.

Additionally, in comparing government acquisition strategies, cost per operational year implies not just the cost per operational year on orbit but also the cost per operational year in the Five Year Defense Plan (FYDEP). These are not the same variable. Cost per operational year on orbit refers to the number of years of capability derived from the total investment during acquisitions (and the on-orbit support cost), divided by the number of years on orbit for which the asset delivers value. Cost per operational year in the FYDEP refers to the amount of money spent in the current year to procure future capability. Spending in a present year in the FYDEP is important as it is the budget constraint in a current year as outlined by the President's budget, but the cost per operational year on orbit is not realized until the future (and really cannot be calculated until the satellite is taken out of service). The time lag between cost savings in the current year versus cost savings when satellites are on orbit can be a difference of decades. Thus, when comparing two acquisition strategies both cost metrics must be considered. This relates back to the problem of myopic decision making; it is possible that the implementation which minimizes the current year cost in the FYDEP may incur substantially larger FYDEP costs in future years. It is also possible that the policy which decreases current year costs may produce less capability; and potentially in a non-linear fashion (e.g., saving 10% in the current year may cut more than 10% of the capability in years of operational capability delivered to orbit, resulting in an increase of more than 10% in the cost per operational year once on orbit).

The United States government has shown a preference for keeping satellite production open and buying at a steady, predictable rate. One positive consequence is that this enables the

contractor to size a workforce and facilities for predictable acquisition levels. Additionally, and arguably more important, this style of contracting avoids the need to restart a closed pipeline in the event that additional unexpected capability must be procured, a process which can be extremely costly and time consuming. In practice an acquisitions pipeline is rarely closed until a follow-on contract is opened. In GPS, this is clearly seen where the production and launch time of the last IIFs coincides with the first IIIAs (2016). It is also seen in the crossover of all 4 of the blocks in the II series (A, R, R-M and F). In the IIA to IIR transition, two of the IIRs were launched before the last IIA. There was a seven-month gap between the last IIR and the first IIR-M, and nine months elapsed between the last IIR-M and the first IIF. The DoD clearly intends to continue this policy of an open pipeline as a hedge against an unexpected need for additional satellite capability. On this account, this behavior of programs being sequenced to begin and end to prevent a "closed pipeline" ever occurring, was encoded into the SD model in Chapter 3. This, however, creates another difficulty for comparisons across time. Since the model must start a new acquisition as soon as the previous acquisition finishes, this inserts a potential bias in favor of the BATNA because it, unable to maintain the performance threshold without extra on-orbit life, spreads acquisitions across a longer time period. This has the potential to make the BATNA seem more attractive than it really is as no account is given for what might happen if on-orbit extensions of deign life fail. A program delay might increase the number of years for which the program is being acquired, and this may artificially deflate the cost per year of acquisition, if only the cost per operational year in the FYDEP is considered. In Chapter 7 the reality of different policies being extended once on orbit will be examined. In this chapter it is assumed that satellites only last their design life, the exception being the BATNA, as this is a behavior we are trying to move away from, and the cost of such a move must be calculated.

Figure 6-1 has been constructed to illustrate these two problems. The model's forecast for the GPS BATNA is displayed in blue, and a radically different and substantially more expensive architecture is shown in purple. The colored squares represent the time for each acquisition, generations one through four. It can be seen that approximately four generations of the alternative acquisition occur within the same length of time as three generations of the GPS BATNA. (This graph also illustrates the changing cost of production across generations, which is considered later in the chapter.) The problem of direct comparison is: should the first purple square be compared against the first blue square in terms of their production cost per year, or cost per operational year based on the capability put on orbit during their respective time periods? In point, the problem is even more complicated than just comparing across generation or time, it also extends to how many years of operational capability are acquired while spending resources.
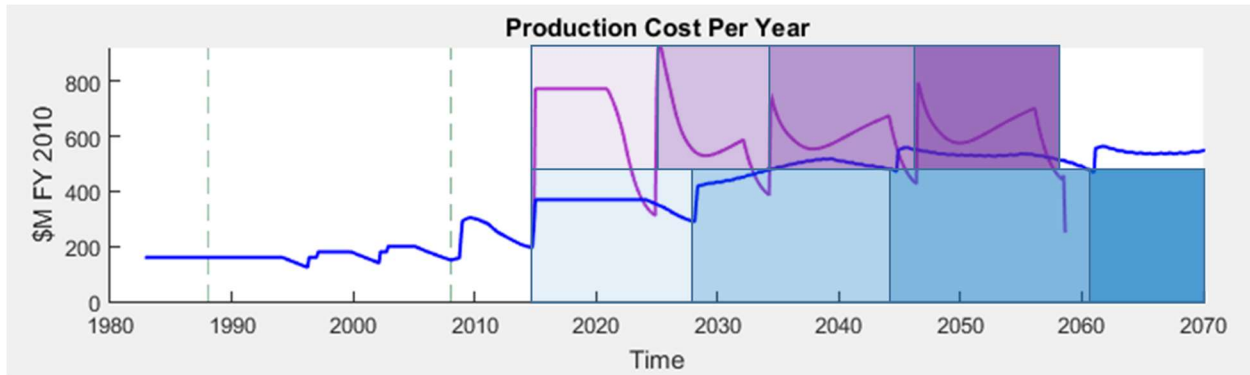
Figure 6-1: Comparing Acquisitions Across Time BATNA vs. Higher Cost and Faster Advancement Acquisition

To enable appropriate comparisons of the different acquisition strategies considered in this chapter, results are presented for four variables which answer different questions about cost while providing the most direct comparison across time possible:

1. **Cost per Production Year:** This metric directly compares the total cost of the acquisition in a generation versus generation comparison. The total cost of all program elements are summed and divided by the number of years over which the program elements are acquired. The advantage of this approach is its direct comparison of the cost of two (or more) acquisitions. It does not consider time: if one acquisition completes faster than the other, it accrues no benefit for spreading the total cost over fewer years. In fact, it will appear to have a higher cost per production year. For example, a program which completes in 10 years but costs the same as one that completes in 11, would appear to be 10% more expensive per year based on this comparison metric, even though both delivered equal capability and the alternate implementation completed one year faster. Ten percent per year additional funding may or may not be acceptable, even if overall it delivers capability at a lower cost.

2. **Cost to Acquire a Year of Operational Capability:** The model assumes that every year the GPS pipeline must produce on average 24 years of operational capability in order to maintain 24 satellites on orbit. (Each satellite consumes one year of capability per year. The model targets 27 as the goal in production.) This metric compares how much is spent to acquire one year of on-orbit capability. A program with higher efficiency will likely perform better with respect to this metric. Nonetheless, while one program may be able to acquire capability at a more efficient level, since this metric does not consider time, it may also cost more on a per year basis (as noted for the first metric, Cost per Production Year). The appeal of this metric is that it speaks to the efficiency of the acquisitions system, lowest cost being best. This may or may not translate into overall savings, as one may spend more to capture greater efficiency. The decision-maker must decide if the premium over the GPS BATNA is worth the efficiency gained.

3. **Cost at the End of Production, Policy Cost per Year Relative to BATNA:** This metric seeks to answer the question of the average cost per year to acquire at a specific point in time (specifically at the end of one acquisition in comparison to the BATNA). This metric provides a direct comparison of the cost between 2008 and the end of a policy acquisition versus the BATNA. Unfortunately, this metric suffers from end game effects—based upon

when generations complete, a program may look better or worse at one given year depending upon when the GPS BATNA shifts from one generation to the next. Acquisition approaches that advance technology faster, typically look worse with respect to the BATNA based on this metric.

4. **Compensate for Difference in Production Rate:** This variable divides the Cost at the End of Production (the third metric) by the Cost to Acquire a Year of Operational Capability (the second metric). This hybrid value speaks to both efficiency and cost of the system at a point in time. This is a reasonable metric for determining whether one program is "better" or "more efficient" within a generation. The cost per production year (the first metric) must always be considered as well. The additional cost of the program on a per-year basis with respect to the FYDEP is captured by the first metric and is excluded from this metric. With that in mind, this is the value to consider if one is seeking to evaluate future strategies which do not rely on extending satellite operational life beyond design life in order to meet performance thresholds.

6.1.1 Possible Additional Performance Metrics

While this work focuses primarily on the cost to acquire capability, there are some additional metrics which can be of value when comparing architectures.

1. **Time Between NRE (Technology Refresh) and First Production Unit:** The time between program origination and the first production unit being launched. (e.g., for IIIA the flight of the first unit is currently considered to be 2008 to 2017 nine years.) It would be desirable to see this time decrease, as this would speak to shorter development cycles which would be less vulnerable to sources of entropy such as requirements creep or technological change during development. To put this span of time in perspective, GPS IIIA's development is only one year shorter than the entire history of the iPhone (2007); the first Intel core i3-i5-i7 came out in 2008 as well, and the entirety of President Obama's time in office will complete before a single IIIA is launched.

2. **Years of On-Orbit Capability Produced per Year:** The second cost metric, Cost to Acquire a Year of Operational Capability, recognizes that 24 satellites must be produced per year to maintain GPS capability. It may, however, be desirable to know not just the cost to produce this capability, but also the raw number produced. The model caps on-orbit capability at 32. (Beyond this production is slowed and the non-production claimed as cost savings.) This metric allows recognition that a program which can keep 32 satellites operating within their design life on orbit is superior to one which can maintain only 20 and depends on equipment lasting beyond design life to meet the performance threshold. This metric also grants insight into what happens when programs take longer to complete than designed. It interfaces with the causal loops concerning the backlog in the pipeline, the Firefighting Loop and the concept of pushing work into out years.

3. **Technology Advancement Rate:** If programs complete more quickly than expected, or at least are not delayed (as has happened in the last 15 years), they advance technology faster. As each generation of technology delivers more precise PNT services, a faster generation implies faster capability maturation as well.

4. **Upgrade Path:** In the BATNA, the upgrade path is adding another signal to the next satellite and making the satellite bigger. In the 5x-6x-7x Disaggregation example, the upgrade path is to put a new signal on its own bus and increase the size of the constellation by 24 satellites. Some upgrade paths may prove easier than others. This is also related to

the idea of replacing a lost satellite; different configurations provide different ways to replace or recover from a loss of satellites.

5. **Time to Replace an Asset:** If a satellite is needed, how long does it take from ordering to placement on orbit; how long does it take to move through the pipeline? As noted earlier, the DoD keeps pipelines/contracts open to enable acquisition of assets in case of unexpected loss (to reduce the time required for contract origination, which may be years). However, the time through the pipeline may be considered a performance metric as well. Some acquisition approaches may be able to procure replacement, or adjust to a higher production level more efficiently than others. For example, producing two satellites and doubling to four may be achieved more easily under disaggregation than the BATNA.

6. **Survivability/If an Asset Is Lost, the Impact on Signal Delivery:** The primary reason for preferring disaggregation is that it provides graceful degradation—as satellites are lost, only those signals which are on those satellites are lost. The evaluation of the survivable disaggregated policy shows that substantial assets can be lost before any satellite performance is lost.

6.1.2   Impact of Biases Encoded in the Model on Policy

Throughout Chapters 2, 3, 4 and 5 it was noted that when possible, model assumptions were biased towards the GPS BATNA such that if a different acquisition appeared advantageous, it would be under assumptions that were against it. This was done to mitigate the risk of creating a model designed to predict benefit for a policy change, then testing the policy change, and concluding the policy change was a good idea. Instead, a model designed to tell us the current approach is advantageous was constructed so that if a tested policy change appears advantageous, we can have greater confidence that it is. The most significant biases are:

- Disaggregation does not have part commonality among buses in the basic model. This biases the model to possess an increased cost in NRE for disaggregated implementations, as the cost for the buses themselves is computed as if each bus shared no components.

- There is no complexity gain/penalty for integration and test based on the number of payloads. In theory one of the larger benefits of disaggregation is the shift (or even reduction) of complexity on the individual satellite. This complexity may shift elsewhere, such as the ground station, but it would be logical to assume that a satellite bus with one payload is easier to field than one with seven. While it may be countered that fielding seven satellites will likely be more expensive due to the quantity of activity; the model includes the increased difficulties in additional mass and cost for disaggregated policies while withholding a benefit from reduced complexity.

- The model requires that old technology (such as L1 C/A and M1) must be refreshed as often as new technology going forward. It is unlikely that R&D costs for aging technology will be quite as high after the technology reaches a sufficient level of maturity. This creates a bias against programs which push technology faster (which is intertwined with many advantages of disaggregation and Tick-Tock strategies). One specific example would be the 3x Disaggregation or Galileo-sized implementation (which has been used for illustrative purpose throughout Chapters 2, 3 4 and 5) with the old bus should require less cost to refresh/produce than the model charges it. This is because existing payload cost models are regression models based on first time creation of payloads, not sequential cost updates.

- On-orbit operations costs are computed to be equal to current on-orbit operations costs for the first 27 satellites to match the GPS BATNA. Disaggregated approaches incur substantially more on-orbit operations costs because they field between two and seven times more satellites. Each additional satellite costs 95% of the previous for on-orbit operations costs beyond the first 27. It is possible that increased automation of GPS satellites (currently they must be able to operate for 180 days without intervention from a control segment), and the inclusion of cross-links for instant communications amount the constellation will not force an increase in operations costs even if constellation size grows. This assumption, about increased satellite on-orbit costs beyond the first 27, heavily favors the GPS BATNA, on the order of $100M per year for the 7x disaggregated approach. This is up to 12.5% of the cost per operational year.

6.2 Single Variable Changes

To begin analyzing the effects of possible policy and architectural changes, a series of single variable changes to the GPS BATNA were examined as part of testing the model. Examination of the results builds confidence in the operation of the merged models well as illustrating how a single change may propagate its effects across time. Table 6-1 lists the six core variables examined. In this section the results of changes in two of these variables, Design Life and Number of Satellites Ordered in a Generation are discussed. Each of these changes produces results which seem intuitive, while also revealing some non-obvious, causal effects of seemingly small changes.

Table 6-1: Single Variable Changes Possible in Model

Variable	Values	Notes
Design Life	3 to 21 or "float"	This value is used to set a different satellite design life than the desired length computed by the SD model. Use of the "float" value implements the design life needed to meet the objective performance requirement of 27 satellites on orbit. Changing the design life is implemented through the TSE model.
Number of Satellites per Generation	4,8,12,16,24,32	This variable controls the number of satellites requested in a generation. In disaggregated architectures this number is a multiple of the level of disaggregation.
Production Funding Increase	0 to infinity	The input value defines the length of a fixed time period for which additional funding will be available in an attempt to reduce firefighting behavior and clear the pipeline backlog.
Requirements Decrease	0 to 1	This variable captures expectations about how performance requirements will change over a fixed time period. A one will "freeze requirements at start" and zero "keep in line with technology." A .5 would indicate the abstract concept of requesting only half the

		potential gains being requested (as computed by the time to double capability).
NRE Pulse	0 or 1	A one represents the year in which a NRE pulse occurs, this updates technology.
Number of SVs to LVs	1 to maximum allowed by mass	Dual launch in theory is possible for Block IIIA on a "Heavy LV." Multi launch is logical for disaggregation (but not free). This sets a limit on the number of SVs which can be placed on an LV.

6.2.1 Change Design Life

In this section the model was run with only the design life of the satellites changed. This is not a real policy that is being proposed, but rather is used for illustrative purposes to examine change across time. The blue line (as always) represents the tuned implementation of the GPS BATNA. The red line represents a design life of 6 years, magenta 8 years, yellow 10 years, orange 12 years, and purple 20 years. In Figure 6-2 the production cost per year of this policy is change is seen.

The first observation about Figure 6-2 is that, as expected, the satellites which provide the fewest years of capability also require the largest amount of money per year to produce equivalent years of operational capability. This is in keeping with standard satellite design and optimization as previously discussed with respect to current trends in the industry; the additional mass and complexity to extend design life is small relative to the years of on-orbit capability gained. The second observation from this figure is that the shorter the design life, the faster the acquisitions must come in succession and the faster each acquisition must complete. This is also logical, as from the variable Years of Operational Capability on Orbit we note that a satellite with 7.5 years of operational capability would only last half as long as one that possessed 15 years of operational capability, implying that in the same time period two satellites would be required to provide capability over the same time.
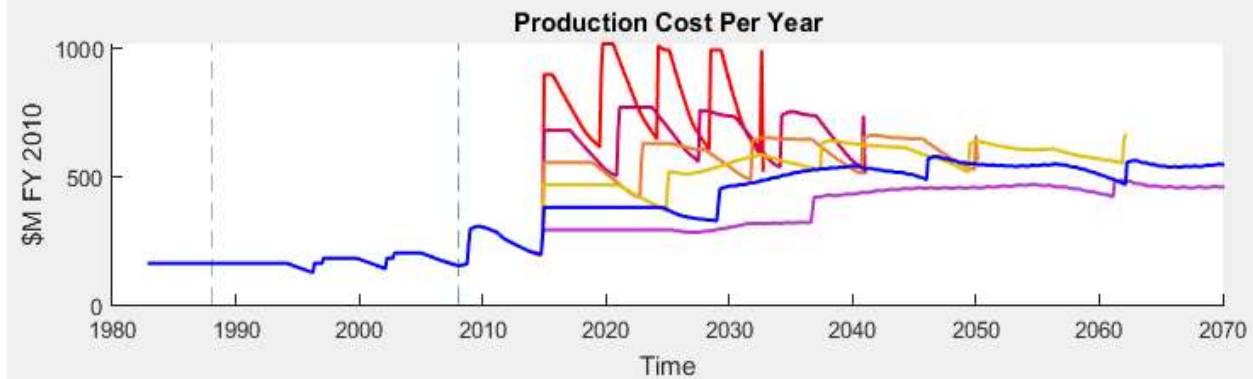
Figure 6-2: Policy Testing, Production Cost per Year, Changing Design Life (6, 8, 10, 12, 15 and 20 years)

Figure 6-3 removes the lines for design lives of eight, 10, and 12 years for clarity in examining the effect of varying design life on technology refresh intervals and decay. Having fixed the number of satellites to be produced at 24, and the design life of each being varied, the time between new generations of satellites must become shorter. This also implies that the time between technology refresh periods (NRE events) will also shorten. If one wanted to keep the refresh interval the same while changing the design life, they would also need to change the production quantity or else a capability gap on orbit would emerge. The figure creates a compelling visualization of differences in timing of technological refresh. First, note how the historical data placed three technology refreshes in the 1990s and then how the BATNA plans to dramatically increase the time between technology-refresh events. Second, note the greater speed with which tech refresh occurs with a six year versus the BATNA's 15 and a possible 20-year design life.

One positive impact of shortening the design life is less technology decay between generations. One negative impact is that the cost for more frequent NRE events is larger in terms of total dollars. If technology refresh events exceed three half-lives, it appears that each future generation of GPS satellites will require nearly 100% updating of all technology involved with the GPS program—the line on the graph has reached nearly 0% of technology remaining. Notice that the difference between the blue and purple lines, at the bottom of their curves are already very close to zero. This implies that in terms of the percentage of technology refresh required: nearly 100% already needs to be refreshed. The difference in time over which the technology is allowed to decay from the blue to the purple is, however, five years longer per generation. This leads to the advantage that a longer time between NRE events pushes down total acquisitions cost (the NRE is spread over five more years). But this delay brings with it the increased difficulty associated with dealing with older technology (a factor not represented in the graph but influencing production cost, as outlined in Chapter 3).
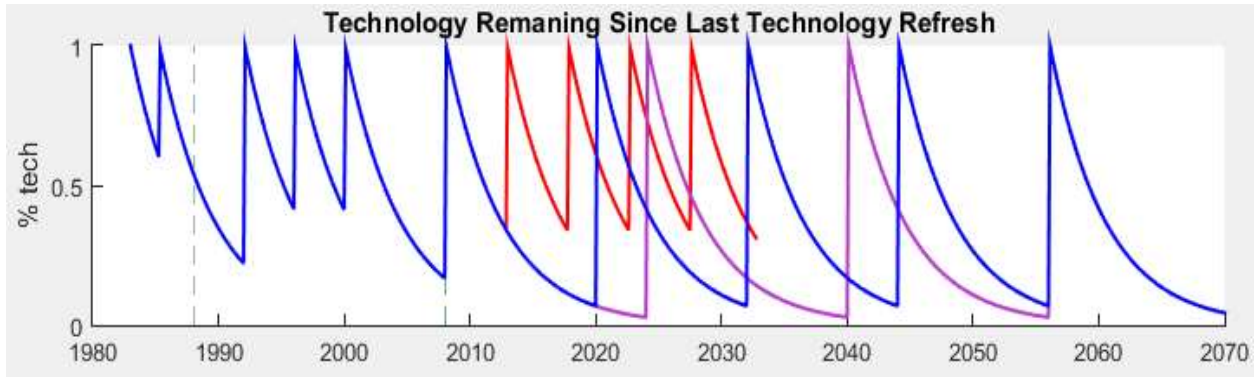
Figure 6-3: Policy Testing, Technology Refresh, Changing Design Life (6, 15 and 20 years)

Based on additional production funding, shorter time between technology refresh events and the change in the number of satellites produced in the same time period, Figure 6-4 captures the change in efficiency of the system. It is no surprise that the program with the most activity (satellite production) and investment (NRE) is the most efficient: this is the six-year design life program. The longer the design life, the less efficient a program becomes. This metric, however, tells us nothing about overall program cost. Recall that the production costs shown in Figure 6-2 for six-, eight- and 10-year design lives were never less than the BATNA (the red, magenta, orange and yellow lines were all above the blue line), so it is unlikely that when factoring in other programmatic costs shorter design lives will be anything but more expensive. The gains in Efficiency do not compensate for the production costs associated with additional satellites. (The overall cost per operational year for varying design lives is presented below in Table 6-2.)
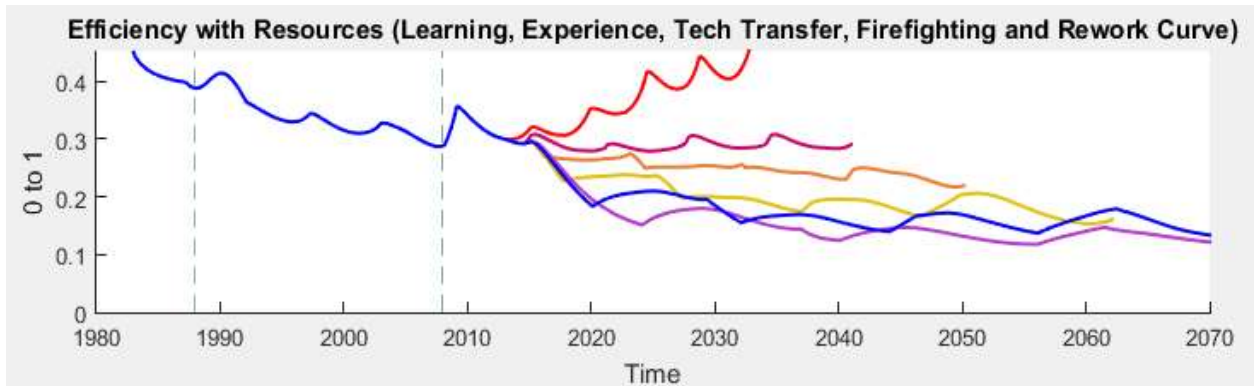
Figure 6-4: Policy Testing, Efficiency, Changing Design Life (6, 8, 10, 12, 15 and 20 years)

As expected, the longest lasting satellites also possess the longest Process Cycle Times. Based on the design of the SD model, we theorized a positive relationship between the Process Cycle Time and the rate at which experience from production translates into a higher Efficiency as seen in Figure 6-4: Policy Testing, Efficiency, Changing Design Life (6, 8, 10, 12, 15 and 20 years). It is unclear, however, whether cost savings are possible. It is also unclear if the relationship between Process Cycle Time and technology half-life will impact cost across generations. The SD model draws a relationship between technology half-life—the time over which entropy impacts the system—and Process Cycle Time—the time over which experience impacts the system. If these can be brought into alignment, it is conceivable that a virtuous cycle may be initiated.

208

What is somewhat unexpected is the stability in the red and magenta lines where the oscillatory behavior becomes more uniform. Interestingly, the design life of 12 years (orange line—identical to the IIF program) continues to extend the process cycle time to longer intervals whereas the 10-year design life (yellow line) seems to put the Process Cycle Time in a near perfect equilibrium. Typically in SD, knowledge about equilibrium states is valuable, as it indicates when loops are balanced against each other.
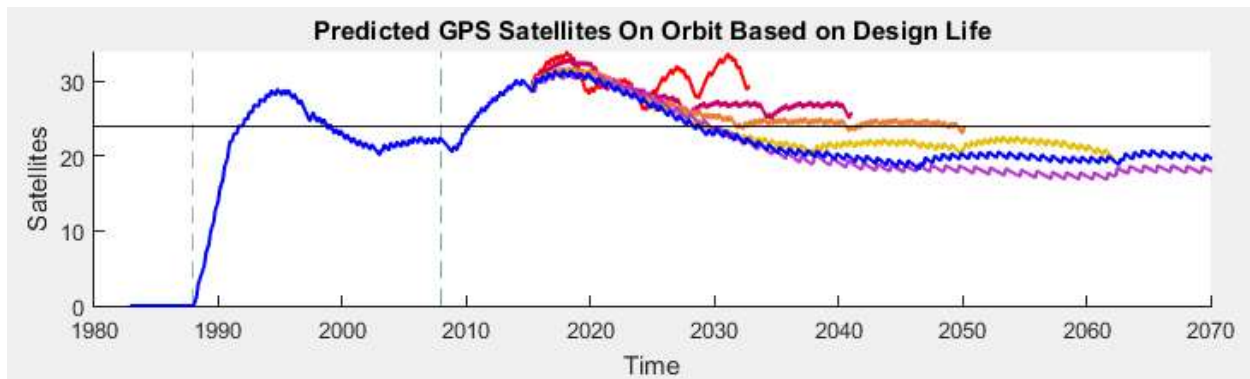
Figure 6-5: Policy Testing, Satellites on Orbit, Changing Design Life (6, 8, 10, 12, 15 and 20 years)

Figure 6-5: Policy Testing, Satellites on Orbit, Changing Design Life (6, 8, 10, 12, 15 and 20 years) displays the initial results of the model when tuned to the GPS BATNA, and displays the prediction that on average the BATNA is and will produce only ~21 years of operational capability (while 24 needs to be produced to maintain the constellation). This results in the need for satellites initially designed to last 15 years to last on average ~19.2 years to cover this production gap. Thus, a direct comparison with respect to Cost per Operational Year is not fair because programs with design lives of six, eight and 10 years are predicted to always be able to keep 24 satellites on orbit. It is more appropriate to look to a metric, such as the number of years of operational capability produced in each year of production, when considering the acquisitions performance of such a policy. This is one of the secondary metrics which may be of use when evaluating performance of different acquisition approaches. This metric will be an influence in computing cost metrics examining cost per operational year on orbit, but not with respect to the FYDEP.
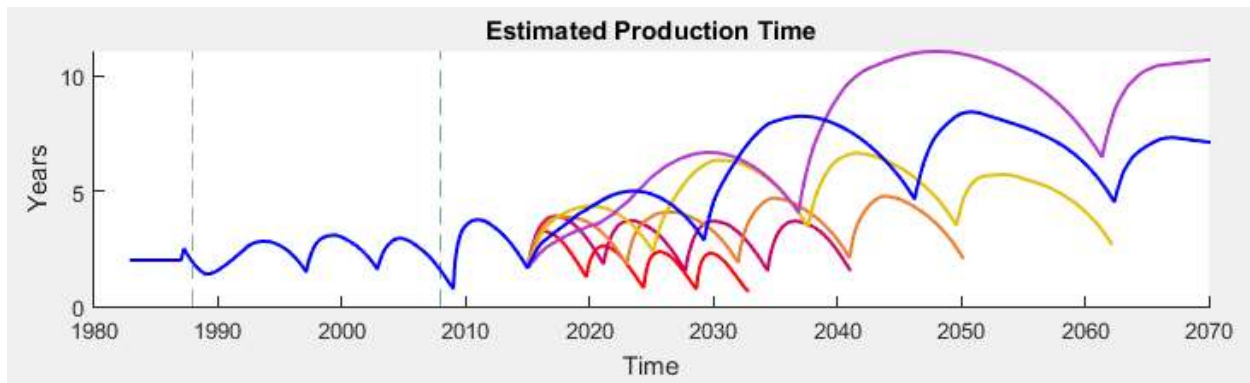
Figure 6-6: Policy Testing, Process Cycle Time, and Changing Design Life (6, 8, 10, 12, 15 and 20 years)

Table 6-2 presents a comparison of cost per production year for varying design lives. This table presents only the first cost metric, a generation-against-generation comparison. These results are an extreme comparison: the first generation for the design life of six years ends in 2019 and the first generation for the 20-year design ends in 2036. This concludes with a fourth and final generation for the six-year design life ending in 2032 versus 2079 for the BATNA. While this comparison gives no deference to time, it is useful for examining the model's basic results as this data should follow a predictable trend.

Table 6-2: Policy Testing, Change in Cost per Operational Year When Changing Design Life (6, 8, 10, 12, 15 and 20 years)

Design Life (years)	Cost Change per Operational Year Gen 1	Cost Change per Operational Year Gen 2	Cost Change per Operational Year Gen 3	Cost Change per Operational Year Gen 4
6	189.48%	144.70%	136.49%	131.21%
8	149.52%	121.41%	119.86%	117.37%
10	126.12%	107.70%	109.50%	108.59%
12	112.88%	106.10%	108.97%	109.06%
15	100.00%	100.00%	100.00%	100.00%
20	87.30%	89.90%	89.80%	N/A

One would expect that a satellite of design life 7.5 years should (minus operational cost) cost 200% of one lasting 15 years. Interestingly, in Table 6-2 the cost of the six- and eight-year design life satellites are both below 200% the cost of the 15-year satellite design in the first generation. This reduction against the expectation is attributed to the efficiencies gained in production when greater quantities of satellites are built and there are faster refreshes of technology. Not

surprisingly, either is a poor choice of policy as all the implementations cost more than the BATNA (189% for the six-year and 150% for the eight-year design life in the first generation). Across multiple generations, however, production cost does decline dramatically and the gap does narrow, though almost all the cost savings possible are gained by the second generation. Definitively, if only design life is considered, a shortening always results in a cost increase in the FYDEP.

At the other end of the spectrum, one would expect that an increase of five years (from 15 to 20) would yield a 25% cost savings. Yet Table 6-2 shows a cost savings of only ~11% to ~13%. This is due in part to the increased mass of the longer lasting vehicles, but more importantly, it is a result of loss of production capability due to longer design life. (This is illustrated by the purple line on Figure 6-4). It is for this reason that most of this thesis focuses on policies which increase productivity. Eventually there will be a break point where design life cannot be extended to continue cost saving. It is believed that getting ahead of this problem sooner rather than later is preferable.

It is worth comparing the changes in mass associated with changes in design life. Table 6-3 displays the mass for the first generation as well as the second generation where additional capability in the form of cross-links, spot beams and an additional signal is added. One might consider the "Overhead Mass" of the design life change to be the difference between the masses in this table. The dry mass in kilograms for each of the satellites increases in a predictable and expected fashion as the design life is extended.

Table 6-3: Policy Testing, Change of Satellite Mass When Changing Design Life (6, 8, 10, 12, 15 and 20 years)

Satellite Mass		
Design Life (years)	Generation 1 (kg)	Generation 2 (adds crosslink, spot beam and L4) (kg)
6	3326	4053
8	3394	4136
10	3515	4284
12	3583	4366
15	3701	4511
20	3888	4738

6.2.2 Change Order Quantity

We now turn to examining the impact of changing the quantity of satellites ordered from 24 (as with the GPS III BATNA) to 12; half the current plan. This is also an interesting number because 12 is very close to the number of IIR, IIRM and IIF satellites actually produced, whereas

the proposed current plan for Block III will reuse the bus for at least 24 satellites. This may give some insight into how procuring in different block sizes changes the cost of acquisitions. In Figure 6-7: Policy Testing, Production Cost per Year, Changing Order Quantity (12 vs. 24), and the impact of the extra NRE events is clearly seen on the red line where the generation shifts occur more frequently. It can also be extracted from this plot that the additional technology refresh dollars (one can think of this as acting as risk mitigation for long development items) speeds up the time between generations when compared to the BATNA. Interestingly the overall cost of production is about the same across the same timeline with some small savings towards the end of each generation, but likely not enough to compensate for the $1B+ technology refresh cost.
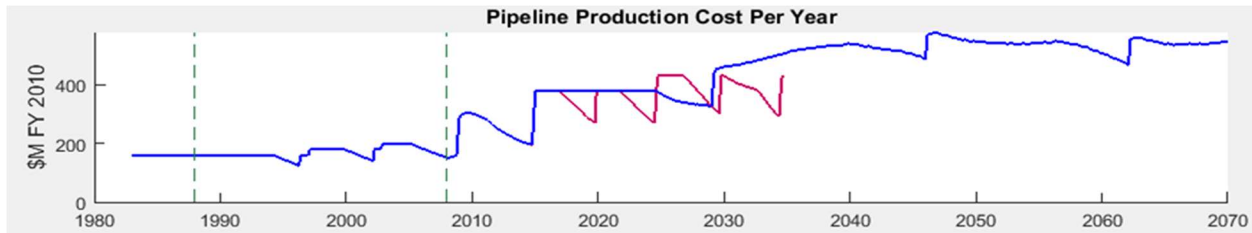
Figure 6-7: Policy Testing, Production Cost per Year, Changing Order Quantity (12 vs. 24)

Figure 6-8 displays each satellite launch for four future generations of purchases in blocks of 12. The black bars indicate the years in which the NRE pulses will be required to implement block buys of 12 satellites—they are 7.5 years apart. Comparing Figure 6-8 with Figure 6-9, the launch schedule for the GPS BATNA (blocks of 24; NRE pulses represented by black bars 15 years apart), several differences are seen. The major difference is the completion date of the second generation for the order quantity of 12 (2025) versus order quantity of 24 (2028). Another major difference is the time between the NRE pulse of 2020 and first production of the Block IVs. With the GPS BATNA (Figure 6-9), the model forecasts that it will take approximately nine years. The time is reduced to approximately six years with purchases in blocks of 12. One might explain this in three ways. With the knowledge that only 12 of this design will be ordered and that a new design will be arriving in six years, it is less critical to get every possible upgrade. It might also be that the additional ~$1.2B in NRE funding was able to assist with risk reduction and lead time development, thus reducing the amount of time required for development of the new design. Finally, it might be that as the time between generations is now only half as long, less technology needs to be reengineered and as less of the design changes it takes only six rather than nine years to build the theoretical first unit.

212
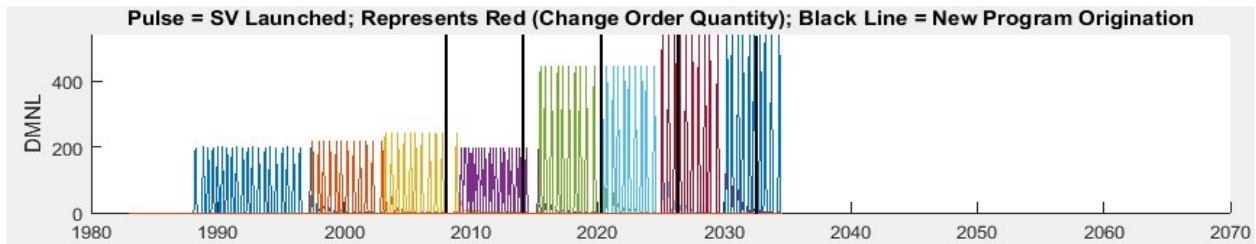
Figure 6-8: Policy Testing, Satellite Launches, Changing Order Quantity (12 vs. 24)
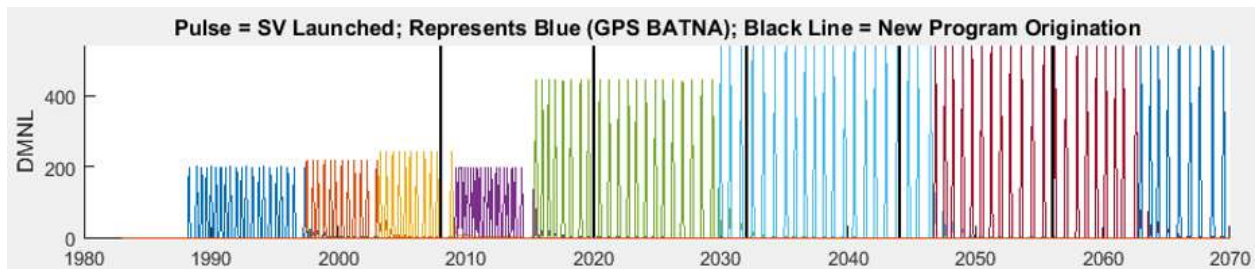
Figure 6-9: Policy Testing, Satellite Launches, GPS BATNA Launches

To directly compare the impact of three NRE pulses versus two pulses by 2020 and splitting the acquisition into two blocks of 12 as opposed to one block of 24, Table 6-4 contains the cost estimates for each policy. Rows eight through 11 present the four cost metrics. Additional cost estimates are shown in rows three through seven.

- Row 3, the NRE costs between generations. It is logical that in Generation 1 (2008) the cost of the update is identical. In Generation 2 the cost for a set of 12 rather than 24 is 70% less. Since the NRE is occurring sooner, less technology needs to be refreshed, so costs are less. That being said, the reduction is not 50%, because more than 50% of the technology has become outdated in the 7.5-year time interval between Generations 1 and 2. Thus NRE, as expected, is captured as a source of extra cost with respect to this policy change.
- Row 4, the cost of the first production unit to come off the production line. Across generations the cost of the first production unit decreases, indicating that buying in blocks of 12 rather than 24 may result in initial units starting at slightly lower cost points and offering the potential for cost savings. The reason for such a decrease is attributed to a shorter time between first production units resulting in more lessons and technology from the previous generation being applicable to the next.
- Row 5, Replication Costs. These are operationalized as the area under the red line in the SD model's variable production cost per year (seen in Figure 6-7: Policy Testing, Production Cost per Year, Changing Order Quantity (12 vs. 24)) As the SD model computes the expenditure of resources into the production of satellites, the amount of money required to produce the satellites enables the learning module to compute expenditures across the entire acquisition based on the dynamically changing acquisitions environment.
- Row 6, Launch Costs. The launch cost for Generation 1 with a block of 12 is 50% of the BATNA with a block of 24. This is logical as with 12 satellites versus 24, only half as many rockets are needed. In other implementations, such as a disaggregated approach, the one rocket to one satellite relationship, as discussed in Chapter 2, does not hold. This

213

variable ensures if extra rockets are required, their costs are properly factored into the total acquisition cost.

- Row 7, On-Orbit Operational (or Ops) Cost per Year. Unlike the Launch Costs, this number is not exactly 50% even though the same number of satellites is procured. The reason for this difference is that the model computes "Ops Costs" based on the number of satellites on orbit, not satellites in production. As these two policies change the number of satellites on orbit across time, there is a predicted variance in operational costs. This variable ensures that architectural implementations with greater operational costs properly include these costs in the total cost.

While the addition of extra NRE events certainly increase efficiency of the system, they do not result in cost savings and the baseline cost of the program would, on average, need to increase the FYDEP by ~140% in the first generation and ~125% every generation thereafter. (See Row 8.) Thus, simply spending more money to improve efficiency is not a good policy to reduce the cost of the GPS system. This infusion of capital is able to solve the problem of satellites being forced to last beyond design life to meet threshold capability of 24 satellites, however, there are more efficient ways to solve that problem than dumping $1B into technology push activities every 7.5 years. In future plots the variables in rows three through seven will be hidden and only the four cost metrics will be displayed for ease of readability. Interestingly, Row 9 shows that the cost to acquire a year of operational capability in the first generation is 98% of the BATNA and decreases to ~75% thereafter. This implies that while blocks of 12 cost 125% of the FYDEP baseline, every year of operational capability produced comes at cost of 75 cents on the dollar. The more the purchasing: the greater the efficiency for those that are produced.

Table 6-4: Policy Testing, Satellite Launches Changing Order Quantity (12 vs. 24)

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	12 vs 24	2	12 vs 24	2	12 vs 24	2	12 vs 24
3	NRE This Generation	3	100.00%	3	70.83%	3	79.80%	3	79.80%
4	Cost 1st Production	4	89.38%	4	53.91%	4	47.17%	4	45.32%
5	Replication Costs (SD)	5	33.36%	5	19.38%	5	23.57%	5	20.39%
6	Launch Costs	6	50.00%	6	50.00%	6	50.00%	6	50.00%
7	Ops Costs	7	49.95%	7	51.92%	7	53.27%	7	53.28%
8	Avg Cost Per Production Year Gen vs. Gen	8	140.27%	8	125.40%	8	121.95%	8	127.01%
9	Cost to Acquire a Year of Operational Capability	9	98.43%	9	70.07%	9	77.52%	9	73.13%
10	Cost at End of Production, Policy Cost per year Relative to BATNA	10	140.27% in 2020	10	141.37% in 2025	10	143.07% in 2030	10	133.72% in 2035
11	Compensate for Difference of Production Rate (Time & Performance)	11	98.43% in 2020	11	79.00% in 2025	11	90.94% in 2030	11	76.99% in 2035

One final difference between buying in blocks of 12 versus 24 is that BATNA relies upon on-orbit operational life to exceed design life (of 15 years), while purchasing in blocks of 12 keeps not only the 27 desired satellites on orbit but achieves the upper limit of 32 satellites in the constellation on orbit at all times without any assumptions about exceeding design life. This is seen in Figure 6-10 where the predicted number of satellites for the GPS BATNA is shown in Blue and the single variable change to an order quantity of 12 is shown in red. While one might consider that this additional capability might be delayed in launch or production in an attempt to capitalize on the increased efficiency associated with blocks of 12, the logical extension of such an idea would place the GPS acquisition in the exact same position as the BATNA. Thus, cost savings achieved through greater NRE investment do not result in realized cost savings, but would reduce the risk of being unable to field 24 satellites. (But then again spending a lot money usually does buy down risk.) The important take away is that the model provides insight into both the FYDEP cost per year as well as the cost per operational year of the system fielded. It also illuminates why

the design point for the current GPS BATNA has pushed to where it is today, if minimizing the FYDEP cost per year was desired. That is, the most direct way to save cost in a block buy of 12 is to buy one more, after which the most direct way to save cost becomes to buy another. Eventually, the policy of buying 12 in a block becomes a policy of buying 24 in a block (and in Block IIF the DoD pushed for a block of up to ~32, which is in agreement with these findings, if you can expect longer on orbit operations this saves money. Block III has options with the A, B, C and D options to get to 32 in sets of 8). Along the way the number of satellites fielded drops from the efficiency of acquisitions going down, requiring satellites to last longer than expected, but still delivering satellite-capability ~40% cheaper than buying in blocks of 12.
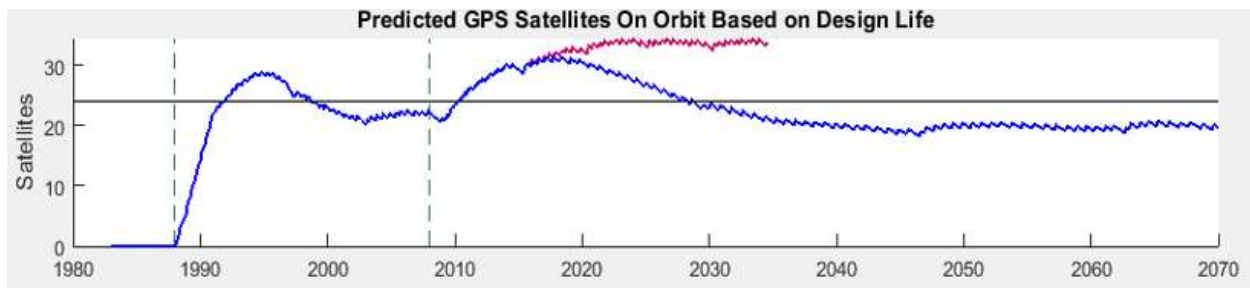
Figure 6-10: Policy Testing, Satellites on Orbit, Changing Order Quantity (12 vs. 24)

Holding Design Life at 15 Years

6.3 Policy Test Matrix

The above single-variable changes can be combined into potential policies related to how GPS satellites might be acquired in the future. Table 6-5 lists the policies which have been examined by the model.

Table 6-5: Policy Test Matrix

Policy	Implementations	Logic
Number of Disaggregated Satellites	2,3,4,7	Changing the payload alignment and the disaggregation of payloads across busses as outlined in the TSE model.
Design for Survivability	Payload alignments of signals on disaggregated busses L1 and M1 L1 and L2 L2 and M2 M2 and L1 Upgrade adds a satellite e.g.,	The amount of disaggregation shifts the risk posture of the GPS constellation. Losing one satellite currently equates to the loss of one signal, but disaggregated satellites might be more prone to failure. To compensate, a disaggregated survivable architecture was outlined in the TSE Chapter which allows up to 25% of satellites to be lost without a reduction in performance. This creates "flavors" (or sets of design points) of disaggregated survivable architectures.

215

	M2 and L5 L5 and L1	Other flavors of survivable disaggregated are possible but this puts an upper limit on the "gold-plated solution's" cost.
Flavors of Reducing Requirements	Fix to Technology Half-life Curve	It is possible that future generations of GPS satellites will require no increase in performance in terms of signals and signal strength. In this future, technology can achieve cost savings through mass reduction. This variable works in conjunction with assumptions about half-life and the context variable, Technology Half-life.
Tick-Tock Model	Update Bus Gen 1 Update Payload Gen 2 Update Bus Gen 3 Update Payload Gen 4	Intel updates Architecture, then Photolithography offset by 18 months to create a three-year cycle for a complete product update. The Tick-Tock policy interleaves updating the bus (tick) and the payload (tock), establishing a shorter time between NRE events to better combat entropy through technology advancement.
Firefighting Correction	% of budget to compensate for and when to trigger	If a program is behind, should it be funded to just the level needed to cover the overrun? Or, should policy makers fund beyond the minimum required? The model implements Fire-Fighting through the Nunn-McCurdy Loop and allows re-baselining at 125%. Policy could, however, be written to increase funding faster, or to provide more funds immediately to clear backlogs and combat firefighting behavior more effectively. The model can examine if additional funding has any chance of saving money over the long run.

In Figure 6-11 the policies of disaggregation combined with single variable changes in design life, production quantity, and various upgrade paths are plotted against their average cost per operational year in a direct generation to generation comparison. The blue dots are acquisition approaches similar to the GPS BATNA. Yellow dots are those incorporating a 2x Disaggregation or Military and Civilian split of payloads. Orange represents 3x Disaggregation or Galileo-sized implementation. Red dots represent Full Disaggregation, one payload per bus. Finally, purple represents survivable disaggregated implementations which possess more capability than the other disaggregated approaches. It can be seen over generations how the impact of different policies spreads the cost per operational year. It also appears that over time the current GPS BATNA (identified on the bottom line by the green star) shifts from the lowest cost implementation to lagging behind many other implementations. The numbers on the Y-axis have no meaning other than corresponding to their points in the memory tree, which makes for easy access and identification of the points. The more interesting points in these graphs will be examined

throughout the remainder of this chapter. While not clearly identifiable, it is worth mentioning that some of the points which appear to be low-cost implementations in Generations 2 and 3 are not the same points which appear in Generation 4. These disappearing points represent policies which manifest myopic decision making: they capture short-term gains but hurt the program down the line. An obvious example can be seen in Generation 2, where the yellow dots are dominated by orange dots. By Generation 4 the yellow dots dominate the orange ones. The model thus provides us with an approach to defeat myopic decision making. Throughout this work, when testing a set of design points, this technique was implemented as a way to extract the lowest cost solutions. The same technique was also implemented on the other cost metrics, to better understand the models behavior across time.
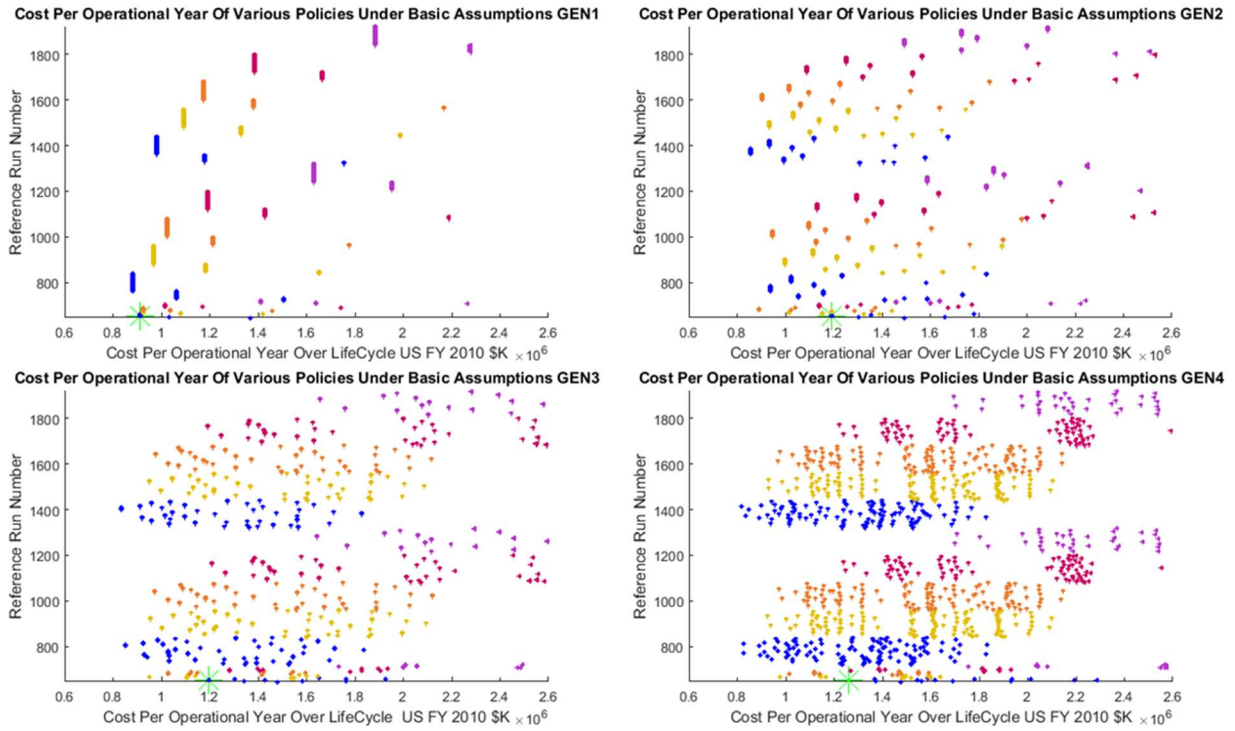
Figure 6-11: Execution of different Disaggregated Approaches Across Four Generations

6.4 Tick-Tock

In Chapter 3 in the section Model Conceptualization, Intel's technology maturation policy, known as Tick-Tock, was discussed. Here the graphic from Intel's website is reproduced. (Intel, 2015)
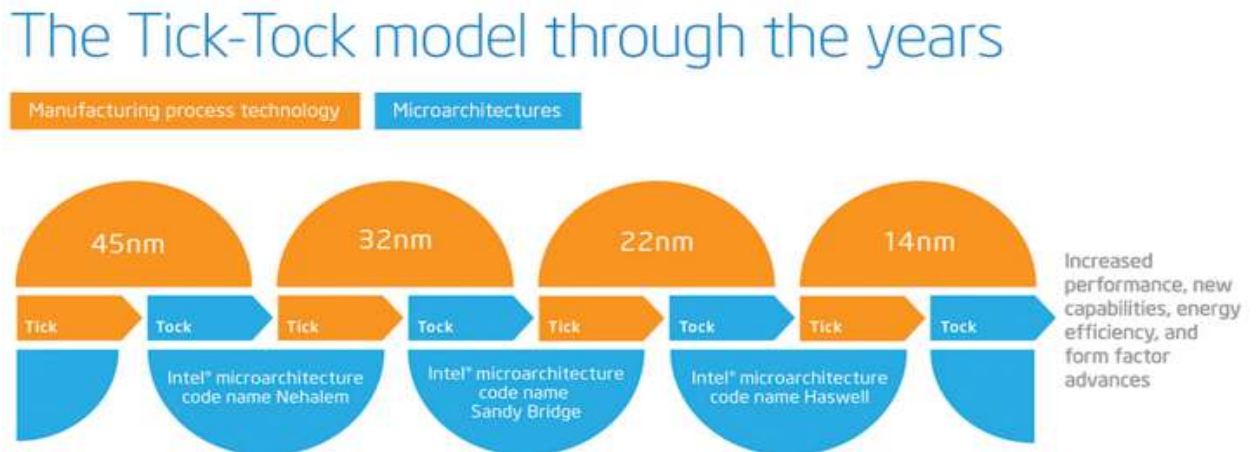
Figure 6-12: Intel's Tick-Tock Model

This approach to technology updates was developed by Intel as a way to mitigate complexity and drive development in microprocessors. As Intel manufactures processors, the "tick" relates to the photolithography (physical tracings of the computer chip) and the "tock" is the actual architecture of the processer being designed. There are several advantages to such an arrangement, in theory only half of the experience is lost at any given time, as half the design is fixed. As only half the design changes, the number of interfaces that require modification is also reduced. Naturally, systems engineering work must still be accomplished to manage the upgrade path of these interfaces, but this allows for focusing on half of the problem in each generation. This also sets a fixed time interval to which both teams (the tick and tock) can work towards, with a specific set of improvements. It also implies that as tick and tock are in three- year design cycles, there exists a potential for multiple ticks and tocks to be underway if any technology with longer than three-year development time is required. (Intel has in truth implemented a 10 year+ development line with multiple ticks and tocks in the pipeline.)

With the model constructed in this thesis we can evaluate the implications of a Tick-Tock policy with respect to satellite acquisitions. Such an arrangement has the potential to combat entropy/requirements creep/complexity in satellite manufacturing where tick becomes the bus update and tock the payload update. The obvious disadvantages are that additional NRE will be required and there is a loss of in-generation learning, as only half as many satellites in a specific configuration will ever be produced. This research has, however, already indicated that in-generation learning is weak across a 20-year time span with respect to the GPS BATNA, so this second point may not be detrimental, depending on the architecture implemented.

The model contains a bias, as usual, in favor of the BATNA. In Tick-Tock, even though half of the design is fixed, it is assumed that some changes will be required to manage the interface properly across generations. As such, the technology refresh costs associated with integration and test are assigned to each acquisition even though one of the theoretical benefits would be reduced integration complexity and reduced integration cost. The underlying logic is that anticipatory work will need to be performed to ensure the design is ready for the next tick or tock.

Experience with Process

Experience with Process : GPS BATNA
Experience with Process : GPS BATNA Tick Tock
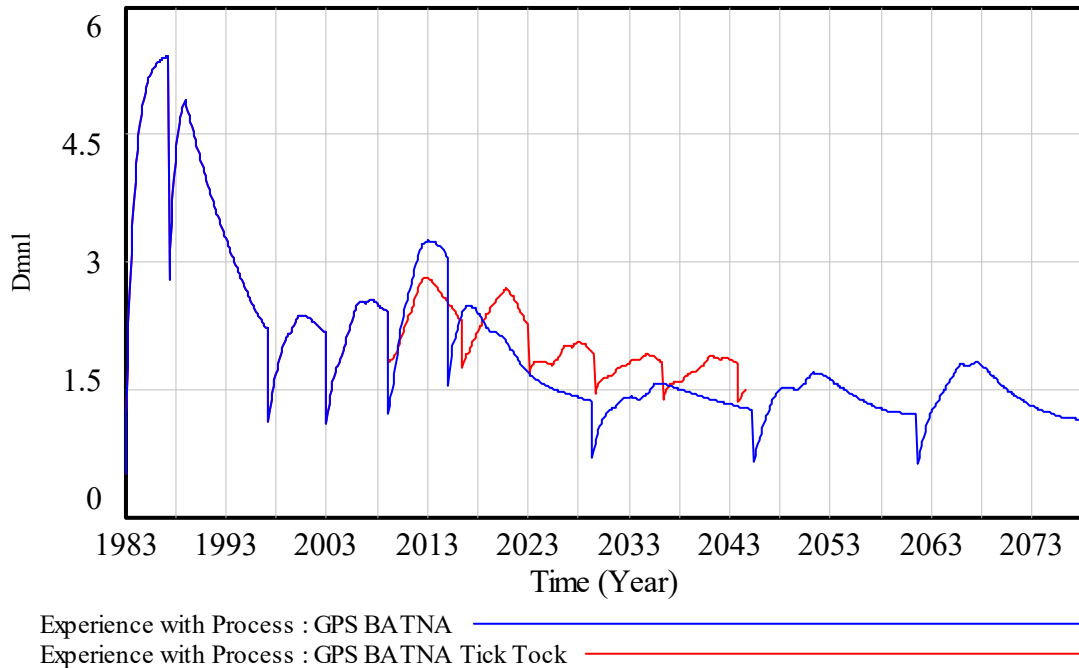
Figure 6-13: Policy Testing, Experience with Process, Tick-Tock (12+12)

The full run of the Tick-Tock model can be found in the Appendix Tick Bus Update (12) →
Tock Payload Update (12). Here we will examine some of the more important features and results.
Taking a look "under the hood" of the SD model we can look directly at the variable Experience
with Process shown in Figure 6-13. The red line representing the Tick-Tock implementation stays
above the blue Experience with Process line expected for the GPS BATNA, and the drops at
transitions between generations are also smaller. In sum, the policy is able to conserve a greater
amount of experience across the same time period.

In Figure 6-14, the technology refresh pattern of the Tick-Tock program (red) is compared to
the GPS BATNA's technology refresh (blue). For the Tick-Tock model instead of a block of 24
satellites, two blocks of 12 satellites are implemented. This means that, all else being equal, two
NRE pulses must occur for Tick-Tock in the same time period as one would happen for the GPS
BATNA. As the technology refreshed is only half of the technology in any single GPS BATNA
NRE event, the average technology never returns to "1" or "full" in the Tick-Tock implementation.
The red line, representing the average decay of the technology of the GPS satellites in production
notes the average number of half-lives that have elapsed and the amount (percent) of technology
which must be refreshed at the next interval. Overall, the Tick-Tock policy when applied to
satellite production smooths the average age of technology being used. This adds a constant level
of difficulty in working with technology but avoids ever working with very old technology. This
may be preferable to the expected BATNA pattern of refreshing and working with technology that
is three half-lives old.

220
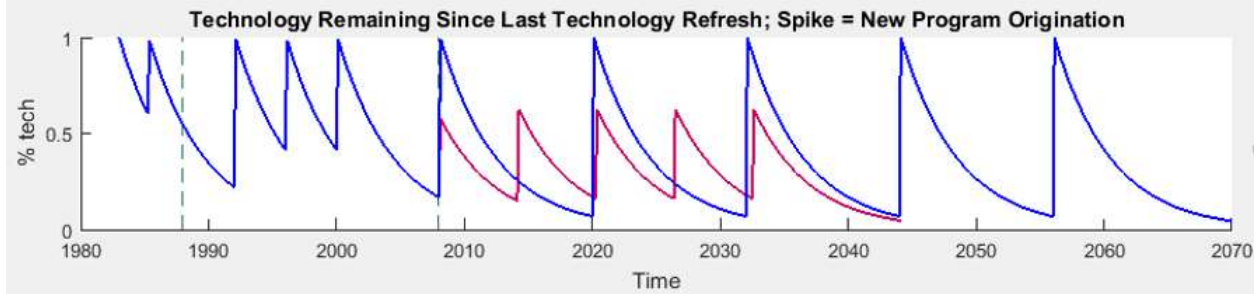
Figure 6-14: Policy Testing, Technology Refresh, Tick-Tock (12+12)

The expectation of the Tick-Tock policy is to fix the Production Cycle Time in a uniform and predictable time sequence. In Figure 6-15, it can be seen that Tick-Tock does fix the Process Cycle Time into a uniform stable oscillatory pattern across generations as illustrated by the red line. Production Cycle Time for the GPS BATNA is predicted to oscillate, but in an increasingly variable pattern.
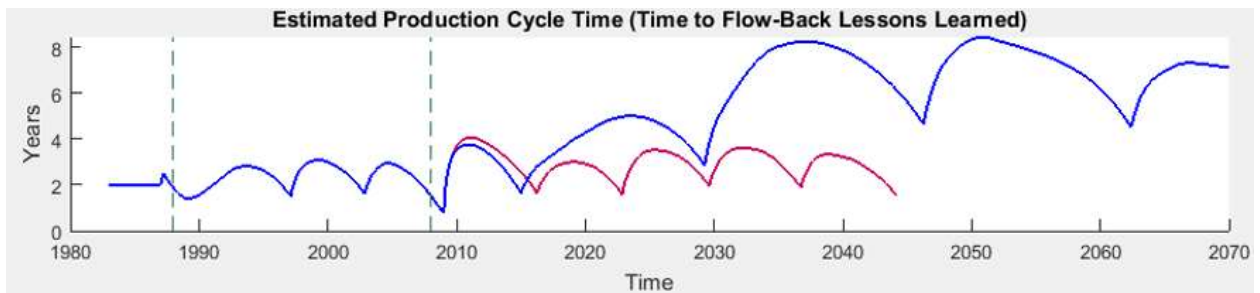
Figure 6-15: Policy Testing, Production Cycle Time, Tick-Tock (12+12)

Figure 6-16 compares Production Cost per Year for Tick-Tock versus the GPS BATNA. Costs are less for Tick-Tock: the red line is under the blue line slightly in the first two generations and significantly lower in the second two. (Note: the spike in the last plotted point is erroneous and is not in the data set). This implies that Tick-Tock can achieve cost savings over the BATNA in production units despite requiring increased NRE in the first generation. The figure also shows that the first two tick-tocks take a year longer to complete than the GPS BATNA but the second tick-tock (third and fourth generations) completes three years before the second generation of the GPS BATNA. This indicates there will be some initial difficulty in implementing Tick-Tock, but speed in production within and across generations will improve over time.

221
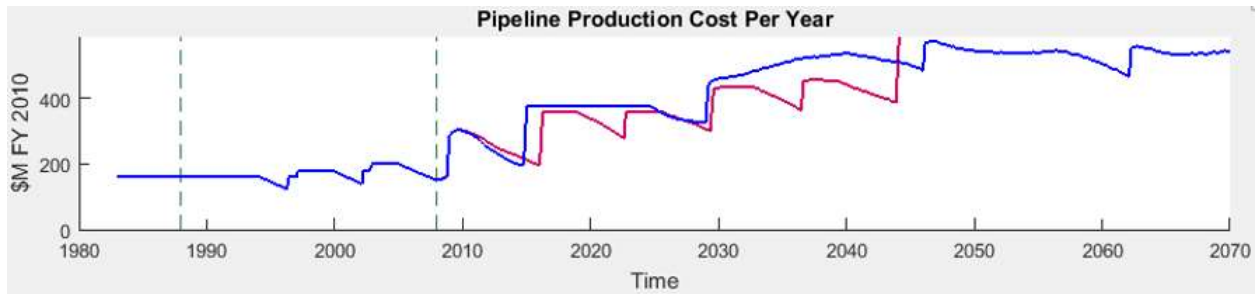
Figure 6-16: Policy Testing, Production Cost per Year, Tick-Tock (12+12)

To compare the costs of Tick-Tock versus the GPS BATNA, the four cost metrics are shown in Table 6-6: Policy Testing, Generation 1 + Generation 2, Tick-Tock (12+12). In the first generation Tick-Tock requires no increase over the FYDEP, and may achieve a greater efficiency—on the order of approximately seven percent—by 2030. We can expect that this greater efficiency will translate to more satellites on orbit for the same price and that is observed in the Appendix P: GPS BATNA Versus Tick-Tock.

Table 6-6: Policy Testing, Generation 1 + Generation 2, Tick-Tock (12+12)

	Variable	vs BATNA
1	Generation Number(s), Design Life of Satellite (years)	Gen 1 & 2, 15
2	Number Satellites Produced	12 + 12 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	99.41%
4	Cost to Acquire a Year of Operational Capability	93.38%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	99.06% in 2030
6	Compensate for Difference of Production Rate (Time & Performance)	92.98% in 2030

Table 6-7: Policy Testing, Generation 3 + Generation 4, Tick-Tock (12+12) directly compares the third and fourth generation of Tick-Tock against the second generation of the GPS BATNA. Improving over the first tick-tock, the second tick-tock (third and fourth generations) is forecast to cost four percent less than the GPS BATNA while producing capability at a discount of 18% over the GPS BATNA by 2044. In brief, the model forecasts for four percent less cost Tick-Tock could provide 18% more years of operational capability versus the GPS BATNA.

Table 6-7: Policy Testing, Generation 3 + Generation 4, Tick-Tock (12+12)

	Variable	vs BATNA
1	Generation Number(s), Design Life of Satellite (years)	Gen 3 & 4, 15
2	Number Satellites Produced	12 + 12 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	96.14%
4	Cost to Acquire a Year of Operational Capability	82.10%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	96.19% in 2044
6	Compensate for Difference of Production Rate (Time & Performance)	82.04% in 2044

These results indicate that if no other changes are made, consideration should be given towards implementing a Tick-Tock policy for the GPS acquisition pipeline. Yet, an examination of efficiency (see Figure 6-17: Policy Testing, Efficiency, Tick-Tock (12+12)) reveals an unfortunate

reality. This policy has not "fixed" the underlying issues within the industry as modeled. The erosion/decay in Efficiency continues unabated. Tick-Tock treats the symptom but not the disease underlying lack of efficiency with resources in the industry. Still, sometimes this is all that can be accomplished.
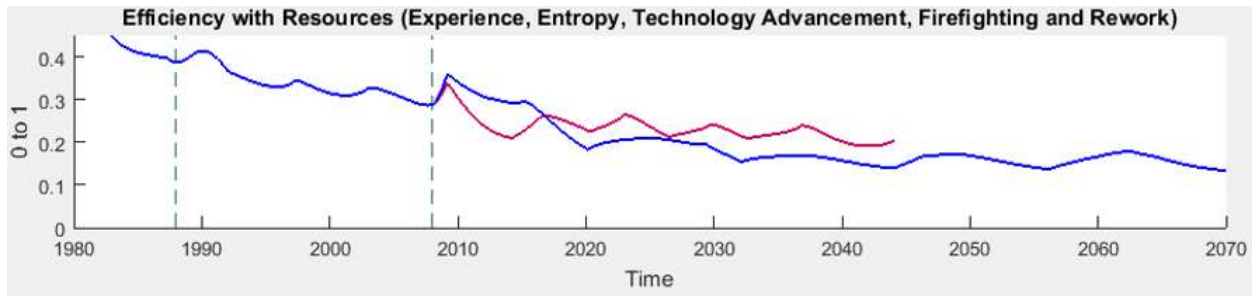
Figure 6-17: Policy Testing, Efficiency, Tick-Tock (12+12)

One might also want to know what happens if extra NRE is paid in 2008 to "jump-start" the process and not rely upon the payloads of the IIF. Figure 6-18 adds a purple line representing extra NRE to the Figure 6-17 Tick-Tock (red) and BATNA (blue) lines. The additional NRE to refresh 100% of the technology in 2008 and then implement the tick-tock policy stops the initial decay in entropy, however, over time the Efficiency of the purple and red lines become nearly equal; again the erosion in the industry continues because the underlying issues are not resolved (the reinforcing loops still work against satellite production).
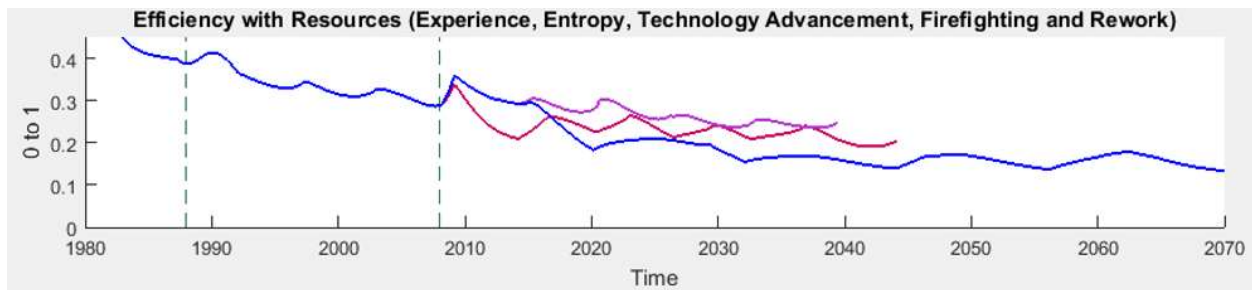
Figure 6-18: Policy Testing, Efficiency, Tick-Tock (12+12 and Extra NRE)

Extra NRE also affects Production Cycle Time. Figure 6-19 adds a purple line representing extra NRE to Figure 6-15. A shift in time occurs with the new policy with respect to the time at which each of the ticks and tocks complete. In Figure 6-19 we see that the purple oscillatory wave is ahead of phase of the Tick-Tock oscillatory feature (in red) though they are of the same period and amplitude. From this perspective, the extra NRE is purchasing speed in the first tick-tock, but nothing else, which is logical because after two decides previous investment would have decayed and the model finds the same equilibrium, though now out of phase.
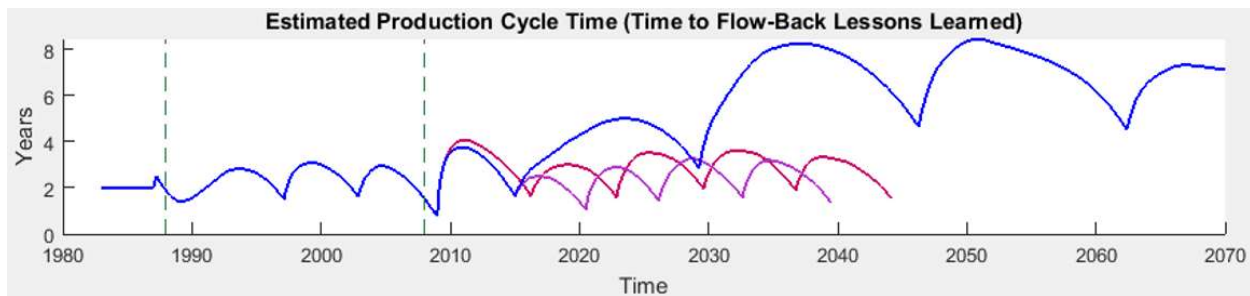
Figure 6-19: Policy Testing, Production Cycle Time, Tick-Tock (12+12 and Extra NRE)

Table 6-8 and Table 6-9 compare Tick-Tock with an extra initial NRE pulse in 2008 versus the GPS BATNA. Again, Generations 1 and 2 of the Tick-Tock policy must be combined to equal the first generation of the GPS BATNA (to achieve an equal comparison of 24 satellites across the same time period) and Generations 3 and 4 must be combined to compare against the second generation of the GPS BATNA.

Table 6-8: Policy Testing, Generation 1 + Generation 2, Tick-Tock (12+12 and Extra NRE)

	Variable	vs BATNA
1	Generation Number(s), Design Life of Satellite (years)	Gen 1 & 2,15
2	Number Satellites Produced	12 + 12 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	111.95%
4	Cost to Acquire a Year of Operational Capability	87.49%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	111.96% in 2026
6	Compensate for Difference of Production Rate (Time & Performance)	87.40% in 2026

Compared with the Tick-Tock policy without additional NRE, this implementation would cost 12% more than the GPS BATNA baseline (seen in row 3 of the above table versus row 3 of Table 6-6). This program would, however, complete in 2026, four years faster than Tick-Tock without the additional funding and three years before the GPS BATNA. This policy would produce satellites 12.5% more efficiently in 2026 than the BATNA (see row 6), however by 2026 on average 12% more money would have been spent on every year. Nonetheless, it would prevent overruns and stabilize the acquisition process and eliminate reliance on space vehicles lasting beyond their design lives.

Table 6-9: Policy Testing, Generation 3 + Generation 4, Tick-Tock (12+12 and Extra NRE)

	Variable	vs BATNA
1	Generation Number(s), Design Life of Satellite (years)	Gen 3 & 4, 15
2	Number Satellites Produced	12 + 12 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	97.39%
4	Cost to Acquire a Year of Operational Capability	76.74%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	100.34% in 2040
6	Compensate for Difference of Production Rate (Time & Performance)	78.95% in 2040

224

Compared with the Tick-Tock policy without additional funding in 2008, this policy stabilizes to nearly an identical position by 2040. This program's second tick-tock finishes the same four years sooner from the gains in the first tick-tock but does not gain any additional speed in the second tick-tock. The program also stabilizes with approximately the same cost in production over the GPS BATNA as the Tick-Tock policy without the additional investment, indicating this is a cost neutral policy across a long time-frame, but results in 21% greater efficiency with resources. It results in the completion of this acquisition six years faster than the GPS BATNA while simultaneously keeping 24 satellites on orbit without relying on design life extensions on orbit.

As previously noted, the model possesses a belief about the decay rate of technology of around 4.5 years. As such one might believe that an inflection point for the Tick-Tock model would exist if the time between tick and tock were less than four years. Unfortunately, positive behavior (cost savings) does not emerge for any combination of Tick-Tock, design life and order quantity which could shorten the time between tick and tock to under 4.5 years. While the lowest cost option for Tick-Tock turned out to be the 12+12 split of the current implementation, the model indicated that an 8+8 split would be almost as efficient. The optimal range for Tick-Tock exists between eight and 12 satellites in a block and approximately six to eight years between ticks and tocks. The reason for this is straightforward. Due to low production quantity, experience with process cannot be gained fast enough to drive down production cost. The policy is able to keep the Process Cycle Time short so that experience can be quickly capitalized upon, but not enough experience is generated. For example, a design life of 15 years and a Tick-Tock time of four years results in approximately six satellites produced per cycle, and these six satellites, must be built in close enough succession that the lessons of the first cannot reasonably be applied to the other five as they are already into the pipeline. Thus, Tick-Tock fails for GPS in this region where it was expected to function well. Naturally, the question becomes if a lack of experience is the reason for this failure, will a Tick-Tock policy work with disaggregated approaches for which more experience is generated?

6.4.1   Model Saturation Region Detected in Tick-Tock

The model detected that the outcome of certain Tick-Tock policies cannot be computed for non-obvious reasons. For example, the model finds it "impossible" to tick-tock given current time parameters (in the tuned SD model) for a design life of six years producing eight satellites in a generation. "Technically" this computation should have been possible, but the model indicates pipeline failure; it computes this change from the baseline to be too great for the acquisition pipeline to cope with (i.e., the government/contract could not execute this program). In brief, the positive effects of the feedback loops could not raise system Efficiency fast enough to compensate for the work being added to the pipeline based on the estimated acquisition cost. This is different from a design point in TSE failing to meet a performance threshold and thus being excluded from results. This failure stems from overwhelming the pipeline with too many changes and the pipeline being too slow to be able to adjust to the change. This is the model's interpretation of an acquisition system attempting to take on a task which it is not currently suited to perform. The initial state of the acquisitions system matters: if the people and processes currently in place cannot execute the plan, then the acquisition strategy would fail. The state of the acquisitions system is, of course, encoded in the time delays seen in the SD model and the efficient level (stock) at the time of the acquisition.

6.5 Disaggregation

Previously in examining the consequences of a Tick-Tock policy, we noted that an initial spend of extra NRE created stability of Process Cycle Time. Since this stability did not translate to a shortening of the time required from NRE to first production unit over the four generations, this indicates that Tick-Tock did not initiate a virtuous cycle, but rather was being kept in balance by the additional capital. Removal of the additional capital would return the acquisitions process to its unstable state. We will now examine Tick-Tock in combination with disaggregation, with an eye towards the same variables: shortening of time between NRE and first production unit, the stability and magnitude of Process Cycle Time and the total cost of production. We want to see if any disaggregated approaches can make the major SD loops work for the acquisition system and address the underlying issues which lead to decreasing efficiency both in and across generations of satellites. Based on the work in Chapter 2 (running a TSE model for a disaggregated approach in 2008) (This is clearly seen in the Generation 1 plot in Figure 6-11: Execution of different Disaggregated Approaches Across Four Generations where the blue dots dominate the left side of the plot), it is clear that any disaggregated approach costs more than the current implementation in the first generation. Can a Tick-Tock policy and disaggregated architecture achieve a short Process Cycle Time and higher Efficiency for no additional cost, or will higher Efficiency always exact a higher price within the current state of satellite procurement? In this work, four flavors of disaggregation have been examined (summarized above in Table 6-5: Policy Test Matrix). The plots in this section use the following color scheme:

- Blue: GPS BATNA (as always)
- Yellow: Military/Civilian Implementation (2x Disaggregation)
- Orange: Galileo-Size Implementation (3x Disaggregation)
- Red: Full Disaggregation (5x-6x-7x)
- Purple: Survivable Disaggregated (4x-5x-6x)

The exact configurations of payloads and satellites required in each generation are available in Appendixes J through N. These arrangements were computed to deliver equivalent satellite performance with respect to the number of signals and signal strength delivered to earth. The upgrade paths across time vary for each disaggregation approach. Upgrade paths were designed such that each generation would obtain new capability near in time to when the GPS BATNA is forecast to obtain new capabilities, however, due to the causal nature of this work and the uneven program start and stop times it was not always possible. These arrangements are recapped here:

- GPS BATNA: More signals are added to the single bus as performance increases are desired.
- Military/Civilian Implementation (2x Disaggregation): If the signal is for military purposes it is placed on the military bus, otherwise it is placed on the civilian bus.
- Galileo-Size Implementation (3x Disaggregation): One bus becomes the "Legacy Signals," the second becomes the "New Civilian Signals" and the final bus becomes the "Military Signals and Capability."
- Full Disaggregation (5x-6x-7x): Add another satellite with a single signal to the constellation. The reason for 5x-6x-7x is each generation must add an additional 24 satellites for every signal added.

- Survivable Disaggregated (4x-5x-6x): Another satellite is added with two signals on the new buss. The upgrade path continues the trend where the dual status of each signal is always maintained and two satellites always have each signal.
  - This implies that at any time there are 48 transmitters for each signal on orbit, double the minimum threshold capability.
  - The arrangement of payloads to buses enables 0 loss of capability in the loss of up to 25% of on-orbit assets.
  - Beyond 25% losses satellites can be moved within their planes to close gaps in coverage up to 50% loss of on-orbit assets. This depends on which satellites are lost and in which planes.
  - Depending on the satellites lost beyond 50% losses some capability may be maintained.

In addition to cost savings or efficiencies in production, disaggregated approaches offer other potential advantages, foremost being survivability. In a disaggregated approach it is assumed that similar to the GPS BATNA, 27 satellites are the desired equivalent capability to keep on orbit. For either approach, up to three satellites might be removed and full coverage be maintained (given that 24 is the threshold for performance). In these disaggregated implementations it is reasoned that the loss of any individual satellite (below the threshold of 24) will create a capability gap only for the signals on the satellite which is lost. It is left to future work to determine the specific probabilities of loss of capability associated with removing various satellites on orbit. While this is briefly discussed in the final chapter, it is primarily an optimization problem which is not the focus of this work.

In Table 6-10 the number of satellites required in each generation for the BATNA and each disaggregated approach and the minimum number of satellites to maintain equivalent satellite capability is listed.

Table 6-10: Number of Satellites Required on Orbit per Generation in Disaggregation for Capability Equivalent to GPS BATNA

Number of Satellites Required on Orbit per Generation	Generation 1	Generation 2	Generation 3	Generation 4
BATNA	24	24	24	24
Military/Civilian Implementation (2x Disaggregation)	24x2=48	24x2=48	24x2=48	24x2=48
Galileo-Size Implementation (3x Disaggregation)	24x3=72	27x3=72	24x3=72	27x3=72
Full Disaggregation (5x-6x-7x)	24x5=120	24x6=144	24x7=168	24x7=168
Survivable Disaggregated Implementation	24x4=96	24x5=120	24x6=144	24x6=144

Figure 6-20 displays the production rate per year for the various flavors of disaggregation. Each of the generations orders satellites at the constant rate needed to keep the equivalent of 27 satellites on orbit at all times (with a minimum acceptable level of 24). The most obvious feature is the early spike associated with Full Disaggregation (red line). 3x Disaggregation (orange line) and 2x Disaggregation (yellow line) follow the expected pattern in terms of quantity where orange is second highest and yellow is below orange. Upon closer inspection, it can be seen that each of the flavors of disaggregation tends to bunch up. The reason for this is fairly straightforward, the first few satellites take longer to produce than later ones. As the last satellites in a generation are produced, there is a hold-over period before production can fully ramp up for the next generation. Due to the oscillatory nature of this bunching it is interesting to see that sometimes the yellow line crosses over the orange line. One would expect that in a stable pipeline this would never happen, however, as generational changes act as large exogenous shocks the model encodes this variance. Not surprisingly, Full Disaggregation is associated with greater variability with respect to production rate out per year than any other flavor of disaggregation. All flavors of disaggregation achieve greater production than the BATNA. The model predicts that at no time does production drop to zero, as this is an "open pipeline" desired by DoD acquisitions. Due to the fact that the shock of switching to a disaggregated approach is greatest in the first generation, the rate of output is most uneven in the first generation. As the model reaches stability by the fourth generation, the production rate out stabilizes. (The purple line representing survivable disaggregated architecture has been removed from these initial graphs and will be discussed separately below)
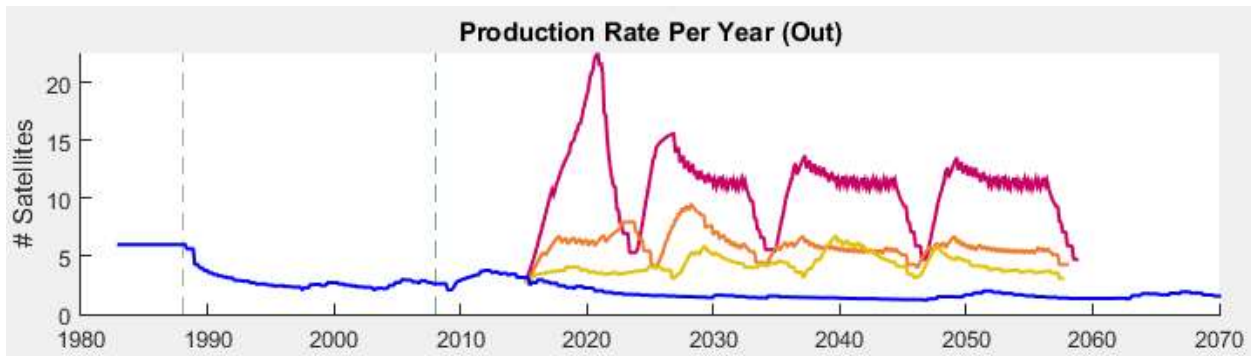
Figure 6-20: Policy Testing, Disaggregation, Production Rate per Year (Out)

Figure 6-21 displays the equivalent number of satellites which must be kept on orbit for the various flavors of disaggregation. Note that with the disaggregated approaches, capacity is initially overshot, but eventually stabilizes. The most important finding is that for all of these approaches the number of satellites kept on orbit is always above the critical threshold (shown by the horizontal lines), implying that all three approaches would eliminate the need for satellites to last beyond design life in order to meet the performance threshold.
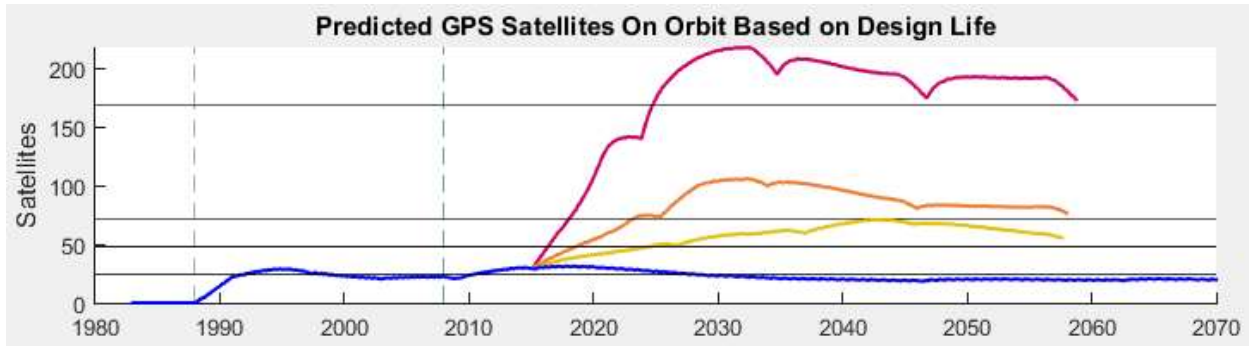
Figure 6-21: Policy Testing, Disaggregation, Satellites on Orbit

Figure 6-22 tracks the Production Cycle Time for satellites across multiple generations. The Full Disaggregation approach drops the cycle time to approximately six months inside the first generation, that is, over a span of 10 years. This is likely because Full Disaggregation involves relatively small satellites ordered in relatively large quantity. The Galileo-sized implementation is almost able, in a single generation, to drop the Process Cycle Time to its minimal level (seen in orange). In this model a policy has reached its maximum effectiveness when it has stabilized to the minimal level achievable. A policy which can transition more quickly to its stable region will be faster to provide cost savings in reproduction. In addition, a policy with a lower Process Cycle Time can theoretically capitalize on learning and transition lessons learned back to the next unit faster. While the graph depicts the disaggregated approaches achieving low Process Cycle Times (unlike previous policies examined), they are not saturated. The model is operating within a valid region and a different policy could in theory drive the Process Cycle Time even lower.
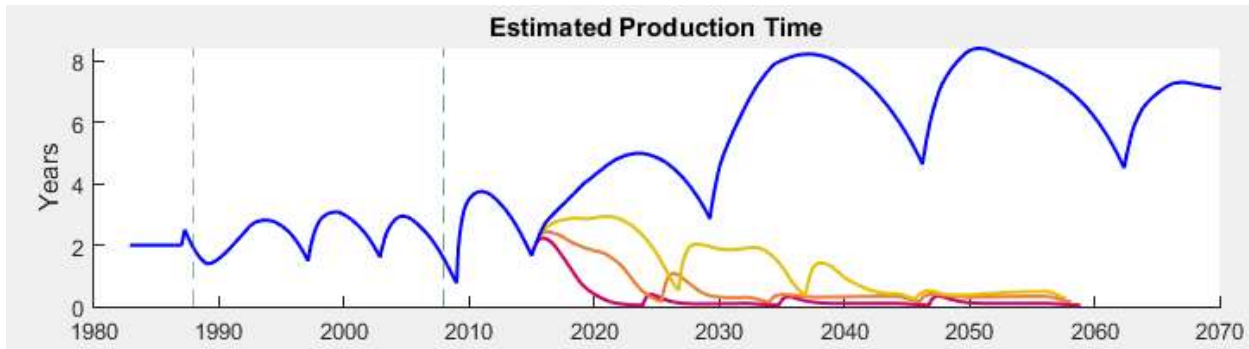
Figure 6-22: Policy Testing, Disaggregation, Production Cycle Time

Figure 6-23 displays the relative production cost per year for each of the disaggregated implementations. One can visually extract the end time of each generation from the spikes in funding after the drop-offs in production costs toward the end of each generation. Examination of the figure shows four generations of disaggregation completing in the same time as three generations of the GPS BATNA. This occurs because disaggregated approaches are able to complete acquisitions on time, or even early. As generations must sequentially follow in order to capitalize on learning effects across generations, the next program starts after the preceding finishes. This has the result of potentially faster generations. Most importantly, we see that by 2035 the production cost for each of the disaggregated architectures is below that of the GPS BATNA. This indicates that by ~2032 changes in experience and cycle time for disaggregation should be

able to compensate for the additional quantity of production required. (This graph includes program overhead and integration/test activities, but does not yet factor in NRE, Launch, or Ops costs.) Also of interest is that while the 3x disaggregated approach (orange line) is less expensive in the second generation than the 2x disaggregated approach (yellow line), by the fourth generation this reverses and the 2x costs slightly less than 3x. It would appear that the model forecasts that the difference between 48 versus 72 satellites in a generation can cause a faster transition to the equilibrium state (maximum effect from policy change).
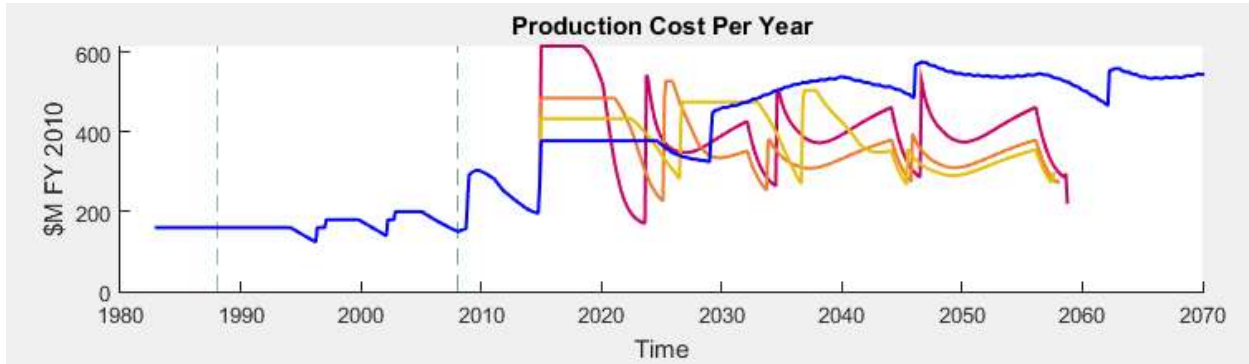
Figure 6-23: Policy Testing, Disaggregation, Production Cost per Year

Figure 6-24 presents the relative efficiency of various approaches to disaggregation in production of GPS satellites. There is clearly a substantially non-linear gain from the difference between 3x and 7x Disaggregation. An interesting observation involves the 2x Military/Civilian approach to disaggregation (yellow line) which slowly creeps up to its maximum efficiency over the course of all four generations. This slow creep explains the behavior of cost decreasing seen on the yellow line, generation across generation, seen in the production cost per year (Figure 6-23). The 7x Disaggregation involves so much activity that it can in one generation achieve its highest level of efficiency; the 3x Disaggregation can reach its highest stable point in two generations and 2x Disaggregation achieves equilibrium in three generations. The trend of erosion in efficiency in the BATNA (blue line) is reversed by all tested disaggregation strategies. This is clearly linked with the data of decreasing Process Cycle Times seen in Figure 6-22. One might ask, which comes first? The answer is neither; the additional experience in combination with the smaller size of more quickly manufactured satellites slowly pushes the model to get the reinforcing loops to work for, rather than against production. Eventually the Process Cycle Time becomes short enough that learning is transferred quickly and the system becomes robust to the shock of transition across generations.
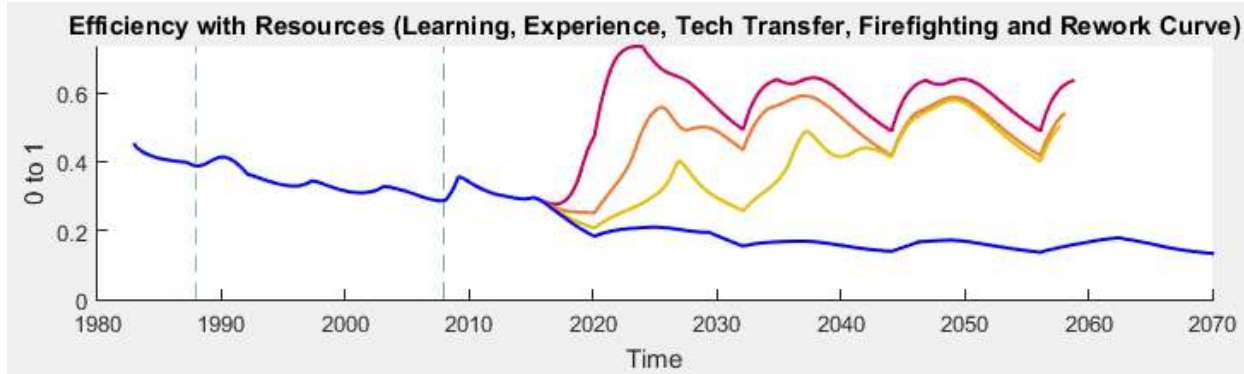
Figure 6-24: Policy Testing, Disaggregation, Efficiency

Table 6-11: Policy Testing, Disaggregation, Total Dry Mass for Equal Performance shows the cumulative dry mass of the satellites to be built across generations and across disaggregated implementations. The data follow the expected pattern wherein the BATNA possesses the lowest mass, and the more disaggregated the implementation, the greater the total dry mass (over-head mass) which must be launched to operate the same signal capability on orbit. The similar mass for the Military/Civilian versus Galileo-Size implementation in later generations is primarily due to the cross-link mass. The crosslink on the Military/Civilian implementation is thought to be almost equal in size to the BATNA, whereas the Galileo-Size implementation is able to reduce the size required.

Table 6-11: Policy Testing, Disaggregation, Total Dry Mass for Equal Performance

Total Dry Mass for Equal Performance	Generation 1	Generation 2	Generation 3	Generation 4
BATNA	3.701e+03	4.511e+03	4.511e+03	4.511e+03
Military/Civilian Implementation (2x Disaggregation)	3.8637e+03	4.948e+03	4.948e+03	4.948e+03
Galileo-Size Implementation (3x Disaggregation)	4.0255e+03	4.5599e+03	4.9724e+03	4.972e+03
Full Disaggregation (5x-6x-7x)	4.5109e+03	5.2071e+03	5.6884e+03	5.688e+03
Survivable Disaggregated Implementation	6.6586e+03	7.8892e+03	9.1198e+03	9.532e+03

6.5.1 Military/Civilian Implementation (2x Disaggregation)

The exact arrangements of payloads to busses and their evolution over multiple generations can be seen in Appendix K Upgrade Path for 2x Disaggregation (Military and Civilian). The full results of this procurement strategy are seen in the Appendix, Military/Civilian Implementation

(2x Disaggregation). Figure 6-25 contains the four cost metrics computed for this implementation versus BATNA. Note that the additional experience combined with smaller satellites results initially in a requirement to increase the FYDEP by 122% with no increase in efficiency in the first generation. By the fourth generation in 2058, such a plan would require an increase of six percent over the FYDEP and realize an increased efficiency in procurement of ~22.5%, indicating a potentially desirable arrangement. Considering that the model is biased towards preferring the GPS BATNA, it is possible that over 30 to 40 years this would be a superior approach to GPS satellite acquisition. Superiority is derived from the increased survivability and ability to keep the threshold number of satellites on orbit; cost savings is unlikely with this implementation.

Variable	vs BATNA	vs BATNA	vs BATNA	vs BATNA
1 Gen #, Design Life (years)	1 Gen 1, 15 vs 15	1 Gen 2, 15 vs 15	1 Gen 3, 15 vs 15	1 Gen 4, 15 vs 15
2 Number Satellites Produced	2 48 vs 24	2 48 vs 24	2 48 vs 24	2 48 vs 24
3 Avg Cost Per Production Year Gen vs. Gen	3 122.40%	3 125.21%	3 129.77%	3 106.56%
4 Cost to Acquire a Year of Operational Capability	4 100.92%	4 70.89%	4 74.44%	4 77.50%
5 Cost at End of Production, Policy Cost per year Relative to BATNA	5 122.40% in 2027	5 128.92% in 2036	5 136.99% in 2046	5 106.85% in 2058
6 Compensate for Difference of Production Rate (Time & Performance)	6 100.92% in 2027	6 72.99% in 2036	6 78.59% in 2046	6 77.71% in 2058

Figure 6-25: Policy Testing, Cost Metrics, Military/Civilian Implementation (2x Disaggregation) vs. BATNA

6.5.2   Galileo-Size Implementation (3x Disaggregation)

The exact arrangements of payloads to busses and their evolution over multiple generations can be seen in Appendix L Upgrade Path for 3x Disaggregation (Galileo Implementation). The full results are seen in the Appendix, Galileo-Size Implementation (3x Disaggregation). Figure 6-26 presents the cost metrics for the Galileo-Size implementation. As with the 2x Military/Civilian arrangement, no cost savings or efficiency is gained within the first generation. Unlike the 2x Military/Civilian arrangement, gains are made in the second. In the third generation, from 2034-2045, the model forecasts this implementation would require funding equal to 111% of the FYDEP but would deliver capability at 83 cents on the dollar compared to the GPS BATNA. Since 3x achieves cost savings faster, it may appear superior to 2x, however, it would require an increase of up to 40% in the FYDEP for up to 20 years before achieving the gains.

Variable	vs BATNA	vs BATNA	vs BATNA	vs BATNA
1 Gen #, Design Life (years)	1 Gen 1, 15 vs 15	1 Gen 2, 15 vs 15	1 Gen 3, 15 vs 15	1 Gen 4, 15 vs 15
2 Number Satellites Produced	2 72 vs 24	2 72 vs 24	2 72 vs 24	2 72 vs 24
3 Avg Cost Per Production Year Gen vs. Gen	3 138.87%	3 142.45%	3 111.85%	3 111.06%
4 Cost to Acquire a Year of Operational Capability	4 101.11%	4 72.27%	4 83.24%	4 80.77%
5 Cost at End of Production, Policy Cost per year Relative to BATNA	5 138.87% in 2025	5 149.92% in 2034	5 118.47% in 2046	5 110.93% in 2058
6 Compensate for Difference of Production Rate (Time & Performance)	6 101.11% in 2025	6 76.06% in 2034	6 88.16% in 2046	6 80.68% in 2058

Figure 6-26: Policy Testing, Cost Metrics, Galileo-Size Implementation (3x Disaggregation) vs. BATNA

6.5.3   Full Disaggregation (5x-6x-7x)

The upgrade path for Full Disaggregation is seen in Appendix M Upgrade Path for 7x Disaggregation (Full Disaggregation) and the complete results are seen in the Appendix, Full Disaggregation (5x-6x-7x). Figure 6-27 contains the cost metrics for this implementation. Examination of this figure makes clear that that Full Disaggregation is not a desirable implementation. In the first generation 178% of the FYDEP would be required and acquisition of capability would be 11% less efficient. It is true that over several generations the cost of acquiring capability equalizes near the BATNA. (See rows 4 and 6.) But even with equal efficiency the

program would require in excess of 130% of the BATNA. While not an advantageous policy, it does provide a good test of the model's upper limit for disaggregation. Furthermore, it answers the question of what would happen if we artificially inflated production: the answer is that the program never breaks even relative to the BATNA. This is due to the increased on-orbit operations and launch costs. In all three disaggregated variants the savings in production from learning effects was able to overcome the requirement to produce more satellites.

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	168 vs 24	2	168 vs 24	2	168 vs 24	2	168 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	178.23%	3	137.44%	3	127.27%	3	138.31%
4	Cost to Acquire a Year of Operational Capability	4	111.00%	4	86.91%	4	95.70%	4	100.59%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	178.23% in 2024	5	146.04% in 2035	5	134.23% in 2047	5	137.80% in 2059
6	Compensate for Difference of Production Rate (Time & Performance)	6	111.00% in 2024	6	92.35% in 2035	6	100.93% in 2047	6	100.22% in 2059

Figure 6-27: Policy Testing, Cost Metrics, Full Disaggregation (5x-6x-7x) vs. BATNA

6.5.4   Survivable Disaggregated Architecture

The upgrade path for survivability is seen in Appendix N Upgrade Path for Survivable Disaggregated Architecture. Survivable Disaggregated provides a clear upgrade path, but it is relatively large in number of satellites and mass on orbit. This version of survivable disaggregated solutions represents the upper end of the "gold-plated" solution to ensuring GPS coverage. In this configuration up to 25% of the satellites in the constellation could be lost and no degradation in performance would occur. Even beyond 25% losses it is possible that by moving satellites inside their planes, full capability could be maintained. This is because there are 52 transponders for each signal on orbit at all times; if a "hole" in the constellation appears, satellites can be shifted to cover the gaps.

There are many other configurations which could provide survivable disaggregated capability. For example, instead of aligning two signals to each bus, three signals could be aligned. Another option would be to design the satellites such that each has only enough power to supply one signal at a time; in the event that satellites go offline, a decision-maker could determine which signals to degrade first and to what level. This would provide survivability of core capability when it counts most, while reaping the benefits of increased production and smaller satellites for acquisition. In short, this test serves as a worst case or most expensive variant of Survivable Disaggregation. We can have confidence that no other such implementation would cost more than this. Figure 6-28 contains the four (purple) generations associated with Survivable Disaggregation plotted against the four (blue) GPS BATNA generations. It is immediately clear that the production cost of this increase in capability in the presence of increased experience is always more than the BATNA across all four generations.
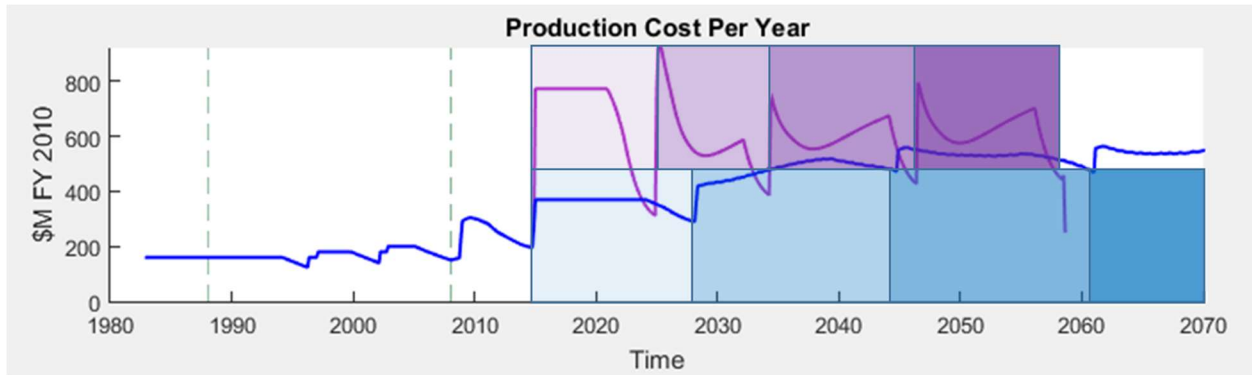
Figure 6-28: Policy Testing, Production Cost per Year, Survivable Disaggregated vs. BATNA

To compare the efficiency of Survivable Disaggregation over time against the other disaggregated approaches, this approach is added to the efficiency curves of the other flavors in Figure 6-29 as a purple line. Based on the raw number of satellites required, it is no surprise to see that its efficiency falls within the region between the 3x and 7x disaggregated approaches.
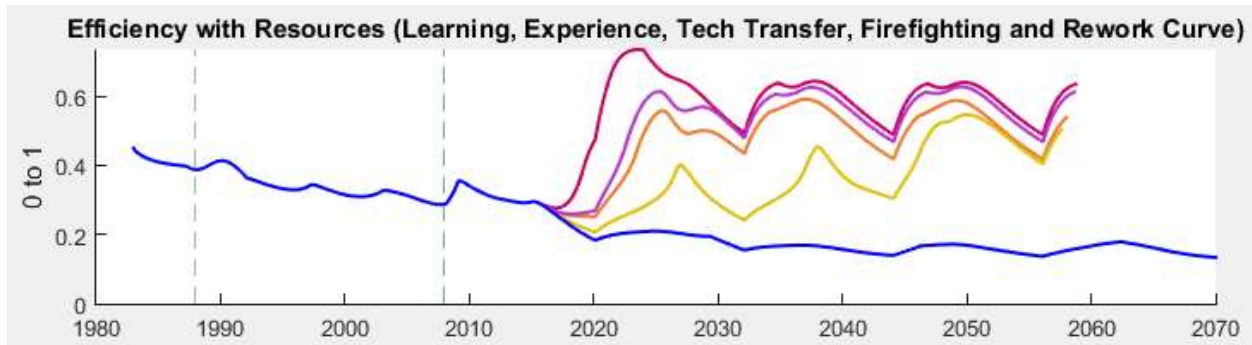
Figure 6-29: Policy Testing, Efficiency, all Disaggregation Policies

These results are not favorable for adoption of such an implementation from a cost savings perspective. While increased survivability is valuable, it comes at a very high cost, and one that decision-makers may be unwilling to pay. Figure 6-30 contains the cost metrics for this implementation. It appears that the FYDEP would on average need to be increased by ~90% in the first two generations and by 60% in the second two. Enhanced performance would also come at a 35% premium over the GPS BATNA. These cost estimates will be challenged when assumptions are varied to include less bias towards the GPS BATNA. Nonetheless, this provides insight into a worst-case Survivable Disaggregation policy. While more expensive than the GPS BATNA, as seen with the other disaggregated approaches, this implementation always delivers the threshold number of satellites on orbit without requiring on-orbit extension of design life.

234

Variable	vs BATNA	vs BATNA	vs BATNA	vs BATNA
1 Gen #, Design Life (years)	1 Gen 1, 15 vs 15	1 Gen 2, 15 vs 15	1 Gen 3, 15 vs 15	1 Gen 4, 15 vs 15
2 Number Satellites Produced	2 144 vs 24	2 144 vs 24	2 144 vs 24	2 144 vs 24
3 Avg Cost Per Production Year Gen vs. Gen	3 186.08%	3 186.77%	3 158.99%	3 163.06%
4 Cost to Acquire a Year of Operational Capability	4 135.48%	4 100.25%	4 119.55%	4 118.59%
5 Cost at End of Production, Policy Cost per year Relative to BATNA	5 186.08% in 2025	5 196.06% in 2035	5 167.94% in 2047	5 162.55% in 2059
6 Compensate for Difference of Production Rate (Time & Performance)	6 135.48% in 2025	6 105.24% in 2035	6 126.28% in 2047	6 118.21% in 2059

Figure 6-30: Policy Testing, Cost Metrics, Survivable Disaggregation vs. BATNA

6.5.4.1 Extending Survivable Design Life to 20 Years

A more direct comparison to the existing BATNA might be to involve satellites designed to last 20, rather than 15 years. The full results of this comparison are available in Appendix: Survivable Disaggregated: Extend Design Life to 20 years. The summary is shown here in Figure 6-31which presents the cost of fielding such a system from 2015 to 2058. A 20-year design life would require an increase of 50%-60% in the FYDEP, and even though efficiency would improve, the premium paid would be on the order of 10%. (See row six in Generation 3.)

Variable	vs BATNA	vs BATNA	vs BATNA
1 Gen #, Design Life (years)	1 Gen 1, 20 vs 15	1 Gen 2, 20 vs 15	1 Gen 3, 20 vs 15
2 Number Satellites Produced	2 144 vs 24	2 144 vs 24	2 144 vs 24
3 Avg Cost Per Production Year Gen vs. Gen	3 163.38%	3 161.39%	3 144.46%
4 Cost to Acquire a Year of Operational Capability	4 113.94%	4 105.91%	4 107.51%
5 Cost at End of Production, Policy Cost per year Relative to BAT	5 163.38% in 2028	5 161.87% in 2042	5 147.56% in 2058
6 Compensate for Difference of Production Rate (Time & Perfor	6 113.94% in 2028	6 106.22% in 2042	6 109.82% in 2058

Figure 6-31: Policy Testing, Cost Metrics, Survivable Disaggregation @ 20-year Design Life vs. BATNA

6.5.4.2 Changing Survivable Quantity in Production from 24 to 36 Satellites

A follow-up question worth answering is: would slowing the technology advancement rate and procuring 32 satellites instead of 24 provide cost savings? The total results of this investigation can be seen in Appendix: Survivable Disaggregated: Build Capability of 32 Versus 24, but the short answer can be seen in Figure 6-33, where rows 3 through 6 can be compared against rows 3 through 6. This policy does not result in cost savings, but rather cost growth over the BATNA and over the survivable disaggregated approach buying in a quantity of 24. In Figure 6-33, the sequencing of such satellite launches is seen. The increase in order size leads to an increase in the duration of production in each generation. The exact completion dates of each generation are seen on the plot and ultimately result in the cost figures for each generation as seen in Figure 6-32. The underlying reason for this growth in cost is the same as explains the cost increase when the GPS BATNA is extended from a production run of 24 to 32. A more expensive acquisition occurs primarily for the large legacy costs and the increased entropy/legacy costs experienced for the last eight produced. Beyond this, the next acquisition is also faced with updating old technology leading to a more expensive NRE.
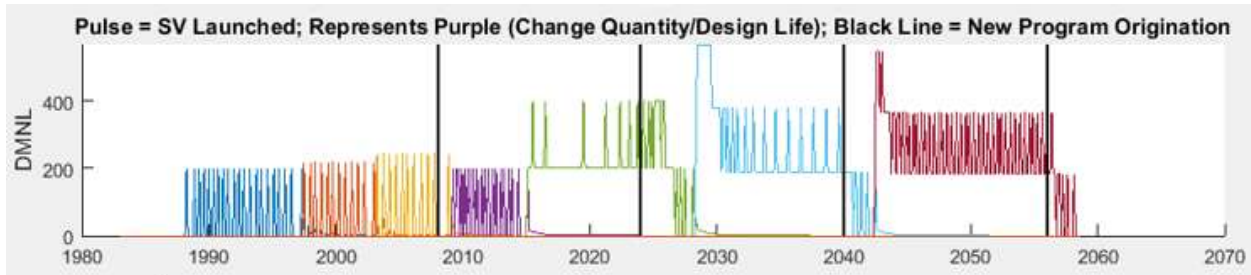
Figure 6-32: Policy Testing, Cost Metrics, Survivable Disaggregation, Production @ 36 vs. BATNA

	Variable		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15
2	Number Satellites Produced	2	192 vs 24	2	192 vs 24	2	192 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	199.94%	3	193.94%	3	173.47%
4	Cost to Acquire a Year of Operational Capability	4	140.74%	4	128.41%	4	129.10%
5	Cost at End of Production, Policy Cost per year Relative to BAT	5	199.94% in 2028	5	194.47% in 2043	5	176.89% in 2059
6	Compensate for Difference of Production Rate (Time & Perfor	6	140.74% in 2028	6	128.76% in 2043	6	131.64% in 2059

Figure 6-33: Policy Testing, Cost Metrics, Survivable Disaggregation, Production @ 36 vs. BATNA

6.5.4.3   *Adding Tick-Tock to Survivable Disaggregation*

In Figure 6-34 the blue line now represents the Survivable Disaggregated architecture and the purple line represents the same architecture implementing the policy of Tick-Tock. It appears that Tick-Tock is able to smooth out the efficiency and cause a faster drop in the Production Cycle Time. Nonetheless, the additional NRE required overwhelms the smoothing of the efficiency curve and the slightly faster decrease in Production Cycle Time. The final result can be seen the Appendix: Survivable Disaggregated: Tick-Tock, but Tick-Tock likely increases cost by six to 11% over Survivable Disaggregation without Tick-Tock. This is the same pattern observed for all variants of disaggregation. Combining Tick-Tock and a disaggregated approach does not create an additive effect under these conditions.
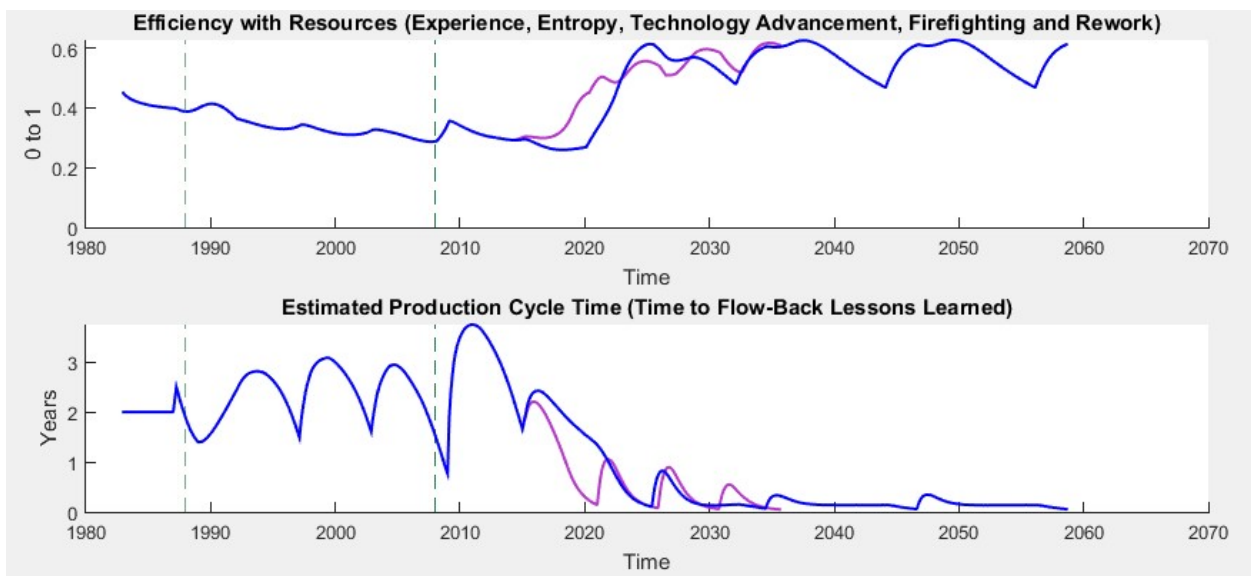
Figure 6-34: Survivable Disaggregated with and Without Tick-Tock

236

7 Varying Assumptions on GPS Policies

In Chapter 2 a context vector for the TSE module was expressed in such a way that the results of a TSE model execution could be examined against assumptions or future uncertainty:

{Year, RF Configuration, Mass Model Tuning, NRE Cost Model Tuning, Production Cost Model Tuning, Launch Costs, On-Orbit Operations}

After computing the results in Chapter 6, this context vector can now be implemented to test assumptions across the Tradespace. For this chapter the full results of each analysis are available in the Appendix R: Disaggregation under Expectation of Budget Cuts and Longer On Orbit Service Life. While each of the context variables was examined, not every variable could be examined with fine resolution—the design-space of all possible context vectors is much too large. Thus, reasonable assumptions grounded in likely future possibilities and their impact on the results in Chapter 6 were implemented. Table 7-1 contains the context variables and the region over which the current model can be examined. While model simulations were executed for many assumptions, not every outcome is discussed in Chapter 7.

As the technique outlined in this work implements a SD model to track time, implementation in this merged model of a context vector will be different for some variables than it is traditional in TSE or Epoch Era Analysis. One example is changes in launch cost which will be discussed in the section 7.2 Launch Cost Reduction.

Two variables which the reader may expect to be present do not appear in Table 7-1:

- Year is not included because it is not a value which is manually changed by the modeler. It functions as a context variable to the TSE module but is passed by the SD model and is unmodifiable. It is the time of the request for a new acquisition, in conjunction with an NRE pulse that impacts how the SD model "closes out" the last program, and starts the new one.
- The RF Configuration module enables examination of assumptions about the link closure, but this is not influenced by any activity in the SD model. These values would be changed in the RF configuration model if link closure elements to include power or antenna size were desired to be examined. The fidelity of the RF model implemented in this work is sufficient.

Table 7-1: Assumption and Context Variables Included in the SD Model

SD Variable → Impact on TSE Context Variable	Possible Values	Notes
Technology Half-life → NRE Cost Model Tuning	Integer 2,3,4,5,6,7	The SD model is tuned to a half-life of 4.5 years. If desired this can be changed to examine accelerating or decelerating technology development. Lower values will increase the entropy injection rate into the SD model. The impact of faster technology change is to increase NRE cost for the same time elapsed in the TSE model.
Parts Commonality → NRE Cost Model Tuning	0 to 100%	This variable is not influenced by any causal links. It is set as a pure context variable which reduces NRE cost. If there is a desire to test assumptions about parts commonality, the level selected indicates the desired percentage reduction for some bus and payload development activities.
Difficulty Under Disaggregation → Production Cost Model Tuning	.01 to infinity	1 implies linear mass complexity. This is the value to which the model has been tuned. In a disaggregated implementation it is possible that elements of architecture production other than increased experience and faster product cycle times exist. This variable allows for testing these assumptions. Values less than 1 will result in less work being added to the production pipeline but the same number of satellites being produced. This has the likely causal effects of satellites costing less and being produced more quickly, all else being equal.
Launch Cost	.01 to 10	This variable tests assumptions about future launch costs. It is not causally linked to any structures. A value of one indicates the same cost as today; two would represent twice today's costs.
Ground Operations Cost	.01 To infinity Needs cost of first unit. Additional unit cost/scaling factor default is $5M and .95	This variable tests assumptions about future ground operations costs. It is not causally linked to any structures. A value of one indicates no cost scaling and that each satellite costs $5M per year to operate. Realistically, if this were the case then a disaggregated approach would

		consume any savings in operations costs and be non-viable. Consequently, a default value of .95 is implemented so that there will be a cost reduction. Each unit will cost 95% of the previous.
Performance Increase Desired	.01 to 1 to infinity	This variable can be used to represent a general desire for an increase in performance. For example, if the GPS Block V wanted to increase "performance" by 25% but there is as yet no knowledge about what that performance would involve, then 1.25 could be input. Technically if performance decreases are desired to be examined, values below 1 can be input as well.

7.1 Identical Operations Costs and Excluding Launch Costs

One of the more significant drawbacks of disaggregated approaches is the anticipation of larger on-orbit operations costs for larger constellations and the need for more rocket launches to place additional over-head mass on orbit. In Chapter 6 the change in replication cost for various disaggregated architectures was seen; the figure is replicated here in Figure 7-1. In every disaggregated configuration examined the replication cost starts higher than the replication costs for the GPS BATNA. In Figure 7-1 when the colored line (red for 7x, orange for 3x, and yellow for 2x) crosses below the blue line (GPS BATNA), the disaggregated approach costs less than the BATNA in production costs per year. However, in Chapter 6 it was also concluded that when all other program elements are factored in, savings in production costs never compensated for the additional costs from NRE, Launch and On-Orbit Operations.
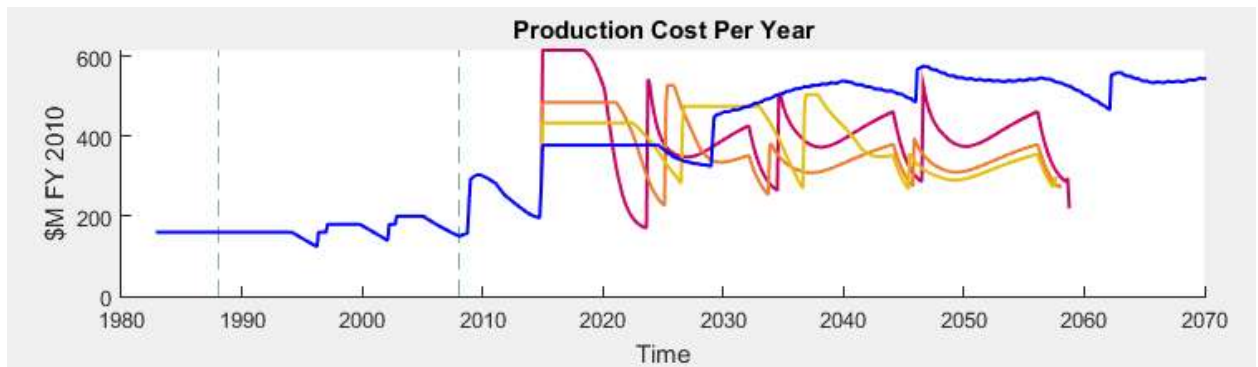
Figure 7-1: Production Cost per Year for Various Disaggregated Architectures

To initially examine the impact of on-orbit operations and launch costs, a generation-against-generation comparison with the GPS BATNA can be conducted with the ops cost or the launch cost removed. This draws either Operations or Launch outside the model boundary to give insight into the generational cost comparison minus that component. This is helpful before testing policies against uncertainty as it provides a bound to how much a component might impact the overall lifecycle cost. The four tables below (Table 7-2 through Table 7-6) present the different flavors of disaggregation. The first row shows the generation-across-generation cost relative to the BATNA.

(These are the same results seen in Chapter 6.). The second row shows the comparison against the GPS BATNA if operations costs are removed from analysis and the third row compares against the BATNA if launch costs are removed from comparison.

In Table 7-2 we can see that excluding operations costs achieves savings for a military and civilian disaggregation no sooner than the fourth generation. If launch costs are excluded, cost savings for equivalent capability emerge in the second generation, though this still requires ~20 years of time.

Table 7-2: Generation-Across-Generation Cost Relative to the BATNA Varying Assumptions, Military/Civilian (2x Disaggregation), Excluding On-Orbit and Launch Costs

Versus BATNA	Generation 1	Generation 2	Generation 3	Generation 4
All Program Elements	115.17%	116.45%	121.15%	99.72%
Excluding Operations Costs	113.99%	107.34%	111.00%	92.64%
Excluding Launch Costs	107.01%	96.99%	90.30%	76.87%

Table 7-3 examines the 3x Disaggregation approach. As noted in Chapter 6, Galileo-Size disaggregation is able to break even with the GPS BATNA in the third generation, a full generation before the 2x implementation. Nonetheless, as discussed in Chapter 6, it requires an increase of 30% over the FYDEP for upwards of 30 years before this is achieved. It would appear that excluding either operations costs or launch costs achieves equilibrium with the GPS BATNA slightly more quickly than as for the 2x disaggregated approach. (Excluding operations costs achieves savings in the third rather than fourth generation, while excluding launch costs continues to achieve savings as soon as the second generation.) The cost of a constellation of 48 versus 72 satellites when considering total life cycle costs is not appreciably different. Launch costs also do not negatively impact the 3x Disaggregation more than the 2x Disaggregation and the "launcher select" subroutine believes the three satellites could fit on the same launch vehicle as the equivalent two. In both these cases, the launch vehicle will be larger and cost more than the BATNA. The raw numbers show that the BATNA costs ~$120M for a launch whereas the 2x and 3x Disaggregation would cost on the order of ~$140M.

Table 7-3: Generation-Across-Generation Cost Relative to the BATNA Varying Assumptions, Galileo-Size Implementation (3x Disaggregation), Excluding On-Orbit and Launch Costs

Versus BATNA	Generation 1	Generation 2	Generation 3	Generation 4
All Program Elements	128.51%	130.07%	103.21%	102.39%
Excluding Operations Costs	126.55%	115.95%	93.90%	93.97%
Excluding Launch Costs	114.64%	104.42%	81.59%	80.11%

From Table 7-4 It is clear that the 7x Disaggregation continues the trend of pushing the equilibrium point from the fourth generation for the 2x Disaggregation, to the third generation. While operations costs are now becoming a bigger piece of the total life-cycle cost and we see a gap of 15 percentage points in the third and fourth generation (versus five points for the 2x and 3x implementations). The real difference is seen in the launch costs. Referencing Chapter 6, this is no surprise as launch costs are believed to be in excess of 250% of the BATNA. This is consistent with the values in this table as well.

Table 7-4: Generation-Across-Generation Cost Relative to the BATNA Varying Assumptions, Full Disaggregation (5x-6x-7x), Excluding On-Orbit and Launch Costs

Versus BATNA	Generation 1	Generation 2	Generation 3	Generation 4
All Program Elements	165.13%	126.79%	116.62%	127.09%
Excluding Operations Costs	163.81%	109.50%	101.81%	112.82%
Excluding Launch Costs	127.94%	93.73%	91.09%	95.36%

Table 7-5 compares the increased capability of the survivable disaggregated implementation where the upgrade path puts 96 satellites on orbit in the first generation, 120 in the second and 144 in the third and fourth. This makes for substantial changes in this table across time as the number of launches and number of satellites on orbit grows versus the BATNA across generations. Interestingly it appears that the relative portion of the life cycle costs remains fairly constant in face of this change, likely because the addition of 24 satellites generation over generation also grows the NRE and reproduction costs. It is also seen in face of this growth that learning effects can be found and some cost savings is made possible in replication of the survivable disaggregated satellites. This implementation does not however, break even with the BATNA, even for the BATNA.

Table 7-5: Generation-Across-Generation Cost Relative to the BATNA Varying Assumptions, Survivable Disaggregated, Excluding On-Orbit and Launch Costs

Versus BATNA	Generation 1	Generation 2	Generation 3	Generation 4
All Program Elements	186.08%	186.77%	158.99%	163.06%
Excluding Operations Costs	172.72%	176.75%	150.62%	154.60%
Excluding Launch Costs	157.64%	135.52%	120.85%	124.30%

7.2 Launch Cost Reduction

It is possible that over time launch costs may become lower. For example, SpaceX was able to successfully place the SES-9 communications satellite with a wet-mass mass of ~5000 kg into geosynchronous orbit on March 4th 2016. (Space Daily, 2016) This implies that a SpaceX launch vehicle is capable of putting any of the disaggregated satellites envisioned in this work into a MEO orbit. Since SpaceX launches are cheaper than those now being achieved, switching to SpaceX could enable lower launch costs. Earlier, SpaceX placed 11 satellites (each weighing ~273 kg) simultaneously into an LEO implying multiple launches under a mass ceiling may also become available at potentially lower cost. (SpaceX, 2015) If cost savings come to fruition, it will impact some architectures more than others (i.e., those for which launch costs represent a larger fraction of their overall life-cycle cost).

In the model developed in this work, context variables can be implemented as traditionally done in TSE, through use of a single change variable within a context vector. This would apply a constant factor to a single generation of GPS satellites. For example, one could imagine a 25% cost reduction in the second generation being applied as a fixed constant in the context vector. In this work, because SD tracks variable changes across time, a different implementation is possible, one that ensures the closest possible apples-to-apples comparison.

One of the advantages of a time-based model for representing change of a variable over time is the ability to draw a trend line and the ease with which it can represent a varying level across all time points. In a diverse analysis it is possible that variables will behave in different fashions at different points in time. Often a subject matter expert will be better able to communicate expectations through drawing a trend line than choosing a specific value which is expected to influence a variable.

In Figure 7-2: Context Variables Across Time, six different potential trends in variable change are shown. Typically, a context vector for TSE (such as the one in Chapter 2) would implement such a relationship via a function or look-up table. While there is nothing in TSE that stops modelers from using any type of equation to examine change over time, nonetheless, the TSE body of literature indicates that most modelers have implemented either linear or discrete implementations of variables when testing model results under future uncertainty. It is possible that since TSE is a point optimization, it inherently constrains some modelers to think in a binary fashion. Within SD any of these trend lines can be implemented but the implementation is more natural and as the computation occurs across time every point is implemented not just a single value as it would be with a point-in-time optimization. This makes the model less susceptible to a

single point in the trend line being wrong as every point on the line carries an equal weight. In a TSE implementation only the value at the year when the computation is done could be input into the model. In Epoch Era Analysis, individual Epochs may occur at different time points, however, each Epoch would still only derive a single number—not the continuous trend evaluated at all points in time.
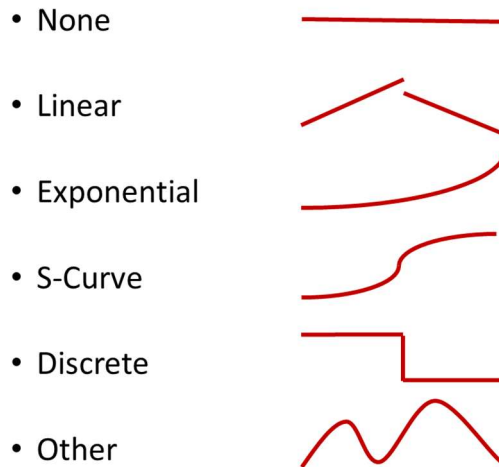
Figure 7-2: Context Variables Across Time

In Figure 7-3, the launch profile for the GPS BATNA is plotted with a blue line laid over top. The Blue line represents future launch, where in 2020 launch costs come down 10% and by 2045 have reduced 40%, with a final 50% reduction being achieved in 2090. This line is for illustrative purposes and does not represent a real projection. A subject matter expert could easily change the line, and the result be recalculated in a matter of minutes. This line could take any shape or form, of which primary examples are seen in Figure 7-2: Context Variables Across Time.
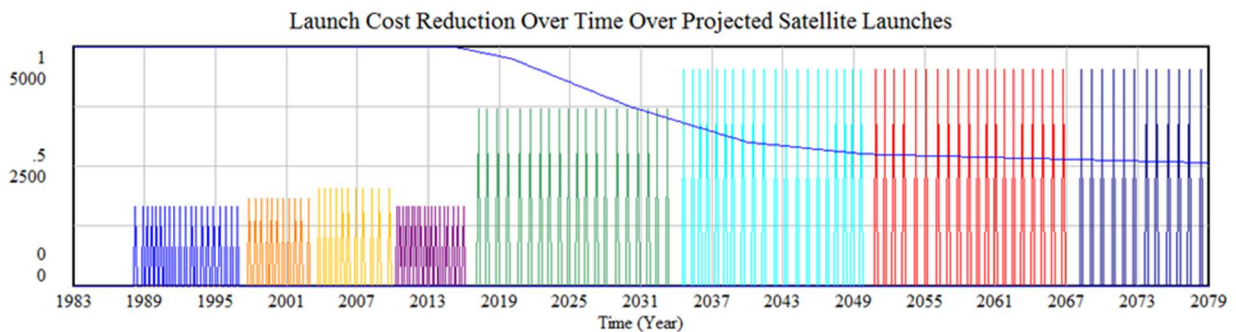
Figure 7-3: Varying Assumptions Launch Cost Reduction over Time, GPS BATNA

In Figure 7-4, the same launch cost reduction line (blue) is laid over the projected launches for the Full Disaggregation architecture. As this architecture completes at different time points, this method of implementing a context variable is superior to implementing a fixed constant at the time satellites are "created" in the TSE modeling routine. This enables a decoupling of the launch cost computation from the TSE routine and ensures the cost reduction applies across time even if

the satellite acquisitions do not. If this were implemented as in traditional TSE, then the near 50% reduction seen in the fourth generation of the GPS (the dark blue pulses in 2070) would need to be applied in 2047 on the Full Disaggregation fourth generation when plotted in Figure 7-4 for a different architecture.
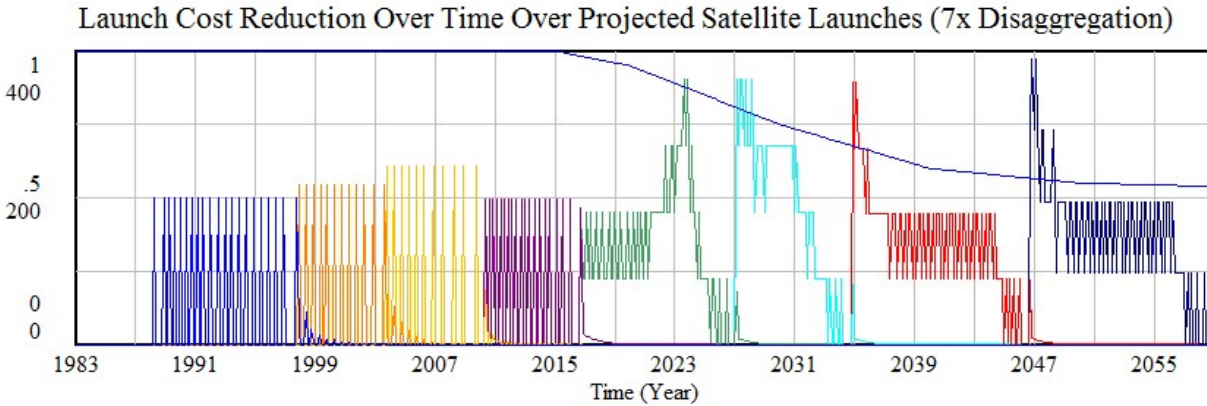
Figure 7-4: Varying Assumptions, Launch Cost Reduction over Time, Full Disaggregation (5x-6x-7x)

The results of the launch-cost reduction curve assumption can be observed for the same four cost metrics used throughout Chapter 6. In Table 7-6, Table 7-7, Table 7-8 and Table 7-9 the impact of this assumption is seen for the four flavors of disaggregation. This assumption does not drastically shift the results of Chapter 6, however, it does enhance the attractiveness of each disaggregated implementation relative to the BATNA. Unlike the results in Chapter 6, however, none of the major trends or timeline associated with capitalizing on learning change. Implementing such an assumption about the future can be valuable in conjunction with other assumptions about future context to properly analyze the future, but it is easy to conclude that a drop in launch costs do not shift the total costs of disaggregated systems to make them appear favorable against the GPS BATNA.

Table 7-6: Varying Assumptions Launch, Cost Reduction over Time, Military/Civilian Implementation (2x Disaggregation)

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	48 vs 24	2	48 vs 24	2	48 vs 24	2	48 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	121.90%	3	130.32%	3	128.18%	3	95.69%
4	Cost to Acquire a Year of Operational Capability	4	100.51%	4	77.62%	4	69.55%	4	69.59%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	121.90% in 2027	5	132.55% in 2037	5	131.84% in 2046	5	95.43% in 2058
6	Compensate for Difference of Production Rate (Time & Performance)	6	100.51% in 2027	6	78.95% in 2037	6	71.54% in 2046	6	69.41% in 2058

Table 7-7: Varying Assumptions Launch Cost Reduction over Time, Galileo-Size Implementation (3x Disaggregation)

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	72 vs 24	2	72 vs 24	2	72 vs 24	2	72 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	137.98%	3	134.65%	3	102.49%	3	100.57%
4	Cost to Acquire a Year of Operational Capability	4	100.46%	4	68.32%	4	76.27%	4	73.14%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	137.98% in 2025	5	139.13% in 2034	5	105.73% in 2046	5	99.87% in 2058
6	Compensate for Difference of Production Rate (Time & Performance)	6	100.46% in 2025	6	70.59% in 2034	6	78.69% in 2046	6	72.63% in 2058

Table 7-8: Varying Assumptions Launch Cost Reduction over Time, Full Disaggregation (5x-6x-7x)

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	144 vs 24	2	168 vs 24	2	168 vs 24	2	168 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	175.34%	3	134.82%	3	125.86%	3	123.61%
4	Cost to Acquire a Year of Operational Capability	4	109.20%	4	86.24%	4	93.66%	4	89.90%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	175.34% in 2024	5	140.17% in 2035	5	129.38% in 2047	5	122.65% in 2059
6	Compensate for Difference of Production Rate (Time & Performance)	6	109.20% in 2024	6	89.67% in 2035	6	96.28% in 2047	6	89.20% in 2059

Table 7-9: Varying Assumptions Launch Cost Reduction over Time, Survivable Disaggregated Implementation

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	96 vs 24	2	120 vs 24	2	144 vs 24	2	144 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	195.94%	3	186.78%	3	156.21%	3	159.24%
4	Cost to Acquire a Year of Operational Capability	4	142.66%	4	100.26%	4	117.46%	4	115.81%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	195.94% in 2025	5	192.71% in 2035	5	160.83% in 2047	5	157.94% in 2059
6	Compensate for Difference of Production Rate (Time & Performance)	6	142.66% in 2025	6	103.44% in 2035	6	120.93% in 2047	6	114.86% in 2059

7.3 Part Commonality

A major assumption underlying NRE and technology refresh costs is a lack of part commonality among disaggregated space vehicles. This is likely a false assumption: in most of the designs a nearly identical bus and control software could be implemented, and for most payloads the atomic clock would also be nearly identical. To challenge this assumption is easy for this model: NRE costs associated with the second through n^{th} vehicle are reduced by 50% for all components. The first satellite still pays the full NRE cost, but the NRE cost for the remaining satellites' bus is reduced. (No reduction is offered for payloads, overhead programmatic costs, or integration and test.) The NRE for the payloads (signals) is not assumed to be reduced, due to the fact that the large NRE cost of GPS payloads is well fit to existing historical development and no cost models are available to analyze such an implementation. One would need to argue that

building more unique payloads (NRE not production) would cost less than the existing payload suite fielded. This is not likely.

Part commonality is not to be confused with the assumption that the overall complexity in production of satellites my change under disaggregation. The model makes the assumption that production of a satellite with one GPS signal is as difficult as producing a satellite with seven GPS signals. Logically the number of interfaces will rise, increasing the difficulty of manufacturing a satellite with more signals. It is unclear if in disaggregation this complexity decreases or if it is transferred to other parts of the system (such as the ground control segment). This is a different assumption that could also be challenged. The model is already expecting the construction of disaggregated vehicles to cost more and relying on enhanced learning to counter this. There is an unmitigated bias from complexity inside the satellite, but as previously discussed, this bias is desirable in this investigation to ensure conservative estimates for potential cost savings/growth under a new architecture or set of policies.

Table 7-10 shows the impact of the assumption of part commonality of 50% in the theoretical first unit's bus across system lifecycle costs within each generation, all else equal when compared to the GPS BATNA with no part commonality. To achieve this plot, the model results in Chapter 6 are compared against an identical run where now part commonality is changed in the TSE model's cost routine; the new generation life-cycle cost is divided by the original numbers from Chapter 6.

Table 7-10: Impact of 50% Part Commonality if NRE @ 15 Years All Levels of Disaggregation

Impact of 50% Part Commonality if NRE @ 15 Years	Generation 1	Generation 2	Generation 3	Generation 4
Military/Civilian Implementation (2x Disaggregation)	97.05% in 2027	97.00% in 2037	96.72% in 2046	96.80% in 2058
Galileo-Size Implementation (3x Disaggregation)	96.27% in 2025	95.66% in 2034	96.13% in 2046	96.10% in 2058
Full Disaggregation (5x-6x-7x)	96.35% in 2024	95.66% in 2035	95.98% in 2047	95.95% in 2059
Survivable Disaggregated Implementation	96.99% in 2025	96.01% in 2035	95.98% in 2047	95.92% in 2059

If the time between NRE events is shortened from 15 years to 7.5 years, the number of NRE events must double and consequently, the impact of the assumptions around part commonality changes. They represent a different relative proportion of the overall system cost; this can be seen in Table 7-11. In Chapter 6, the shortening of time between NRE events was viewed negatively. Now the data in this table give insight to why even under assumptions about part commonality the

model results still favor pushing the time between NRE events out to ~15 years. NRE is responsible for upwards of 20% of the life-cycle cost, thus even with part commonality (cost reduction of approximately four percent in conjunction with the other benefit, lower legacy costs and smaller NRE), there is still a larger overall life-cycle cost for short NRE intervals.

Table 7-11: Impact of 50% Part Commonality if NRE @ 7.5 Years All Levels of Disaggregation

Impact of 50% Part Commonality if NRE @ 7.5 Years	Generation 1	Generation 2	Generation 3	Generation 4
Military/Civilian Implementation (2x Disaggregation)	94.48% in 2020	95.22% in 2025	95.12% in 2029	95.20% in 2034
Galileo-Size Implementation (3x Disaggregation)	93.48% in 2021	93.61% in 2025	93.93% in 2029	94.22% in 2035
Full Disaggregation (5x-6x-7x)	93.93% in 2021	93.21% in 2025	93.63% in 2030	93.97% in 2035
Survivable Disaggregated Implementation	94.63% in 2021	94.06% in 2025	93.56% in 2030	93.65% in 2035

7.4 Launch Cost Reduction and 50% Part Commonality

If the above assumptions of launch-cost reduction and 50% part commonality are used in combination, there may be a different assessment of the premium which disaggregated architectures impose across time and generations. The trends seen in Chapter 6 are still intact, however, the premium paid for the different disaggregated approaches is less; decision-makers may be willing to pay this level of premium for the additional satellite capability presented by the various disaggregated approaches. In the fourth generation of the 2x implementation and the third generation of the 3x Disaggregation these two assumptions push the cost below 100% of the GPS BATNA. This indicates that in these generations the cost savings from learning effects in production now makes up for the additional NRE, Launch and on-orbit costs associated with the disaggregated implementations.

Table 7-12: Varying Assumptions, 50% Part Commonality and Launch Cost Reduction over Time, Military/Civilian Implementation (2x Disaggregation)

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	48 vs 24	2	48 vs 24	2	48 vs 24	2	48 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	118.19%	3	114.54%	3	111.25%	3	91.78%
4	Cost to Acquire a Year of Operational Capability	4	97.45%	4	64.85%	4	63.82%	4	66.75%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	118.19% in 2027	5	116.73% in 2036	5	114.45% in 2046	5	91.41% in 2058
6	Compensate for Difference of Production Rate (Time & Performance)	6	97.45% in 2027	6	66.09% in 2036	6	65.65% in 2046	6	66.48% in 2058

Table 7-13: Varying Assumptions, 50% Part Commonality and Launch Cost Reduction over Time, Galileo Implementation (3x Disaggregation)

Variable	vs BATNA	vs BATNA	vs BATNA	vs BATNA
1 Gen #, Design Life (years)	1 Gen 1, 15 vs 15	1 Gen 2, 15 vs 15	1 Gen 3, 15 vs 15	1 Gen 4, 15 vs 15
2 Number Satellites Produced	2 72 vs 24	2 72 vs 24	2 72 vs 24	2 72 vs 24
3 Avg Cost Per Production Year Gen vs. Gen	3 132.66%	3 120.55%	3 91.68%	3 95.72%
4 Cost to Acquire a Year of Operational Capability	4 96.58%	4 61.16%	4 68.23%	4 69.62%
5 Cost at End of Production, Policy Cost per year Relative to BATNA	5 132.66% in 2025	5 124.68% in 2034	5 94.59% in 2046	5 95.00% in 2058
6 Compensate for Difference of Production Rate (Time & Performance)	6 96.58% in 2025	6 63.26% in 2034	6 70.39% in 2046	6 69.09% in 2058

Table 7-14: Varying Assumptions, 50% Part Commonality and Launch Cost Reduction over Time, Full Disaggregation (5x-6-7x)

Variable	vs BATNA	vs BATNA	vs BATNA	vs BATNA
1 Gen #, Design Life (years)	1 Gen 1, 15 vs 15	1 Gen 2, 15 vs 15	1 Gen 3, 15 vs 15	1 Gen 4, 15 vs 15
2 Number Satellites Produced	2 144 vs 24	2 144 vs 24	2 168 vs 24	2 168 vs 24
3 Avg Cost Per Production Year Gen vs. Gen	3 168.66%	3 121.27%	3 110.37%	3 117.02%
4 Cost to Acquire a Year of Operational Capability	4 105.04%	4 76.69%	4 82.99%	4 85.11%
5 Cost at End of Production, Policy Cost per year Relative to BATNA	5 168.66% in 2024	5 126.27% in 2035	5 113.49% in 2047	5 116.02% in 2059
6 Compensate for Difference of Production Rate (Time & Performance)	6 105.04% in 2024	6 79.84% in 2035	6 85.34% in 2047	6 84.38% in 2059

Table 7-15: Varying Assumptions, 50% Part Commonality and Launch Cost Reduction over Time, Survivable Disaggregated Implementation

Variable	vs BATNA	vs BATNA	vs BATNA	vs BATNA
1 Gen #, Design Life (years)	1 Gen 1, 15 vs 15	1 Gen 2, 15 vs 15	1 Gen 3, 15 vs 15	1 Gen 4, 15 vs 15
2 Number Satellites Produced	2 96 vs 24	2 120 vs 24	2 144 vs 24	2 144 vs 24
3 Avg Cost Per Production Year Gen vs. Gen	3 189.81%	3 178.06%	3 148.54%	3 151.20%
4 Cost to Acquire a Year of Operational Capability	4 138.19%	4 95.58%	4 111.69%	4 109.96%
5 Cost at End of Production, Policy Cost per year Relative to BATNA	5 189.81% in 2025	5 183.75% in 2035	5 152.93% in 2047	5 149.96% in 2059
6 Compensate for Difference of Production Rate (Time & Performance)	6 138.19% in 2025	6 98.63% in 2035	6 115.00% in 2047	6 109.06% in 2059

7.5 Anticipating Longer On-Orbit Operations

Throughout this work it has been noted that the BATNA, to which all changes have been compared, relies heavily upon satellites far exceeding their design lives when in operation in order to achieve its cost point. As all satellites considered in this thesis have been designed with the same reliability, despite construction under different policies/architectures, one could reasonably assume they will last as long as the BATNA design when actually on orbit. Thus, it is also reasonable to conclude that decision-makers may fall into the trap of undoing the benefit of policies by expecting disaggregated implementations to also last beyond their design lives. If initial gains in learning lead to decreasing production costs, and then an extension of on-orbit service life in future GPS generations occurs, a slowing of production will occur which may give back the gains made. Conversely, it is also reasonable that if offered extra utility, in the form of on-orbit life extensions, the DoD would be incorrect to simply discard working assets. The DoD would like a policy where it can capitalize on emergent extra capability, but not at the expense of the space industry's experience/efficiency.

In Chapter 6 it appeared that even in the face of legacy costs and the difficulty associated with working with old technology, the extension of a 15-year design life satellite to 20 years provides a 13% cost savings across the life-cycle of an individual space asset. Given these

assumptions, in this section we will examine the consequences of extended operational design life. The model is asked to deliver similar capability and operate under the same assumption for the disaggregated architectures as the BATNA where threshold capability can be achieved in expecting satellites to operate beyond their design life. To perform this calculation two contexts are changed: first, the model no longer strictly enforces the threshold number of satellites on orbit and second, it aggressively cuts cost in production when possible. As a consequence, production inside a generation will be stretched across a longer time horizon and it can be anticipated that this will lead to lower levels of efficiency in comparison with the results seen in Chapter 6. It is unclear, however, what impact this will have on Process Cycle Time, experience levels and most importantly, the cost of acquisition.

While not encoded as one of the original context variables in Table 7-1, it is very easy to change the SD model to analyze this question using the existing tools. There are actually two ways to alter the calculations to achieve the desired simulation performance. The first and simplest route is changing the pipeline representing the on-orbit capability. When a satellite is added, it is added with additional years of operational capability. For example, instead of 180 months of capability (15*12), 240 months (20*12) can be added. (Not to complicate the explanation, but this could also be encoded as a slower degradation rate and mathematically achieve the same result. Due to the causal loops of the SD model, this will automatically slow the acquisition rate, and the unspent additional funding will be captured as a cost savings.) It is theoretically possible that (as occurs for the BATNA) this activity would lead to over-runs or Nunn-McCurdy breaches in future generations -- as longer design life will lead to less work, less experience, and longer development cycles placing future generations in a worse alignment with respect to efficiency in the model. The model will capture this (as it does for the BATNA) if a 25% violation of the baseline occurs.

The second approach to changing the SD model, and the way actually implemented, is to think of this problem as equivalent to the question: What if budget cuts are imposed during production? Imposing a reduction on funding has the causal effect of reducing the number of satellites produced and requiring satellites to last longer on orbit than initially designed. This perspective is closer to the reality facing the DoD than the first viewpoint, which rests on the assumption that satellites are launched with optimistic expectations of extra capability.

To begin to explore the impact of budget cuts, we look first at the effect of 10% and 20% reductions in production funding for the GPS BATNA. In Figure 7-5 the blue line represents the BATNA, the orange line represents a 10% reduction in funding, and the red line represents a 20% funding reduction. With reductions in funding, production costs continue to rise, but by less than the amount saved by getting "free" capability on orbit from existing assets. Note that in Figure 7-5 the funding profile is not flat, the curves are a result of the Nunn-McCurdy Loop kicking in to request additional funding. In this simulation the additional funding is delivered only to ensure that the Firefighting Loop does not overwhelm production. Funding to achieve constellation strength of the threshold 24 satellites is not provided. Otherwise the Nunn-McCurdy Loop would just add back in the cost reduction and if the Firefighting Loop was not mitigated by this additional funding then inefficiency in the system would grow to such a level that the reinforcing loops would "hard-break" and no satellites would be produced. The difference between the initial production cost and the curve in the line can be viewed as the cost of keeping the pipeline open. This simple analysis is akin to budget-cut drills or the impact of across-the-board spending cuts on the GPS program's ability to deliver value.
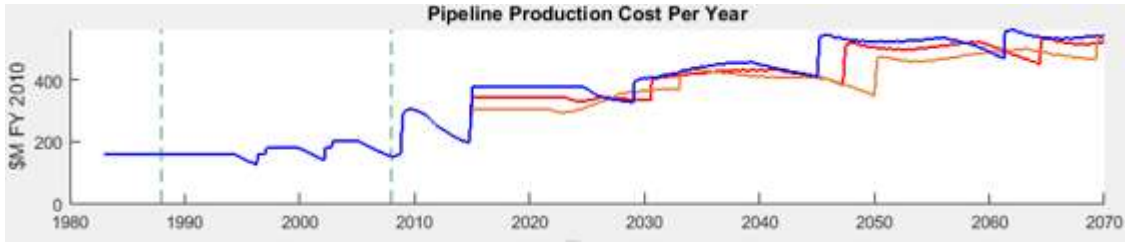
Figure 7-5: Varying Assumptions, GPS BATNA, 10% & 20% Pipeline Production Cost Reduction

Figure 7-6 displays how many satellites would be on orbit in each scenario if each GPS satellite on average only lasted for their design life of 15 years. The model has been instructed not to strictly enforce keeping 24 satellites on orbit; this allows for a computation of how long the satellites must now last beyond their design life to keep 24 satellites on orbit. The figure shows that on average, the 15-year satellites of the BATNA will need to last 19.21 years on orbit to maintain constellation strength. In the face of a 10% cut in production that number extends to over 21 years and in the case of a 20% budget cut the requirement approaches 24 years. This requirement continues expanding as fewer resources being sent to production reduces production of satellites. This in turn places the DoD in a position where satellites must last longer in order to maintain constellation strength; this is a continuation of the trends that already characterize the industry.
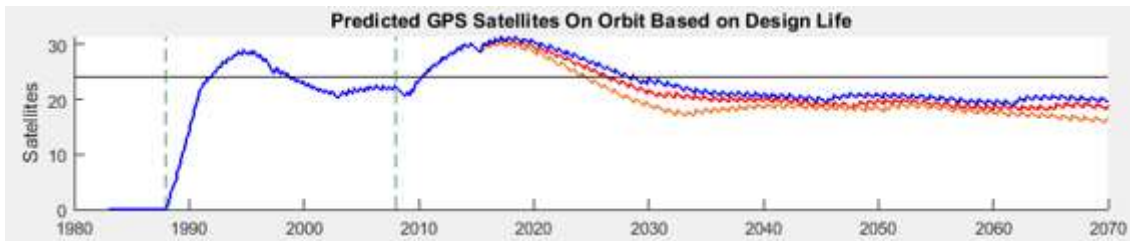
Figure 7-6: Varying Assumptions, Satellites on Orbit, GPS BATNA, 10% & 20% Pipeline Production Cost Reduction

If the extended useful life is achievable, reducing funding by 20% (yellow line), results in a cost savings of 17% over the model's projection for the BATNA for the first generation. (See row 3 in Table 7-16). Admittedly, this continues the cycle of weakening the industry, furthers reliance on longer on-orbit service lives, and slows technology advancement, but until there is either a "hard break" in the system or satellites design life can no longer be extended. (Note that in the second generation the cost savings is only 6%).

As seen in Table 7-16 rows 4 and 6, after initial savings the cost to acquire equivalent capability will slowly creep up, as efficiency in producing satellites declines. In Generation 4 the efficiency of the system is 10% worse but cost savings are still possible. All this is predicated on the belief that the average GPS III, and future generations also designed for 15 years, will last 24 years. It is also interesting (and reasonable) that the model does not suggest that the difficulty in dealing with 24-year-old technology, rather than 15-year-old technology outweighs the benefit of nine "free" years of on-orbit capability. Rather, the downside of this approach to acquisitions is that if any satellite is lost before the end of its extended design life, a gap in coverage opens that will take years to close, and if multiple satellites are lost, substantial coverage gaps may exist for

years. Also, this acquisitions style is not "agile" and cannot generate capability quickly if assets are lost prematurely.

Table 7-16: Varying Assumptions, Cost Metrics, GPS BATNA, 20% Reduction in Production Funding per Year

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	24 vs 24	2	24 vs 24	2	24 vs 24	2	24 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	83.00%	3	94.01%	3	88.44%	3	92.37%
4	Cost to Acquire a Year of Operational Capability	4	106.30%	4	99.89%	4	104.76%	4	110.13%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	82.26% in 2033	5	90.69% in 2050	5	87.83% in 2070	5	92.33% in 2089
6	Compensate for Difference of Production Rate (Time & Performance)	6	105.35% in 2033	6	96.36% in 2050	6	104.05% in 2070	6	110.09% in 2089

7.5.1   Military/Civilian Implementation (2x Disaggregation)

Now that the effect of cutting production costs has been analyzed for the GPS BATNA, it is time to examine the consequences for the disaggregated approaches. There is recognition in Chapter 6 that the GPS BATNA is already capitalizing on longer on-orbit life and the ability to lower production funding each year. Thus, the just-considered 10% and 20% reductions were additional cuts for a system already failing to maintain constellation strength. Now the model reports on how underfunding will impact the disaggregated implementations and see if they also fail to meet the threshold capability under cuts to production costs.

Recall that cumulative learning effects across time are linked to the speed at which lessons learned can be flowed back both within generation and across generations. Funding below the estimated level year over year will impact both these activities. In Figure 7-7, Figure 7-8, and Figure 7-9, the blue line represents the GPS BATNA, the red line represents the 2x Military/Civilian Disaggregation and the orange line represents the 2x Military/Civilian Disaggregation with a 20% reduction in production funding in each generation.
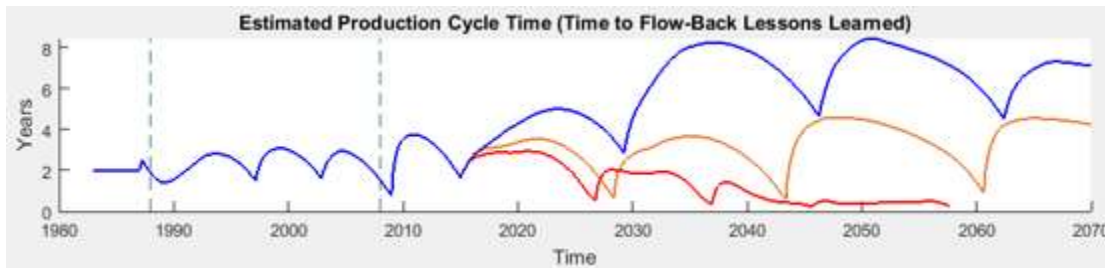
Figure 7-7: Varying Assumptions, Production Cycle Time for GPS BATNA, Military/Civilian, and Military/Civilian with Reduction in Production Funding per Year
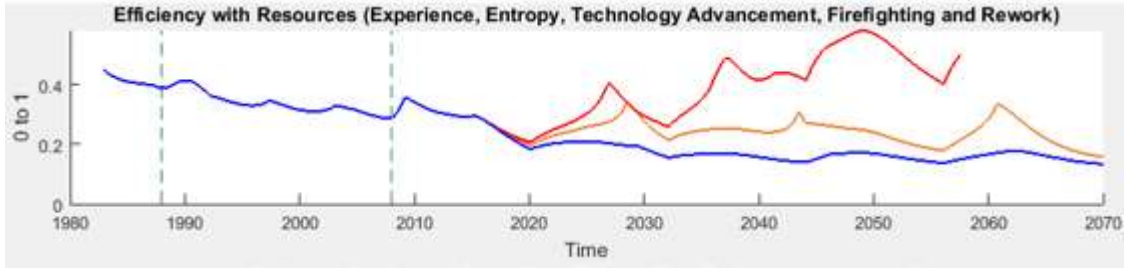
Figure 7-8: Varying Assumptions, Efficiency for GPS BATNA, Military/Civilian, and Military/Civilian with Reduction in Production Funding per Year
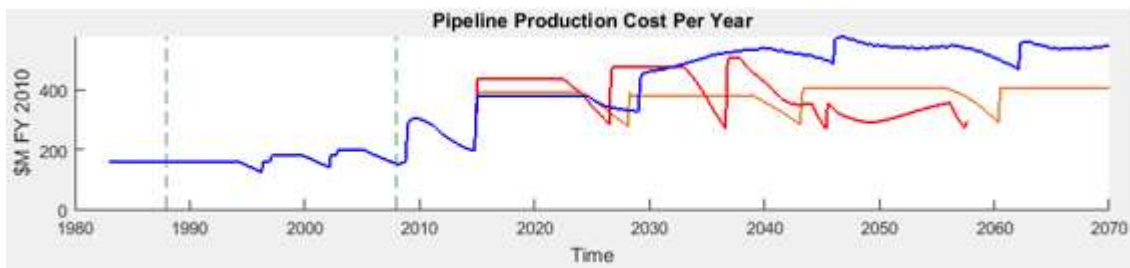
Figure 7-9: Varying Assumptions, Efficiency for GPS BATNA, Military/Civilian, and Military/Civilian with Reduction in Production Funding per Year

The impact of cost cutting on the 2x Military/Civilian disaggregated approach is clearly seen in the graphs. Production Cycle Time is no longer reduced sufficient to counteract the erosion in efficiency, and hence the cost savings of the first and second generations are lost in the third and fourth generations (but this does not lead to a substantially higher production cost per year looking at the orange line over the red line in 2045-2060). It is no surprise that the pipeline production cost per year in the reduced funding case (orange) is higher than for the base-case (red-line) where funding is not withheld. The cost for a year of operational capability is higher than was seen in Chapter 6 (row 4 in Table 7-17). Average costs (for the FYDEP) seen in rows 3 and 5 are, however, substantially lower than the results in Chapter 6 for the disaggregated implementation. They are now so much lower that they offer a cost savings over the BATNA as soon as the second generation, while originally no cost savings were ever possible. The conclusion here is striking, if we expect satellites to last longer on orbit, and this is how acquisitions will be conducted, then a 2x disaggregated approach offers savings over a long time period, and will cost no more than a single large satellite. Nonetheless, 2x Disaggregation possesses an unstable and non-virtuous Process Cycle Time and an eroding efficiency across time. The model forecasts that this approach will not be able to achieve substantial gains over the BATNA before 2045 with respect to efficiency. Between 2028 and 2043, however, ~15% extra years of operational capability would be produced for the same cost.

252

Table 7-17: Varying Assumptions, Cost Metrics for GPS BATNA vs. Military/Civilian with Reduction in Production Funding per Year

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	48 vs 24	2	48 vs 24	2	48 vs 24	2	48 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	103.02%	3	95.76%	3	86.83%	3	83.42%
4	Cost to Acquire a Year of Operational Capability	4	96.69%	4	84.49%	4	92.89%	4	94.80%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	103.02% in 2028	5	96.45% in 2043	5	87.67% in 2061	5	83.42% in 2079
6	Compensate for Difference of Production Rate (Time & Performance)	6	96.69% in 2028	6	85.10% in 2043	6	93.79% in 2061	6	94.80% in 2079

7.5.2   Galileo-Size Implementation (3x Disaggregation)

Turning now to 3x Disaggregation, Figure 7-10, Figure 7-11, and Figure 7-12 show the GPS BATNA with a blue line, the results of the 3x Disaggregation (from Chapter 6) with a red line and the effect of a 20% cut in production costs on 3x Disaggregation with an orange line.

Unlike the Military/Civilian 2x Disaggregation, the implementation of production cost cuts for 3x Disaggregation does not cause as great a loss in efficiency (but clearly puts efficiency well below its previous level in Figure 7-10 and it is unclear if the erosion has been stopped). Part of the reason for the slightly better performance is the greater number of space vehicles being built and another part is the Process Cycle Time, which is no longer a virtuous cycle (shown by the red line), though stable in its oscillating pattern (orange line in Figure 7-11). This is unlike the 2x Disaggregation (seen in Figure 7-7) where the Process Cycle Time grows progressively longer generation over generation). **The implications of this on production cost per year can be seen in** Figure 7-12: Varying Assumptions, Production Cost per Year for GPS BATNA, 3x Disaggregation,**Figure 7-12 where the attempt to cut costs results in less capability, being more slowly delivered and costing more over the production run.** Had learning efects taken hold this would not be the case, but as the improvbements from this policy arte insufficent to capitalize on learning effects, attempting to decrease funding has a negative impact on acqusitions.
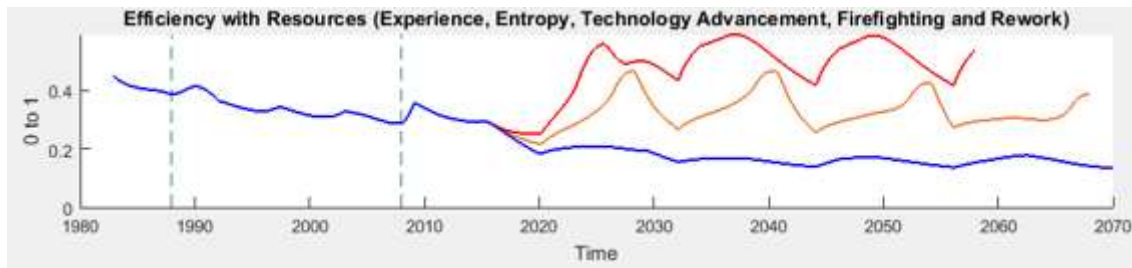
Figure 7-10: Varying Assumptions, Efficiency for GPS BATNA, 3x Disaggregation, and 3x Disaggregation with Reduction in Production Funding per Year
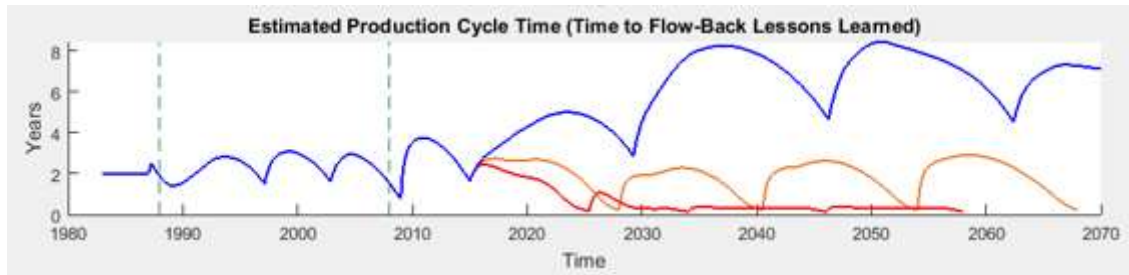
Figure 7-11: Varying Assumptions, Production Cycle Time for GPS BATNA, 3x Disaggregation, and 3x Disaggregation with Reduction in Production Funding per Year
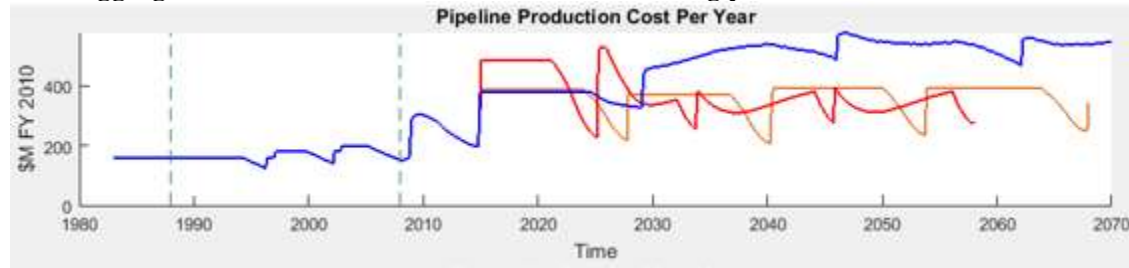
Figure 7-12: Varying Assumptions, Production Cost per Year for GPS BATNA, 3x Disaggregation, and 3x Disaggregation with Reduction in Production Funding per Year

Clearly, this implementation faces substantial losses in efficiency. Nonetheless, even under budget cuts 3x Disaggregation does not require satellites to last beyond their 15-year design life to maintain the performance threshold, unlike both the BATNA and 2x Disaggregation. (See Figure 7-13.) In brief, 3x Disaggregation is preferable to 2x Disaggregation or the BATNA across the entire life-cycle of the program as it would not increase the FYDEP in any generation (Table 7-18 line 3), and would deliver capability on orbit for about 19% less (Table 7-18 line 4), thus closing the capability gap (maintaining the equivalent of 24 satellites on orbit). This policy is robust against the DoD acquisition pipeline and unexpected budget cuts; it will provide protection against funding cuts and enable capturing on-orbit life extensions without harming the acquisition.

254

Table 7-18: Varying Assumptions, Cost Metrics for GPS BATNA vs. 3x Disaggregation with Reduction in Production Funding per Year

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	72 vs 24	2	72 vs 24	2	72 vs 24	2	72 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	104.60%	3	98.09%	3	97.74%	3	95.89%
4	Cost to Acquire a Year of Operational Capability	4	95.43%	4	72.12%	4	81.82%	4	81.36%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	104.60% in 2028	5	99.26% in 2041	5	100.01% in 2054	5	95.74% in 2068
6	Compensate for Difference of Production Rate (Time & Performance)	6	95.43% in 2028	6	72.99% in 2041	6	83.73% in 2054	6	81.23% in 2068

Figure 7-13: Varying Assumptions, Production Cost per Year for GPS BATNA, 3x Disaggregation, and 3x Disaggregation with Reduction in Production Funding per Year

7.5.3   Full Disaggregation (5x-6x-7x)

With Full Disaggregation a different trend emerges. Again in Figure 7-14, Figure 7-15, and Figure 7-16 the blue line represents the GPS BATNA, the red line represents the 7x Disaggregation and the orange line represents the 7x or Full Disaggregation when subject to budget cuts. In the 2x and 3x implementations cost cutting had the impact of breaking the virtuous cycles of reduced cycle time and experience. Yet for Full Disaggregation, even in the face of extreme reductions in production funding the Process Cycle Time in generation over generation is kept down by the reinforcing loop. (The orange line is similar to the red.) This is the desired result, indicating a successful change to policy, finding conditions under which either production can be increased or cost savings can be extracted while maintaining the same level of performance. While efficiency becomes more volatile (to both the up and down side of the red line), it maintains an average high level equal to that seen in Chapter 6.
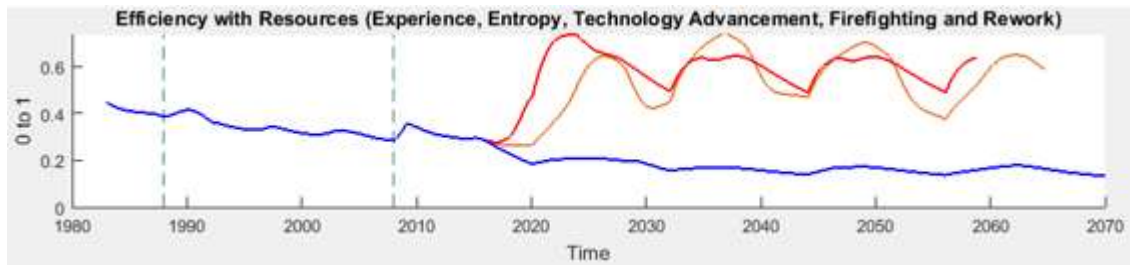
Figure 7-14: Varying Assumptions, Efficiency for GPS BATNA, Full Disaggregation, and Full Disaggregation with Reduction in Production Funding per Year
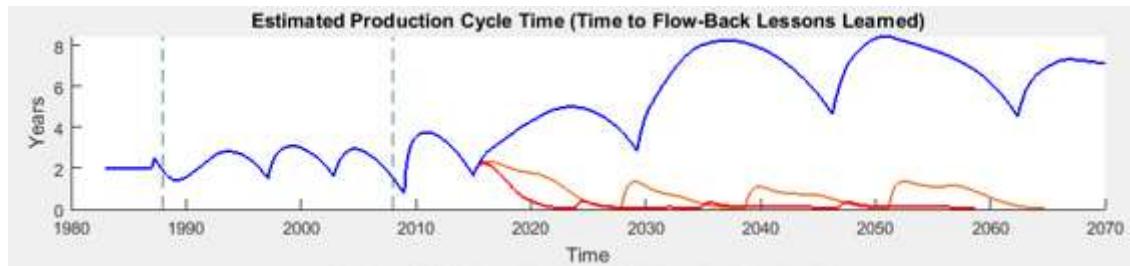
Figure 7-15: Varying Assumptions, Production Cycle Time for GPS BATNA, Full Disaggregation, and Full Disaggregation with Reduction in Production Funding per Year
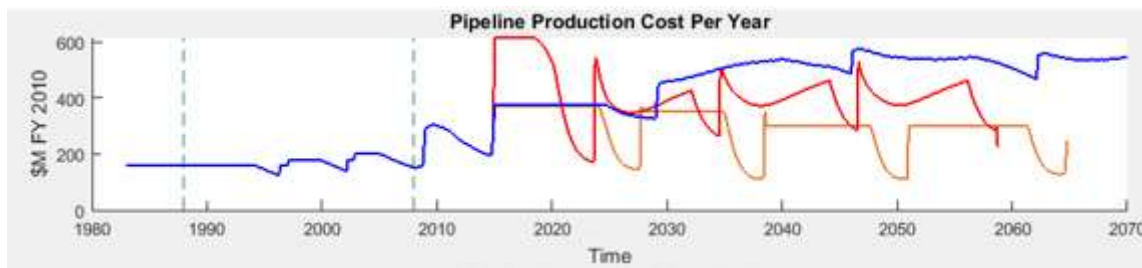
Figure 7-16: Varying Assumptions, Production Cost per Year for GPS BATNA, Full Disaggregation, and Full Disaggregation with Reduction in Production Funding per Year

Due to the emergence of this virtuous cycle, in future generations, substantial savings in production cost emerge even in the presence of delayed acquisitions from budget cuts. As with 3x Disaggregation, this implementation is able to maintain threshold constellation strength despite a slightly slower acquisitions profile as seen in Figure 7-16. Most surprisingly, Full Disaggregation, which appeared to be a very poor choice in Chapter 6 now emerges as requiring only a 10% premium to the FYDEP over the GPS BATNA. (See Table 7-19.) Not shown in the table, but extracted from the underlying data used to compute the total lifecycle cost, despite the 7x Disaggregation requiring 250%+ in launch and 180%+ in on-orbit operations costs, these small satellites are made in such large quantities that they are able to save so much in production costs across time that Full Disaggregation is nearly able to break even relative to the BATNA. (See row 3.)

256

Table 7-19: Varying Assumptions, Cost Metrics for GPS BATNA vs. Full Disaggregation with Reduction in Production Funding per Year

Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1 Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2 168 vs 24	2	168 vs 24	2	168 vs 24	2	168 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3 113.47%	3	118.56%	3	109.09%	3	102.86%
4	Cost to Acquire a Year of Operational Capability	4 102.52%	4	74.97%	4	84.56%	4	84.94%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5 113.47% in 2028	5	120.23% in 2039	5	112.85% in 2051	5	102.67% in 2065
6	Compensate for Difference of Production Rate (Time & Performance)	6 102.52% in 2028	6	76.03% in 2039	6	87.48% in 2051	6	84.78% in 2065

It might appear (from Figure 7-16) that the production costs of the second generation might also be cut however, doing so drops the efficiency and substantially increases cost of the third and fourth generations. Cutting in the second generation can save five percentage points in average cost per product year in the second generation (dropping the 118.56% value to 113%), however, this also lengthens the program from 2039 to 2044 and has the consequence of delaying all technology by an additional half-life. This necessitates additional funding in generations equal to three and four, erodes the efficiency, and costs rise back up in those later generations. This is the limit to which this implementation is robust to cost cuts: anymore and the efficiency will lose its virtuous cycle.

Thus, no cuts beyond those shown in Figure 7-16 can be made and still reach a high level of efficiency by 2039 and maintain that level in the future. Figure 7-17 displays the consequences of an additional 10% cut to funding in the second generation with equivalent funding in the third and fourth generations; the efficiency is now eroding. Unfortunately, due to the increased launch costs, for the 7x disaggregated approach at 250% and the increase in on-orbit operations costs, seen at ~180% of the BATNA, Full Disaggregation still can not only break even with the BATNA in 2039. Yet in comparison to the 2x and 3x disaggregated approaches (which can save money), this is the only approach which is able to truly capitalize on learning. The cost savings in 2x and 3x Disaggregation come from increased learning, but only here is a true virtuous cycle born. An acquisitions decision-maker needs to consider if this justifies further consideration of Full Disaggregation. One must also take into account other assumptions such as part commonality and launch costs before reaching a final conclusion about whether such a substantial shift in value (GPS signal) delivered is worth adopting. If, however, one wants a policy to stabilize the industry that is robust to changes in funding profiles, and enables capture of extra emergent on-orbit operational life, a disaggregation level of above roughly six is a way to achieve this.
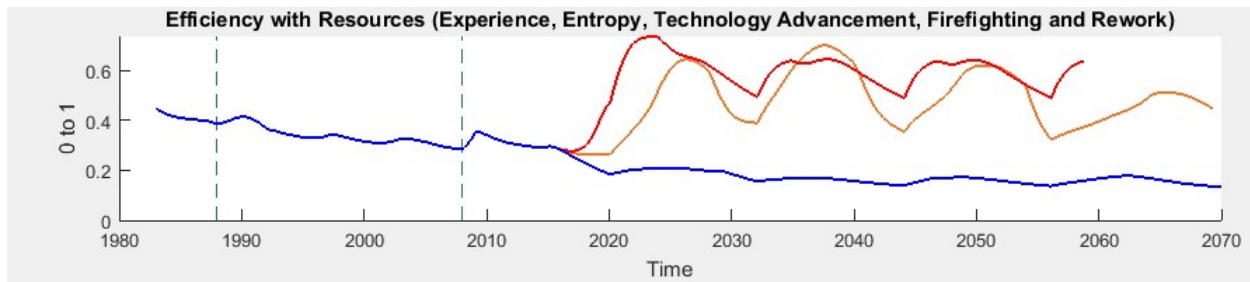
Figure 7-17: Varying Assumptions, Production Cost per Year for GPS BATNA, Full Disaggregation, and Full Disaggregation with Broken Efficiency due to Reduction in Production Funding per Year

7.5.4 Survivable Disaggregated Architecture

The same computations were run for the survivable disaggregated implementation which requires production levels in excess of 5x the current BATNA. With this approach can a virtuous cycle be maintained as it is with Full Disaggregation if production funding is cut and on-orbit life extended? If such behavior is observed, to what level does this decrease the premium paid or increase the survivability delivered by such an architecture? In Figure 7-18, Figure 7-19, and Figure 7-20, the GPS BATNA is shown by a blue line, the results associated with Survivable Disaggregation are displayed by a red line and the results of subjecting Survivable Disaggregation to cost cutting in production are represented by an orange line.
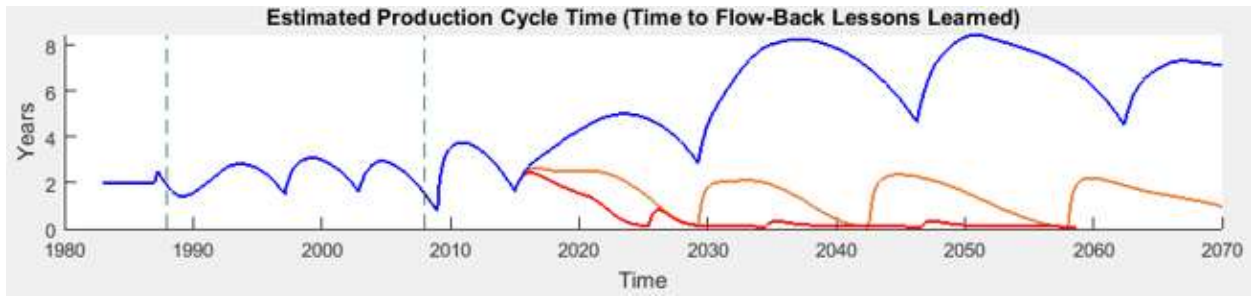
Figure 7-18: Varying Assumptions, Production Cycle Time for GPS BATNA, Survivable Disaggregation, and Survivable Disaggregation with Reduction in Production Funding per Year
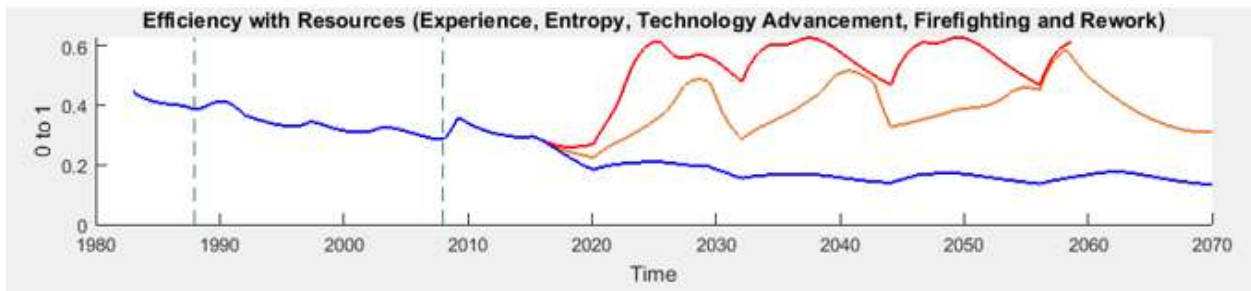
Figure 7-19: Varying Assumptions, Efficiency for GPS BATNA, Survivable Disaggregation, and Survivable Disaggregation with Reduction in Production Funding per Year
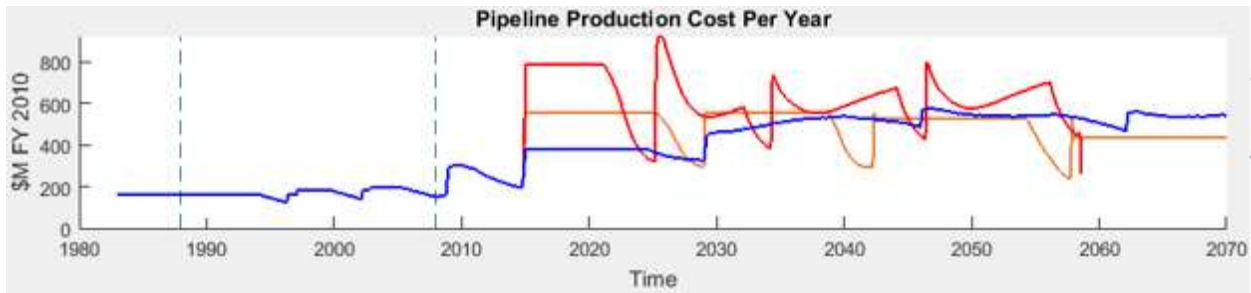
Figure 7-20: Varying Assumptions, Production Cost per Year for GPS BATNA, Survivable Disaggregation, and Survivable Disaggregation with Reduction in Production Funding per Year

Figure 7-19 shows that efficiency takes a substantial loss. This appears due to the extended time taken to produce satellites resulting from reductions in production funding seen in Figure 7-18. The lower production rate appears to push experience to a level at which a virtuous cycle cannot be maintained. Nonetheless, as seen in Figure 7-20, production cost per year is significantly decreased generation over generation when compared with the results from Chapter 6, especially in the first and second generations. When compared with the BATNA, production costs appear to become approximately equal around 2040. Table 7-20 reveals that under this assumption the premium paid for Survivable Disaggregation over the GPS BATNA is ~40% in the first two generations, ~30%in the third and only ~12% in the fourth. This is still a considerable amount of money to increase the FYDEP, however, this is a substantially more survivable architecture.

259

Table 7-20: Varying Assumptions, Cost Metrics for GPS BATNA vs. Survivable Disaggregation with Reduction in Production Funding per Year

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	96 vs 24	2	120 vs 24	2	144 vs 24	2	144 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	141.75%	3	142.27%	3	129.31%	3	111.84%
4	Cost to Acquire a Year of Operational Capability	4	141.75%	4	110.89%	4	124.29%	4	122.01%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	141.75% in 2029	5	142.27% in 2043	5	131.10% in 2058	5	111.88% in 2076
6	Compensate for Difference of Production Rate (Time & Performance)	6	141.75% in 2029	6	110.89% in 2043	6	126.02% in 2058	6	122.05% in 2076

7.5.4.1 *Longer On-Orbit Operations and Implementation of Tick-Tock on Survivable Disaggregated*

Chapter 6 uncovered little benefit to implementing a disaggregated architecture and a Tick-Tock policy in conjunction with each other as the gains associated with Tick-Tock (shorter production cycle) were already being achieved through smaller, less complicated satellite design. The reality of lowering production rate in anticipation of longer on-orbit life is also the reality of longer cycle times, thus it is worth rechecking to see if gains in this policy of combined disaggregation and Tick-Tock are now achievable. For Figure 7-21 and Figure 7-22 the blue line no longer represents the GPS BATNA, it now represents the survivable disaggregated implementation with a reduction in production funding. The orange line represents the survivable disaggregated implementation with a reduction in production funding with the Tick-Tock policy applied.

Examination of these two figures reveals that a reduction in production funding appears to slow Production Cycle Time. Given this, the addition of the Tick-Tock policy shortens Process Cycle Time and places the model in a virtuous cycle. At the same time, efficiency stays high with Tick-Tock implemented. This places a total of 72 satellites in each tick and tock making the investment even more attractive as in-generation learning can occur before the shift from one tick to the next tock.
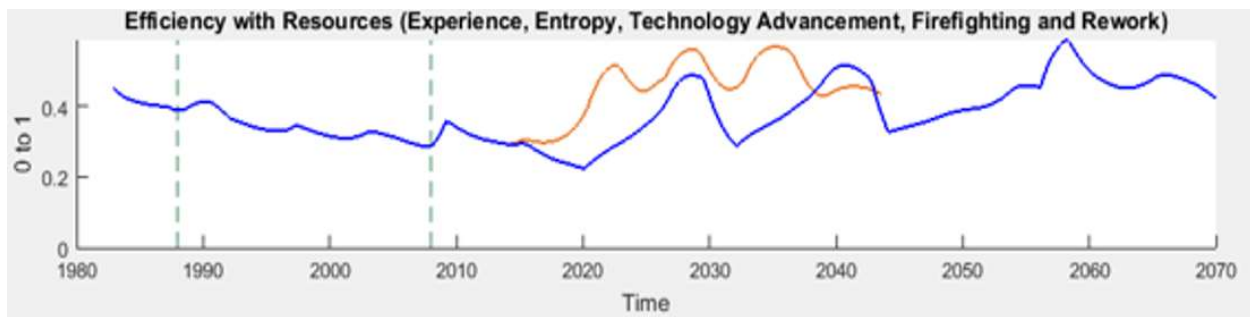
Figure 7-21: Varying Assumptions, Efficiency for Survivable Disaggregation with Reduction in Production Funding per Year vs. Survivable Disaggregation with Tick-Tock with Reduction in Production Funding per Year and Tick-Tock Policy
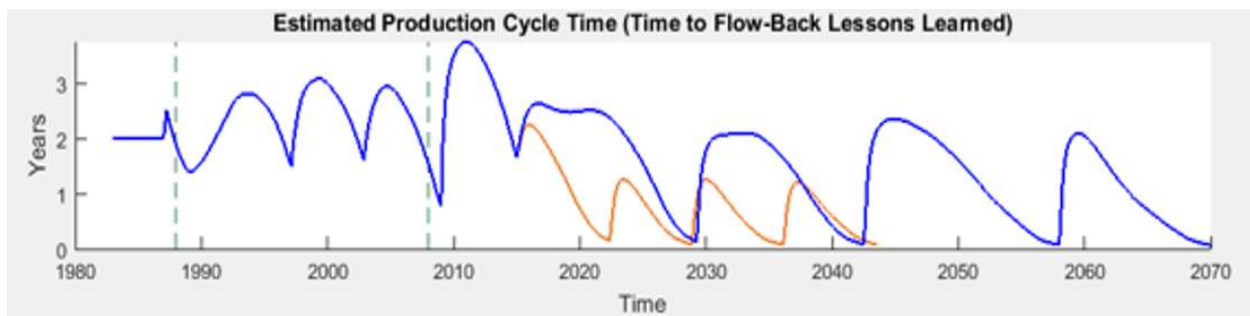
Figure 7-22: Varying Assumptions, Production Cycle Time for Survivable Disaggregation with Reduction in Production Funding per Year vs. Survivable Disaggregation with Tick-Tock with Reduction in Production Funding per Year and Tick-Tock Policy

The GPS BATNA can now be compared against survivable disaggregated architecture in conjunction with a tick-tock policy in a future in which the DoD is expected to attempt making use of additional on-orbit life. These comparisons are shown in Figure 7-23 and Figure 7-24 in which the GPS BATNA is shown by a blue line, the results associated with Survivable Disaggregation with a reduction in production funding by a red line and the results of Survivable Disaggregation and Tick-Tock policy with cost cutting by an orange line. The quantity of satellites has increased and this makes a difference for in-generation learning. These Survivable Disaggregated satellites while in total mass weigh nearly 2x the GPS BATNA, are individually small and more easily designed and manufactured. Thus, they, like the Full Disaggregation approach (with the help of the Tick-Tock policy), are able to maintain the virtuous cycle in learning. Also, the orange line is substantially higher in efficiency than the red line in Figure 7-23. This pipeline is able to stave off erosion while enabling the DoD to capture emergent extra life with on-orbit assets unlike the BATNA. Also, worth noting, if extra assets are ever required this implementation is able to fulfill the need more quickly.
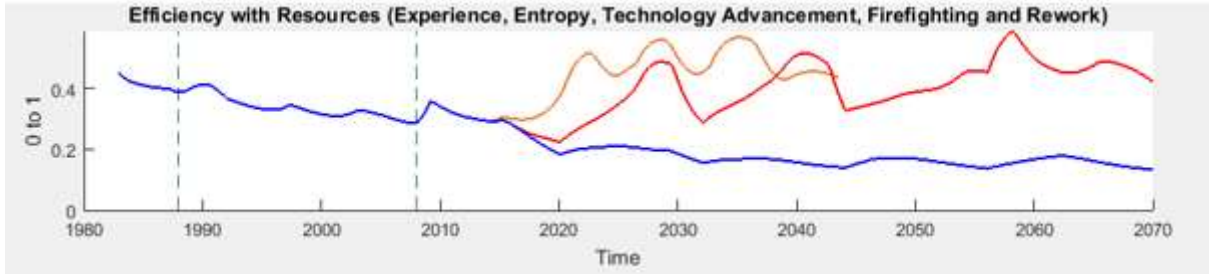
Figure 7-23: Varying Assumptions, Efficiency for GPS BATNA, Survivable Disaggregation with Reduction in Production Funding per Year vs. Survivable Disaggregation with Tick-Tock with Reduction in Production Funding per Year and Tick-Tock Policy
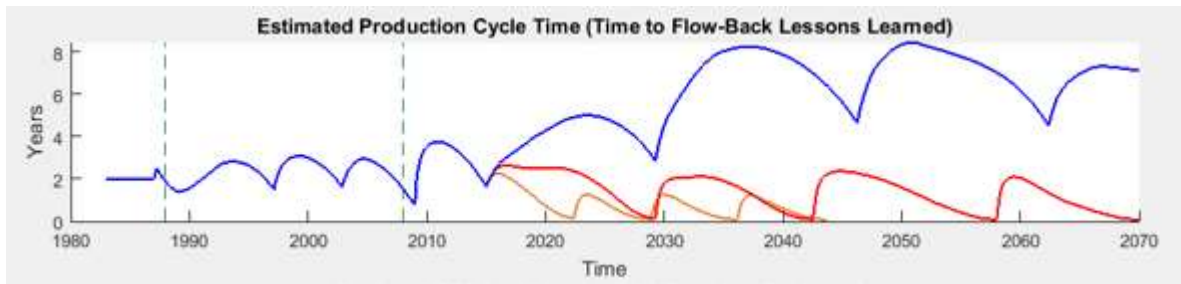
Figure 7-24: Varying Assumptions, Production Cycle Time for GPS BATNA, Survivable Disaggregation with Reduction in Production Funding per Year and Survivable Disaggregation with Tick-Tock with Reduction in Production Funding per Year and Tick-Tock Policy

To directly compare this Survivable Disaggregation and Tick-Tock implementation under the assumption that the DoD will try to extract extra value from additional on-orbit operations, Table 7-20: Varying Assumptions, Cost Metrics for GPS BATNA vs. Survivable Disaggregation with Reduction in Production Funding per Year rows 4 through 7 must be compared with rows 7 through 10 in Table 7-21 and Table 7-22. The 127% in row 7 of Table 7-21 directly compares to the 141% seen in Table 7-20. The 127% of Table 7-22 compares directly to row 7 with the 142% seen in Table 7-20. These values imply that the combination of Survivable Disaggregation and Tick-Tock might be realistically affordable in the 2029 to 2044 timeframe and is certainly worthy of an independent cost analysis. Nonetheless, from 2015 to 2029 such an implementation would require a FYDEP increase of 43%.

Table 7-21: Varying Assumptions, Cost Metrics for GPS BATNA Generation 1 vs. Survivable Disaggregation with Tick-Tock and Reduction in Production Funding per Year Generations 1 & 2

	Variable	vs BATNA
1	Generation Number(s), Design Life of Satellite (years)	Gen 1 & 2,15
2	Year of Production Completion & Number Satellites Produced	72 + 72 vs 24
3	Non-Reoccurring Engineering (Technology Refresh Costs) this Generation	95.33%
4	Cost of First Production Unit	203.18%
5	Replication Costs of Production Units (Sum of Production Costs)	124.19%
6	Launch Costs	222.83%
7	Cost Per Operational Year, Gen vs. Gen (Compares Performance Not Time)	143.37%
8	Total Cost Cost Per Acquisition (Compares Performance Not Time)	139.13%
9	Cost at End of Production Policy Relative to BATNA (Compares Time Not Performance)	142.82% in 2029
10	Compensate for Difference of Production Rate	139.07% in 2029

Table 7-22: Varying Assumptions, Cost Metrics for GPS BATNA Generation 2 vs. Survivable Disaggregation with Tick-Tock and Reduction in Production Funding per Year Generations 3 & 4

	Variable	vs BATNA
1	Generation Number(s), Design Life of Satellite (years)	Gen 3 & 4, 15
2	Year of Production Completion & Number Satellites Produced	72 + 72 vs 24
3	Non-Reoccurring Engineering (Technology Refresh Costs) this Generation	96.81%
4	Cost of First Production Unit	100.21%
5	Replication Costs of Production Units (Sum of Production Costs)	79.30%
6	Launch Costs	272.81%
7	Cost Per Operational Year, Gen vs. Gen (Compares Performance Not Time)	127.87%
8	Total Cost Cost Per Acquisition (Compares Performance Not Time)	110.94%
9	Cost at End of Production Policy Relative to BATNA (Compares Time Not Performance)	128.28% in 2044
10	Compensate for Difference of Production Rate	111.31% in 2044

One other advantage of Tick-Tock can be seen in Figure 7-25: even with a reduction in production funding, Tick-Tock is able to push out more satellites in the same time.
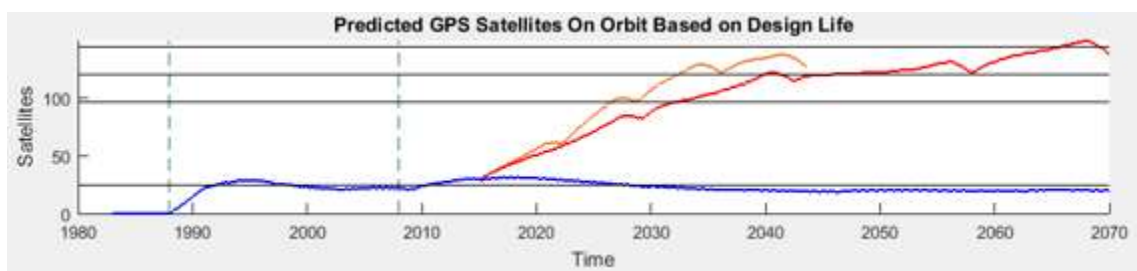
Figure 7-25: Varying Assumptions, Satellites on Orbit for Survivable Disaggregation with Reduction in Production Funding per Year vs. Survivable Disaggregation with Tick-Tock with Reduction in Production Funding per Year and Tick-Tock Policy

Finally, one must also examine the bias in the model to evaluate the utility of this implementation. Underlying assumptions and biases include:

- Ground costs are modelled to increase per additional unit. If this can be brought down, this will reduce the cost of this implementation.

- A 50% part commonality among buses is assumed. If a higher part commonality among buses is possible, or if integration and test costs are reduced due to part commonality, additional savings may be possible.
- The cost of launch as a fraction heavily impacts this implementation (up to 225% more than the BATNA in the fourth generation). If launch costs can be brought down, this too would increase the appeal of this implementation.
- Most importantly, the model assumes that the complexity of satellites increases or decreases linearly with respect to the number of payloads/interfaces. The effect of this bias cannot be tested at present. The existing model has no parameter to input such a change. As such it will be left unexamined.

The first three of these assumptions can be tested with this model if reason or hard data support replacing the tested values and re-running the model. At an upper bound, this model forecasts that by 2044 the USAF could field a disaggregated survivable architecture with Tick-Tock and pay 128% over the FYDEP and an 11% premium on capability. This would capture some additional utility from satellites lasting beyond design life while simultaneously avoiding the negative effects of such behavior under the BATNA—where capturing extra on-orbit life leads to erosion of efficiency.

8 Modeling Weather and Climate Sensing Satellite Acquisitions

In this thesis, a merged modeling technique is developed in Chapters 2 through 5 and is used to analyze GPS program policy alternatives in Chapters 6 and 7. In this and the next chapter, this technique is implemented on a different space mission area, Weather and Atmospheric Measurement. The goal of these two chapters is to answer the methodological question, "Can the merged TSE and SD modeling technique be extended from one mission area to another?" If the technique proves amenable, it will enhance the utility of this approach, speak to the extensibility of such a model implementation and indicate that a similar approach might be tried in other domains.

To begin adaptation, the model is tuned with historical data from the USAF's acquisition of the Defense Weather Satellite System (DWSS) Block 5D-2 and Block 5D-3 satellites. The tuning period has a time horizon of 1983 to 2002 and, in theory, sets the model's levels such that it is ready to simulate acquisition of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program and forecast the outcomes of that acquisition. As noted in the Introduction, NPOESS was a combined program for the AF, NASA, and NOAA's weather and climate measurement objectives. As such, the decision to use the AF precursor program for tuning is not a perfect abstraction of all acquisition efforts prior to NPOESS. Nonetheless, using the most stable, and longest running program to tune the model probably provides the best set of assumptions. In addition, the DWSS program has a wealth of information on production rate, satellite mass, cost data and payload specifications with which to tune the model.

In Chapter 8 the following work is described:

1. Changes to cost and performance models presented in Chapter 2 required to adapt them from GPS analysis to Weather and Atmospheric Measurement.
   a. Attaching Weather Payloads instead of GPS Payloads.
   b. Changing mass and cost equations to LEO and earth-observing space craft.
2. Changes to SD Model described in Chapter 3 required to adapt it from GPS analysis to Weather and Atmospheric measurement.
   a. Replacing historical GPS data with historical DWSS data, using Block 5D-2 and Block 5D-3 for tuning.
   b. Implementing weather-specific policy and quantities desired, but changing no model structures.
   c. Note the impact of satellites lasting longer on orbit and the capitalization on this emergent capability.
3. Simulation of the prediction for NPOESS based on TSE model cost and quantity demands.
   a. Reevaluation of the model's predictions under complexity levels as described in Dwyer's thesis, considering complexity in design and in programmatic elements (Dwyer, 2015).
4. Exploration of the model's prediction for the effect that disaggregation could have had on the NPOESS program as a way to build confidence in the model's abstraction of Weather and Climate Sensing satellite production.

This enables examination of an initial set of questions:

1. Does the model predict that NPOESS would have a cost over-run (as it in fact did)?

a. If not, what additional penalty factors (complexity) need to be assumed before an overrun is predicted?

2. Would a disaggregated approach have offered potential benefit to the NPOESS program (from a cost basis)? If not the NPOESS program, its follow-up program?

Chapter 9 will turn to questions dealing with the reality of the USAF failure to acquire the NPOESS program. The failed NPOESS program will be left in the model, likely reducing the efficiency level in the system, as well as leaving gaps in on-orbit capability. This will enable predictions about the subsequent Joint Polar Satellite System (JPSS) program and its follow-up programs. Specifically, it will enable asking the policy question of whether disaggregation would benefit the acquisition of JPSS and subsequent programs.

8.1 Modification of Trade Space Exploration for Weather and Climate Analysis

To adapt the TSE module developed in Chapter 2 for construction of GPS satellites to NPOESS, several modifications are needed. As the original code was developed with the concept that Architectures are comprised of Satellites and Satellites are comprised of Payloads it is across these three levels that changes are required.

8.1.1 Payload Modification

For the GPS system, payloads are communications payloads for which mass and power requirements could be computed based upon signal strength required at earth's surface and distance to the satellite. Weather payloads are typically earth-observing (optics) and have radically different costs of development and production. The primary payloads for the NPOESS program include:

- Visible Infrared Imaging Radiometer Suite (VIIRS) (NASA, 2016)
- Conical Scanning Microwave Imager/Sounder (CMIS) (Chauhan, 2003)
- Cross-track Infrared Sounder (CrIS) (NASA, 2016)
- Advanced Technology Microwave Sounder (ATMS) (NASA, 2016), (Blackwell, Cull, Czerwinski, Leslie, & Osaretin, 2012)
- Earth Radiation Budget Sensors (ERBS cross-track scanning, ERBS-biaxial scanning)
    - ♦ Many of the estimates for ERBS are based on its heritage from CERES and CERES is being flown on JPSS (ESA, 2016)
- Ozone Monitors (OMPS-Limb, OMPS-Nadir) (OSCAR, 2016), (NOAA, 2016)
- Total and Spectral Solar Irradiance Sensor (TSIS)
    - ♦ This sensor is not flown on JPSS but is a candidate for future JPSS satellites
- Aerosol Polarimetry Sensors (APS)
    - ♦ This sensor is flown on the GLORY satellite and is a candidate for future JPSS satellites

Data from these eight primary payloads in the NPOESS program are utilized in the model. Table 8-1: NPOESS Sensors and Specifications presents the Mass, Power, Data Rate, and Associated Data Source for each of the sensors.

Table 8-1: NPOESS Sensors and Specifications

Sensor Name	Mass	Power	Data Rate	Source of Data
Visible Infrared Imaging Radiometer Suite (VIIRS)	275 kg	200 W	10.5 Mbit/s – 8mb/s	(NASA, 2016)
Conical Scanning Microwave Imager/Sounder (CMIS)	373 kg	350 W	~500 kb/s	(Chauhan, 2003)
Cross-track Infrared sounder (CrIS)	85 kg	117 W	1.5 Mbit/s (max)	(NASA, 2016)
Ozone Monitors (OMPS-Limb, OMPS-Nadir)	56 kg	120 W	409 kbit/s	(OSCAR, 2016), (NOAA, 2016)
Advanced Technology Microwave Sounder (ATMS)	75 kg	100 W	30 kbit/s	(NASA, 2016) (Blackwell, Cull, Czerwinski, Leslie, & Osaretin, 2012)
Clouds and the Earth's Radiant Energy System (CERES)	45 kg	45 W	10.5 kbit/scanner (average)	(NOAA, 2016), (European Space Agency, 2016)
Aerosol Polarimetry Sensors (APS)	69 kg	55 W	160 kbit/s	(Dwyer, 2015)
Total and Spectral Solar Irradiance Sensor (TSIS)	41 kg	65.3 W	2.5 kbit/s	(University of Colorado Boulder, 2016)

The cost values from the 2006 Congressional hearing (published in 2007) on the NPOESS program are presented in FY 2006 dollars. The model converts these costs into 2010 dollars (applying a factor of 107.5%). These cost estimates can be found in the above sources for the specific sensors and are aligned with those listed below in Table 8-2. The APS and TSIS sensors are not included this figure as they were not payloads on NPOESS. They are potential candidate sensors for performing similar measurements. (Commitee on Science, House of Representatives, 2007)

Table 8-2: Table of Cost Estimates from Committee on Science, House of Representatives Results of the Nunn-McCurdy Review

Sensor	Status	Cost through FY 2006 ($M)	Cost to Complete Design & EDU ($M)	Recurring Cost for each Flight Unit ($M)	Number of Flight Units
Visible/Infrared Imager/Radiometer Suite (VIIRS)	Engineering Development Unit (EDU) in Thermal Vacuum Testing	$372	$689	$255 (average per unit)	• 3 Engineering and Manufacturing Development (EMD) • 2 production
Conical Scanning Microwave Imager/Sounder (CMIS)	Stop-work in place Termination proceeding	$209	N/A Effort to be Terminated	N/A Effort to be Terminated	N/A Effort to be Terminated
Cross-track Infrared Sounder (CrIS)	NPOESS Preparatory Project (NPP) Flight Sensor in Electromagnetic Interference (EMI) testing	$190	$166	$98	• 2 EMD • 1 Production
Advanced Technology Microwave Sounder (ATMS)	NASA Procured NPP Flight Unit Delivered	$14 (NPOESS) contract cost)	$114	$53	• 1 NASA procured • 1 EMD • 1 Production
Ozone Mapping and Profiler Suite (OMPS)-Nadir	NPP Flight Unit in subsystem assembly and test	$97 (Includes Limb development)	$66	$50	• 2 EMD • 1 Production
Clouds and the Earth's Radiant Energy System (CERES)	NASA Procured Sensor complete and in storage	NASA cost data not available	$0 (Sensor Complete)	$0	• 1 NASA procured

8.1.2 Satellite Modification

While actual mass, power, data rate and cost information were used for the payloads, all satellite data were computed using the Unmanned Space Vehicle Cost Model (USCM8) and the NASA Instrument Cost Model (NASA, 2010), consistent with common practice for estimating satellite mass and cost based on payload requirements. A different cost model was used for satellite designs assumed to possess a dry mass less than 500 kg. The Small Spacecraft Cost Model (SSCM) (Aerospace Corperation, 2015) reflects the cost reality that while even a small satellite carries large overhead costs associated with programmatic elements, integration, and test, physically smaller objects are easier to develop, and in some respects less complicated, leading to lower costs of development.

8.1.3 Architecture Modification

As initially written, the code was not able to perform computations for multiple common busses. In the GPS example, either all busses were able to share part commonality or none were.

A capability to assume multiple classes of commonality (e.g., disaggregation with two busses carrying 300 kg of payload and two busses carrying 100 kg of payload) needed to be added. This was accomplished through the addition of logical statements depending on the upgrade path selected. (Chapter 9 examines the consequences of different upgrade paths for the future of JPSS in conjunction with multiple part commonality.)

The implementation selected is not a robust implementation, as the code can construct commonality among busses only if it is already known before execution. Future work would enhance the capability to select disaggregated space vehicles that are within a tolerance and then decide to create a common implementation (e.g., if total mass of a space vehicle is within ~20% assume/force/enable common bus for implementation).

In traditional TSE with much larger data sets, the form of the solution will not always be assumed. (In this work the data set was smaller than the full Tradespace to save on computational time.) This will have several consequences for policy examination. First, coarse examination is required, and then in-depth analysis can be performed to find the optimal solutions. Second, it is possible that an even greater global minimum might be missed, thus this work cannot conclude it has exhaustively searched all possible implementations. Finally, the work will only examine sets of disaggregated solutions. There are thousands of possible disaggregated combinations of buses and sensors. However, most of these combinations poses different levels of performance (and associated utility). In this work only the disaggregated architecture which grant equivalent capability as the BATNA are considered. As this work seeks to prove the extensibility of the technique from a methodological perspective and to extend existing research on a set of disaggregated approaches for weather and climate measurement, the preexisting solutions are acceptable for this analysis. Future work, in keeping with TSE practice, would likely attempt to implement a more complicated utility function to enable examination of a larger set of Tradespace across the time horizon under examination.

8.2 Modification of Deductive System Dynamics for Weather and Climate Analysis

This section documents the changes implemented to enable the SD model to represent Weather and Climate Sensing satellites. The appeal of using the GPS program for developing and testing the merged model was the large amount of data available for GPS, as well as the relative simplicity of the satellite design and predictable rate of acquisition. This allowed development in Chapter 5 of the concept of the GPS baseline, based on historical block acquisitions as well as future planed block acquisitions—the GPS BATNA. A Weather BATNA is not so easily determined, nor is the future as clear. Consequently, the tuning (see Chapter 4 for the GPS constellation) cannot be executed for Weather satellite acquisitions. To gain insight into the acquisition of Weather satellites it is mandatory that no change occur to any time constants in the SD model. If the time constants were changed, the statistical validity of the SD model representing the time associated with acquisitions would be invalidated. As no re-tuning is performed on the model after being converted to Weather satellites. This creates a general assumption that the system acquiring Weather satellites changes with the same "stability" as the GPS pipeline. This assumption has good face validity as the arrangements among government, contractor, funding sources and third-party watch-dog organizations are similar and likely impose the same time delays. All variables and their values used for the Weather simulation (known as the "Command"

file for Vensim, which instantiates the SD Weather model) are included in Appendix S: Weather Command Script for Vensim Initialization. A comparison to the Command file for GPS satellites will show that no time constants are changed.

For the acquisition pipeline (designed in Chapter 3 and tuned in Chapter 4), the validity of any modification to represent the acquisition of Weather and Climate Sensing satellites must be defended. Every change to the SD model threatens the claim that a generic space-vehicle acquisitions model developed in SD can represent the acquisition of another class of vehicle. One of the greatest powers of the SD methodology is the ability to abstract a problem using generic structures and by so doing enable modeling of a system too complicated to be modeled without high-level abstraction. But this is also often considered to be the greatest threat to any work in SD: by using generic structures the answers received will depend too heavily on the structures chosen. That is, if we use the same generic structures to represent GPS as we do for Weather, we may get the same answer for both. If we get identical answers it is possible that as Weather shares an industrial base with GPS, the similar answers and conclusions are correct. Yet, it is also possible that similar solutions indicate a flawed methodology, or a model that is too abstract and misses the core elements of each unique problem. Ultimately, the truth may be a mix of all these possibilities. This section thus documents the changes required to enable the SD model to represent weather satellites.

While keeping the time constants and the model structures (causal loops) the same as for GPS, the unique elements of a Weather acquisition are implemented in the model through changes in the following exogenous inputs:

1. Loading the 5D-2 and 5D-3 DWSS satellites as precursor programs to the NPOESS program.
2. Setting the order quantity to keep four on orbit with a design life of seven years. (This produces a larger number of satellites than currently planned for the JPSS program.) This would keep the capability desired in four orbits (divided by plane, not elevation):
   a. The Early-Morning Orbit
   b. The Mid-Morning Orbit
   c. The Afternoon Orbit
   d. An additional day, or potentially dusk, orbit
3. Setting the design life to five years for the 5D-2 satellites and seven years for the 5D-3 satellites.
4. Setting the mass of the 5D-2 to the historical ~800 kgs and the 5D3 to the historical ~1200 kgs.
5. Setting historical funding levels to an average of $160M FY 2010 dollars from 1983 to 1995 and $200M FY 2010 dollars from 1995 to 2002. These averages provide the start point for the SD model.
6. The model was initially constructed for GPS satellites such that a single external variable could calibrate the relationship between cost of satellite production and the size and complexity of the satellites. (In fact, this was one of the key parameters used in tuning the model in Chapter 4.) Because the cost relationship of RF satellites in MEO and GEO is different than for earth observing satellites in LEO, this variable also needs to be adjusted to ensure the proper construction rate of satellites given the historical funding profiles of the DWSS program.

In the GPS example, the number of satellites on orbit given a fixed design life was computed. The difference between the number of GPS satellites on orbit and the full constellation strength of 24 satellites was defined as the extra design life required assuming no additional funding was provided and no change to acquisition was made. This assumed that the GPS pipeline wanted to maintain a constant funding level and extra on-orbit life could compensate for emergent gaps in capability. For Weather satellites, the model is instructed to force the equivalent of four satellites on orbit. This is not a change to the model structure—it changes neither the time constants of the model nor its execution. But rather than externally setting funding levels, for Weather satellites the SD model will internally decrease funding in the face of extra on-orbit life as well as increase funding in face of a capability shortfall. This is the same causal loop (the Nunn-McCurdy Loop) and the same policy as in the GPS example (though now controlled from a different vantage point); this change enables a more direct analysis of program overruns due to capability shortfalls. Even granting the SD model the ability to control funding does not guarantee that four satellites will be kept on orbit. If an architecture struggles due to the time constants and the ability to "detect" when additional funding is needed, some policy and architectural decisions may make enabling full strength impossible.

In the course of executing the simulation some additional, minor deviations from the GPS model were required. None appear to threaten the validity of the model but they are documented here for full disclosure and consideration:

- Initially the update time for Experience (a stock) was linked to the physical production of a satellite (a pulse). In the GPS BATNA this meant that the model updated the experience level about twice every three years.
  - ♦ In Full Disaggregation the GPS program updated substantially faster and at or near the maximum rate possible of eight times per year, or equal to the model TIME STEP.
  - ♦ This does not change the level that the experience stock was trying to achieve: it changes how often it can update to the appropriate level. A faster versus slower update time can change results across time as the integration rate can change the rate at which compound values in a non-linear system build upon each other. If the update time to a stock is too slow, it can have a negative impact on model execution—such as failing to capture the proper level across time. For Weather satellites, where it is possible that five years may elapse without a satellite being produced, this update time is too slow. Consequently, the update time was set to the TIME STEP value in the model of .125 or one-eighth of a year.
  - ♦ This poses a small threat to the original work in that the GPS BATNA update, if run faster, might compound small elements differently. As the GPS BATNA was, however, relatively robust against small changes in all the major loops, it is unlikely this would substantially change the findings of Chapters 6 and 7. Also, as the GPS BATNA was calculated to possess an eroding Efficiency variable, a slower update would favor the GPS BATNA (as the erosion would be delayed), consistent with other model bias to prefer the fully aggregated BATNA.
- The update time for Process Cycle Time was also linked to the physical production of a satellite. The change made to Experience above was also made to Process Cycle Time update for the same reasons.

8.3 Inductively Tuning the Model for Weather and Climate Measuring Missions

To represent the acquisition of Weather satellites, the SD model is loaded with DWSS 5D-2 satellites, shown as the first generation (blue spikes) in Figure 8-1. The model is instructed that satellites will be replenished based upon a design life of five years with the same 12th order smoothing function applied in the GPS case study. This creates an average of six years of on-orbit service life (with a long right tail representing some residual capability beyond six years). The model is given an NRE pulse to transition from the 5D-2 to the 5D-3 DWSS satellites in 1994. The model then constructs 5D-3 satellites. These are represented by the red spikes. Thus, the tuning period for the model is 1983 to 2002. In this time period stock levels stabilize such that when the NRE pulse occurs in 2002 to initiate the NPOESS program, the model is ready to simulate its acquisition. The orange spikes represent NPOESS-class satellites launched from 2009 to 2025. The y-axis is a dimensionless variable which represents the model's internal "work" per satellite required; it gives a relative measure of how much work is required for a satellite in each generation and when that work is complete the spike occurs denoting the production of a satellite. (This value is multiplied by Efficiency in each model TIME STEP to compute how much of a satellite is produced in that time slice.)

.

SVs Completed

SVs Completed[Gen1] : Initial Model On Orbit Life Equals Design Life
SVs Completed[Gen2] : Initial Model On Orbit Life Equals Design Life
SVs Completed[Gen3] : Initial Model On Orbit Life Equals Design Life
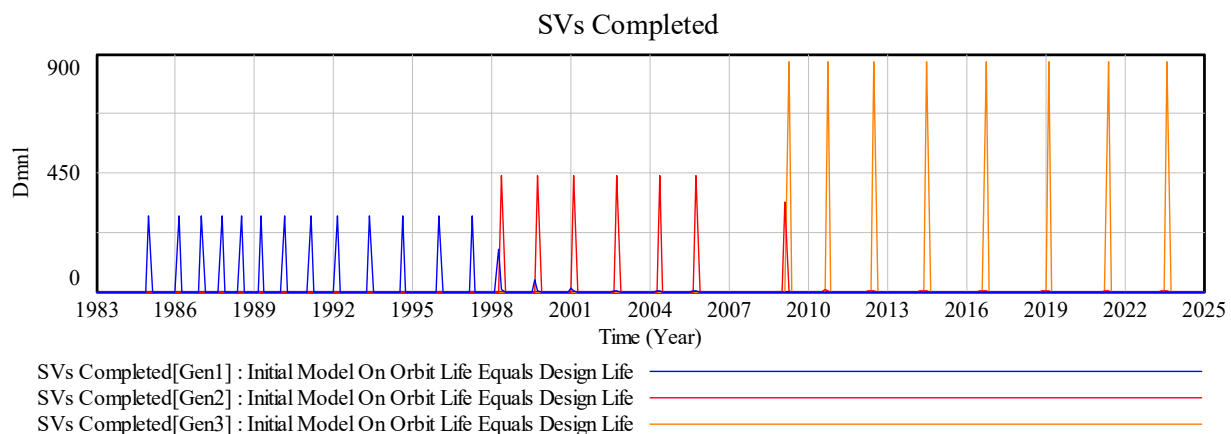
Figure 8-1: Weather and Climate Sensing Model Construction, Satellites Completed

Applying this acquisition sequence and the assumption that design life equals on-orbit life to the historical acquisition of Weather satellites results in slightly more satellites being produced in the model than actually occurred. In reality 14 to 15 5D-2 DMSP satellites were produced and launched whereas the model builds 18. (Data are available through search at NASA.gov (NASA, 2016)). In the actual 5D-3 generation, four to five satellites were produced and launched; the model believes that seven are necessary. One of the 5D-2s was lost in launch and it is unclear at the time of writing whether the last 5D-3 will be fielded—which leads to the slight variance with respect to the actual quantity produced and launched. We can see this in Figure 8-2 which shows actual and modeled weather satellites on orbit from 1983 through 2019. Blue represents the aggregate total, red the 5D-2 generation, orange the 5D-3 and the modeled representation of NPOESS is yellow.
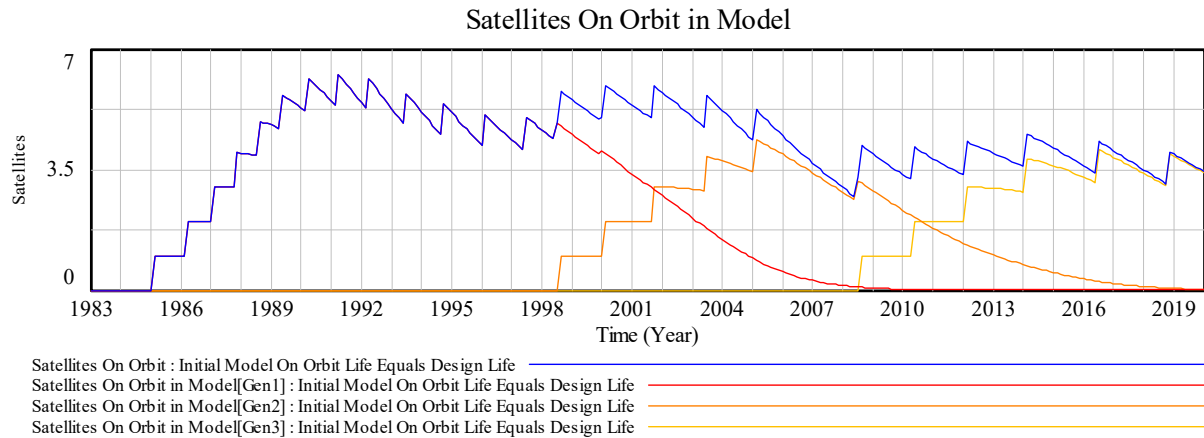
Figure 8-2: Weather and Climate Sensing Model Construction, Satellites on Orbit

Looking at the Efficiency metric associated with such a plan, we see a peak in the late 1980s followed by a decline with the introduction of the NPOESS program (seen in Figure 8-3). The Weather satellite pipeline shows the same erosion that was observed for the GPS pipeline. The model hits its high point in efficiency in the late 1980s when the majority of the 5D-2 satellites were constructed and launched. (We can clearly see the relationship between this and the previous graph showing the satellites placed on orbit.) There is a stabilization followed by slow erosion during the 1990s, the period of time during which the majority of the 5D-3s were constructed.
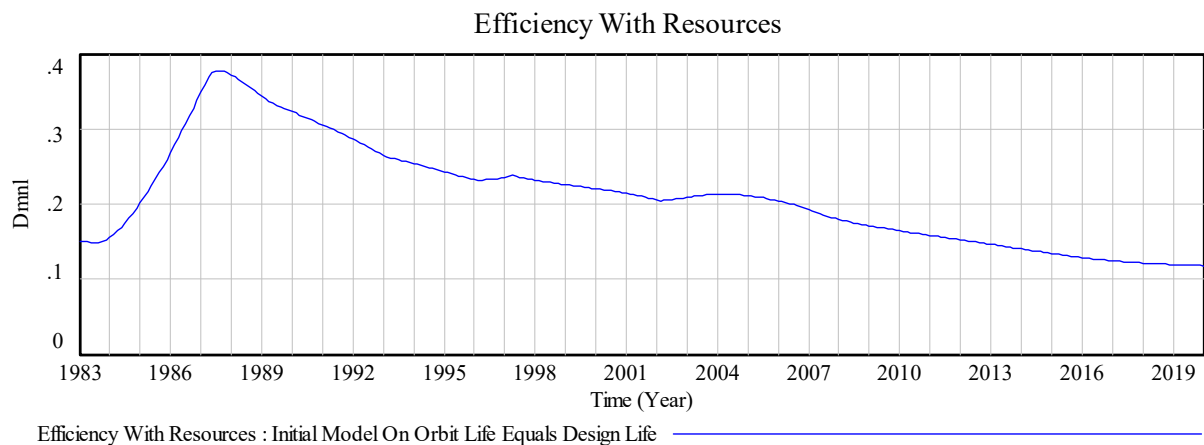
Figure 8-3: Weather and Climate Sensing Model Construction, Efficiency with Resources

With GPS, it was observed that over time the amount of additional on-orbit life required to provide the required number of satellites on orbit increased. For Weather and Climate monitoring the design life is fixed at seven years and not allowed to float. Even though the design life is fixed, it is worth examining the Design Life that the SD model believes would be required to keep the desired number of satellites on orbit. This provides insight into how well the model is tuned and able to match reality. Recall that the Peanut Butter Spread SD Loop pushes design life up slowly over time as a way to save money/reduce work in the industry. Figure 8-4 gives some confidence that the time constants imported from the GPS work will serve appropriately in the Weather satellite acquisition model, as the model—instructed to begin with five years of design life—

slowly pushes up to near seven years by the 5D-3 generation. The model computes the required design life to be 6.83 years, very close to the actual seven expected of this generation of Weather satellites in the real world. (This is the outcome of a run without any adjustment to the time constants in the model.) The model indicates an additional increase in design life (to above eight years) will be required for the NPOESS program.

Design Life Required

Design Life Required : Initial Model On Orbit Life Equals Design Life ─────────────
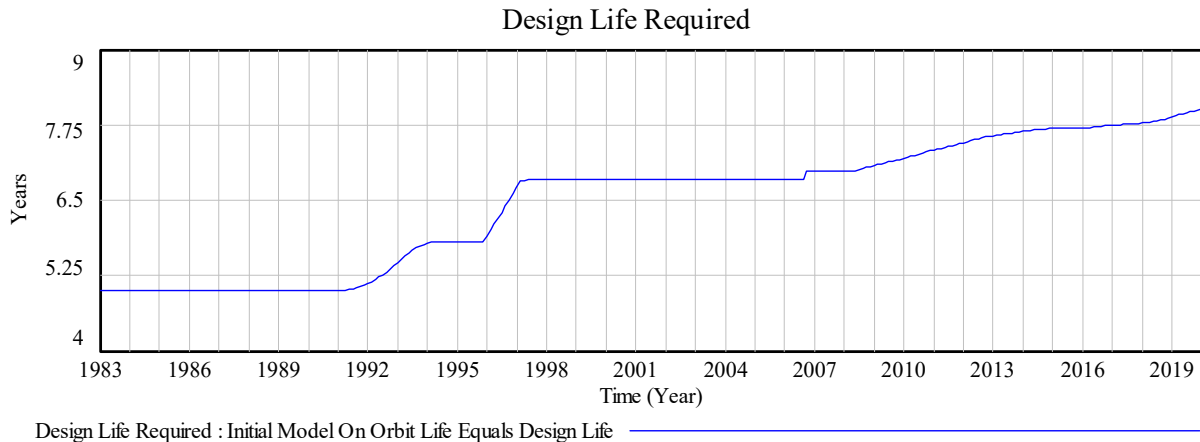
Figure 8-4: Weather and Climate Sensing Model Construction, Design Life Required

In Figure 8-5 we gain some insight into what is causing the decreasing efficiency: a rising production time across generations. This is logical as the increased design life is spreading out across generations and the extra on-orbit life pushes out the time between acquisition events. While not immediately obvious, this increasing production time possesses a different shape than seen in the GPS case study. In the GPS work, the production time (defined as the Process Cycle Time in the Efficiency metric) formed slow rolling humps. (See Figure 6-5: Policy Testing, Satellites on Orbit, Changing Design Life (6, 8, 10, 12, 15 and 20 years) for an example.) For Weather satellites the production time seems to form a peak and a trough. The reason for the faster rise and fall is primarily the production time of the satellites (smaller units designed with shorter on-orbit life). Replication of Weather satellites is achievable in a shorter time, such that typically the third unit in a production run can benefit from the lessons learned with the first. One consequence of the model's abstraction of reality is that fewer units in the production pipeline (simulated as a FIFO queue) enable a faster decrease in the production time (FIFO queue size divided by completion rate). This is a reasonable abstraction as fewer physical items to work on can enable a nimbler approach and allow for faster change.
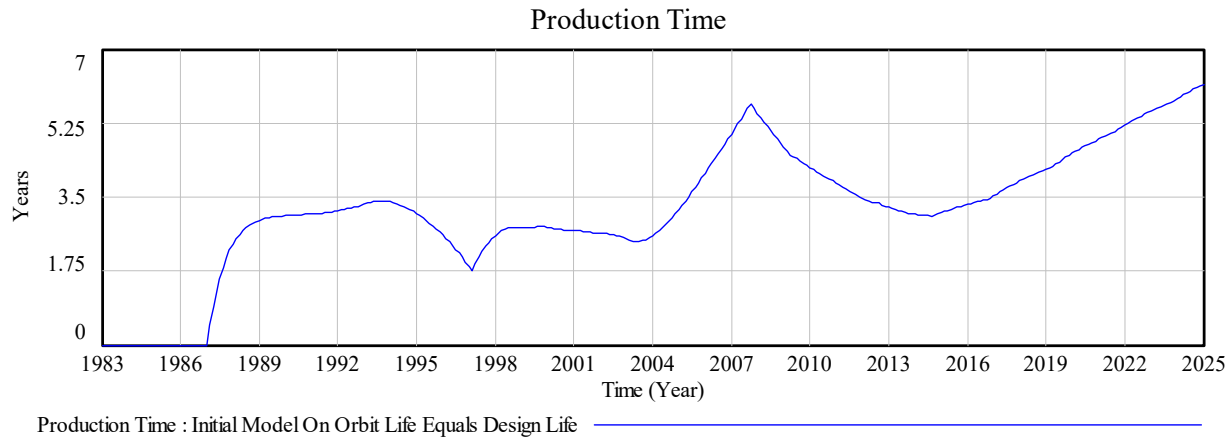
Figure 8-5: Weather and Climate Sensing Model Construction, Process Cycle Time

While the initial run of the model anticipates an eroding Weather satellite industry with increasing production times and associated process cycle times, it does not yet represent reality closely enough because the historical policy of capturing extra on-orbit life has not yet been implemented.

8.3.1 Implementing a Policy to Capture Emergent On-Orbit Life

The original model included the Peanut Butter Spread Loop to recognize extending design life as a common strategy for reducing pressure resulting from backlogs. It was seen that this loop is able to model the desire for additional design life over time. The loop, however, is not designed to capture the reality where satellites last longer on orbit so that fewer satellites are built or those built are "kept in the barn" until needed, thus delaying the start of the next procurement. This reality can be implemented in the model without changing the model structure, by making an exogenous change. To implement extra on-orbit life, the time that satellites are allowed to stay in the "On Orbit" stock is extended by 25% (literally multiplying the time on orbit by a factor of 1.25 in the delay function). The impact of this change for Weather satellites can be seen in Figure 8-6. Now the model produces exactly 15 5D-2 and five 5D-3 satellites to meet the on-orbit needs of the weather system. The timing of the satellites for the 5D-3 generation now also aligns to within one year of when the actual 5D-3 satellites were produced.
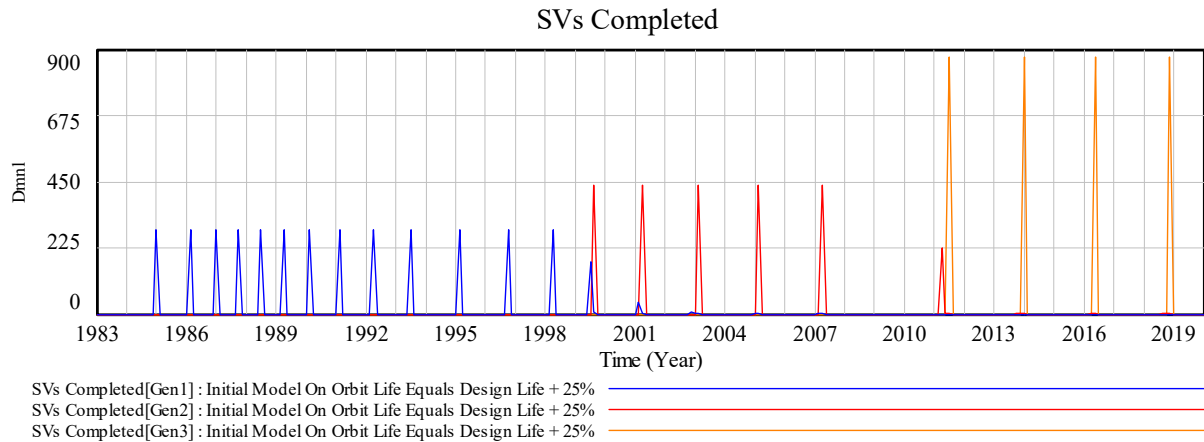
SVs Completed

Figure 8-6: Weather and Climate Sensing Model Construction, Extended On-Orbit Life, SVs Completed

It would be expected that, all else being equal, the production of fewer satellites in the same time period and larger satellites requiring construction over a longer time period would result in a lower Efficiency stock. This appears in Figure 8-7 where the red line representing the industry capturing an additional 25% on-orbit service life is in a lower state of efficiency. Further building confidence in this model tuning, there is an increase in efficiency in the blue line from 2000 to 2004, indicating that the model predicts efficiency would have stabilized during the time period of highest rate of production for the 5D-3 satellites. Due to the long time period and low production rate, no real gains were ever actually made (as shown by the red line during this same time period). The change in trend in the blue line is, however, very reassuring that the model is sensitive to this level of change. If the model had predicted no change to the slope it would cast doubt on the model's sensitivity to changing satellites produced quantity and time in a generation.

Efficiency With Resources
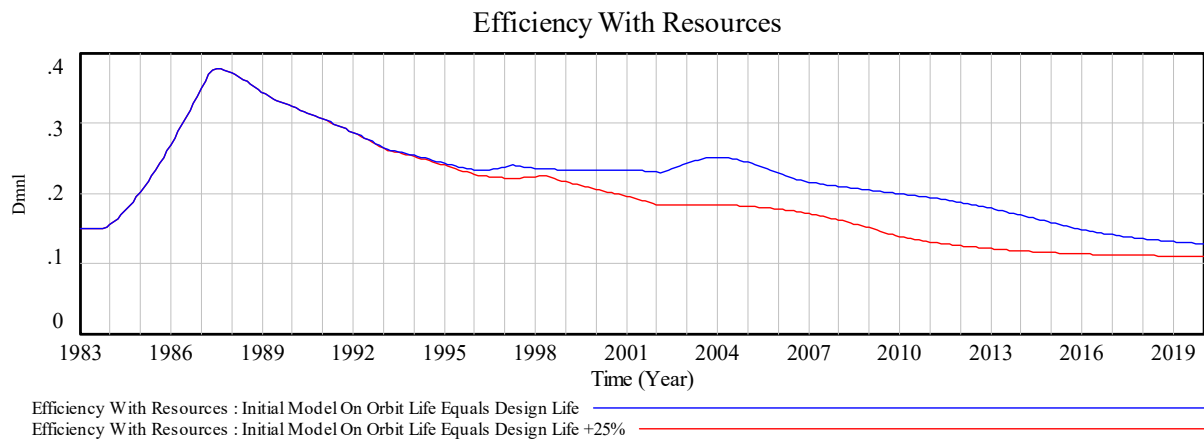
Figure 8-7: Weather and Climate Sensing Model Construction, Extended On-Orbit Life, Efficiency with Resources

With the addition of the extra 25% on-orbit service life, the model tracks the production time associated with the later start date of the NPOESS program as well as its longer development phase due to the state of technology (the amount to be refreshed) and the larger satellite size. In Figure

8-8, the blue line represents the original production time for the theoretical NPOESS program and the red line shows the production time with on-orbit life 25% greater than design life. The difference is clearly seen as a non-linear effect for both the 5D-3 generation from 1999 to 2009 and the longer production time for the NPOESS program. This is in line with the original estimates for the NPOESS program, that with a start in 2002 a theoretical first unit could be ready by 2009 to 2010. The model gives two reasons for this delay. First, lower efficiency with resources leads to longer production time and second, satellites lasting longer on orbit than expected allows for the slowing of production to save money (which the model as a proxy for any senior decision-maker is more than happy to do). These two reasons are not, however, the actual reason for the lengthy development time of the NPOESS satellite. The real reason was difficulty in producing sensors and the cascading difficulty in producing the bus for said sensors. This is a reason that is outside of the model and as such cannot be directly considered by the model. This is an example of a major complaint against the utilization of a generic structure for the representation of an acquisitions pipeline: we may get an answer that is close to correct, but it rests on only those factors known to the model. The model provides an answer in the correct direction, but not for the reason known to history. Of course it is also possible that even if the sensors had been produced on time and at cost, the model would still be correct and due to the low efficiency of the system, the potential clones of the NPOESS satellite would have, as predicted, overrun their program baselines.

Production Time

Production Time : Initial Model On Orbit Life Equals Design Life
Production Time : Initial Model On Orbit Life Equals Design Life + 25%
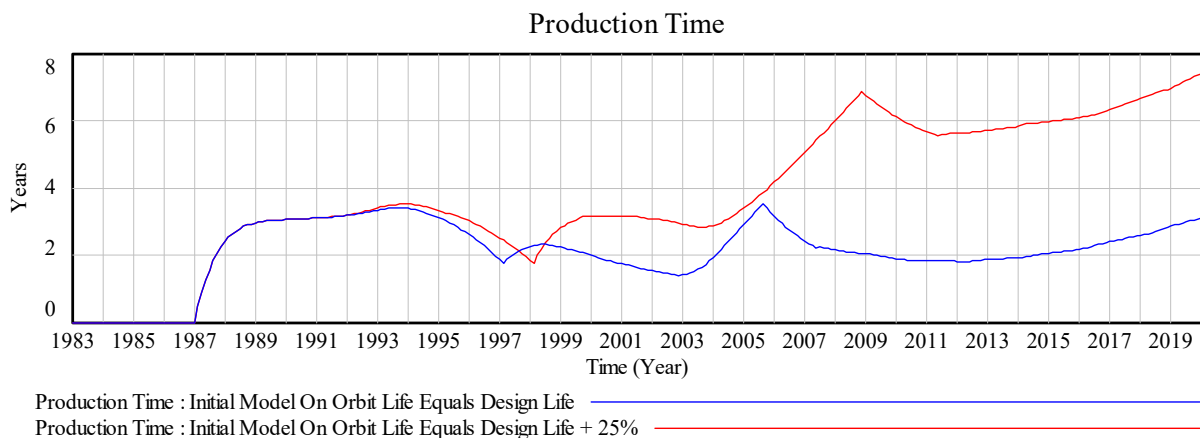
Figure 8-8: Weather and Climate Sensing Model Construction, Extended On-Orbit Life, Process Cycle Time

In the analysis of the outputs of the modeling of the GPS program, it was seen that quite often low efficiency programs were able to save money for several reasons:

- Emergent on-orbit capability where the on-orbit service life is longer than the design life can be considered free utility.
- Extending the value of NRE over a long time frame lowers the total cost of NRE for the same time period.
  - ◆ While older technology makes it harder to replicate satellites and forces a larger update at each generation, this policy has an overall net positive effect on saving money.
- Fewer rockets are required in the same time period.

- Less work in production is required for the same time period, which alleviates work backlog. This in turn makes production easier, all else being equal, as there is less to manage.

With this in mind, the model's "Nunn-McCurdy" Loop can be examined to determine if the model predicts that NPOESS would have difficulty in production given the lower state of efficiency ascribed to it by the model. While the model developed in this thesis can grant insight to the time elements associated with the development (NRE) of satellites, a significant strength of this model is in evaluating the effect of learning with respect to production. As such, when evaluating Weather and Climate Sensing satellites, which historically have had more problems in development than production, we must note where the model is valid to develop this insight. The model as designed is incapable of predicting problems with NPOESS in 2006; it cannot predict anything until a program goes into production. Consequently, problems would be observed only after it computes the entire acquisition and determines if the program would have overrun its baseline at any point in production.

Having noted the model does not compute the potential of an overrun until the program goes into production, we can still look "under-the-hood" at the variables to see what trends are emerging before production. This gives the ability to see if problems are emerging in the development phase but we can't "know" this is a problem until the acquisition is complete: the nature of SD models is such that an instant spike, if smoothed, may be acceptable and not indicative of a problem. The model due to its nature must reach an equilibrium before an opinion can be formed. In short, the model is unable to capture program breaches in the NRE phase. It is, however, able to detect problems (if specifically asked to do so) caused in the development phases and their impact on the production phases and compute increasing or decreasing NRE costs across time. (In the GPS example, a very long development caused by any number of factors (technology, time, weak learning, complexity etc.) would translate into a higher chance of issues occurring in production.)

Figure 8-9 answers the question about potential cost overruns for NPOESS. The blue line represents the fictitious universe where satellites last only as long as their design life. The red line represents the close-to-reality approximation of an additional 25% on-orbit life and a 12th order smoothing, which can examine if cost overruns should be expected in production. The model forecasts no more than a 10% to 13% cost increase over the baseline for the NPOESS program (the red line from 2009 to 2019). As with previous generations, if design life can be stretched even further this increase could be mitigated and would certainly fall below the threshold for scrutiny from Congress. This model simulation does not predict a Nunn-McCurdy breach for NPOESS. (Note: The reason the blue line is not at exactly one during the tuning period of 1988 to 2002 is a result of the difference between the TSE estimate and the SD computation of production during the time period as well as the 12th order smoothing function.)
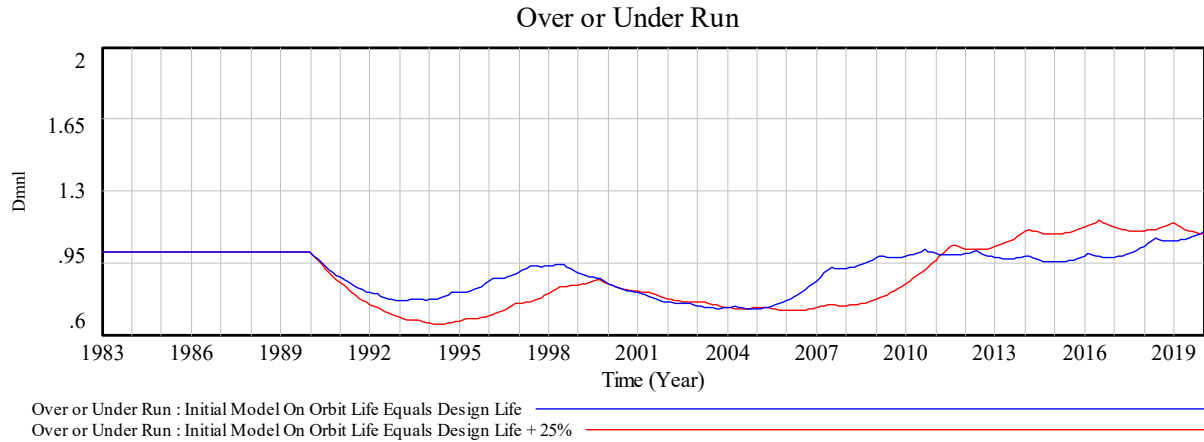
Figure 8-9: Weather and Climate Sensing Model Construction, Extended On-Orbit Life, Nunn-McCurdy Loop Under-Overrun

Utilizing the metric of production cost per year, Figure 8-10 displays the difference that 20 years of decreased production and longer process cycle times can have on the NPOESS program. (Note how the red line rises above the blue line.) These are identical satellites, however, they now cost more to acquire due to the lower efficiency in the industry. This relates to the idea expressed in discussion of the construction of the Efficiency metric in Chapter 3, that where you start on the efficiency curve matters. The model predicts rising costs inside the NPOESS program regardless of the starting point, but the red line and the blue line do not quickly converge on a new equilibrium, indicating the model forecasts that the decision to procure NPOESS will continue the decrease in efficiency, not stabilize the pipeline.
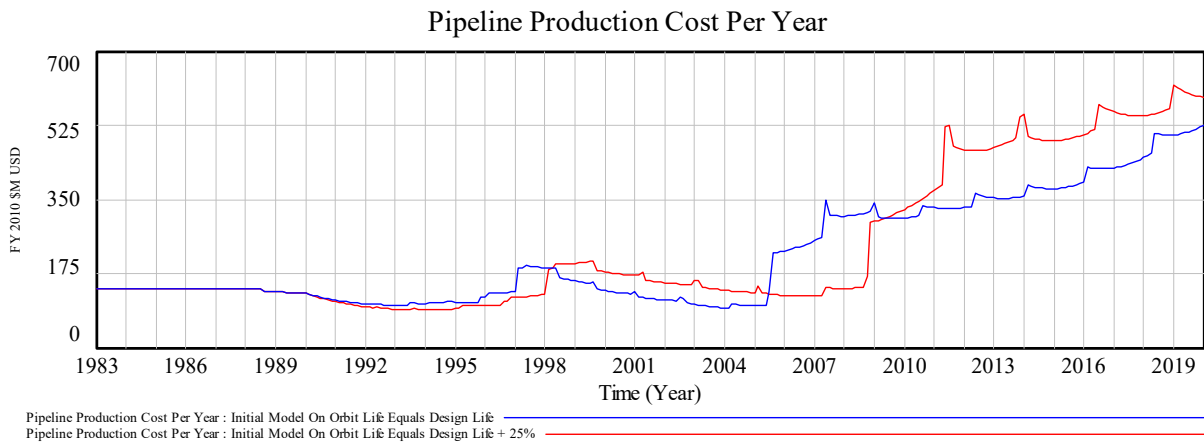
Figure 8-10: Weather and Climate Sensing Model Construction, Extended On-Orbit Life, Pipeline Production Cost per Year

Still, the model also predicts that despite the forecast of lower efficiency, as long as an additional 25% design life (and the 12th order smoothing function) is experienced, full constellation strength should be maintained and the NPOESS program acquisition should be achievable. This is shown in Figure 8-11 where the acquisition (represented by the red line) is able to maintain a constellation of four satellites on orbit without creating an overrun in cost as was previously seen

in Figure 8-9. It is thus concluded that the current model is insufficiently tuned to match the historical reality of weather and climate acquisitions without an additional factor.
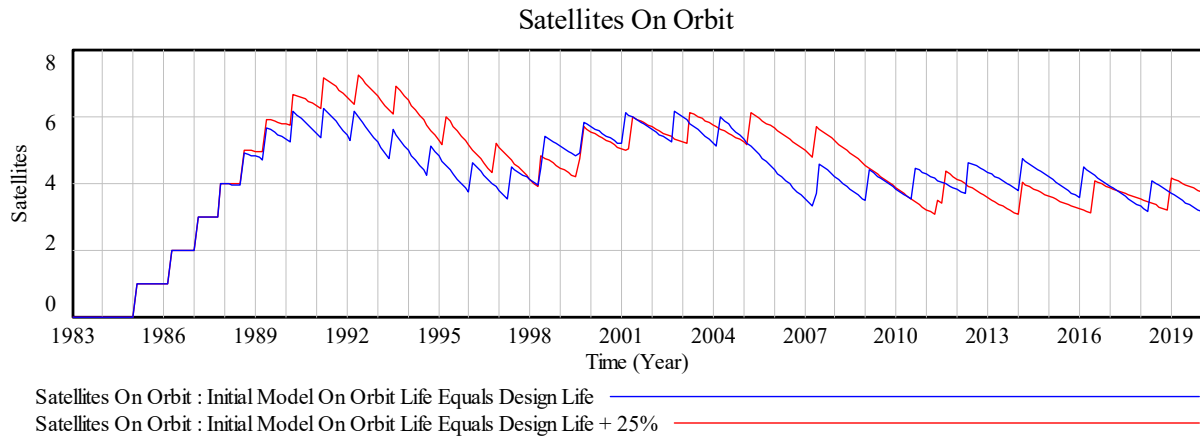
Figure 8-11: Weather and Climate Sensing Model Construction, Extended On-Orbit Life, Satellites on Orbit

8.3.2 Implementing Complexity on Capturing Emergent On-Orbit Life

In SD, when the model does not match reality another cause must be considered, implemented and the results examined. In actual fact, the NPOESS acquisition was unsuccessful but the model, while predicting some difficulty, does not predict failure. One possible source for this discrepancy may lie in one of the assumptions derived from the GPS model, specifically, the issue of "complexity." Complexity was encoded as an exogenous variable and held constant in all generations—recall that one of the primary assumptions in the GPS work was that smaller satellites would be as "difficult" to produce as larger ones. This is an assumption that biases the model towards preferring a large aggregated system. This assumption could be challenged, but was required as there is no solid data to support exactly how much easier a smaller satellite might be to construct. According to Dwyer, satellite and programmatic complexity of NPOESS increased due to the joint USAF, NASA, and NOAA acquisition (Dwyer, 2015). Her work breaks complexity into several categories:

- Instrument Design Complexity based on Technology Readiness Level (TRL)
- Bus Complexity based on number of instruments
- Bus Complexity based on high data rate requirements
- Bus Complexity due to mass (size of satellite)
- Architectural Complexity based on number of instruments in the same area blocking field of view
- Architectural Complexity based on jitter (specifically references the CMIS sensor)

The code base used for this thesis is easily adjusted to recognize these complexity additions. Table 8-3 shows how these exogenous constants are applied to the merged model's implementation of the NPOESS satellite. Not all of these variables come into play directly in the SD module; many of the changes occur in the TSE module and are then propagated through the appropriate exogenous variables. (In Vensim this is accomplished through modifying game variables at runtime.)

Table 8-3: Addition of Complexity Metrics to Weather Model from Dwyer's Thesis

Dwyer's Complexity Metric (Dwyer, 2015)	Change required	Adaptation to Merged Technique
Bus Design Complexity for additional instruments	+5% to total mass	Inserted into final TSE module for designs with additional instruments
Bus Design Complexity for multiple orbital plane ubiquitous design	+5% to total mass	Inserted into final TSE module for each satellite being flown in a separate plane
Bus Design Complexity – High Data Rate	+2%	Inserted into final TSE module for satellites with data rates above 5 mb/s
Bus Design Complexity – High Mass	+5%	Inserted into final TSE module result for designs with mass greater than 3000 kg
Bus Design Complexity – Pointing Requirements (specific to some sensors)	+5% Bus hosts instruments with high pointing requirements (select sensors)	Inserted into TSE module for satellites carrying payloads with sensors requiring high pointing accuracy
Architectural – Mechanical Interaction (CMIS)	+5% Jitter inducing instrument hosted with sensitive instruments, specifically from CMIS payload	Inserted into any satellite including the CMIS sensor
Architectural – Optical Interaction	+5% Instruments with conflicting fields of view hosted on same bus	Inserted into mass module in TSE for satellites with multiple optical payloads
Architectural – Programmatic	+5% Multiple instruments managed by same program	Inserted into NRE cost estimate
Architectural – Reliability	+5% Multiple "critical" instruments hosted on same bus	Satellites designed to host VIS-NIR sensor, conical microwave imager-sounder, CrIS, ATMS pay penalty

Note: Instrument Design Complexity Increase based on TRL was not implemented as actuals mass and power requirements were available and used in place of models

Dwyer's final calculations place the NPOESS at 20% over standard-cost models and JPSS at over 12% by mass parametric alone. As the code base for this thesis leverages some of the same

cost models, it would be expected that the merged model's computations would produce a similar result. Before inputting each metric into the TSE and SD models and running the combined model, a quick analysis can be performed to see the impact of an increase of 20% in complexity. This is accomplished as a single constant through the "Engineering Work Required" variable. (In Chapter 9 all of the above penalty functions will be imposed on all architectures proposed.) The impact of an additional 20% complexity on the over-underrun can be seen in Figure 8-12, as an orange line added to the previously presented on-orbit life matches design life (blue) and on-orbit life lasts 25% longer than designed (red). The additional 20% complexity does not equate to a linear 20% increase in cost overrun, but it does yield an overrun of between 25% and 29% above the 13% overrun initially forecast.
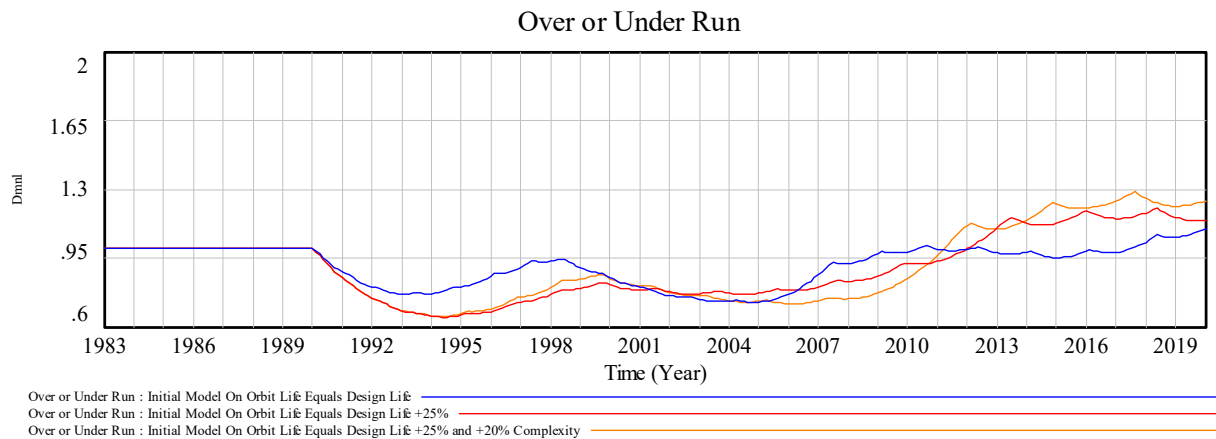
Figure 8-12: Weather and Climate Sensing Model Construction, Extended On-Orbit Life and Adding Complexity, Nunn-McCurdy Loop Over-Under Run

In Figure 8-13, the orange line represents the additional cost per year in production predicted from the addition of the adjustments for complexity. It also shows that the additional complexity will delay the production of the first NPOESS satellite by more than one year compared to the initial estimate. The increased complexity cannot alter the time prior to 2009 when the DWSS 5D-3 program ceases production because complexity adjustments are applied only to the NPOESS program. (Thus the orange line overlaps the red line through 2009.) The increased cost is not seen until ~2011, after which the costs continue to grow at a faster rate than previously computed. The delay of approximately one year is due to the increased complexity requiring more work to be done on each individual NPOESS satellite, which pushes out the completion time by about a year. The consequence of this delay for the first production unit is that the DWSS 5D-3 program is extended by one year from the model's perspective.

Pipeline Production Cost Per Year
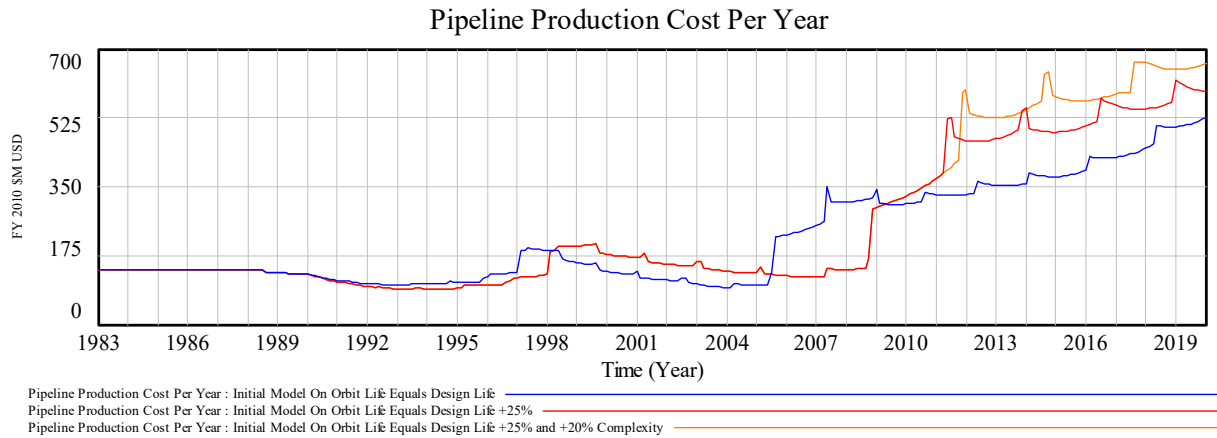
Figure 8-13: Weather and Climate Sensing Model Construction, Extended On-Orbit Life and Adding Complexity, Pipeline Production Cost per Year

Looking into the pipeline itself, the stock of "Work in the Industry" seen in Figure 8-14 can also help explain what is happening. In the previous generations of DWSS 5D-2 and 5D-3 the blue and red lines show an industry which is taking on the work of new programs, finding an equilibrium where satellites are requested and produced at an equal rate, and then tapering off as the old program ends. For the NPOESS program (represented by the orange line), however, the model with complexity added is unable to find an equilibrium state, and the Firefighting Loop comes into full effect. As the backlog builds up, it makes completing work harder and efficiency drops. In the short run this poses a nuisance but as the years pass and the amount of entropy increases, the program becomes unrecoverable and an overrun is predicted. Even though large amounts of money are being spent and work is being achieved, the program can never get ahead of the problems facing it: while satellites may be produced they will come in over budget and behind schedule until the orange line levels off its growth curve. Historically, once a program is in this mode of failure only a re-baselining (adding a lot more money) or completion (cancellation) of the program and moving onto the next are possible remedies.

SVs Work In Industry
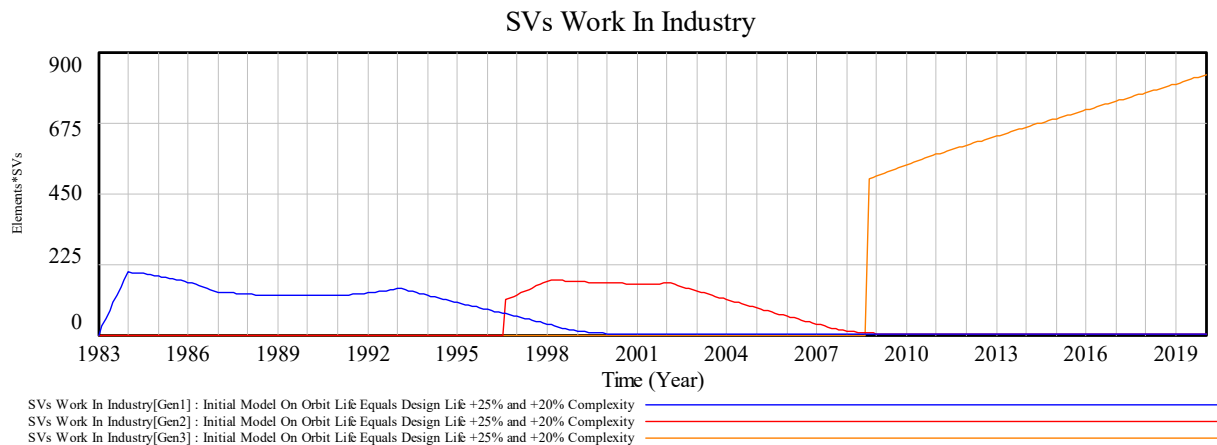
Figure 8-14: Weather and Climate Sensing Model Construction, Extended On-Orbit Life and Adding Complexity, Work in Pipeline

With an overrun now forecast by the model, the number of satellites predicted to be kept on orbit drops below the NPOESS target of four. As the model continues to overrun unless ever-increasing amounts of capital are added, satellites must be extended even longer on orbit or performance gaps will emerge. This is displayed in Figure 8-15.
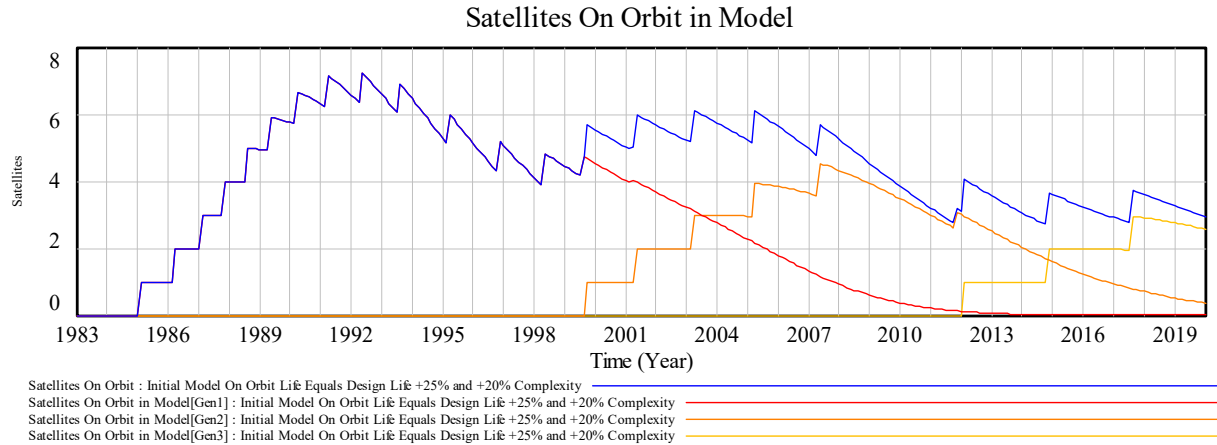
Figure 8-15: Weather and Climate Sensing Model Construction, Extended On-Orbit Life and Adding Complexity, Satellites On Orbit

The SD model may now be considered tuned with respect to NPOESS and previous DWSS acquisitions. While the problems forecast are not the same as those actually experienced by NPOESS, the tuned model forecasts that NPOESS would experience an overrun in production cost due to difficulty associated with acquisition. Since NPOESS was cancelled before ever reaching production we cannot confirm the accuracy of the model's prediction.

8.3.3   Examining Disaggregation on the NPOESS Program

As with GPS, in order to evaluate the model bounds and to gain trust in the model results, Full Disaggregation provides a good place to start. What would the NPOESS program look like as six separate satellites? Dwyer reasoned that a disaggregated approach would reduce complexity over the baseline. In a fully disaggregated approach many of the complexity factors are removed, the exceptions being those for high pointing accuracy which are tied to specific payloads, ability to operate in common planes and increased reliability for mission-critical sensors. Dwyer also concluded that if a common bus was to be implemented in a disaggregated architecture this would bring additional complexity in other areas to such an acquisition. Disaggregation, while a net decrease in complexity with respect to the satellites themselves, is not computed simply by removing complexity factors. Each individual architectural decision must be considered.

We will refer to the previous modeling of NPOESS in this chapter as the NPOESS Baseline (shown as an orange line in the above figures which include Dwyer's complexity metrics). This work agrees with hers and predicts a Nunn-McCurdy breach. Thus, we will use her work as justification for inclusion of the various complexity factors in the model which result in the overrun. This also implies that unlike GPS, where disaggregation was not inherently beneficial to the architectural design, the complexity metrics associated with the aggregated design will be

removed in Full Disaggregation as the issue seen above in Table 8-3: Addition of Complexity Metrics to Weather Model will no longer apply to the design. For the remainder of this chapter a blue line will represent the NPOESS Baseline. Figure 8-17 shows a modest increase in efficiency with resources if NPOESS is fully disaggregated.

Efficiency With Resources
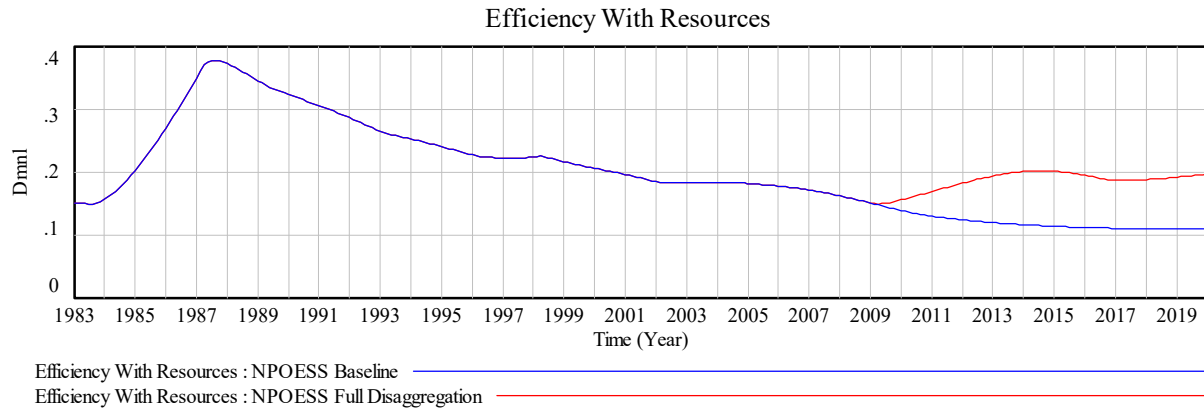
Figure 8-16: Weather and Climate Sensing Model, NPOESS Baseline vs. NPOESS Full Disaggregation, Efficiency with Resources

While the increase in efficiency is not visually impressive, the pipeline production cost per year seen in Figure 8-17 suggests that a Fully Disaggregated architecture might offer considerable cost reduction. After an initial period of high spending (approximately three years), the cost of a Fully Disaggregated architecture might return to DWSS levels in procurement while the aggregated NPOESS program is expected to continue to grow in cost. This cost is only with respect to production of satellites in the pipeline and has not considered total lifecycle cost (NRE, Launch, and on orbit and data processing).

Pipeline Production Cost Per Year
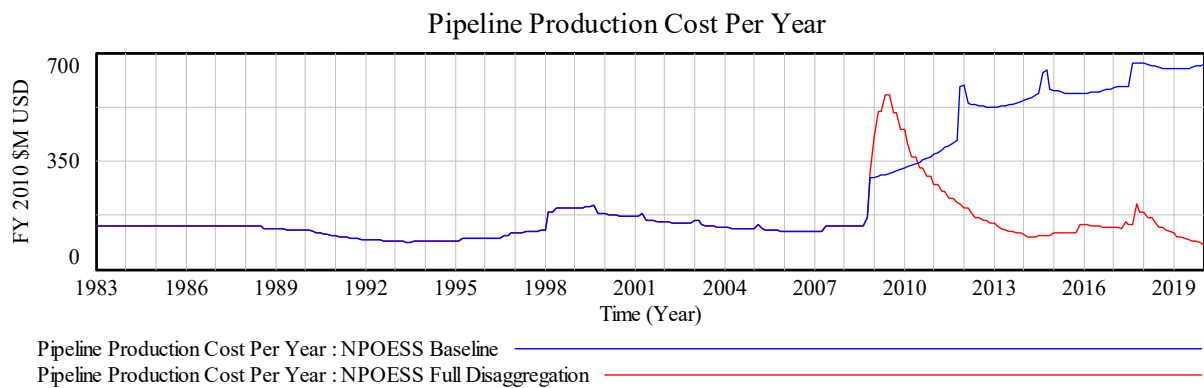
Figure 8-17: Weather and Climate Sensing Model, NPOESS Baseline vs. NPOESS Full Disaggregation, Pipeline Production Cost per Year

Looking inside the pipeline at the amount of work, in Figure 8-18, we see the NPOESS Baseline display an uncontrolled increase in work starting in 2009 (green line). This line is the same one representing NPOESS in Figure 8-14. (In both graphs Generation 1 represents the 5D-2 acquisition and Generation 2 the 5D-3 acquisition.) In contrast, the Fully Disaggregated NPOESS

(purple line), reaches a stable equilibrium point and then tapers off as the last of the four equivalent satellites of capability are produced (similar to the previous two generations of DWSS satellites).

SVs Work In Industry
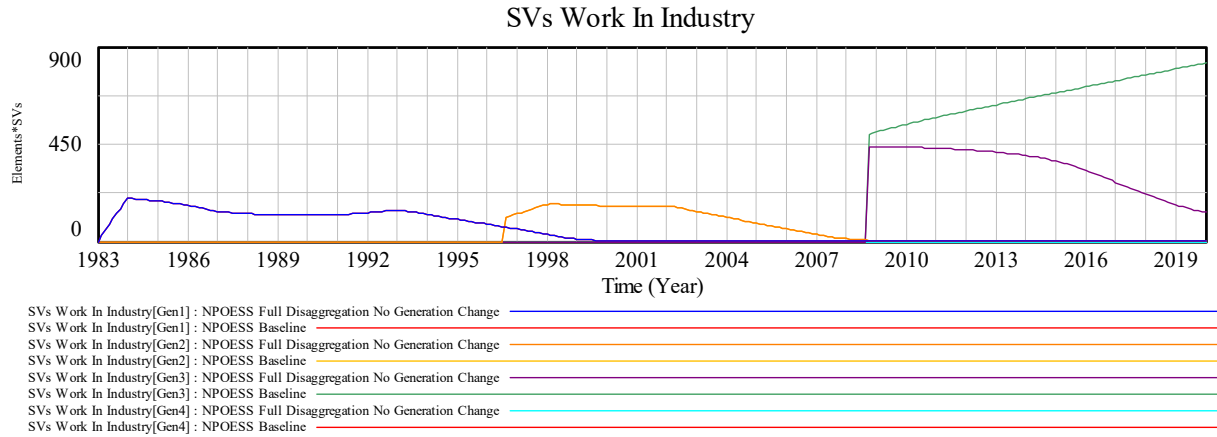
Figure 8-18: Weather and Climate Sensing Model, NPOESS Baseline vs. NPOESS Full Disaggregation, Work in Industry

As a check on model correctness, Figure 8-19 displays the number of satellites kept on orbit. The model attempts and is able to keep the required 24 satellites on orbit, indicating that the model has been able to shift the constellation to the Fully Disaggregated architectural configuration. With a fictitious, Fully Disaggregated NPOESS program started in 2002 with first production in 2009, the last satellite would complete around 2018, at which point production of a new generation would start (barely visible in the corner as a maroon line).

Satellites On Orbit in Model
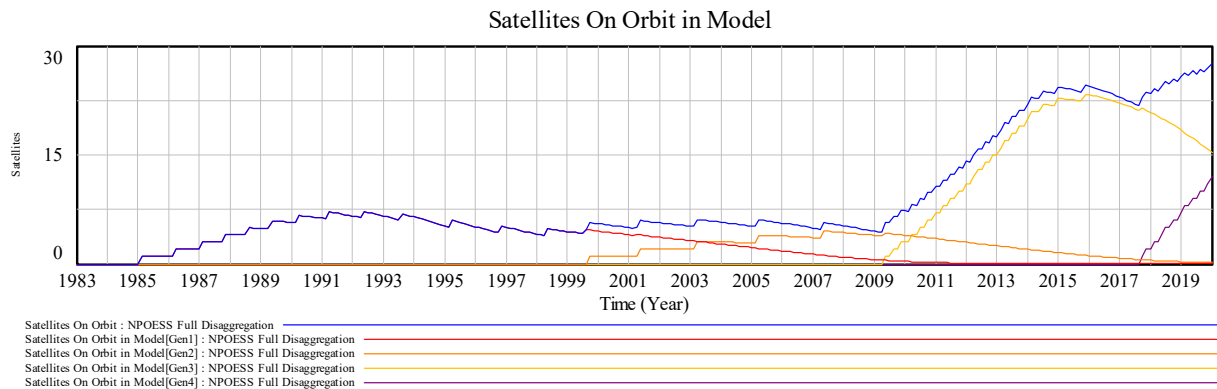
Figure 8-19: Weather and Climate Sensing Model, NPOESS Baseline vs. NPOESS Full Disaggregation, Satellites on Orbit in Model

The small increase in efficiency under Full Disaggregation seen in Figure 8-16 may seem surprising given the large spike associated with Full Disaggregation for GPS satellites. Initially one might think that the model may be incorrectly finding an equilibrium point near the historical DWSS data; however, this is not the case. To better understand the relatively small rise in efficiency under Full Disaggregation the model was re-run under another condition, one where no future program beyond NPOESS is predicted. Figure 8-20 captures this reality (in the first run only four satellites of capability are produced). Without a program after NPOESS, the model continues

to order and produce equivalent capability but with disaggregated NPOESS satellites. Under this assumption, the model is able to reach equilibrium, and achieve a much greater efficiency with resources, as shown by the orange line. This gives an initial insight to the number of satellites which may need to be ordered inside a single generation to reach maximal efficiency. Apparently the production of 24 Fully Disaggregated satellites (the equivalent of 4 NPOESS satellites) does not reap the full benefit of the experience being generated. The reason for this is likely tied to fact that a satellite in production cannot take advantage of the learning associated with satellites that came before it until those satellites are completed.

Efficiency With Resources

Efficiency With Resources : NPOESS Baseline
Efficiency With Resources : NPOESS Full Disaggregation
Efficiency With Resources : NPOESS Full Disaggregation No Generation Change
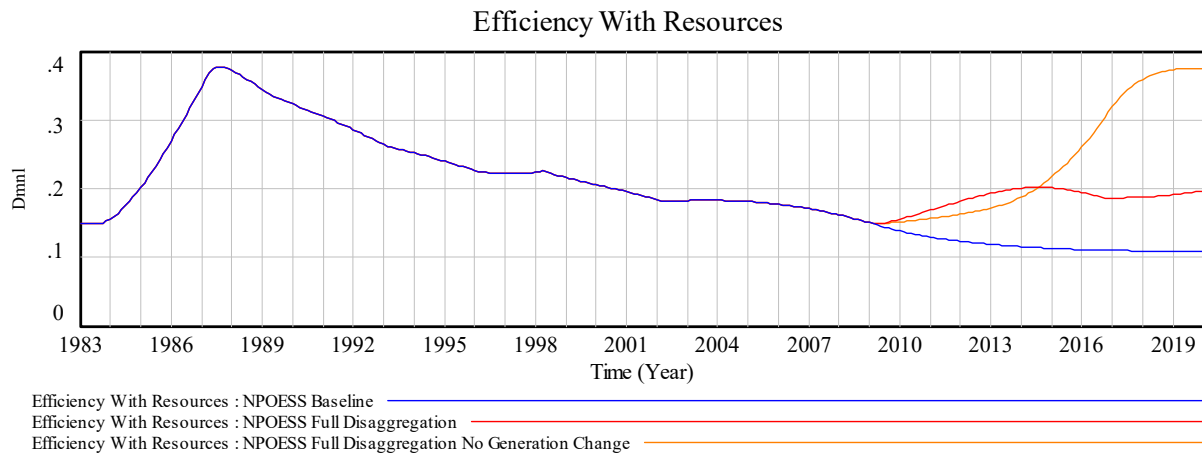
Figure 8-20: Weather and Climate Sensing Model, NPOESS Baseline vs. NPOESS Full Disaggregation, Efficiency Run to Equilibrium

The astute observer may question why, if the orange line represents the same Full Disaggregation program but without the changes required for follow-up generations, the orange line is ever below the red line. The reason for this is, in the time between 2002 and the first production satellite in ~2009, all the requests for the fully disaggregated NPOESS have already been placed and are in the pipeline. By 2009 a new program, or NPOESS follow-on, must already have been started in order to meet the need date of 2017. This technically reduces the amount of work in the industry because by 2009 no more work is added to the first generation—all requests are in the pipeline and new requests are now being placed in the program which will follow NPOESS. The red line captures this future. In comparison, a Fully Disaggregated architecture with no follow-up generations (the orange line) starts off with a full pipeline and continues to order at such a rate that keeps the pipeline full. In 2009 this makes production more difficult, as not only are 24 satellites on order but more orders keep coming in for this generation. Over time, however, learning effects appear and the additional work inside the generation raises the efficiency to an even higher level.

While a few runs are not sufficient to answer all questions about the impact of disaggregation across generations with respect to NPOESS and its follow-up JPSS, the above discussion indicates that there is plenty of evidence that the merged model technique presented in this thesis is amenable to investigating Weather, and that the model is tuned sufficiently to represent the acquisition of Weather and Climate Sensing satellites.

9 Policy Testing for Weather and Climate Sensing Satellite Acquisitions

With the tuned model of Chapter 8 and the determination that there is potential for disaggregated approaches to benefit the acquisition of Weather satellites, it is time to turn to consideration of the full system, including launch and ground operations. In this chapter the Joint Polar Satellite System (JPSS) will be evaluated as the program which follows the failed NPOESS program. The concept of a failed and cancelled program (generation) was not encoded into the original model built for the GPS satellite program, however, the impact of missing satellites can be implemented in the simulation by deleting the failed generation at the time of the Nunn-McCurdy breach. To delete the NPOESS program from the production pipeline while maintaining the effects of the acquisition, the impact across the major causal loops must be considered and adjustments made, if warranted.

- Production Pipeline: The work remaining in the NPOESS production pipeline must be removed. This is achieved with an outflow of the stock.
- Satellite Work Completed: As no satellite was produced, the work completed for NPOESS-class satellites is also removed from the pipeline. While it is likely that some of the production resources (tangible assets/designs) for payloads transferred to the JPSS program, the majority was spent on NRE and this is not reflected in the pipeline for production units.
- Technology Half-life: As the technology for payloads was not refreshed between the NPOESS and JPSS programs, the technology will continue to decay. This will likely impact the program that follows JPSS and increase the cost of production units for the payloads. The JPSS bus is produced by a different contractor and comes with an NRE pulse for the bus technology. These two elements (aging payload technology and new contractor) will impact the entropy levels for the JPSS program and associated costs.
- Experience: As money was spent and experience was gained in the NPOESS program, the decision was made not to adjust the Experience stock. Even failure leads to experience, though it is a different type of learning.
- Process Cycle Time: The model naturally adjusts the Process Cycle Time with the change in generation, thus over time the Process Cycle Time will correct to the proper level. As a result, no modification is made to the Process Cycle Time.
- Pipeline Production Cost per Year: The money was spent, even if no satellite was produced for the JPSS program. Consequently, no change is made to the pipeline production cost per year. In fact, there was a year or two during which the JPSS program did not exist: to model this, the pipeline is cleared for the time period of 2008 to 2010. Despite this clearing of work in the pipeline, the model does not drop funding to zero during these years as that would introduce a shock which would create an oscillatory wave in the system. Instead, funding is set to the level in 2008, holding the model to equilibrium during this period of time. The control module begins measuring cost at the beginning of JPSS program in 2010, and while the exact level of funding in 2010 may be imperfect and incorrectly weighted with respect to the NPOESS program, it will quickly stabilize to the proper level when production of JPSS satellites begins. By 2017 and beyond, the model will no longer be affected by this modification.
- Spacing of DMSP 5D-3 satellites: while in reality the launch of 5D-3 satellites was slowed to the maximum, this is not entered into the model because the time required for production

did not change and experience degrades equally whether satellites are sitting on the ground or on orbit. The lack of change in this variable is intentional. A consequence of this is that the 5D-3 satellites appear to launch earlier than in reality. Nonetheless, as the model grants experience only at time of completion, the time when experience is considered to be obtained aligns well with reality.

Figure 9-1 presents the results of these alterations for production of Weather satellites. The 5D-2 satellites are shown in blue and 5D-3 in red. NPOESS satellites are not shown in Figure 9.1 as no NPOESS satellites were produced. (The model still labels the generation—indicating it knows of the generation's existence even though no satellite was produced.) The model begins building JPSS satellites in 2017 (represented by orange spikes) and attempts to replenish the constellation. As the JPSS constellation is not hindered by the complexity associated with the NPOESS acquisition and the removal of the CIMS and other payloads, the system now finds a new baseline. JPSS represents an acquisition that is simply one payload larger and increases the dry mass by only approximately 300 kg (from approximately1200 kg to approximately 1500 kg) over the DMSP 5D-3. Based on the model's prior behavior, it is reasonable to assume that the model would likely compute the JPSS to be a successful acquisition. Nonetheless, there are some factors resulting from the failed NPOESS acquisition that need to be recognized: specifically, a lower initial efficiency, a greater backlog of work, and older technology with no refresh on the sensors since 2002. The model must thus be executed to understand the full impact of all these variables, on the pipeline and future acquisitions.

Part of the value of this analysis is to obtain understanding of how the weakened position of Weather satellite manufacturing due to the failure of NPOESS will impact the efficiency of the system going forward. Originally, JPSS 1 was scheduled to be put on orbit in early 2016; it is now slated for 2017. An initial analysis, shown in Figure 9-1, appears to indicate that the NPOESS failure will have little impact on JPSS's first production unit's completion time; the model expects a launch in 2017 (though with further tuning this will not be the case). Recalling that in Chapter 8 the initial model required the addition of some complexity factors to tune to match reality, the complexity metrics proposed in Dwyer's thesis were also implemented for the JPSS program and any tested disaggregated implementations (Dwyer, 2015). The code to implement the mass increase due to complexity is presented in Table 8-3: Addition of Complexity Metrics to Weather Model from Dwyer's Thesis. These metrics will influence the execution of the SD model and the SD model will predict, based on the start of the acquisitions pipeline and these requests, the cost outcome of such a program. The value of this approach is that the resources (dollars) provided to the SD model are based on the computation without the complexity metrics. The requirements (satellite mass) passed to the SD model, however, are the full requirements, thus, the program might be considered "under-funded." This creates a model simulation similar to the real world where a budget is initially set without full knowledge of the requirements and costs of the system to be produced. The SD model attempts to create the satellites with the resources available. It can slow production to save money as well as increase funding, if required. This approach will also enable examination of whether disaggregated approaches will fare better across time than a heavily aggregated approach, if the satellites are more difficult to produce than initially assumed.
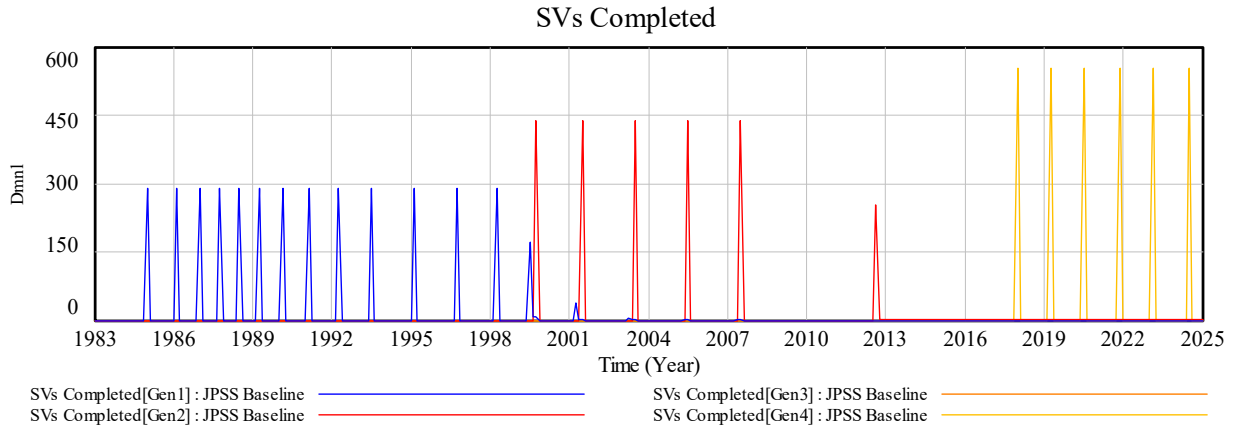
Figure 9-1: Weather and Climate Sensing Model Satellites Completed

Table 9-1: JPSS Metrics with and Without Complexity Compared to Actuals displays the cost and mass model results for the JPSS satellite with and without the addition of the complexity metrics. With the complexity metrics added, the JPSS satellite represented in the model is very close to reality. They are similar in both dry and wet mass.

Table 9-1: JPSS Metrics with and Without Complexity Compared to Actuals

	JPSS Without Complexity	JPSS with Complexity	JPSS Actuals
Dry Mass	1534 kg	1926 kg	1979 kg
Wet Mass	2114 kg	2654 kg	2540 kg launch mass (280 kg) usable propellant
Payload Costs first (second)	$1.72B	$1.72B	$1.92B ($456M)
Program Costs first (second)	$403M($7M)	$403M($7M)	Unknown w/large legacy components
TFU Cost	$2.68B	$2.68B	Unknown w/legacy NPOESS and DMSP components for sensors
Next Unit Cost	$610M	Replication Handled in SD Model	$655.5M
Solar Area	~13 m^2	~13 m^2	12 m^2
Power	1858 W BOL	1858 W BOL	1932 W (BOL) 1619 W average

290

Note 1: The wet mass includes only on-board fuel based upon the satellite and its on-orbit design life. It does not include the mass of a kick-motor for insertion into a polar orbit. The mass requirement placed on the launch vehicle includes an additional 40% wet mass for the vehicle dedicated to kick-motor requirements for orbital insertion.
Note 2: After complexity is added to mass, the requirements for fuel and the kick-motor are recomputed based on the new dry mass in the mass, cost, and launcher select models.

Figure 9-2: Weather and Climate Sensing Model, Satellites Completed Including Complexity, shows the effect of the addition of the complexity metrics. The first JPSS satellite is now delayed ~1.5 years over the model without complexity, shown in Figure 9-1. The interval between JPSS satellites is also extended (there are only 4 launches from 2019 to the end of the figure).
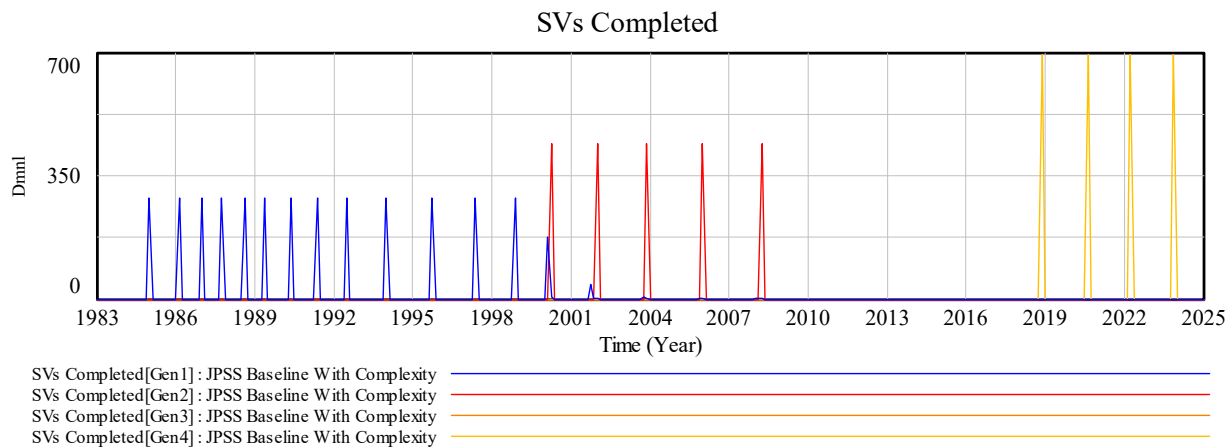
Figure 9-2: Weather and Climate Sensing Model, Satellites Completed Including Complexity

Further examination of the SD model reveals that the production time and Process Cycle Time appear to be stabilizing but at levels which will not translate into high efficiency. As shown in Figure 9-3, efficiency is slow to recover from the NPOESS failure. It will, however, be able to acquire the capability with allotted funding without a Nunn-McCurdy breach—even under complexity metrics.

The pipeline does not recover quickly if the JPSS program is executed as a single satellite cloned four times. Considering that JPSS is simply a new bus for five of the payloads started in 2002, this may be a reasonable projection. The model recognizes that the technology is old and consequently, introduces a lot of entropy, depressing the Efficiency stock. This recalls the concept of "Failure Begets Failure." The government twice failed to acquire NPOESS. To break the cycle of failure while delivering some capability, JPSS was designed to reduce requirements and acquire that which realistically could be acquired. It is thus an effort at stabilization. Gains in efficiency will, however, have to wait for the program that follows JPSS. The question thus becomes, what will happen to the follow-up to JPSS given increased requirements, or funding and what will be the impact of older sensor technology (started in 2002)? For GPS satellites, disaggregation provided paths to increase efficiency in production, the same possibilities can be examined for JPSS.

Efficiency With Resources

Efficiency With Resources : JPSS Baseline With Complexity ————
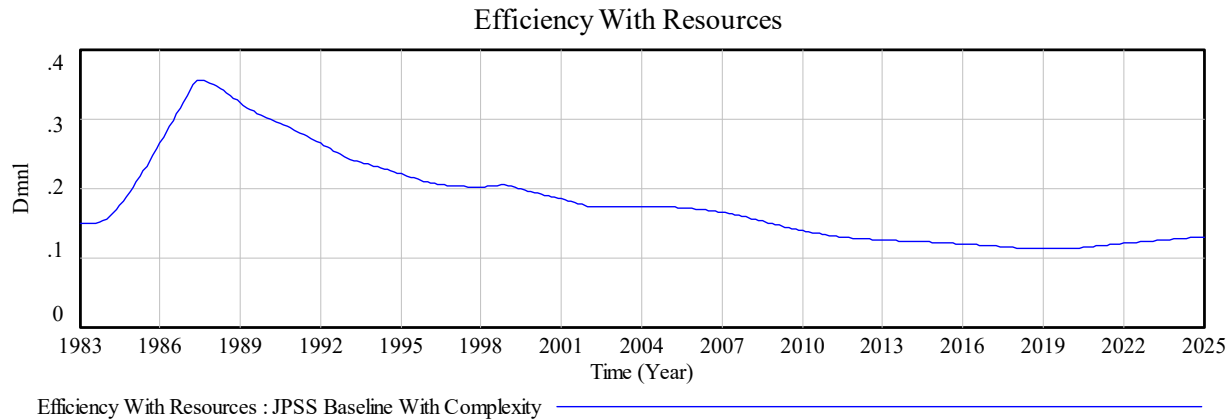
Figure 9-3: Weather and Climate Sensing Model, Efficiency with Resources Including Complexity

At the time of writing, Orbital ATK has signed a contract to produce three clones of the JPSS satellite. Thus, there will be a switch in contractor after the first JPSS flight unit (from Ball Aerospace to Orbital ATK). Orbital ATK's fixed price contract includes the bus and integration, assembly and test for each of the additional three JPSS satellites: $253M for the first, $130M for the second, and $87M for the third. This is a substantial reduction from the $655.5M paid to Ball Aerospace for the first unit. While the Orbital ATK bid was based upon possession of an existing bus which could be modified relatively easily, it remains to be seen if they can deliver capability at these price points. If, however, they are able to deliver, it would significantly change assumptions about learning effects within a generation and assumptions about the ability to transfer efficiency from one program to another. The price drop of ~40% from the original contractor moves production of the next JPSS unit to a completely different price point. If Orbital ATK can deliver the first unit at $253M, a drop in cost of nearly 50% from the first to the second unit is in line with existing cost models. The reduction from the second to the third satellite of an additional 33% is, however, much greater than historical examples would predict.

9.1 Flavors of Disaggregation for Weather

This section will consider possible future architectures involving disaggregation versus the JPSS BATNA. Upfront, it should be clear that if future JPSS-class systems plan to generate benefit at or below the level currently produced by a single JPSS satellite on orbit at all times, there is no reason to disaggregate climate and weather sensors from a single, aggregate bus. If, however, more and increased capability over the next decades is required, then this analysis may reveal options other than building bigger satellites, which can deliver value. The model is tuned to begin simulation in 2010. As with the GPS analysis, the model will look across four generations. Unlike the GPS analysis, the third and fourth generations will be identical. Identical final generations ensure that the model reaches a stable equilibrium as well as avoids end-game effects that could result from the considerably shorter JPSS generations. This is discussed in greater detail later in this chapter.

In the absence of an existing plan other than the manufacture and launch of four JPSS satellites through 2024, it is recognized that future generations of JPSS payload need to be aligned with increased capability across the various blocks. The configuration used in this work is based on Dwyer's work with Weather satellite payload alignment. Dwyer lays out nine variants of a

Weather/Climate Split NPOESS mission and eight variants of the ARMS CrIS Free Flyer option for NPOESS. For each configuration, a benefit is computed. In her work the highest-value configuration is selected for the first generation. This is adopted in the current work. For future generations, sensors are added following an upgrade path as they add value based upon Dwyer's normalized benefit estimates. Different payload alignments lead to very different futures with different cost drivers. In Dwyer's work, direct comparison of options is not a pure comparison against performance, rather the benefit or utility of a configuration is weighed against the cost (as is practice in TSE modeling). In this work, the upgrade paths will attempt to keep near-equivalent performance in each design to enable an apples-to-apples comparison.

Dwyer compares the number of spacecraft against the performance delivered and the costs incurred (accepting solutions with less than 100% satisfaction of mission requirements). As is in line with TSE practice accepting lower performance if the cost savings are sufficient, or paying more if the capability is worth the cost increase is logical; in this work we stabilize performance for an equivalent comparison of capability.

Adapting Dwyer's work on payload alignment, this work constructs five possible disaggregated approaches, each with a unique way of adding capability across future generations:

1) A fully aggregated future where JPSS adds capability (sensors) to a single bus in later generations.
   a. The CMIS sensor is added back in, in the third generation. If CMIS is not added back in, this could be considered an abstract representation of ~400 kg more sensor capability to be added in the third generation.
   b. By the third and fourth generation the JPSS satellite has become something that looks very much like the original NPOESS satellite.
      i. This does create programs which overrun in the third generation, but not all implementations overrun.
   c. This is referred to as Full Aggregation and is represented by the color blue in this chapter.
2) A future where weather and climate sensors are split into two different satellites.
   a. In this future, the goal is to create a common bus between the weather and climate systems, as suggested by Dwyer's research.
   b. This is referred to as Weather/Climate Split and represented by the color yellow in this chapter.
   c. This approach requires a third satellite in the third generation consisting of a CMIS "free-flyer" or a bus with only the CMIS payload and some additional small sensors.
3) A future where JPSS is split into three satellites.
   a. In the second generation the alignment enables a common bus across all three satellites.
   b. In the third generation the addition of a CMIS or equivalent sensor (up to 400 kg in mass) forces a fourth satellite.
      i. The system can either make a second bus or make one common bus where each of the four satellites can host up to 400 kg of payload.
      ii. The model prefers to create four satellites each with a common bus and not use each to their full capacity.
   c. This is referred to as 3x Disaggregation and represented by the color orange in this chapter.
4) A future where four satellites are constructed.

a. Two satellites will host ~300 kg of payload mass and two satellites will host ~100 kg of payload mass.
b. In the third generation it will add a fifth satellite, the same CMIS "free flyer" or single payload bus, as in the Weather/Climate Split option.
c. This is referred to as 2 Large and 2 Small Satellites and represented by the color red in this chapter.
5) A fully disaggregated future.
a. This is not technically full disaggregation (with GPS each bus only had one payload in full disaggregation)—the upgrade path below indicates satellites five and six will both carry two sensors. Based on mass of the sensors this enables a common design among four of the satellites, each carrying under ~125 kg of sensor mass.
b. This is referred to as Full Disaggregation and represented by the color purple in this chapter.

The exact configurations of payloads to satellites for the above five aggregation possibilities is listed in Table 9-2: Disaggregated Options and Capability Increase for JPSS Across Four Generations.

Table 9-2: Disaggregated Options and Capability Increase for JPSS Across Four Generations

Disag-gregation Options (Color)	Generation 1	Generation 2	Generation 3	Generation 4
Full Aggregation (JPSS BATNA) (Blue)	SV1-VIIRS,CRIS, ATMS, OMPS_NADIR,OMPS_LIMB,ERBS,ERBS1	SV1-VIIRS,CRIS, ATMS, OMPS_NADIR,OMPS_LIMB, ERBS,ERBS1,TSIS, APS	SV1-VIIRS,CRIS, ATMS, OMPS_NADIR,OMPS_LIMB, ERBS,ERBS1,TSIS, APS,CMIS	SV1-VIIRS,CRIS, ATMS, OMPS_NADIR,OMPS_LIMB, ERBS,ERBS1,TSIS, APS,CMIS
Weather/ Climate Split plus CMIS Free Flyer (Yellow)	SV1-VIIRS,ATMS, OMPS_NADIR,CrIS SV2-OMPS_LIMB, ERBS,ERBS1	SV1-VIIRS,ATMS, OMPS_NADIR,CrIS SV2-OMPS_LIMB, ERBS,ERBS1,TSIS, APS	SV1-VIIRS,ATMS, OMPS_NADIR,CrIS SV2-OMPS_LIMB, ERBS,ERBS1,TSIS, APS SV3-CMIS	SV1-VIIRS,ATMS, OMPS_NADIR,CrIS SV2-OMPS_LIMB, ERBS,ERBS1,TSIS, APS SV3-CMIS
3x Dissag-gregation plus CMIS Free Flyer (Orange)	SV1-VIIRS, OMPS_NADIR SV2-ATMS,CrIS, OMPS_LIMB SV3-ERBS,ERBS1, TSIS,APS	SV1-VIIRS, OMPS_NADIR SV2-ATMS,CrIS, OMPS_LIMB SV3-ERBS,ERBS1, TSIS,APS	SV1-VIIRS, OMPS_NADIR SV2-ATMS,CrIS, OMPS_LIMB SV3-ERBS,ERBS1, TSIS,APS SV4-CMIS	SV1-VIIRS, OMPS_NADIR SV2-ATMS,CrIS, OMPS_LIMB SV3-ERBS,ERBS1, TSIS,APS SV4-CMIS

2x Large and 2x Small plus CMIS Free Flyer (Red)	SV1-VIIRS, OMPS_NADIR SV2-CrIS,ATMS, OPMS_LIMB SV3-ERBS, ERBS1	SV1-VIIRS, OMPS_NADIR SV2-CrIS,ATMS, OPMS_LIMB SV3-ERBS, ERBS1 SV4-TIS, APS	SV1-VIIRS, OMPS_NADIR SV2-CrIS, ATMS, OPMS_LIMB SV3-ERBS, ERBS1 SV4-TIS, APS SV5-CMIS	SV1-VIIRS, OMPS_NADIR SV2-CrIS, ATMS, OPMS_LIMB SV3-ERBS, ERBS1 SV4-TIS, APS SV5-CMIS
Full Disaggregation (Purple)	SV1-VIIRS SV2-CrIS SV3-ATMS SV4-OMPS SV5-ERBS1/ERBS	SV1-VIIRS SV2-CRIS SV3-ATMS SV4-OMPS SV5-ERBS1/ERBS SV6-APS & TSIS	SV1-VIIRS SV2-CRIS SV3-ATMS SV4-OMPS SV5-ERBS1/ERBS SV6-APS & TSIS SV7-CMIS	SV1-VIIRS SV2-CRIS SV3-ATMS SV4-OMPS SV5-ERBS1/ERBS SV6-APS & TSIS SV7-CMIS

Note1: In a deviation from Dwyer, this work does not examine Windsat, or SSMIS as an alternative to CMIS. These two sensors are excluded from the analysis. Future analysis could compare them or include them in another upgrade path. While JPSS will not be flying the CMIS sensor, the addition of its mass and power requirement in the third generation creates a reasonable approximation for future desired performance increase.

Note 2: The complexity metrics seen in Table 8-3: Addition of Complexity Metrics to Weather Model from Dwyer's Thesis are inserted into each of these disaggregated approaches as applicable.

9.2 Flavors of Disaggregated Weather

The model was run with the following variations, resulting in ~9,000 combinations:

- Aggregation, based on the five possible disaggregated approaches discussed
- Design Life of the satellite, from four to eight years in one-year increments
- Time Between the NRE Pulse, from two satellites to 12 in a generation
- Delaying or accelerating the upgrade path, either skipping a generation and adding capability (sensors) a generation earlier, or delaying capability (sensor) requests by a generation to make acquisitions easier

For these runs, the policy of attempting to keep the equivalent capability of four satellites on orbit at all times was enforced and the model was allowed to request additional funding (overrun) if required. Runs that requested in excess of 125% the baseline were discarded in post-processing, as this breach in program funding was deemed to be a program failure.

The model was run under two conditions: first without the complexity metrics, then with them. Figure 9-4 shows the gains in efficiency in production associated with nearly 1,000 of the higher performing architectures without complexity metrics. Each line is composed of balls and arrows. The ball represents the efficiency level of the disaggregation approach in the fourth generation and the arrow (often covered by the line itself) represents the direction of efficiency. As noted above, the colors each represent a different level of aggregation:

- Blue: Full Aggregation, i.e., the JPSS BATNA
- Yellow: Weather/Climate Split
- Orange: 3x Disaggregation

- Red: 2 Large and 2 Small Satellites
- Purple: Full Disaggregation

As most of these are successful implementations, the arrows primarily point to the right. A left-pointing arrow indicates a policy or architecture that is driving down efficiency across generations. The data show that the various policy and architectural configurations create different levels of efficiency across time. While the most successful implementations push efficiency up to between .45 and .5, some achieve substantially less. Recall that the highest efficiency points possess the greatest potential to capitalize on learning effects, but they are not always the most cost-effective. The cost per operational year of these implementations is examined further, below. Typically, the highest-efficiency futures spend excessive amounts of resources on very fast upgrades and NRE while creating satellites with design lives shorter than required, because efficiency cares very little about cost. These results can still be useful, however, for determining where a good balance might be found.
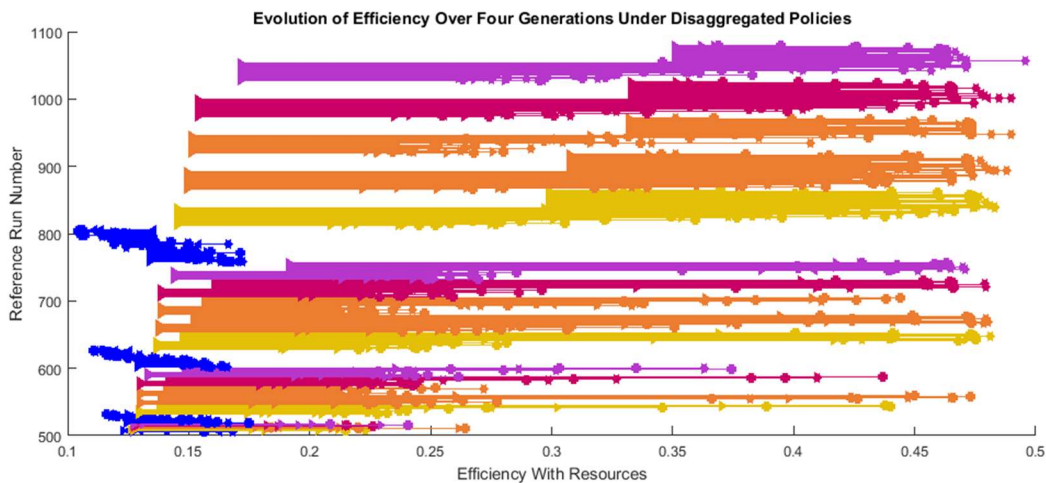
Figure 9-4: Weather and Climate Sensing Model, Evolution of Efficiency over Four Generations for Various Disaggregated Policies

Figure 9-5 presents the results when the model is run with the complexity metrics added. The results shift dramatically. Most notable is the Weather/Climate Split option where under complexity no "high efficiency" futures exist. (None of the yellow lines reach an efficiency of even .25.) As it was determined in Chapter 8 that the complexity metrics are required for proper tuning of the model, all further results in this chapter include the complexity metrics.

It is important to understand that the complexity metrics are not simply subtracted as disaggregation increases. Several remain imposed on all disaggregated architectures. Specifically:

- Mass increase for critical mission payloads
- Mass increase for mechanical jitter from the CMIS payload
- Mass increase for a multi plane bus design
- Mass increase for a common bus design in disaggregation

Disaggregated approaches do reduce other metrics which reduce complexity:

- Physical size of the satellite (less massive)
- Obstruction of field of view due to multiple optical payloads (reduced)
- Mass increase resulting from multiple high data rate payloads (reduced)

Overall, however, complexity metrics add to the higher overhead required for disaggregated approaches. A disaggregated approach with complexity metrics can confront a substantially larger total mass to place in orbit (upwards of 20%). This additional mass is the primary reason for the difference in efficiency between Figure 9-4 and Figure 9-5.
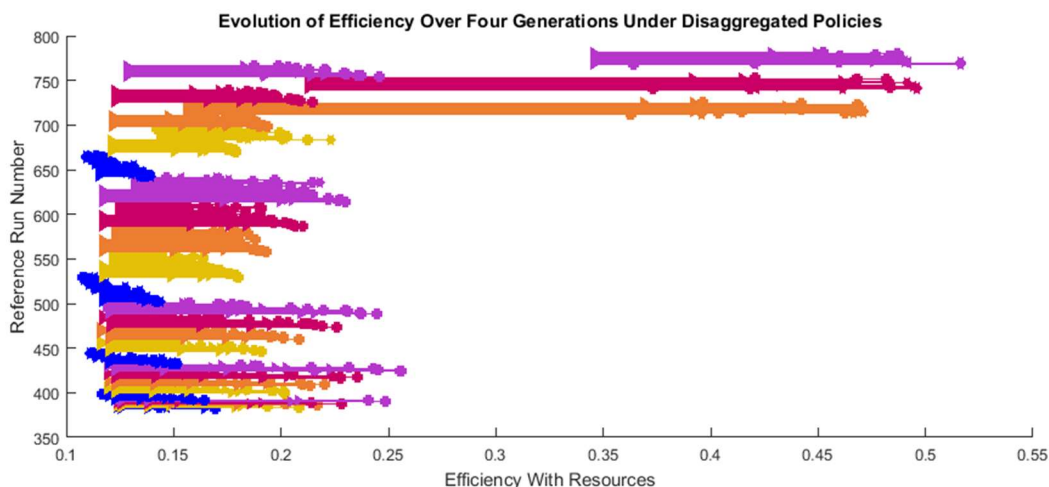
Figure 9-5: Weather and Climate Sensing Model, Evolution of Efficiency over Four Generations for Various Disaggregated Policies under Complexity

9.2.1   Cost per Operational Year Generation over Generation (FYDEP)

In the next four figures: Figure 9-6, Figure 9-7, Figure 9-8 and Figure 9-9, the cost per operational year incurred for the FYDEP for each generation of the architectural and policy implementations is displayed. This is an important cost metric as it relates to absolute cost in the budget, however, it alone does not reveal what might be best from a cost perspective. Other cost metrics need to be considered. Some of these are discussed later in this chapter.

In the following four figures the X axis represents the cost per operational year as represented by the total lifecycle cost of the generation divided by the number of years of operational capability delivered. The model is instructed to place the equivalent capability of four JPSS Weather and Climate Sensing satellites on orbit at all times, where capability is the sensor suite listed in Table 9-2: Disaggregated Options and Capability Increase for JPSS Across Four Generations. This ensures that across generations, capability is always equal. It does not ensure equal time within a generation. Some approaches are able to complete their acquisition more quickly and deliver capability to orbit sooner than the JPSS BATNA. Some are less efficient, but they are discarded in this analysis.

Between the first two figures—Figure 9-6 and Figure 9-7—the differences created by different flavors of disaggregation as the model steps forward across time begin to emerge. By the second

generation, the lowest cost per operational year appears most likely to be associated with Fully Aggregated (blue) and Climate/Weather Split (yellow) strategies. By Generation 3 (Figure 9-8), the increase in demands for capability weakens the Weather/Climate Split option relative to the Fully Aggregated approach (blue appears to the left far more often than yellow). By the fourth generation, seen in Figure 9-9, it is clear that under complexity metrics the model believes the Fully Aggregated (JPSS BATNA; blue) is most cost effective.
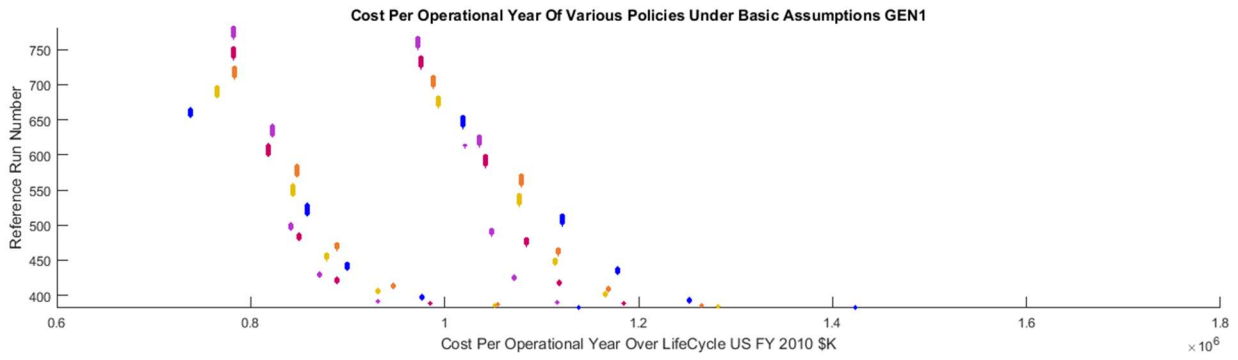
Figure 9-6: Weather and Climate Sensing Model, Cost per Operational Year of Various Policies Under Basic Assumptions Generation 1
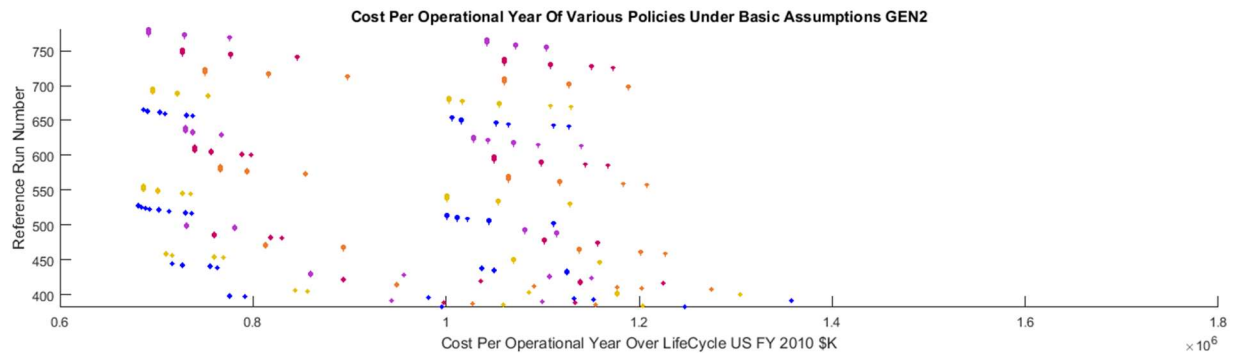
Figure 9-7: Weather and Climate Sensing Model, Cost per Operational Year of Various Policies Under Basic Assumptions Generation 2
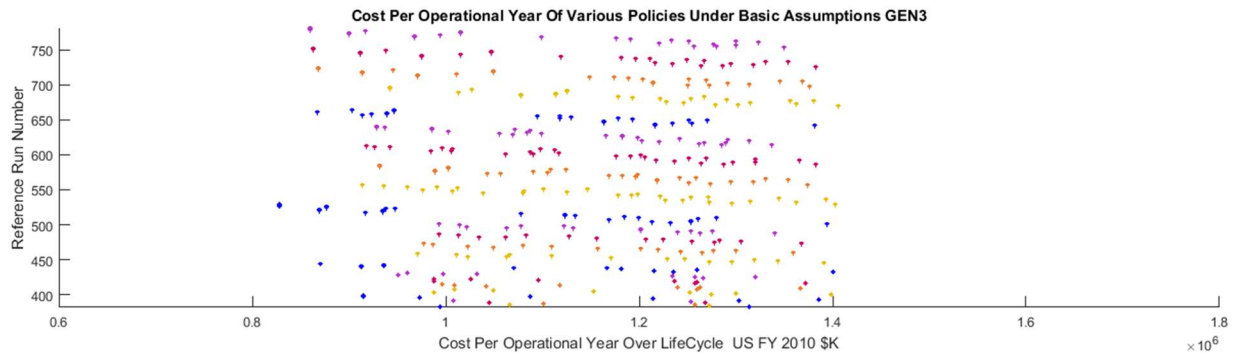
Figure 9-8: Weather and Climate Sensing Model, Cost per Operational Year of Various Policies Under Basic Assumptions Generation 3
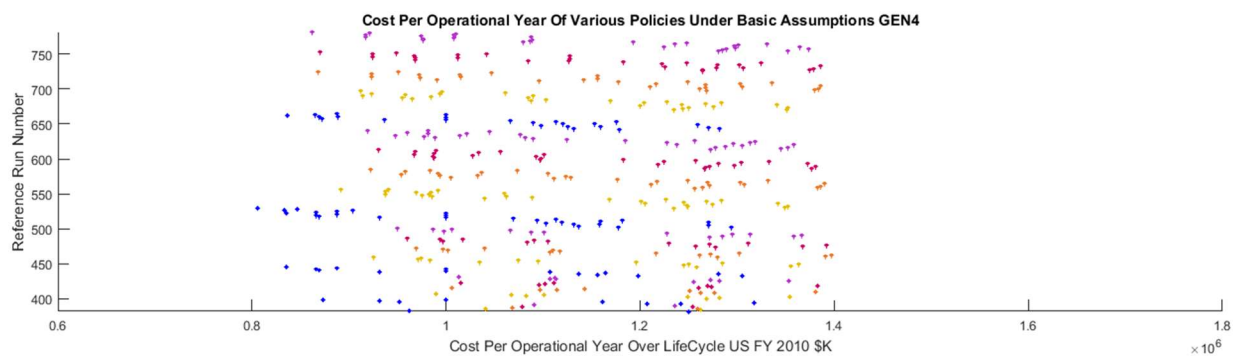
Figure 9-9: Weather and Climate Sensing Model, Cost per Operational Year of Various Policies Under Basic Assumptions Generation 4

There are, however, some problems with the Fully Aggregated/JPSS BATNA implementation. All of the blue dots with a low cost per operational year in Figure 9-9 rely heavily upon on-orbit time extensions to maintain the full constellation strength of four satellites of equivalent capability on orbit. Closer examination of the high performing blue dots reveals that their ability to maintain four satellites on orbit is at best dubious at best and often they fail to do so. For example, the optimal JPSS design point is number 529. Figure 9-10 provides a detailed look at the satellites that would be on orbit with this design point. The blue line represents the sum total of all satellites on orbit; the various colored lines represent satellites in the respective generations. Examination of Figure 9-10 shows that 529 does not really meet the four-satellite requirement. The model is in an equilibrium state after 2035 where it can almost keep four on orbit, but this design point by definition includes on-orbit extensions of 25% plus a 12th -order smoothing function granting an additional 20% to average design life (implemented as a way to abstract the difference between a design life and service life). Figure 9-10 indicates that a gap should emerge between 2009 and 2023. However, this gap has not yet emerged as spacecraft launched in 1994, 1997, 1999 and 2003 are currently still operational (National Snow & Ice Data Center, 2016). However, many satellites launched after these have already exhausted their on orbit life, so the capability being delivered today is more luck than good planning. Thus, the model is a representation of good planning not hoping for a miracle in the next acquisition. While not all satellites in the DMSP constellation have lasted as long as these four, the average of 25% appears

to be a good approximation. This reality of some satellites lasting even longer also lends credibility to the concept that this JPSS BATNA, which keeps between three to four satellites on orbit, would indeed keep the constellation at full strength.
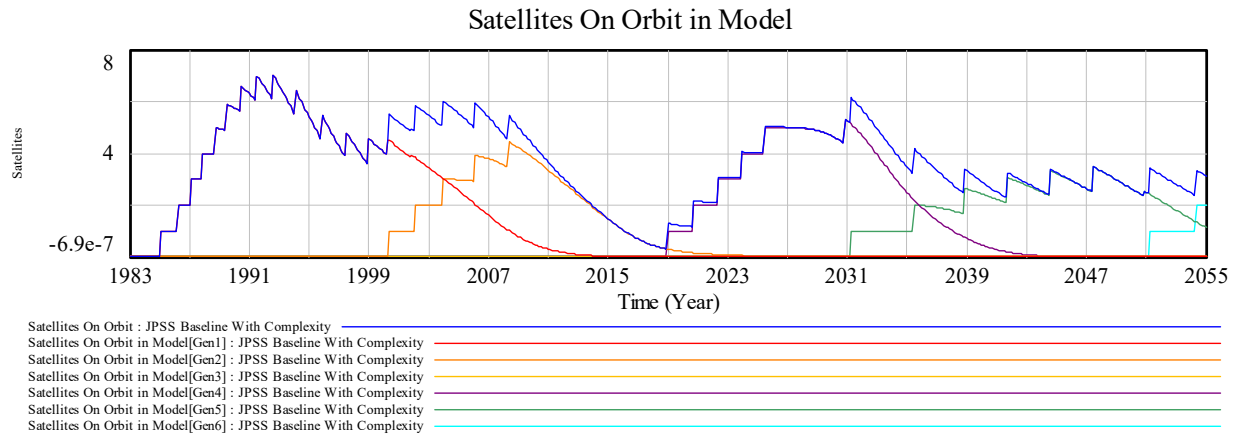
Figure 9-10: Weather and Climate Sensing Model, Satellites on Orbit

Continuing to look at cost per operational year, Figure 9-11 shows a "bow-wave" trend indicating that the JPSS program, while able to complete the satellites is able to avoid a program breach only by stretching resources over a longer time period. The dimensionless Y axis indicates the funding multiple required compared to the TSE estimate of the funding required per year in production. If the value is below one, the model is able to deliver capability below the TSE estimate; above one the cost in production is above the initial estimate. If the value stays above 1.25 for too long, one might conclude that a Nunn-McCurdy breach is likely to emerge. Despite their lower cost, Fully Aggregated designs are projected to fall into the overruns of past Weather satellites once aggregated JPSS requirements again approach the NPOESS design level (Generation 3 as outlined in Table 9-2). This is a precarious position, another exogenous shock or difficulty in acquisition would almost certainly lead to a program breach and possible program failure in that generation. This illustrates the problem associated with adding more sensors to a single bus to gain more capability: eventually it becomes a non-tenable architecture. This is not to say that larger and more complicated space systems will not be built in the future, but only that unless a new technology enables the building of larger structures and better management of the complexity of systems with many interfaces, distributed complexity may offer a more effective solution than additional centralization.

Over Run Projection

Over or Under Run : JPSS Baseline With Complexity
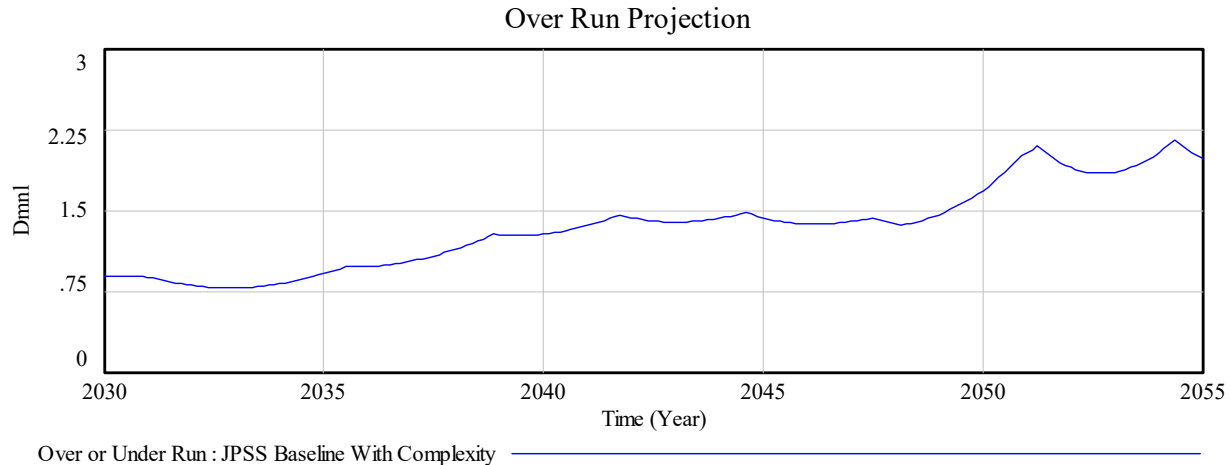
Figure 9-11: Weather and Climate Sensing Model, JPSS BATNA, Over-Run Projection

Figure 9-12 displays the cost per operational year for only the fourth generation—excluding the on-orbit operational costs. This differs from Figure 9-9 which includes all life cycle cost elements. Excluding on-orbit costs allows a clearer picture of the changes in production costs associated with various approaches to disaggregation. Flying four rather than 28 satellites would likely not be cost neutral and a comparison of Figure 9-12 and Figure 9-9 shows a large cost associated with the operation of increased number of satellites. The JPSS BATNA is estimated to cost around $715M for ground operations and data processing during the on-orbit lifespan. The cost estimate for many of the heavily disaggregated implementations reaches $1.4-1.5B for the same time span. Thus, over a 10-year period approximately $70M a year would have to be saved in the cost of producing a disaggregated design to counteract increased on-orbit and data processing costs.

Excluding the on-orbit and data processing costs shows the benefits in production associated with disaggregated approaches for now three implementations (purple, red, orange) are all far to the left of the JPSS BATNA (blue). This indicates the large impact complexity has on both aggregated and disaggregated architectures with respect to lifecycle cost. This is one area in which investment could be of benefit to disaggregated architectures, if ground costs could be kept down as the number of satellites in the constellation go up, it would be beneficial to a disaggregated architecture for weather and climate measuring.
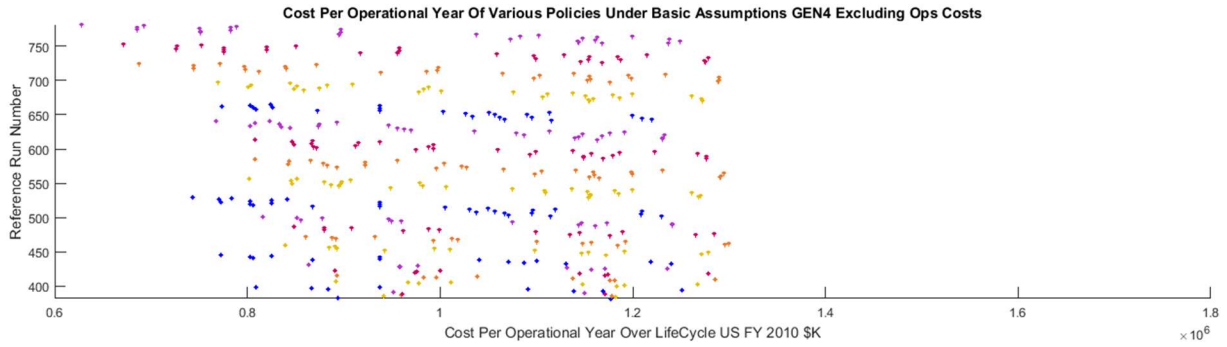
Figure 9-12: Weather and Climate Sensing Model, Cost per Operational Year of Various Policies Under Basic Assumptions Excluding Operational Costs in Generation 4

The model is always "concerned" about the extremely low efficiency noted in the construction of weather satellites. To visually present how fast the efficiency rises given various architectural decisions, Figure 9-13 presents the efficiency curves for the simulations producing the lowest cost per operational year as indicated by the far left points in Figure 9-9: Weather and Climate Sensing Model, Cost per Operational Year of Various Policies Under Basic Assumptions Generation 4. While the lines representing flavors with the greatest disaggregation (red and purple) rise more quickly to their maximal efficiency, they are not much higher than the 3x Disaggregation (orange). After initial gains in production efficiency, there is less benefit obtained from additional production. There is less improvement in efficiency from the 20th to the 24th unit than the fourth to the eighth. And unlike GPS, where up to 144 satellites might be manufactured in a generation and the difference in efficiency was much larger among disaggregated approaches, here the maximal number is roughly 42, which leads to a smaller difference among many of the disaggregated approaches.
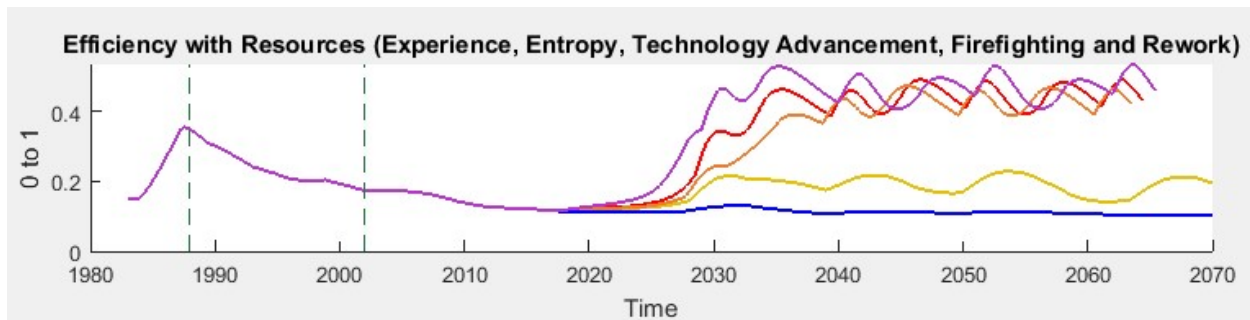
Figure 9-13: Weather and Climate Sensing Model, Efficiency Metric for Lowest Cost per Operational Year Implementation

Figure 9-14 shows the time when the model recommends starting JPSS Generation 2. For the Fully Aggregated JPSS satellite (blue), work on the follow-up program needs to begin in ~2020 in order for the satellite and payloads to be ready by the need date of ~2031. For all disaggregated approaches (yellow, orange, red, purple) the NRE pulse is recommended for approximately five years later—around 2025—to enable production of a greater number of satellites in the first generation. The benefits of producing more satellites are greater than the costs associated with greater entropy associated with the greater age of the technology being worked with and additional NRE in Generation 2.

302
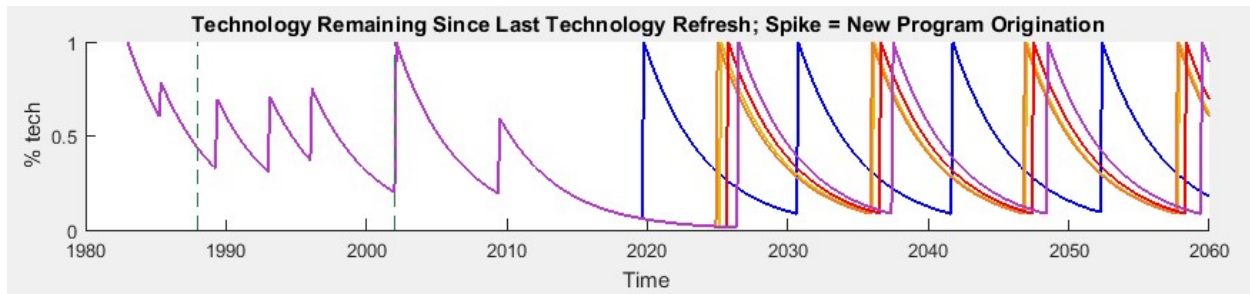
Figure 9-14: Weather and Climate Sensing Model, Optimal Technology Refresh Period

Overall, an optimal JPSS BATNA (fully aggregated implementation) is achieved by:

- Building six satellites in each generation. This minimizes the JPSS cost per operational year. If not six, eight satellites in a generation is better than four.

- Planning a seven-year design life. This conclusion is based on a combination of factors including mass, production rate, and time between NRE events. Satellites that last eight years are preferred to those that last six but near seven appears to be optimal based on multiple constraints.

  ♦ The convergence on this design point is likely due to the relative fuel mass being added and the consequences of placing these satellites with their kick-motors on a single launch vehicle. In the GPS example, the difference of one year of design life was not as significant, but in LEO increase in fuel mass is (nearly) five percent of the vehicle mass with an additional 40% mass for the kick-motor.

These points paint a clear picture of the minimum that emerges for the JPSS BATNA when all potential factors discussed in this work are included. The preferred rate of production and the time between NRE pulses (generations for the BATNA and disaggregated approaches) is presented in Figure 9-14 and associated efficiencies seen in Figure 9-13. For each of the disaggregated approaches, between eight and 10 satellites of equivalent capability are built in the first generation, followed by six satellites per generation. The requirement for the increased duration of the first generation when switching from an aggregated to a disaggregated architecture is logical as the simulation seeks to obtain the maximal benefit from experience, shortening Process Cycle Times and associated higher efficiency before switching to the next generation. The JPSS BATNA has no extra benefit possible and as such requests the earlier NRE pulse as to avoid legacy costs in the next generation.

The above analysis of Weather satellites suggests that if operations costs are included, substantial savings cannot be obtained through any of the disaggregation policies investigated in this work. Not only does the selected JPSS BATNA fail to deliver the four-satellite capability to orbit, but it appears to possess a bow wave with respect to cost overruns—the model's interpretation of a substantial chance that this program will experience a breach in out years. Program acquisitions that avoid these problems would be greatly desired. Thus, from this perspective, programs which are able to deliver at least the four satellites of equivalent capability at all times outperform the JPSS BATNA, and those which deliver that capability and are able to save money are even more valuable.

9.2.2   Cost per Operational Year Delivered to Orbit

When comparing the JPSS BATNA against disaggregated implementations, it is important to use the lowest-cost fully aggregated future (as computed by the model to serve as the BATNA) in order to achieve the most accurate apple-to-apples comparison. This has the added benefit of ensuring that any model errors are applied to both the disaggregated approach and the JPSS BATNA. The blue dot from Figure 9-9 (run 529) is therefore selected as the JPSS BATNA to which all other runs are compared. The next four figures, Figure 9-15, Figure 9-16, Figure 9-17 and Figure 9-18 show the relative percent of money required to place capability equivalent to the JPSS BATNA on orbit. This comparison might also be considered from the perspective of the cents on the dollar required to place equivalent capability on orbit. As discussed in the GPS example, while disaggregation may not save money in the FYDEP, it may place more physical assets or capability on orbit for close to the same cost.

In the first generation, shown in Figure 9-15 nearly every implementation is worse than the JPSS BATNA. (Though consistent with Dwyer's work, there does appear to be a flavor of a Weather/Climate Split (yellow) that is very close to the BATNA.) Thus disaggregation appears likely to offer no savings in Generation 1.
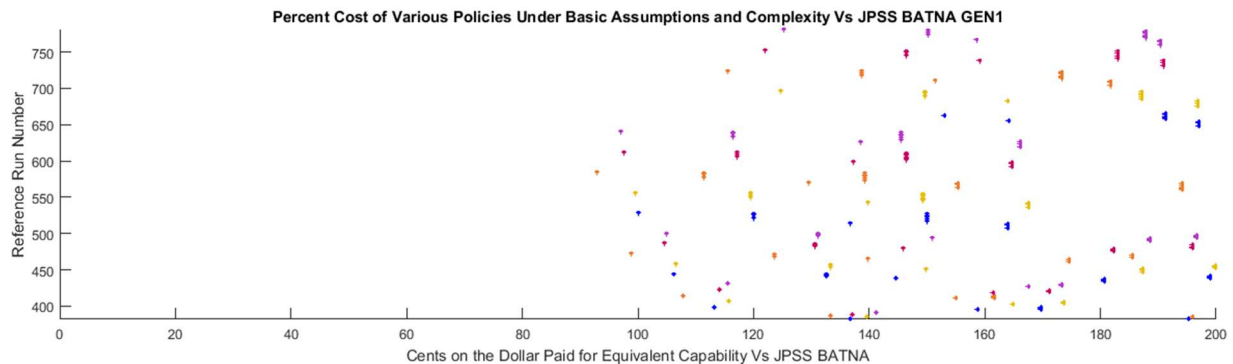
Figure 9-15: Weather and Climate Sensing Model, Percent Cost of Various Policies Under Basic Assumptions and Complexity vs. JPSS BATNA Generation 1

Figure 9-16 shows that in the second generation, after the experience gained in Generation 1 by creating more, smaller vehicles at a faster pace has propagated through the system, some disaggregation options start outpacing the JPSS BATNA. Those at the top of the graph are the same options for which a technology refresh interval was shown in Figure 9-13: Weather and Climate Sensing Model, Efficiency Metric for Lowest Cost per Operational Year Implementation. Policies which do not perform as well often receive an NRE pulse at an earlier (or even later) time.
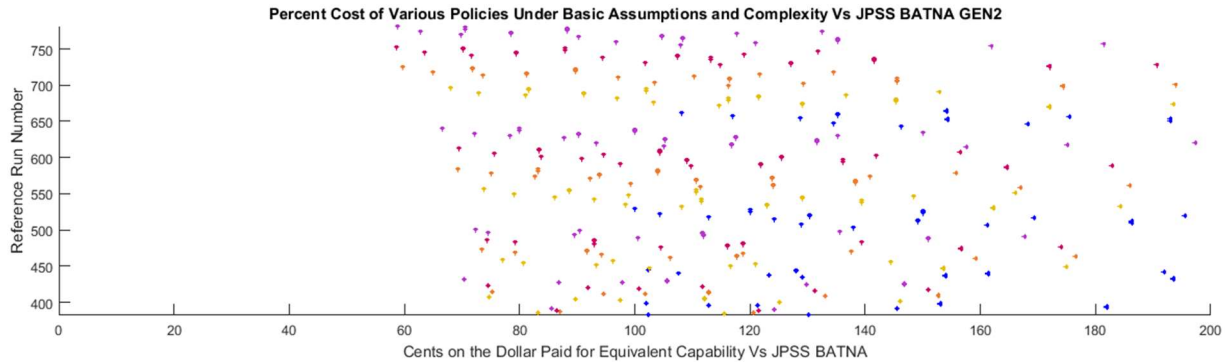
Figure 9-16: Weather and Climate Sensing Model, Percent Cost of Various Policies Under Basic Assumptions and Complexity vs. JPSS BATNA Generation 2

Since the third and fourth generations are identical, Figure 9-17 and Figure 9-18 differ only with respect to the amount by which the model has reached equilibrium. For the most part, the two plots look very similar; by the end of the third generation the model has stabilized without end-game effects.

In the third and fourth generations, a clustering of points which appear to deliver capability to orbit at roughly 60 cents on the dollar emerges. Interestingly, the points representing 3x Disaggregation, 2 Large and 2 Small and Full Disaggregation are nearly the same. It appears that the various combinations of additional cost of the extra satellites, overhead mass and on-orbit operations are for each roughly equivalent to the cost reductions achieved through extra experience and higher efficiency levels. In short, this is a coincidence. The models generating the on-orbit costs are completely separate and unaffected by any endogenous model factor other than the number of satellites.
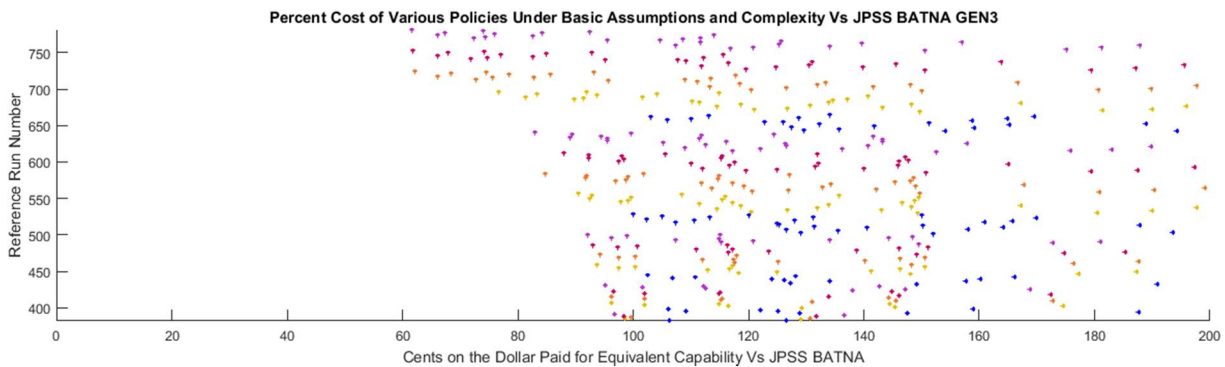
Figure 9-17: Weather and Climate Sensing Model, Percent Cost of Various Policies Under Basic Assumptions and Complexity vs. JPSS BATNA Generation 3

305
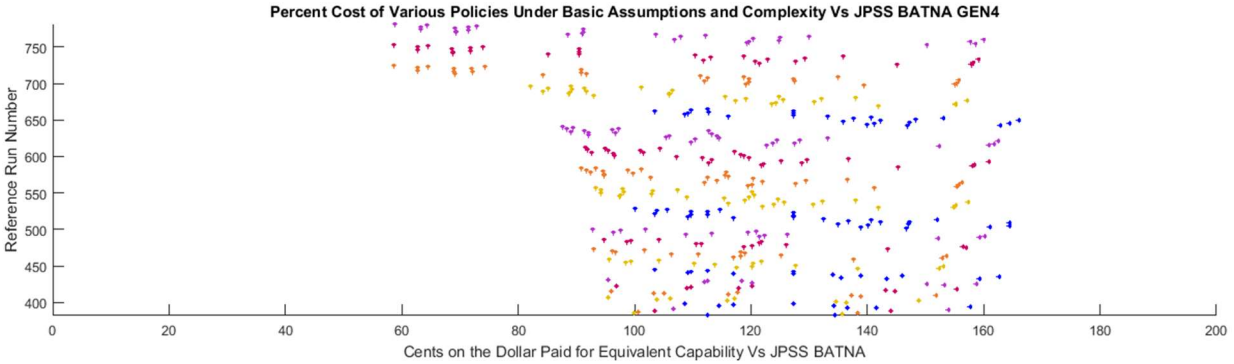
Figure 9-18: Weather and Climate Sensing Model, Percent Cost of Various Policies Under Basic Assumptions and Complexity vs. JPSS BATNA Generation 4

9.3 Results of Weather and Climate Disaggregation

The previous section reveals a set of disaggregation options which, while unable to save money for the FYDEP, are able to reach higher efficiency and deliver additional capability to orbit relative to the JPSS BATNA. These options will be examined in this section. The highest-performing and lowest-cost implementations occur when between six and eight satellites are built inside a generation. Twelve equivalent satellites in a generation is too many, as this creates a gap of approximately 13.5 years between generations. Because six to eight satellites are produced in a timespan of nine years, this also minimizes entropy: this is approximately two technology half-lives. All else being equal, the model would prefer to build six satellites and count on extra on-orbit life to close the performance gap.

It has been observed that the model is substantially more responsive to the translation of experience to experience with process for Weather satellites than it was for GPS satellites. The time when experience becomes available and the addition of one or two satellites within a generation matters more for Weather and Climate Sensing as there are so few satellites to begin with given the fully aggregated approach. The time from completion of a Weather/Climate satellite to the beginning of an identical clone has greater impact in a lower production situation as well, as it is possible that due to the need date, decisions may be locked in which it is not possible to benefit from lessons of the previous construction.

Figure 9-19 re-presents Figure 9-13. As it displays all the efficiency curves, it is useful to reexamine it in order to have a fresh image of how each of the policies of disaggregation changes program efficiency over time, before looking at the raw cost numbers.
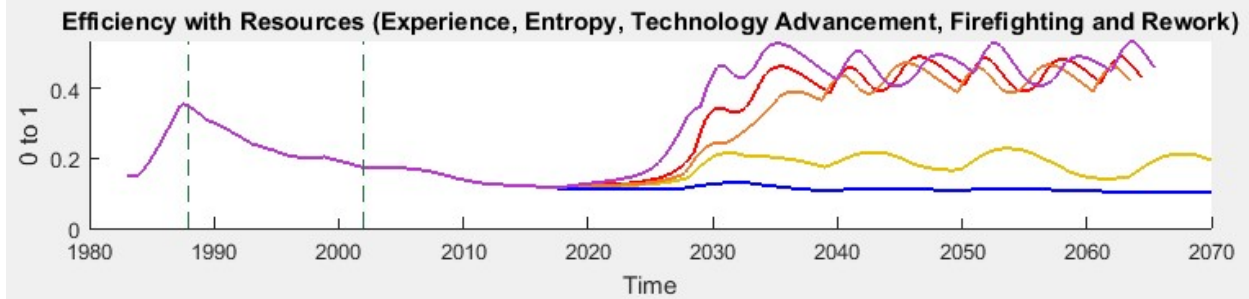
Figure 9-19: Weather/Climate Split, Efficiency of Lowest Cost to Deliver Equivalent Capability Across all Generations

The first disaggregation strategy to be examined is the Weather/Climate Split, represented in yellow in the figure above and cost data in Table 9-3. The raw output of the SD model estimates the cost of this implementation to be nearly identical to the JPSS BATNA in production. (See Figure 9-20.) Examination of row 3 on Table 9-3 reveals that initially a savings of about 10% may be possible. As time progresses, however, and more capability is added, there is an increase in cost of about 13%. The reason for this increase lies in the fact that two satellites instead of one start to aggregate sensors, and the small gain this achieves in efficiency does not compensate for the rising costs of adding new capability and the operation of twice as many satellites on orbit. This implementation would be 25% more expensive in putting equivalent capability on orbit in the first generation, as seen in row 5 of Table 9-3: Weather and Climate Sensing Model, Cost Metrics, Weather/Climate Split + CMIS Free Flyer. Some learning will occur, however, and by 2045 cost savings in capability delivered to orbit may be possible.

Rows 6 and 7 on Table 9-3 and all subsequent tables represent costs at specific points in time. Thus, those two metrics are subject to end-game effects (and the time at which NRE pulses occur) and measuring at specific points in time may well fail to track potential future gains if the Efficiency metric is changing rapidly. If, however, one seeks to answer a question within a time horizon, then they are of value to examine. Since the results for Generations 3 and 4 in this work are typically stabilized, these metrics give an accurate prediction of the costs for those generations. The values in rows 6 and 7 suggest that the Climate/Weather Split is an unattractive implementation which will likely yield little initial cost savings and potentially cost more in future generations.

Table 9-3: Weather and Climate Sensing Model, Cost Metrics, Weather/Climate Split + CMIS Free Flyer

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 7 vs 7	1	Gen 2, 7 vs 7	1	Gen 3, 7 vs 7	1	Gen 4, 7 vs 7
2	Number Satellites Produced	2	16 vs 6	2	12 vs 6	2	18 vs 6	2	18 vs 6
3	Avg Cost Per Production Year Gen vs. Gen	3	89.26%	3	102.23%	3	113.77%	3	113.22%
4	Avg Cost Per Production Year Gen vs. Gen Ex Ops	4	82.40%	4	92.23%	4	107.92%	4	103.59%
5	Cost to Acquire a Year of Operational Capability	5	124.74%	5	67.95%	5	76.61%	5	82.09%
6	Cost at End of Production, Relative to BATNA	6	94.78% in 2032	6	102.33% in 2045	6	118.23% in 2058	6	111.33% in 2073
7	Compensate for Quantity Placed on Orbit	7	132.46% in 2032	7	68.01% in 2045	7	79.61% in 2058	7	80.71% in 2073

One other feature to note appears in the pipeline production cost per year shown in Figure 9-20. The figure shows a cost reduction in 2030 and that is given back over future years as more capability is brought online. The reason for this occurrence in the JPSS BATNA is easily understood. The model produces six JPSS satellites which last beyond their design life, so

decision-makers extend on-orbit life. Due to the stretching of on-orbit life, funding can be reduced, and this results in less production and a decrease in experience, leading over time to a decrease in efficiency. Thus, when Generation 3 starts, a less efficient system is not ready to begin proficiently building that generation's satellites and the cost rises back up: the exact situation which led to the NPOESS overrun.

As noted in the work on GPS, the most successful policies are those that are able to keep the production cost per year down without re-increasing as capability is added in future generations. This is the core of the hypothesis behind the learning model: if learning can create a virtuous cycle, either capability can increase as cost is held constant, or cost can decrease as capability is held constant. The occurrence of learning effects was seen as the outliers delivering capability to orbit for 60 cents on the dollar in Figure 9-18. In Figure 9-20 the Weather/Climate Split disaggregation is clearly unable to achieve learning effects and the addition of the free flyer (CMIS payload or other payload(s) with equivalent mass and power requirements) in Generation 3 causes this policy, like the JPSS BATNA, to return to a high pipeline production cost per year.
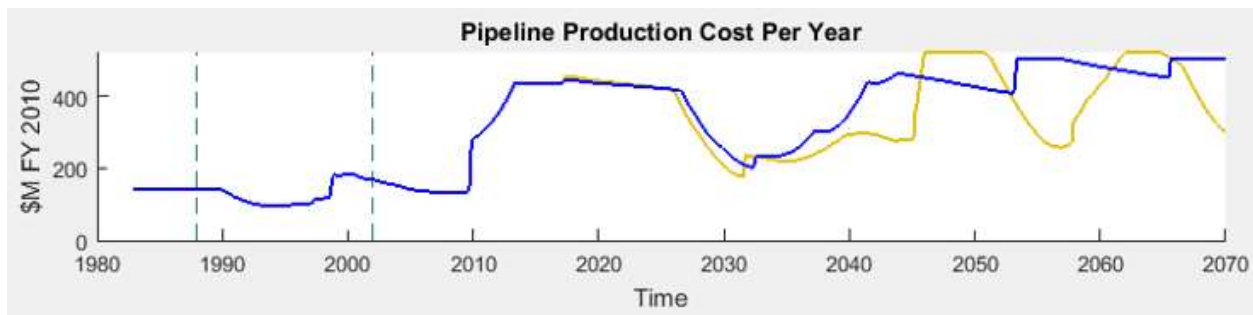
Figure 9-20: Weather and Climate Sensing Model, Pipeline Production Cost per Year, JPSS BATNA vs. Weather/Climate Split

9.3.1   3x Disaggregation for Weather and Climate Sensors

Turning to consideration of 3x Disaggregation, in row 3 of Table 9-4 we see that the cost per production year of this policy generation over generation, is within plus or minus eight to nine percent of the JPSS BATNA across the period of examination. Row 4 indicates that between 10% and 15% of the cost in the system is attributed to the increased on-orbit operations and data processing associated with tripling the number of satellites. Examining row 5, we see that one advantage of this approach is a lower cost to acquire capability on orbit, such that this disaggregation flavor is able to nearly double the years of operational capability placed on orbit. Each program attempts to put on orbit 42 years of operational capability: six satellites of equivalent capability, each lasting seven years. The JPSS BATNA does not quite achieve this goal, but 3x Disaggregation meets it easily and is able to compensate for increased on-orbit costs with higher efficiency.

Table 9-4: Weather and Climate Sensing Model, Cost Metrics, JPSS BATNA vs. 3x Disaggregation + CMIS Free Flyer

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 7 vs 7	1	Gen 2, 7 vs 7	1	Gen 3, 7 vs 7	1	Gen 4, 7 vs 7
2	Number Satellites Produced	2	16 vs 8	2	18 vs 6	2	24 vs 4	2	24 vs 4
3	Avg Cost Per Production Year Gen vs. Gen	3	106.14%	3	108.52%	3	91.71%	3	100.36%
4	Avg Cost Per Production Year Gen vs. Gen Ex Ops	4	101.31%	4	92.97%	4	79.56%	4	85.64%
5	Cost to Acquire a Year of Operational Capability	5	60.41%	5	38.79%	5	54.96%	5	53.40%
6	Cost at End of Production, Relative to BATNA	6	106.14% in 2030	6	107.03% in 2042	6	125.38% in 2053	6	93.81% in 2064
7	Compensate for Quantity Placed on Orbit	7	60.41% in 2030	7	38.26% in 2042	7	75.15% in 2053	7	49.92% in 2064

On Figure 9-21 we see the representation of the pipeline production cost per year of 3x Disaggregation (orange) across time. Unlike the JPSS BATNA and the Weather/Climate Split, when more capability is added in future generations, pipeline production costs do not rise in response. This is a "successful" policy according to the model, as efficiency has risen to such a level that extra throughput in the pipeline is now possible. All policies with greater levels of disaggregation that are successful have production cost curves similar to this. (The full results can be seen in Appendix T: Three common satellites each hosting 300 kg of Payload + CMIS Free Flyer in 3rd Generation)
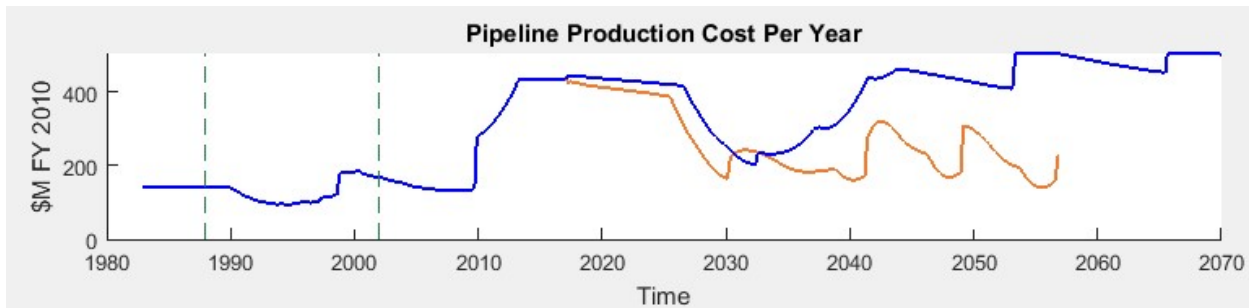
Figure 9-21: Weather and Climate Sensing Model, Pipeline Production Cost per Year, JPSS BATNA vs. 3x Disaggregation + CMIS Free Flyer

Figure 9-22 displays the production times for satellites assuming a 3x Disaggregation option. An added benefit of this policy—a narrowing of time between the NRE pulse (black line) and the first production unit—can be seen. Such an implementation enables acceleration of technology development across generations. This trend continues in the architectures with higher levels of disaggregation. They do not substantially improve in closing the time gap between the NRE pulse and the first production unit.

309
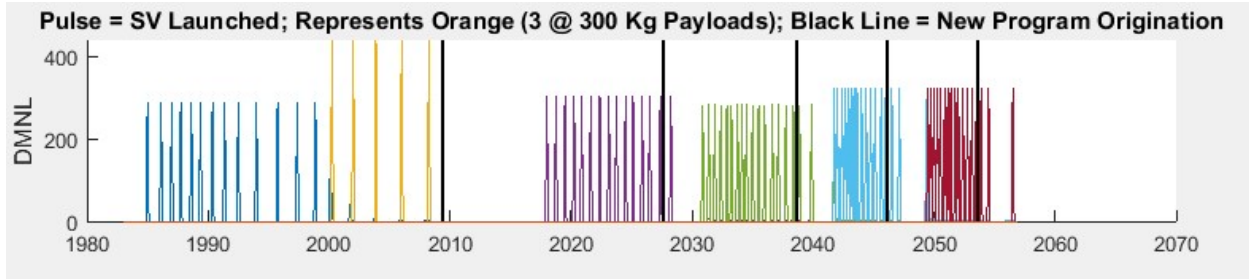
Figure 9-22: Weather and Climate Sensing Model, Satellite Launches, JPSS BATNA vs. 3x Disaggregation + CMIS Free Flyer

9.3.2   2x Large and 2x Small Satellites for Weather and Climate Sensors

The cost metrics associated with the lowest-cost disaggregated implementation, 2 Large and 2 Small satellites plus CMIS free flyer, are included in Table 9-5. Row 3 indicates that cost savings over the JPSS BATNA are not possible. For this option, however, capability delivered to orbit becomes substantially more efficient after the first generation (seen in row 5). The model forecasts this disaggregation strategy to have no trouble maintaining full constellation strength across all four generations. Also of note is that 15 to 20% savings over the JPSS BATNA would be possible if the increase in on-orbit operational costs could be mitigated (see row 4).

Table 9-5: Weather and Climate Sensing Model, Cost Metrics, JPSS BATNA vs. 2 Large and 2 Small Satellites + CMIS Free Flyer

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 7 vs 7	1	Gen 2, 7 vs 7	1	Gen 3, 7 vs 7	1	Gen 4, 7 vs 7
2	Number Satellites Produced	2	24 vs 6	2	24 vs 6	2	30 vs 6	2	30 vs 6
3	Avg Cost Per Production Year Gen vs. Gen	3	91.21%	3	106.70%	3	104.22%	3	107.93%
4	Avg Cost Per Production Year Gen vs. Gen Ex Ops	4	81.28%	4	86.18%	4	88.96%	4	90.31%
5	Cost to Acquire a Year of Operational Capability	5	121.97%	5	58.56%	5	61.84%	5	58.69%
6	Cost at End of Production, Relative to BATNA	6	96.17% in 2031	6	106.79% in 2042	6	114.72% in 2054	6	104.99% in 2064
7	Compensate for Quantity Placed on Orbit	7	128.61% in 2031	7	58.61% in 2042	7	68.06% in 2054	7	57.09% in 2064

9.3.3   Full Disaggregation for Weather and Climate Sensors

Table 9-6 displays the cost metrics for the Fully Disaggregated approach. The values are very similar to the 2 Large and 2 Small satellites disaggregation policy. The reason the results are similar despite the production of approximately 33% more satellites is twofold. First, the on-orbit costs increase even more with more satellites. (Compare row 4 between the two approaches.) Second, for this highly disaggregated architecture to produce the seven satellites which together deliver the same capability as one JPSS satellite, it must fly four different satellite designs: one a common bus (used four times) and the other three unique. The complexity of this arrangement adds to the NRE cost in each generation but more experience is gained as more production is required. Thus, the four satellites of a common bus reduce costs but the other factors increase cost, resulting in a cost structure similar to 2 Large and 2 Small.

310

Table 9-6: Weather and Climate Sensing Model, Cost Metrics, JPSS BATNA vs. Full Disaggregation (7 satellites)

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 7 vs 7	1	Gen 2, 7 vs 7	1	Gen 3, 7 vs 7	1	Gen 4, 7 vs 7
2	Number Satellites Produced	2	40 vs 6	2	36 vs 6	2	42 vs 6	2	42 vs 6
3	Avg Cost Per Production Year Gen vs. Gen	3	91.16%	3	101.62%	3	103.82%	3	106.96%
4	Avg Cost Per Production Year Gen vs. Gen Ex Ops	4	77.37%	4	73.82%	4	83.84%	4	84.47%
5	Cost to Acquire a Year of Operational Capability	5	125.21%	5	58.87%	5	61.60%	5	58.83%
6	Cost at End of Production, Relative to BATNA	6	96.53% in 2032	6	101.76% in 2043	6	112.27% in 2055	6	104.06% in 2066
7	Compensate for Quantity Placed on Orbit	7	132.59% in 2032	7	58.95% in 2043	7	66.61% in 2055	7	57.23% in 2066

Due to the low production quantities, implementation of a Tick-Tock or other similar policy would not appear to benefit this class of satellite. Tick-Tock would require dividing a time frame of seven to nine years into one of three-and-a-half to four-and-a-half years, which does benefit the time between NRE events; however, the additional NRE cost and the loss of half the in-generation learning will increase costs more than any savings possible. Only if technology were pushed as fast as possible with less regard for cost would Tick-Tock be valuable for Weather and Climate Sensing satellites.

9.3.4   Technology Acceleration Across Generations

While the above analysis indicates that most of the savings achieved by the tested approaches to disaggregation may be consumed by the increased cost of on-orbit operations, there is another possible benefit to disaggregation in addition to the placement of more assets on orbit at the same funding level. This benefit is a faster upgrade path. The cost-optimal implementations that we have been considering possess several data points close behind them in efficiency. These architectures replace the building of eight to 10 satellites followed by blocks of six (seen as 8, 6, 6, 6) with a slightly faster upgrade plan. Recall that for Full Disaggregation and the 2 Large and 2 Small options, more capability can be achieved at the same funding level as enough assets are being built to create an efficient pipeline. The 2 Large and 2 Small satellite options would result in the physical production of 32, 24, 20, 20 satellites across the four generations. The Full Disaggregation approach enables an upgrade path of 8, 6, 4, 4 satellites of equivalent capability across the four generations. This results in the 40, 36, 42, 42 physical satellites in row 2 of Table 9-7 while avoiding a rise in cost, as seen in Figure 9-23.

Table 9-7: Weather and Climate Sensing Model, Cost Metrics, JPSS BATNA vs. Full Disaggregation, Under Technology Acceleration

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 7 vs 7	1	Gen 2, 7 vs 7	1	Gen 3, 7 vs 7	1	Gen 4, 7 vs 7
2	Number Satellites Produced	2	40 vs 8	2	36 vs 6	2	42 vs 6	2	42 vs 4
3	Avg Cost Per Production Year Gen vs. Gen	3	98.67%	3	101.85%	3	97.18%	3	79.91%
4	Avg Cost Per Production Year Gen vs. Gen Ex Ops	4	88.11%	4	73.99%	4	78.14%	4	67.64%
5	Cost to Acquire a Year of Operational Capability	5	68.92%	5	44.18%	5	46.13%	5	51.52%
6	Cost at End of Production, Relative to BATNA	6	99.30% in 2031	6	101.98% in 2043	6	109.71% in 2054	6	96.01% in 2065
7	Compensate for Quantity Placed on Orbit	7	69.35% in 2031	7	44.24% in 2043	7	52.08% in 2054	7	61.90% in 2065

Figure 9-23: Weather and Climate Sensing Model, Pipeline Production Cost per Year, JPSS BATNA vs. Full Disaggregation, Under Technology Acceleration

Overlaying the typical time period for production of six satellites inside a single generation from the JPSS BATNA (blue), this faster upgrade path (purple on), does not increase pipeline production cost(the results of which were seen above in Table 9-7) across time, even while adding capability and speeding the technology advancement rate.
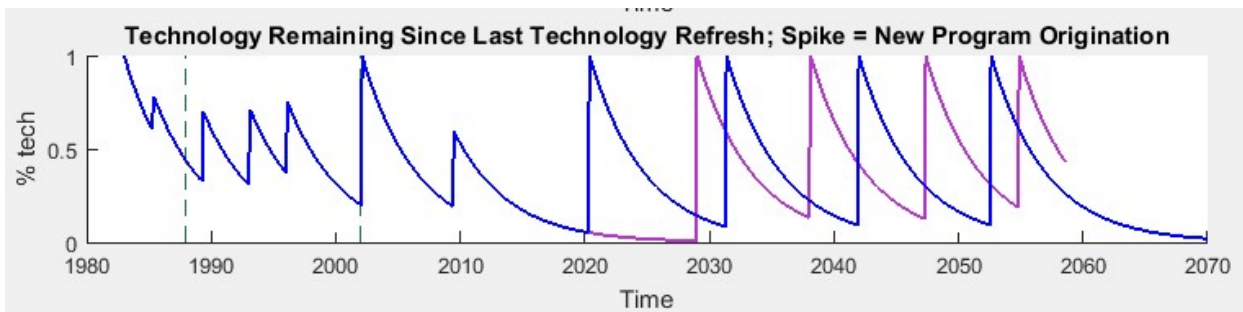
Figure 9-24: Weather and Climate Sensing Model, Technology Refresh Interval, JPSS BATNA vs. Full Disaggregation, Under Technology Acceleration

The Technology Refresh NRE pulses in Figure 9-24 are overlaid as black lines on Figure 9-25 to enable comparison of when an NRE pulse occurs and when the first satellite inside a generation is produced. Figure 9-25 displays the production of the Full Disaggregation design path where the blue and yellow spikes represent the DMSP Blocks 5D-2 and 5D-3. The purple spikes represent the 42 satellites of the first generation of Fully Disaggregated JPSS satellites, the green the second generation of 36, the teal the third of 40 and the red the fourth, 40 as well. The height of the spike, while dimensionless as a variable, gives an indication as to the relative size of the satellite being created across generations. In each generation fewer satellites are built than in the previous, yet the efficiency of the system does not degrade. This is made possible by starting at a higher level of efficiency and keeping the time between generations short enough that even though less experience is generated inside a generation, learning can transfer efficiently across generations.
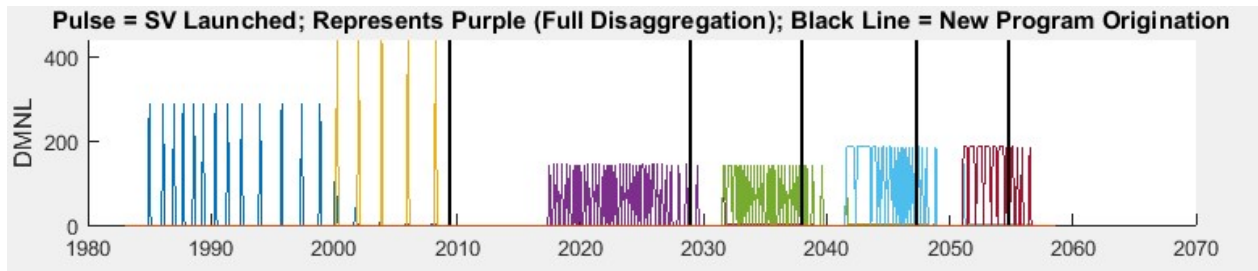
Figure 9-25: Weather and Climate Sensing Model, Satellite Launches, JPSS BATNA vs. Full Disaggregation, Under Technology Acceleration

Considering the cost per operational year and cost to deliver capability to orbit, the JPSS BATNA is less attractive than the Full Disaggregation approach. If a policy maker wanted to push technology faster, or believed that in the future only approximately four satellites' worth of capability would be made in a single generation (this being the historical number of DMSP satellites kept on orbit), these are the production levels one would have to reach in order for learning effects to take hold. The full results of all these comparisons can be viewed in Appendix T: Flavors of Disaggregation for Weather.

10 Conclusions

This thesis addresses both methodological and policy research questions through development of a model of the impact of technological, economic and social constraints on the development of satellite systems. It poses the methodological question of whether merging Tradespace Exploration techniques with those of System Dynamics can produce a viable combined model that moves beyond common industry practice of investigating cost and performance for varied design points at single points in time to provide those estimates across time. This was first examined using the GPS constellation as an example and later extended to Weather and Climate Sensing satellites. It was hypothesized that, system dynamics, being a time native modeling approach would be able to contribute to common industry practices of using Tradespace Exploration to investigate the cost and performance with varied design points across time.

Policy questions include the following:

- Will the current acquisition approach improve, degrade, or leave unchanged the health of the GPS production pipeline over the next thirty years?
  - ♦ What are the implications of current strategy for the health of Weather and Climate sensing?
- Does a reasonable design point or set of points exist that leads to improvement in the cost or performance of the GPS production pipeline over the current design point?
  - ♦ To the Weather and Climate sensing mission?
- How do different design points change the posture of unmanned U.S. space assets with respect to survivability, replenishment, and capability maturation?
- Under what conditions does more activity, generated by disaggregation or through other means, lead to capitalization on learning effects that yield benefits greater than the potential losses in economies of scale when shifting from the current design point?
  - ♦ How do different assumptions measured through exogenous context variables affect these results?

To create the merged model, the required individual components are assembled in Chapters 2 through 4. In Chapter 2, standard TSE practices are introduced using models and data appropriate for the GPS constellation. Special care is taken to examine how the Tradespace Exploration concepts of design vectors, design spaces and context variables operate, as these variables are extended in their application when aligned with a SD model. The concept of an "upgrade path"—which operates as a variable inside the design vector—is also introduced to enable the tracking of performance change across generations while interfacing with design and context vectors. Chapter 2 demonstrates that the TSE model makes reasonably accurate predictions about the characteristics of both GPS IIIA and GPS 2020 satellites, including Dry Mass, Wet Mass, Non-Recurring Engineering (NRE) Cost, Production Cost (Replication Cost), Power Size, Total Power, and Design Life.

In Chapter 3, a System Dynamics model is built to abstract the concept of the GPS production pipeline. The model is constructed using standard SD practices and the use of molecules of structure, building upon existing model concepts and code. Special attention is given to the molecule of structure which models the soft system of experience and learning. This implements Morrison's concept of work/rework as an extension of learning theory (Morrison, 2008). One goal of the SD model in this thesis is to better understand the impact of learning both inside a generation

314

and across generations of satellites. The model balances the counteracting forces of experience and the rate at which lessons flow back against entropy injected into the system (technology change, decay of human knowledge, etc.) and the time frame over which the sources of entropy act. This balancing produces a single variable labeled "Efficiency," which is designed to capture the state of learning effects inside the system. The reproduction cost of satellites is calculated based on the efficiency of the system in turning resources (in FY 2010 dollars) into satellites (where mass is used as a proxy variable). Efficiency is also used to assist in the computation of NRE costs across generations in conjunction with standard TSE cost-estimation practices for communications satellites. Since efficiency tracks the production cost of satellites over time, it improves on existing cost-estimation techniques for the reproduction cost of satellites. The Efficiency metric thus serves as a proxy for the "health" of the production pipeline.

A benefit of a pipeline model is the ability to measure the time from when a satellite is requested to when it is delivered on orbit. In this thesis, three steps (stocks) are involved in abstracting the production pipeline: development of the first unit, production of clones and launch/on-orbit life. Given this sequence, the effect of various policies on the maturation time of technology can be examined. One can observe possible change in the time from the first request for a new satellite to the time the first satellite is placed on orbit. The change in this time over multiple generations can also be examined to see if a policy lengthens, shortens or stabilizes technology maturation time over multiple generations.

Having implemented these two molecules of structure, two primary causal loops form the basis of the SD model now exist: the feedback loop for maintaining quantity in a pipeline and the change in the efficiency of turning resources into satellites as experience with process changes. Next, additional causal loops are implemented specific to the problem at hand. First, is the Process Cycle Time (the time required to flow lessons back from one satellite to the next). This creates a reinforcing feedback mechanism where faster production leads to faster capitalization on translating experience into efficiency in building satellites (naturally, the opposite also holds). Second, is the Nunn-McCurdy Loop that measures the projected quantity of satellites on orbit, and enables the model to increase or decrease funding endogenously. This gives the model the ability to track the cost growth or savings associated with a policy implementation while buffering the assumptions of the TSE module about production cost. Third, the Peanut Butter Spread Loop allows change in the desired design life of satellites. This loop enables the model to increase the design life of satellites as a way of injecting less work into the pipeline, decreasing work over time. This loop interfaces with the primary pipeline as a balance against Firefighting—a condition that arises when the amount of work in a pipeline exceeds the capacity. This usually results in people either completing task with less than 100% proficiency and people switching quickly from one task to another. When people quickly change from one task to another without fully completing the previous task, the efficiency of completing all tasks is further degraded, this leads to an even larger backlog and even greater firefighting behavior. Once in a position of firefighting it is often too hard to get out because even the addition of additional resources are often only sufficient to stop-gap the problem but the system can never get ahead of its problems. The speed at which problems occur is faster than the speed at which they can be solved. Finally, a loop is created connecting the time between satellite generations (implying the age of technology) and the amount of entropy entering the system (the number of technology half-lives that elapse). This loop enables the model to consider the impact of time on the amount of resources required to update technology from one satellite generation to the next. The complete SD model combines a SD pipeline model

with a learning model and the observed behavior of the DoD GPS acquisition pipeline over the last thirty years to represent GPS satellite acquisitions across time.

In Chapter 4, the validity of this constructed SD model is examined. To determine the statistical validity of the deductive model of Chapter 3 it must be inductively tuned against a variety of reference modes comprised of historical data for the GPS program from 1983 through the first six weeks of 2008. The time period of the remainder of 2008 to 2016 is used as hold-back data to determine the goodness of fit of the tuned model. Five variables (Unit Cost, Design life, Total Number of Satellites Produced, Production Rate per Year, and The Number of Space Vehicles on Orbit) are compared against the real world reference modes seen to achieve this tuning. A sixth measure, the time at which programs start and stop, is implicitly encoded in this tuning as well as the discrete nature of some variables forces large errors for tunings which do not implement the correct start and stop times for each programs acquisition. The Mean Average Percent Error (MAPE), Root Mean Squared (RMSE), and the r-square value reveal how well the model's outputs match historical values from 2008 to 2016. The results of this model tuning are similar to, and in some cases better than, the error associated with existing satellite cost models:

1. MAPE for Unit Cost: Tuning 14%, Hold-Back 10%
2. MAPE for Design Life: Tuning 21%, Hold-Back 12%
3. MAPE for Total Number of Satellites Produced: Tuning 13%, Hold-Back 15%
4. MAPE for Production Rate per Year (Out): Tuning 38%, Hold-Back, 22%
5. MAPE for Space Vehicles on Orbit: Tuning 20%, Hold-Back 15%

Having demonstrated that the SD model can construct a representation of GPS satellite acquisitions over time, the merger of the TSE model and the SD model is outlined in Chapter 5. Special consideration is given to how a control module would interface the execution of the TSE runs and the SD simulations. From the perspective of the SD model, all inputs from either a control module or TSE model are exogenous variables which can be controlled externally. From the perspective of the TSE model, the SD model is a function invocation which requires inputs such as: funding levels, number of satellites required, design life of satellites, and time of acquisition, as well as context or assumption variables and which returns cost metrics such as: production cost per year and the efficiency of the system. From the perspective of the control module, a precise execution sequence is required to ensure the design space is properly enumerated to pass the correct values in the correct sequence. The creation of this control module also creates a causal loop that extends outside the SD model. The SD model detects the need for new satellites, this trigger invokes the creation of new satellites in the TSE code. The control module then sets several exogenous variables (design life, pipeline production funding per year, time and amount of NRE for the next generation, the number of satellites to be produced, and the size of the satellites to be produced) which are changed in the SD model in the next time step. Thus, there is a causal loop that travels through the TSE and control module.

This approach is shown to differ substantially from Epoch-Era analysis, a current best practice for evaluating utility over potential future contexts. As described in this thesis utility functions are not implemented and life-cycle cost is used as the basis for comparison while holding performance constant. Future work may include utility functions as well as there is nothing inherent in this technique that precludes their utilization. As Epoch-Era analysis lays out the context variables and sequences the epochs to be examined inside an era causal effects cannot be transferred directly from one epoch to the next. In this work the causal loops in the system dynamics model add

"memory" across time such that each generation is influenced by the ones before it. Naturally, this technique brings an increased work load over Epoch Era Analysis as it requires the formulation of a system dynamics model to represent a process, whereas epoch era analysis can be conducted based on the existence of only cost and performance models (and a utility function).

In Chapters 6 and 7 the results of various questions associated with policy choices, such as levels of disaggregation, and assumptions about future conditions are tested. In these chapters the capability of the model to simulate and examine GPS acquisitions over multiple generations, as well as under a variety of assumptions or "context" variables, is performed. This work demonstrates the merged model's capability to examine technology and policy questions across a wide range of variables and concepts. The results presented in these chapters indicate that merging these two modeling approaches grants insights which the TSE and SD models individually could not address. On its own, TSE is unable to address how experience associated with disaggregation could reduce costs over time, and SD, for its part, is unable to validate the performance of candidate architectures.

These two chapters test the policy hypothesis that disaggregation, either alone or in conjunction with other policies, is able to reduce system life cycle costs across multiple generations. The current plan to procure GPS satellites as understood by the model, was labelled the GPS BATNA, and to this baseline all other policy implementations are compared. The work also examines the possibility that if cost cannot be lowered via disaggregation, perhaps more capability can be delivered for the same cost. Key results associated with policy tests from these two chapters are discussed below, but in general:

1. More NRE (higher-cost) can combat sources of entropy and reduce cost across time under certain conditions. The most cost-efficient implementations of extra NRE are those that are conjoined with programs that complete their acquisition end-to-end in under nine years or two technology half-lives.

   a. If a program cannot complete in under two technology half-lives, then the model prefers delaying NRE refresh to four or five half-lives. Given that after two technology half-lives less than 25% of the remaining technology (and associated knowledge with implementing said technology) can likely transfer from one program to the next, it is logical to space NRE events as far apart as possible, as much of the work must be first-of-a-kind. (This slows technology advancement but saves cost.)

   b. After four to five technology half-lives, the entropy associated with losses in human capital, technology obsolescence, and legacy costs are so great that programs lasting this long or longer are universally poor performers and a technology refresh must occur.

2. Size of a block buy and the design life of satellites directly influences the time between buys. The lowest cost solutions for GPS are purchases in quantities of 12 to 18 (assuming a design life of satellites around 15 years); this aligns with the half-life observation above.

   a. Shortening design life to increase production quantity is typically a bad policy as the increased requirements to achieve extra design life costs less than the additional years of operational capability obtained. Naturally, this has some limitations, as is discussed in Chapter 7.

3. Smaller satellites in disaggregated approaches increase the overhead mass, require larger launch mass on orbit and incur higher launch costs. The increased gains in experience and associated efficiency in producing satellites are typically able to offset the increases in launch cost (but not all lifecycle costs).

4. The impact of Process Cycle Time or the rate at which experience can flow back and be useful for the next production cycle (represented in the SD model as the Process Cycle Time Loop) is currently more powerful (has greater impact on efficiency of building satellites) than the impact of increased Experience from the production of more units. As process cycle time drops the impact of experience becomes more valuable.

   a. While increasing the amount of activity (satellites built) and thus, the amount of experience is helpful, allotting resources to shorten the time between the constructions of satellites is the first place to spend resources.

   b. Current lengthy intervals between construction of satellites means that that there is little to no capitalization on experience regardless of the number of satellites built (i.e., even if you built twice as many satellites that experience would not translate into learning, unless they are also built faster).

   c. Policies of disaggregation create more experience (more satellites built) and shorten the Process Cycle Time (smaller satellites can be built faster). Together this creates the potential for capitalization on learning effects.

5. With the most successful disaggregated policies, investment (increased cost over the Future Years Defense Program (FYDEP), the amount of money allocated by the president's budget) occurs after disaggregation has been implemented, is required in the second generation, and required again 18 to 25 years after the policies are first enacted. After this time period costs may be reduced on the order of 10% (admittedly, not a large savings).

   a. In no model simulation does disaggregation deliver cost savings in the first generation.

   b. With disaggregation, gains in other metrics are more immediate.

      i. There is a more survivable architecture and faster time to recover from catastrophic loss on orbit. (Satellites are more quickly produced and the pipeline is more responsive to increased orders.)

      ii. There is a lower cost to acquire capability ~80 cents on the GPS BATNA dollar even in the first generation in some configurations. Thus, with disaggregation more assets can be placed on orbit in the same time period for the same cost.

6. If decision makers are willing to invest in a highly survivable disaggregate architecture, increases in performance and survivability of the constellation as a whole may be available for an increase of 30% over the FYDEP. This is discussed in greater detail below.

To examine the extensibility of the merged modeling technique developed in this thesis, the model designed to simulate the procurement of GPS satellites over multiple generations was adapted to a different mission area, Weather and Climate measurement. In Chapter 8, The TSE model is changed to invoke mass and cost models associated with LEO Weather spacecraft and

payloads. To demonstrate the generalizability of the SD model, the only modifications were in terms of exogenous changes to the Weather and Climate Sensing satellite constellation requirements, not to the underlying causal loops, model structures, or time constants associated with execution and simulation. Thus, questions about Weather and Climate Sensing spacecraft and the impact of the learning effect associated with their production were addressed using the model developed for GPS as a generic structure.

Results show the merged model as initially tuned closely approximates the production of the DMSP 5D-2 and 5D-3 satellite blocks. When asked to predict the outcome of the NPOESS program (operating as hold-back data), however, the model fails to predict the cost overrun which in fact occurred. In SD modeling, when a model fails to match reality, it is standard practice to add another explanation. In this situation, an additional explanation was derived from the complexity metrics discussed in Dwyer's thesis (Dwyer, 2015). The complexity metrics challenge one of the underlying assumptions encoded in the SD model in Chapter 3: that all levels of aggregation and disaggregation are just as easily produced and the differences associated with cost and mass can be derived from existing satellite cost models. After implementing the complexity metrics, the model's tuning is substantially improved, closely matching the historical mass and cost values for the NPOESS satellite, as well as predicting cost overruns which would trigger a Nunn-McCurdy breach.

With the model tuned to examine the Weather and Climate mission area, Chapter 9 investigates the outcomes of the current JPSS program and the space vehicles which might follow the JPSS program. In order to do this, the model is instructed to terminate the NPOESS program without producing any satellites (on the basis that it predicted a NPOESS overrun) and begin the JPSS acquisition in 2010. This places the model in a position of being tuned through 2010 and ready to examine the JPSS satellite acquisition with the historical reality of a preceding failed acquisition. This chapter mirrors the work in Chapter 6, where the GPS program is examined across multiple generations based on varying assumptions about future desired capability. The results of the analyses in Chapter 9 and the policy implications are discussed below. The ease with which the model was adapted from one mission area to another suggests that this technique may be applicable to more than just the problem of DoD satellite acquisitions. The merged TSE/SD technique should be applicable to other domains where cost and performance models exist and decision-makers wish to examine the outcomes of multiple possible policy decisions across a time horizon.

10.1.1   Cost Comparison for Disaggregation Policies

The final results of the investigation of disaggregation policies applied to the GPS architecture are summarized in this section. While it was initially assumed that cost per operational year would provide a good comparison of cost across time, this variable was not able to capture completely the differences in cost among different acquisition policies. Cost per operational year is calculated by summing all NRE costs, production costs, launch costs and on-orbit costs and then dividing that total by the amount of time the system provides capability on orbit. Policy makers, however, have two budgets to worry about. The first is the FYDEP—the dollars spent per year in production. The cost associated with FYDEP is not reflective of the cost per operational year on orbit as it is dollars spent in a current year to buy capability in the future. The second cost metric is the cost per operational year. As a result of the acquisition policy of keeping a pipeline open, in theory these

two numbers should converge over time. In practice, however, oscillatory effects associated with NRE, program starts/stops and technology advancement make these values very different.

The problem of comparison across time is compounded when the time over which cost is attributed to a program involves multiple program/generations existing in the pipeline at multiple times. Due to the compounding of causal loops across time, implementations that start with similar cost profiles can end at different times (years). Moreover, when the quantity of satellites ordered in a single block buy changes, the procurement time changes as well (e.g., a purchase of 12 or 24 satellites may extend an acquisition from eight to 16 years). Another factor contributing to difficulty in cost comparison is the imprecise reality of on-orbit service life. Historically, satellites often last longer on orbit than their design lives. This enables policy makers either to order fewer satellites inside a block buy, or to push out the time of the next block buy. The analyses of this thesis show that this creates a feedback loop where initially reaping the cost savings benefits of extra on-orbit life leads policy makers to rely upon on-orbit extensions to meet performance requirements, which then further reduces experience, lengthens production times and drives down efficiency. In short, accepting initial cost savings drives future costs even higher.

Given the difficulty in directly comparing the cost of two acquisitions across time even when attempting to hold performance equal, both cost perspectives have been presented in this thesis so that readers can fully understanding the cost and capability delivered to orbit for each architectural design. Percentage cost in the FYDEP is the cost for a tested policy variation relative to the GPS BATNA. This metric is a direct generation-to-generation comparison, with the limitation of not considering the years over which the program is executed. (e.g., If one program runs for 10 years and another for 20, their average FYDEP cost is unaffected by this fact.) Cost to acquire capability on orbit or "pennies on the dollar" for equivalent capability indicates how much the capability being delivered to orbit costs, assuming the performance of the disaggregated approach and the GPS BATNA are equivalent. Comparing the second metric to the first, the acquisition program is still spending the money associated with the first metric but the second provides a relative measure of how much more output the program variation can produce with any changed efficiency.

10.1.2   Disaggregation

The GPS BATNA is the baseline to which all disaggregation strategies are compared. In all initial analyses of disaggregation strategies versus the GPS BATNA, the model is biased to favor the BATNA. For example, no part commonality is assumed for the multiple satellites in these initial policy comparisons with the GPS BATNA. Model bias in favor of the BATNA implies performance will be no worse than computed for any policy of disaggregation and could be substantially better. After the initial analyses, effects of altering certain assumptions that favor the GPS BATNA are summarized.

Table 10-1 presents the results for splitting the GPS satellites into two (e.g., a military satellite and a civilian satellite). The following information is helpful in interpreting the data in this and following tables.

- The first row (e.g., 2x Disaggregation versus GPS BATNA): directly compares the tested disaggregated approach with the GPS BATNA. The percentages in the upper sub-row should be interpreted as the average relative change to the FYDEP over the generations listed. The time period over which this comparison holds true is also listed to give the reader an understanding of the time over which the optimal policy operates.

- ♦ The percentages in the lower sub-row represent the cost to deliver equivalent capability on orbit. If this number is less than 100%, then there is extra capability being delivered on orbit for the change in FYDEP cost above it. Often it is seen that the FYDEP requires an increase over the GPS BATNA, but because the cost per operational year goes down, more years of operational capability on-orbit could be delivered than with the GPS BATNA. For GPS this would imply more transponders on orbit. The additional years of capability delivered to orbit is, on-average, the inverse of the percentage in the lower sub-row. For example in Generation 2, roughly 29% higher FYDEP cost delivers about 37% more years of operational capability.
  - ♦ In some cases, both numbers are below 100%—these are very desirable outcomes in terms of performance and cost.
- Excluding operations costs: The FYDEP cost compared to the BATNA but computed without consideration of on-orbit operations costs. The difference between these values and the first row above reveals how much of the difference between the tested policy and the BATNA is attributable to operations costs associated with the change in the number of satellites being flown.
- Excluding launch costs: The FYDEP cost compared to the BATNA but computed without consideration of launch costs. The difference between these values and the first row reveals how much of the difference between the policy change and the BATNA is attributable to launch costs associated with the change in the number of satellites being launched and the change in the mass being placed on orbit.
- Assuming part commonality and reasonable reduction in launch costs over time: Initially the model assumed static launch costs across all time and no part commonality among disaggregated designs. Here a part commonality of 50% is assumed and a tapering of launch costs, as described in Chapter 7, is implemented.
- Assuming assets last longer on orbit: In all other rows the model is not allowed to utilize extra on-orbit operational life as this decreases the production rate (which is technically a policy of reducing requirements). Here, however, it is assumed the disaggregated assets will experience the same extra on-orbit operational life as the GPS BATNA. This reduces the production quantity of satellites (as now emergent free capability is present) and impacts the SD model, lowering efficiency. The cost presented at the points in time for this metric do not tell the whole story and the efficiency curves must also be examined to understand fully the impact of this policy. (Curves and their discussion appear below.)
  - ♦ Note that the rows showing costs relative to the BATNA where it is assumed assets last longer on orbit do not assume part commonality and reduction in launch costs over time. This is done to make conservative estimates and show the effects of different assumption modifications.

Table 10-1: Military/Civilian (2x Disaggregation) Summary vs. GPS BATNA

Policy For Comparison	Generation 1	Generation 2	Generation 3	Generation 4
2x Disaggregation versus GPS BATNA	122.40% in 2027	128.92% in 2036	136.99% in 2046	106.85% in 2058
	100.92% in 2027	72.99% in 2036	78.59% in 2046	77.71% in 2058

Excluding operations costs	122.33% in 2027	117.05% in 2036	120.54% in 2046	100.18% in 2058
Excluding launch costs	116.56% in 2027	107.68% in 2036	100.82% in 2046	85.17% in 2058
Assuming part commonality and reasonable reduction in launch costs over time	118.19% in 2027	116.73% in 2036	114.15% in 2046	91.41% in 2058
	97.45% in 2027	66.09% in 2036	65.65% in 2046	66.48% in 2058
Assuming assets last longer on orbit (reduction in production funding)	103.02% in 2028	96.45% in 2043	87.67% in 2061	83.42% in 2079
	96.69% in 2028	85.10% in 2043	93.79% in 2061	94.80% in 2079

The first row of Table 10-1 reveals that cost savings are unlikely with 2x Disaggregation under basic assumptions. Even when excluding operations or launch costs, such an implementation would incur additional costs over the FYDEP. Even if part commonality is assumed and launch costs are reduced over time, FYDEP cost savings are not possible. But if these are reasonable assumptions, the amount of capability being placed on orbit and the cost per operational year of that capability on orbit may reach 67 cents on the dollar versus the GPS BATNA over a 20-year time horizon. Thus, for an estimated ~14-18% increase over the FYDEP, a military-civilian split of the GPS constellation is forecast to alleviate the problem of reliance on extended on-orbit design life. Furthermore, if 2x Disaggregation is predicted to grant the same extended on-orbit operational life as the GPS BATNA, 2x Disaggregation looks even more desirable. However, (as with the GPS BATNA), this leads to erosion of efficiency over time. As seen on the last row of the table, after decreasing to 85% in Generation 2, the policy gives back some of the reduction in cost to deliver capability on orbit in Generations 3 and 4. Thus, 2x Disaggregation is not a policy that enables learning to take hold and establish a virtuous cycle benefiting future generations.

In Figure 10-1: Efficiency for GPS BATNA, Military/Civilian, and Military/Civilian with Reduction in Production Funding per Year. Figure 10-1 the efficiency of the GPS BATNA is displayed in blue, the efficiency of the Military/Civilian or 2x Disaggregation in red, and the efficiency of the Military/Civilian or 2x Disaggregation with a reduction in production funding per year as a result of capitalizing on satellites lasting longer on orbit in orange (corresponding to the last line in Table 10-1). A Military/Civilian split of GPS signals (2x Disaggregation) is able to make gains in efficiency generation over generation, however, if these disaggregated satellites are expected to last longer on orbit (essentially a policy of attempting to save cost and yet maintain capability), learning effects do not take hold and efficiency drops again. Even so, this lower efficiency implementation is able to deliver capability at a savings to the FYDEP if part commonality is possible and the disaggregated satellites are able to match the aggregated systems on-orbit life.
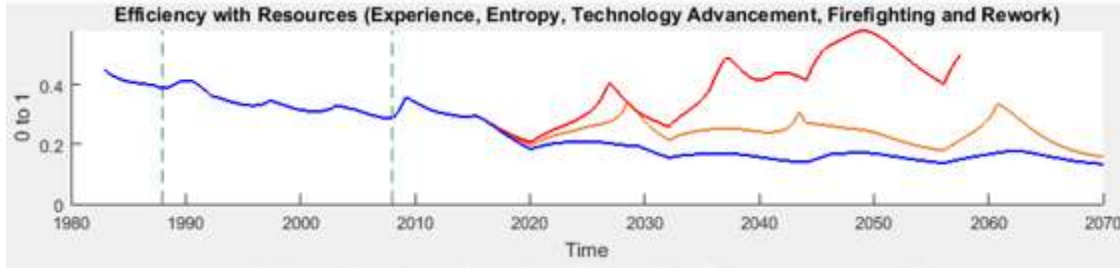
Figure 10-1: Efficiency for GPS BATNA, Military/Civilian, and Military/Civilian with Reduction in Production Funding per Year

In Table 10-2 cost data for 3x Disaggregation (also referred to as the Galileo-size implementation as each of the three satellites is about the size of a Galileo-class space craft), is displayed in the same format as for the 2x Disaggregation implementation. The table reveals that as with 2x Disaggregation no cost savings to the FYDEP are possible, and with this policy the cost may even be 50% more than the GPS BATNA. While the cost per operational year on orbit is slightly lower, this is an inefficient way of paying for more capability. Yet, given the assumptions of part commonality and launch cost reductions, a different picture emerges. By the third generation, learning trumps the additional cost of disaggregation. (While not shown here, the time between generations has also shortened, assisting in technology maturation. By the third generation, this shorter development time also helps reign in cost moving forward.) If these satellites are also assumed to last longer on orbit than their design lives, then this proposal still costs more than the 2X military/civilian split, but is cost neutral to the FYDEP.

Table 10-2: Galileo-Size (3x Disaggregation) Summary vs. GPS BATNA

Policy For Comparison	Generation 1	Generation 2	Generation 3	Generation 4
3x Disaggregation versus GPS BATNA	138.87% in 2025	149.92% in 2034	118.47% in 2046	110.93% in 2058
	101.11% in 2025	76.06% in 2034	88.16% in 2046	80.68% in 2058
Excluding operations costs	138.51% in 2025	129.68% in 2034	103.47% in 2046	103.55% in 2058
Excluding launch costs	128.34% in 2025	119.53% in 2034	92.14% in 2046	90.64% in 2058
Assuming part commonality and reasonable reduction in launch costs over time	132.66% in 2025	124.66% in 2034	94.59% in 2046	95.00% in 2058
	96.58% in 2025	63.26% in 2034	70.39% in 2046	69.09% in 2058
Assuming assets last longer on	104.60% in 2028	99.26% in 2041	100.01% in 2054	95.74% in 2068

orbit (reduction in production funding)	95.43% in 2028	72.99% in 2041	83.73% in 2054	81.23% in 2068

Figure 10-2 displays the efficiency of the GPS BATNA in blue, the efficiency of the Galileo-size or 3x Disaggregation in red, and the efficiency of the Galileo-size or 3x Disaggregation with a reduction in production funding per year as a result of capitalizing on satellites lasting longer on orbit in orange. As with 2x Disaggregation, capitalizing on emergent on-orbit capability leads to degradation of efficiency as experience is decreased over the same time and Process Cycle Times are extended. Once again learning effects do not take hold, however, the shortened Process Cycle Times and greater experience generated by this policy of disaggregation do offer a cost neutral approach to the GPS BATNA and delivery of ~20% extra years capability on orbit.
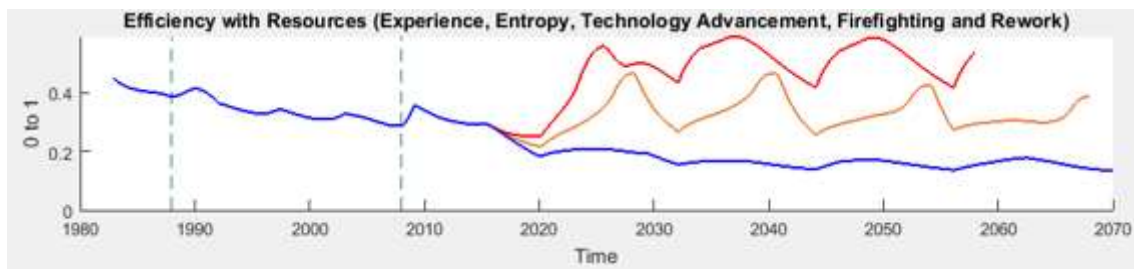
Figure 10-2: Efficiency for GPS BATNA, 3x Disaggregation, and 3x Disaggregation with Reduction in Production Funding per Year

For the policy of Full Disaggregation, each satellite bus hosts only a single payload. The cost data for this policy are displayed in Table 10-3. Unsurprisingly, this strategy creates a massive FYDEP cost spike in the first generation, which is seen across every row in the second column (as much as 178% when compared with the GPS BATNA through 2024). Over time learning does take hold and costs are more controlled, however, even under assumptions about satellites lasting longer on orbit, the additional cost of operating and launching so many more space vehicles (up to 168 satellites in the fourth generation compared to 24 with the GPS BATNA) means that even large gains in production efficiency cannot overcome the increased costs from other areas of lifecycle cost. The last row of the table indicates that this radically different architecture, which may handle an austere or contested environment, may be available for no more than 20% of the GPS BATNA if the same assumptions are made about extended life as is the case with the current aggregated GPS constellation. This is, at first, somewhat surprising as one might not have considered Full Disaggregation to be an efficient use of resources, however, these smaller satellites (many around 800 kg), can be quickly built and lessons learned flowed back to enhance future production.

Table 10-3: Full Disaggregation (5x-6x-7x Disaggregation) Summary vs. GPS BATNA

Policy For Comparison	Generation 1	Generation 2	Generation 3	Generation 4
	178.14% in 2024	146.04% in 2035	134.23% in 2047	137.80% in 2059

7x Disaggregation versus GPS BATNA	110.95% in 2024	92.35% in 2035	100.93% in 2047	100.22% in 2059
Excluding operations costs	163.81% in 2024	109.50% in 2035	101.81% in 2047	112.82% in 2059
Excluding launch costs	127.94% in 2024	93.73% in 2035	91.09% in 2047	95.36% in 2059
Assuming part commonality and reasonable reduction in launch costs over time	168.66% in 2024	126.27% in 2035	113.49% in 2047	116.02% in 2059
	105.04% in 2024	79.84% in 2035	85.34% in 2047	84.38% in 2059
Assuming assets last longer on orbit (reduction in production funding)	113.47% in 2028	120.23% in 2039	112.85% in 2051	102.67% in 2065
	102.52% in 2028	76.03% in 2039	87.48% in 2051	84.78% in 2065

To understand why Full Disaggregation performs as well as it does, Figure 10-3 displays the efficiency of the GPS BATNA in blue, the efficiency of the Full Disaggregation in red (corresponding to the first line in Table 10-2), and the efficiency of the Full Disaggregation with a reduction in production funding per year as a result of capitalizing on satellites lasting longer on orbit in orange (related to the last line in Table 10-2). Full Disaggregation (and the Survivable Disaggregated approach below) represents a program where learning effects take hold. The learning model as implemented should in theory, when efficiency levels reach a high enough level, enable one of two things. First, it should allow cost reductions while delivering the same capability to orbit, or second, permit delivery of more capability for the same cost. With Full Disaggregation efficiency does not decay as funding is reduced (the orange line remains close to the red).

Unfortunately, as seen in the upper sub-row of the rows of Table 10-3, cost savings from a FYDEP perspective are not possible for Full Disaggregation based on current assumptions and despite this model's estimation of reduction in replication costs. Furthermore, the implementation costs more than either 2x or 3x Disaggregation policies, as significantly more mass is placed on orbit and the cost of operating such a large number of satellites eliminates any savings in production cost that result from higher efficiency.
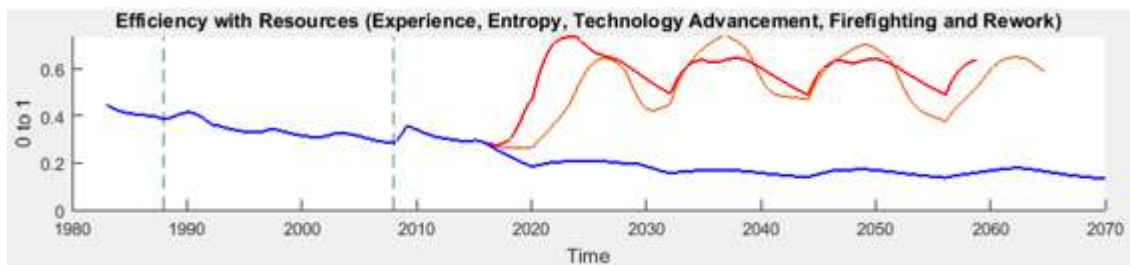
Figure 10-3: Varying Assumptions, Efficiency for GPS BATNA, Full Disaggregation, and Full Disaggregation with Reduction in Production Funding per Year

10.1.3　Survivable Disaggregation

The Survivable Disaggregated approach differs from other disaggregated approaches as it places substantially more capability on orbit. To achieve survivability, the configuration places the signal transmitters in a different configuration from the GPS BATNA and other disaggregated approaches. In the first generation, one GPS satellite is split into four satellites in the following configuration:

- SV1: L1 and M1 signals
- SV2: M1 and L2 signals
- SV3: L2 and M2 signals
- SV4: M2 and L1 signals

Future upgrades to the GPS BATNA place more signals on the signal-aggregated bus; in the Survivable Disaggregated configuration each additional signal requires the addition of a new satellite to the constellation. Thus, the addition of an L5 signal in the second generation would require a satellite with the M2 and L5 signals inserted as SV4 and the new SV5 would carry the L5 and L1 signals. In the third generation, a sixth satellite would be required if an L4 signal was desired. Survivable Disaggregation would eventually result in a constellation operating six times as many satellites as the GPS BATNA and would arrange signals in the following configuration: (This is given as an example, other arrangements may be more logical based upon the size of the payload, the desire to not operate all transmitters at once to save power and size, and/or other constraints outside the scope of this problem. Future capability such as spotbeams and crosslinks are included in this analysis as described in Chapters 6 and 7.)

- SV1: L1 and M1 signals
- SV2: M1 and L2 signals
- SV3: L2 and M2 signals
- SV4: M2 and L5 signals
- SV5: L5 and L4 signals
- SV6: L4 and L1 signals

The end result of such an arrangement is that at full strength there are twice as many transmitters for each signal compared to the GPS BATNA. The gain in survivability is primarily the ability for any satellite to be put out of commission with no degradation in performance (signal delivery to earth). In fact, the constellation can operate with no loss in performance with only 75%

of the satellites. Even beyond a loss of 25% of the satellites, capability may degrade gracefully since the loss of additional satellites will create coverage gaps only with respect to the signals on the buses lost and because many ground receivers make use of multiple signals, even this loss may not fully degrade capability to the end user. From a constellation-wide perspective, if the same orbit and plane configuration as the existing GPS constellation is implemented, it is also possible that SVs could be moved within their planes over a short (multi-day) time period to cover gaps. Other advantages for this design include:

- The possibility for extensive part commonality among designs
- The production of these common parts at a rate between four and six times faster than is currently the case
- The construction of satellites which are substantially smaller than existing designs leading to faster production times (and shorter time to flow back lessons learned)
- The ability to replenish in a targeted manner as capability degrades across time
- Shorter distance between satellites enabling much smaller power consumption for crosslinks (up to four times decreased distance implying up to 16x less power as a consequence of the square of distance law)
- The inclusion of as many L3 payloads as desired; they can be placed on one or more satellites (The L1 and M1 as well as the L1 and L2 satellites are good candidates for easy inclusion)
- The ability to perform more risk-reduction missions as extra space is available on some of the satellites with less payload mass (e.g., flying an extra next-generation atomic clock, transmitter, flight computer or key components for a new signal generator)

The primary disadvantages are:

- Operating a larger constellation
- More rocket launches
- The SD model notes that the system can be overwhelmed initially with the increase in work if insufficient resources are supplied; a careful ramp up of production will be critical

Table 10-4 displays the cost associated with fielding such a capability across time using the same conditions as for the other disaggregated approaches. A new row has also been added to the table versus the previous three, one containing the results for acquisition if a Tick-Tock policy, such as implemented by Intel (a chip manufacture that splits R&D into two phases: architecture upgrades and manufacturing upgrades), is employed. The Tick-Tock policy as applied to GPS splits the acquisition into two parts: one where the bus technology is updated (tick) and payloads from previous missions are flown, and a second (tock) where the payloads are upgraded and the bus remains unchanged. This policy requires more NRE to be spent as well as additional integration and test costs. This does, however, shorten the Process Cycle Time and has the potential to create cost savings versus the same acquisition without Tick-Tock.

Looking at the metrics for "Excluding Launch Costs," it can be seen that launch costs make up a larger fraction of the cost increase associated with Survivable Disaggregation than in the other disaggregated approaches. While the extra performance of Survivable Disaggregation (2x signals and ability to operate at full capacity missing 25% of the constellation) does not come for free, it is a much more cost-effective solution than simply launching twice as many satellites of the GPS BATNA class.

As with Full Disaggregation, when directly compared to the GPS BATNA, Survivable Disaggregation yields a large FYDEP cost spike in the first generation (86%). However, if this design is allowed to reap the benefits of extra emergent on-orbit design life, the increase in performance and survivability comes at a 40% FYDEP premium to the BATNA in the first generation but due to learning effects this decreases to 31% by 2058. Moreover, as noted earlier, the calculation assuming assets last longer on orbit does not implement assumptions about reduction in launch cost or part commonality among designs. This is a worst case computation relative to the GPS BATNA.

Table 10-4: Survivable Disaggregation (4x-5x-6x Disaggregation) Summary vs. GPS BATNA

Policy for Comparison	Generation 1	Generation 2	Generation 3	Generation 4
Survivable Disaggregation versus GPS BATNA	186.08% in 2025	196.06% in 2035	167.94% in 2047	162.55% in 2059
	135.48% in 2025	105.24% in 2035	126.28% in 2047	118.21% in 2059
Excluding operations costs	172.72% in 2025	176.75% in 2035	150.62% in 2047	154.60% in 2059
Excluding launch costs	157.64% in 2025	135.52% in 2035	120.85% in 2047	124.30% in 2059
Assuming part commonality and reasonable reduction in launch costs over time	189.81% in 2025	178.06% in 2035	148.54% in 2047	151.20% in 2059
	138.19% in 2025	98.63% in 2035	115.00% in 2047	109.06% in 2059
Assuming assets last longer on orbit	141.75% in 2029	142.27% in 2043	131.1% in 2058	111.88% in 2076
	141.75% in 2029	110.89% in 2043	126.02% in 2058	122.05% in 2076
Assuming assets last longer on orbit with Tick-Tock policy	142.82% in 2029	128.28% in 2044	Not Computed	Not Computed
	139.07% in 2029	111.31% in 2044	Not Computed	Not Computed

Looking at the efficiency of Survivable Disaggregation, Figure 10-4 displays the GPS BATNA in blue, Survivable Disaggregated architecture in red and Survivable Disaggregated architecture while attempting to reduce costs while capitalizing on extra on-orbit design life in orange. Unlike the 2x and 3x Disaggregated approaches, for Survivable Disaggregation, efficiency increases across all generations. Learning has taken hold and is enabling greater cost savings across time. This is true even when attempts are made to reduce costs by capitalizing on extra on-orbit design life. However, as the orange line is substantially below the red line, one cannot consider this a full capitalization on learning effects—efficiency is still being lost when savings cost are attempted.
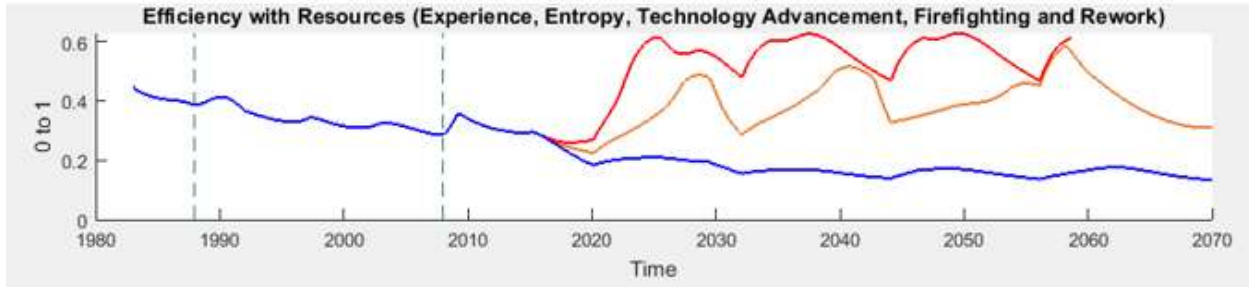
Figure 10-4: Efficiency for GPS BATNA, Survivable Disaggregation, and Survivable Disaggregation with Reduction in Production Funding per Year

Figure 10-5 adds the policy of Tick-Tock (now the orange line). The same acquisition without Tick-Tock is displayed in red (it was the orange line on Figure 10-4). With its shorter and more frequent bursts of NRE, Survivable Disaggregation is more efficient with a policy of Tick-Tock than without and reaches an equilibrium state more quickly (and due to the higher production quantity there are still ~72 satellite builds in each tick or tock, a sufficient number to reap the benefits of learning). This efficiency is high enough to enable learning to take hold and become robust to either requests to deliver more capability for the same cost or attempts to reduce cost while delivering the same capability without eroding the GPS production pipeline. Such an acquisition would be in line with the DoD's goal of recapitalizing the acquisitions work force as this would create experience for an entire generation of acquisitions professionals. This implementation still costs 28% more than the FYDEP from 2028 to 2044, however, this is a substantial performance increase, and policy makers may be willing to pay for such capability.
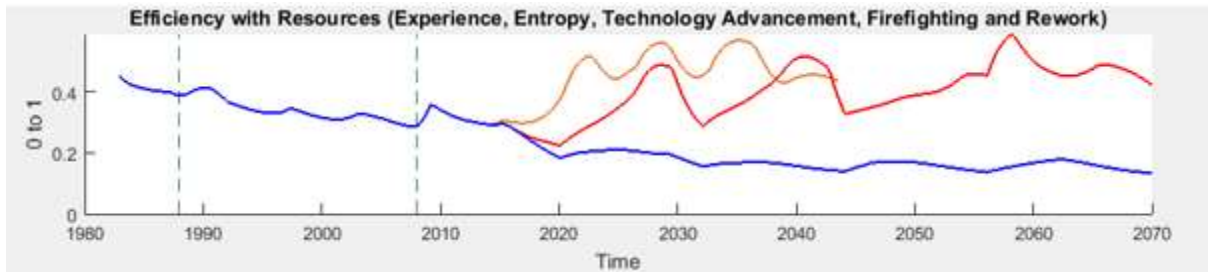
Figure 10-5: Efficiency for GPS BATNA, Survivable Disaggregation with Reduction in Production Funding per Year, and Survivable Disaggregation with Reduction in Production Funding per Year with Tick-Tock

10.2 The Problem of 2020 for GPS

This research also provides a detailed answer to policy research question of "what impact the current acquisition strategy will have on the health of the GPS production pipeline over the next few decades." Based on historical performance of GPS acquisitions and the model simulations resulting from their tuning, in the year 2020 a contract must be signed to create the next block buy of GPS satellites (a theoretical Block IV):

- This work indicates (and is corroborated by historical performance) that it will likely require on the order of 12 years to produce the next GPS acquisition. Since the first of the

next block of satellites must be available for launch in 2032 or a capability gap will emerge, the acquisition process must begin in 2020.

In 2020 the DoD will have ordered approximately eight GPS Block III satellites, and with a planned purchase of 24 satellites (16 remaining) it might seem foolish to begin procuring the follow-up program when the current program has not completed half its order (and from a perspective of learning it is!). However, the GPS III program will have just entered full rate production so it is likely that decision makers will want to wait for GPS III to begin tapering down before they turn their attention to the next acquisition. This forces one of two futures: either the GPS III satellites will have to last longer on orbit than their design life (relying on historical trend), or more than a total of 24 GPS III satellites must be procured.

The concern is that in 2020 the Block IV program needs to be originated but for a policy maker in 2020 it will appear cheaper to delay the NRE for the Block IV to ~2024, as running two major GPS acquisitions simultaneously will not be politically tenable. The decision to delay the start of the Block IV acquisition will be tantamount to expecting the Block IIIAs to last at least ~21 years (and may be required to last as long as 24 years depending on assumptions about how long the Block IIF's last on orbit) on average or purchasing eight more Block III satellites (raising the total quantity from ~24 to ~32). The results of the model simulation indicate that the next eight satellites (24-32) will not be cheaper than the previous eight (16-24). This may seem contradictory—one would theorize that later units should cost less. This is not, however, a quick buy of eight satellites; this requires building the 32nd satellite in 2032 with technology from 2008. Building 1.6 satellites a year is not the same as building a block buy of 32 at once. This technology has legacy costs, and the people building these Block III satellites will probably be the replacements of replacements: entire careers will have lapsed between 2008 and 2032. The value of experience with process will be trumped by entropy as the age of the technology makes it harder and harder to reproduce. According to the model simulations the inflection point where experience is trumped by entropy is around 2026; any GPS III produced after 2026 will cost more than the previous ones.

All of this implies that the next generation (Block IV) will likely require a large amount of NRE spending as little R&D will have been performed since 2008-2016. Over three technology half-lives will have elapsed, leaving Block IV in a position of starting all new technology. Thus, an acquisition program starting in 2024 with a first flight unit complete in 2035 will probably be a "tough" acquisition; all the technology (software and hardware) will likely need to be redesigned form the ground up. The visual representation of the time when the NRE is to be paid for a generation of GPS satellites in the BATNA versus a delay to of NRE to 2024 is shown in Figure 10-6. The longer time intervals during a time when technology is rapidly evolving is a mismatch (and equally pressing, places the time in between events at the same duration as a human career in the workforce, thus each program will be executed by a new workforce, their first experience).
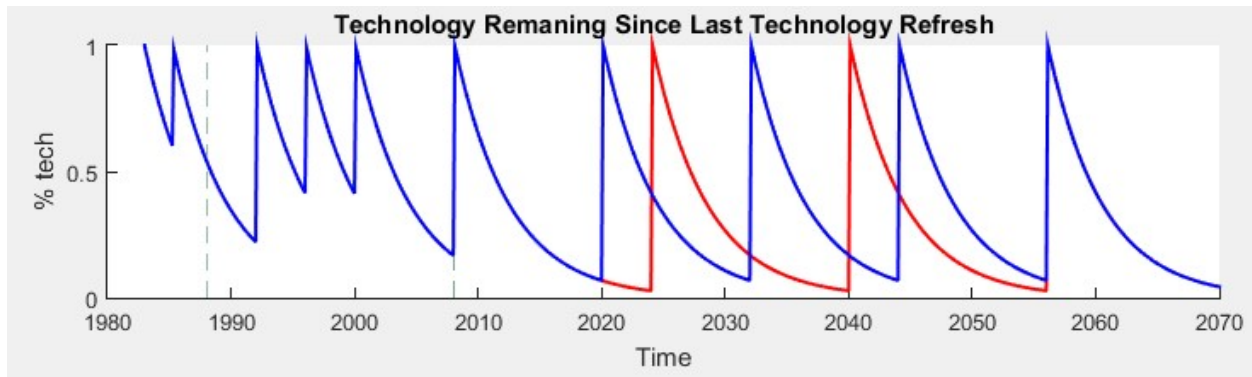
Figure 10-6: Technology Half-life Curve for GPS BATNA and GPS BATNA with Delayed Block IV Procurement.

The impact of the NRE delay on the production cost per year can be seen in Figure 10-7. With the BATNA (blue line) cost begins tapering off in ~2024 and production concludes in ~2028. As noted above, the technology obsolescence as captured by the model is actually increasing cost as of 2026, but as the quantity of satellites in the pipeline is decreasing since the Block III is reaching the end of the program, the production cost decreases until the start of the Block IV acquisition in 2028. This is not the case with the delayed BATNA and request for an additional eight satellites (red line). These additional satellites require an increase in production funding as they are difficult to produce so far in time from the initial technology base. The ripple effect is also seen in the fourth generation as efficiency falls from 2028 to 2035 and now the Block IV program, starting in 2035, costs more than the same program if started in 2028.
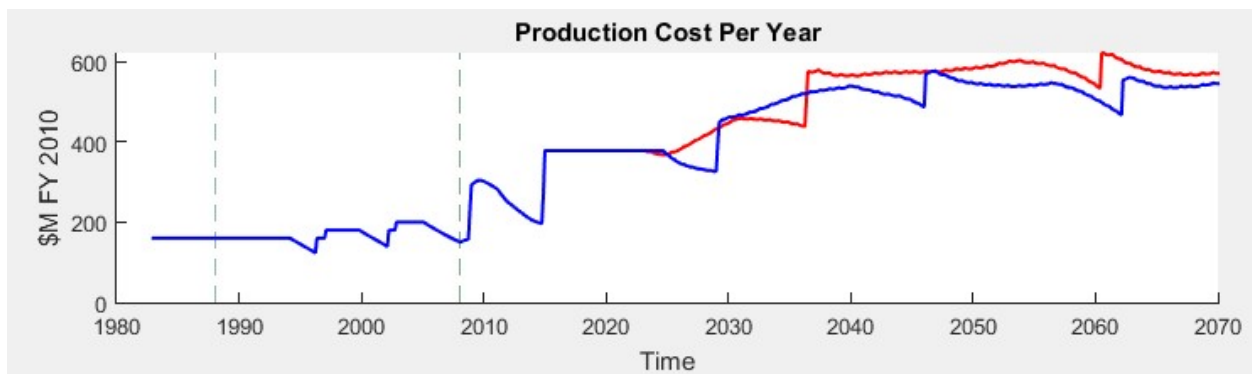
Figure 10-7: Production Cost per Year for GPS BATNA and GPS BATNA with Delayed Block IV Procurement.

Thus, the DoD faces a tough decision on how to mitigate the risks old technology and slow acquisition rates pose given the current plan. As seen above, disaggregation may be one possible solution to this current situation. With the potential for space to become a more contested environment in the coming decades it may be logical to implement a survivable disaggregated architecture to mitigate these technology advancement issues as well.

10.3 General Thoughts About the GPS Program

As GPS is the largest satellite constellation currently fielded, in some respects it drives not only the launch manifest but also the technology for the overall Space and Missile Systems Center (SMC) portfolio. If SMC were ever to be in a position where the balance between production and process improvement was misaligned, or there were little to no R&D effort for their six to seven flagship programs and all resources were being spent on production, such a position would look similar to the productivity trap experienced by a single firm directing all resources to production and none to improving process. This situation could be highly exacerbated by a forced cost reduction imposed by external forces. When the model in this thesis is insufficiently funded relative to its backlog, it responds with firefighting behavior. According to Space Acquisitions 101, the appropriate response to insufficient funding is to complete the acquisition effort by means of a peanut butter spread, distributing the cost of resources across more years. This is a different activity than the loop present in this model (which shares the same name but spreads satellite assets rather than resources over time), but the concept is the same; covering a gap by applying resources to a longer period. Unfortunately, the model shows that experience has a "sticky" property and if one program starts to experience trouble the next program inherits those difficulties since it starts from the position where the last one ended. This means that a program with difficulties (either from government or contractor failings or even simple bad luck) can tip the production pipeline and require that resources be stripped from the next program to finish the current one. This places the next program further into the future, making the loops work against the acquirer and technology further antiquated (and these forces in reality can even be spread across multiple program acquisitions through the implementation of management taxes on programs; the expression used is "robbing Peter to pay Paul").

While not specifically modeled in this thesis, one might consider the risk posture of acquisition professionals in such a situation. An organization could take few risks as all resources would already be committed and no new resources would likely be provided, if an alternate approach or even a test would fail. Most resources would be spent on maintaining current capacity and level of performance and focusing on the present, not the future. A forced cost reduction at this point, say of 10%, would do more than 10% worth of "damage" to efficiency as the system is already in a state of partial firefighting. Likely it would lead to the type of behavior seen in the model (without the ability to re-baseline or internally change the funding profile), where the time between satellite acquisitions would be forced to lengthen to maintain a minimum cost per operational year. Thus, the cancellation of 21 IIF satellites may have been SMC's attempt to get ahead of this problem by saving resources and reapplying them to existing assets to achieve a longer design life that would provide performance across the time period that should have been covered by those missing 21 satellites. From the model's perspective, this would also represent a super firefighting reduction policy because it would clear the backlog of work. Also, since Block IIIA would be purchased from a new vendor, the loss of experience with process would be minimal (this is expected in a contractor switch). There are, however, threats to the success of such a policy decision. First is the entropy threat: Block IIF to IIIA spanned 1996 to 2008—12 years of technology advancement during which the time that technology was expected to be "current" for between four and five years. This would not be helped by this policy, though if the resources meant for the missing IIF satellites were to be transferred to the IIIA, this could combat this problem. Also, the concept of using an existing GEO communications bus might help provide some experience with process. The threat here is that if those funds saved, or held back in reserve, are

not spent improving the next generation, then there is no reason to expect that the forces/causal loops that led to the current problem (with IIF) will go away. When the IIIA program is launched, it will be in a position of a first-of-a-kind activity. It will have little experience to draw upon and, as noted, the existing reinforcing causal effects already present in the system will not disappear. According to the model, the "best" decision is that as soon as the contractor believes additional funding or a management reserve is needed, deploy it. Politically this is a difficult decision to sell. After declaring the IIF acquisition to have been a poorly executed program, the political capital required to claim the IIIA is now in trouble would be difficult to muster. As noted, this is currently a system of reinforcing loops all working against the industry. Policy must be in place to combat these loops until experience or cycle time can work for the production pipeline. Entropy cannot be stopped; it is moving very fast and will continue to do so for the foreseeable future as technology continues to improve. Moving forward in 2032, the Block IVs will probably be placed in the exact same position if nothing changes.

This model shows that under a set of reasonable assumptions, most disaggregated policies offer some attractive changes to the current acquisitions model for the GPS system. There is little reason to believe that disaggregation to two or three satellites will save any money but will likely not cost more than 10% relative to the GPS BATNA. There is substantial evidence to believe that they may alleviating the reliance on orbit extensions as is the norm today; they will improve the efficiency of the acquisition system over time but it will likely take over two decades. These policies also bring risk reduction to overruns and shorten the technology cycle further reducing program risks. It appears that activity levels between four and five times those seen today would be required to "capitalize" on learning effects. However, it also appears that to get to this level of activity through disaggregation adds such large on orbit operational costs that the gains in efficiency would be consumed by the on orbit costs, launch costs do not appear to be a large factor. A policy of Tick-Tock has potential for cost savings to the GPS BATNA and the ability to help reduce costs in the survivable disaggregated implementation. As tick-tock is effectively a policy of trading NRE to shorten Process Cycle Times and align them with external technology advancement rates, both of these architectural implementations find this tradeoff to be favorable (the other flavors of disaggregation do not as the extra NRE does not improve the efficiency enough to counteract its cost, however it still would serve as risk reduction all-be-it one that is paid for not free). This work suggests that as space becomes a more contested environment a movement to a survivable disaggregated architecture may be logical, as it possesses enough activity to create learning effects and delivers desirable capability at a reasonable price-point. An independent analysis of the costs associated with the survivable disaggregated implementation across its lifecycle would serve to determine if this is a viable path forward.

10.4 Extensibility of the Model to a Second Mission Area: Weather

The model initially developed for the GPS pipeline was easily amenable to modeling the acquisition of Weather and Climate sensing satellites. The SD model was not modified in terms of tuning variables and causal loops to preserve the time constants and model response of the DoD acquisitions system. The TSE model was adapted to include the appropriate size, weight, data-rate, and power requirements of the Weather and Climate Sensing payloads. To assist in tuning the model complexity metrics associated with specific sensors, levels of aggregation, and commonality were also included in the analysis based on the work in Dwyer's thesis (Dwyer, 2015). After using the DMSP and NPOESS programs to tune the model, the work focused on

determining the benefit of various disaggregated approaches across time to the JPSS program. The following five policies were tested.

1. A Fully Aggregated future where JPSS adds capability (sensors) to a single bus in later generations.
2. A future where Weather and Climate sensors are split into two different satellites (Weather/Climate Split). In this arrangement, the goal is to create a common bus between the weather and climate systems.
   a. In the third generation a third satellite is added to enable operation of the CMIS sensor.
3. A future where JPSS is split into three satellites, referred to as 3x Disaggregation.
   a. In the first and second generation the alignment enables a common bus across all three satellites.
   b. In the third generation the addition of a CMIS or equivalent sensor (up to 400 kg in mass) forces a fourth satellite.
4. An upgrade path where four satellites are constructed, referred to as 2 Large and 2 Small.
   a. Two satellites host ~300 kg of payload mass and two satellites host ~100 kg of payload mass.
   b. In the third generation a fifth satellite is added, the same CMIS "free flyer" or single payload bus as in the Weather/Climate Split option.
5. A Full Disaggregation future, where each bus caries only one (or two) payloads.
   a. This is not technically full disaggregation (with GPS each bus had only one payload in full disaggregation)—the architectures will place two sensors on two of the buses.
   b. Based on mass of the sensors this enables a common design among four of the satellites, each carrying under ~125 kg of sensor mass. Three other satellites may share parts but must be unique buses.

Table 10-5 presents the best results for each of the above policies of disaggregation when compared against the best results of a fully aggregated JPSS solution (i.e., the JPSS BATNA). The table shows the same two cost metrics, cost to the FYDEP, and the cost to deliver equivalent capability on orbit, as with the GPS work. The general trend is that in the first generation it is unclear whether any benefit is achieved by disaggregation. By the second generation, however, even with the model biased towards the JPSS BATNA, many of the disaggregated approaches offer a cost- neutral approach to the FYDEP while delivering cost-to-orbit at a discount. This translates directly to a higher chance of successfully completing acquisitions and delivering capability to orbit.

The Weather/Climate split appears to provide some initial FYDEP cost benefit, however, as requirements increase in future generations it gives back most of its gains and becomes an unattractive policy.

3x Disaggregation improves its efficiency over time, and not only the cost to the FYDEP but also the cost per operational year decrease generation over generation. The superior performance of this policy to the BATNA and the other disaggregated options is related to one particular sensor, the CMIS. In Generations three and four the CMIS sensor was added back in as a way to model increased performance requirements in future generations. Even if this exact sensor is not desired, it serves as a good proxy for increased performance which might be desired in a future generation. This particular sensor is the element with which most disaggregated approaches struggle to cope due to the CMIS instrument's size, weight and technical requirements. The 3x Disaggregation

deals best with this sensor as it is the only implementation that can support its requirements and maintain part commonality among the satellite buses. In all other implementations the CMIS sensor is flown as a "free-flyer," placing it outside of the problem and incurring the penalty of a free flyer to meet a performance demand. While the work did not specifically investigate Space Weather satellites, it is interesting to note that the five primary Space Weather sensors which are currently hosted on the COSMIC II mission have a combined mass and power requirement which would fit (with about 30% to spare) on another clone of the 3x Disaggregated bus. Thus, this program could be expanded to host five identical buses each with a different suite of weather, space weather and climate sensors. This would likely enhance the learning associated with such an implementation, leading to a lower cost per operational year.

Table 10-5: Various Disaggregated Policies for Weather and Climate Sensing Systems, Cost to FYDEP and Cost per Operational Year Across Four Generations.

Policy for Comparison	Generation 1	Generation 2	Generation 3	Generation 4
Weather/Climate Split	89.29%	102.23%	113.77%	113.22%
	124.74%	67.95%	76.61%	82.09%
3x Disaggregation	106.14%	108.52%	91.71%	85.64%
	60.41%	38.79%	54.96%	53.40%
2 Large & 2 Small	91.21%	106.70%	104.22%	107.93%
	121.97%	58.56%	61.84%	58.69%
Full Disaggregation	91.16%	101.62%	103.82%	106.96%
	125.21%	58.87%	61.60%	58.83%
Full Disaggregation Accelerate Technology	98.67%	101.85%	97.18%	79.91%
	68.92%	44.18%	46.13%	51.52%

The more highly disaggregated buses, both the 2 Large and 2 Small and the Full Disaggregation implementation have limitations which place them below the 3x Disaggregation in terms of desirability. Aside from the issue with the CMIS sensor, the 2 Large and 2 Small cannot make as great use of part commonality. Moreover, the two small satellites complicate both the launch and on-orbit operations. The small savings associated with the increased experience does not offset these increased costs. For the Full Disaggregation architecture to produce the seven satellites which together deliver the same capability as one JPSS satellite, it must fly four different satellite designs: one a common bus (used 4 times) and the other three unique. The complexity of this arrangement adds to the NRE cost in each generation but more experience is gained as more production is required. The additional satellites do not require additional launch vehicles (but do increase the launch cost of the single vehicle) as their mass can still fit on a single launch vehicle. Nonetheless, the on-orbit operation costs are significantly higher (a little over double those estimated for the JPSS BATNA ~$205M per year). Thus, the four satellites with a common bus reduce costs but the other factors increase cost—resulting in an implementation inferior to 3x Disaggregation across multiple generations.

The final row in Table 10-5 shows however that Full Disaggregation is a highly viable policy when consideration is given to its ability to accelerate technology maturation without losing learning effects. While in each of the implementations various elements combine to create various funding requirement profiles which may be superior to the JPSS BATNA, learning effects only take hold in the Full Disaggregation approach. This benefit of these learning effects is a faster upgrade or technology maturation path. The disaggregation strategies already considered (on all other lines of the table) order 10 satellites in the first generation and six in each subsequent generation (seen as 10, 6, 6, 6). The Full Disaggregation approach enables an upgrade path of 8, 6, 4, 4 satellites of equivalent capability across the four generations. This results in the ordering of 40, 36, 42, 42 physical satellites with this approach. This difference between this upgrade path and the JPSS BATNA attempting to order in smaller quantities to shorten time between programs is seen in the final row of Table 10-5, where Full Disaggregation achieves a much lower cost to provide equivalent capability over attempting this with the JPSS fully aggregated BATNA, which struggles to deliver capability to orbit if acceleration is attempted.

Figure 10-8 displays the efficiency for the various disaggregated approaches outlined in this section. The blue line represents the JPSS BATNA, the yellow the Weather/Climate Split, orange 3x Disaggregation, red 2 Large and 2 Small, and purple Full Disaggregation. As expected, those programs which produce more satellites have higher efficiency levels. The clustering of the orange, red and purple lines shows that those programs which produce more satellites are also able to reach their higher performance levels faster as seen in the rise time for the various implementations to a "stable" level. The low and eroding yellow line speaks to the failure of the Weather/Climate Split to capitalize on learning effects. It appears attractive from a cost perspective only because it requires a relative small additional cost for launch and on-orbit operations. So while the Weather/Climate Split appears attractive in the first generation, it will not help the Weather pipeline over a longer time period and should not be considered a viable policy. The 3x Disaggregation is likely the best option over thirty or forty years as it provides the easiest path to incorporate new performance demands, build upon an existing platform and bus with high part commonality, and simultaneously reach a stable level of efficiency which reverses the erosion trend.
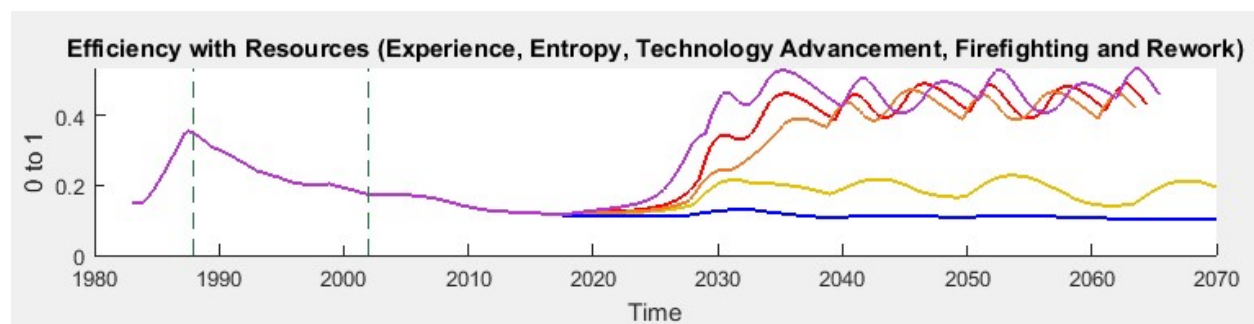
Figure 10-8: Weather and Climate, Efficiency for Various Disaggregated Implementations

10.5 Future work

Having completed this work in merged modeling, outlining an approach to implementation and determining its value for understanding DoD satellite acquisitions, several new veins of research which may complement and enhance this work may emerge.

In this work the SD model used a single stock to measure efficiency for both across-generation and in-generation learning. In satellite production as currently practiced, production quantities are low and production times are long: each satellite is somewhat unique and a true clone is very rare. This supports combining in- and across-generation learning into the same model structure. Yet the nature of learning is substantially different across generations versus within generations. When production reaches high levels, splitting this into multiple causal loops may be appropriate. While this would complicate the model, it may be worth the additional code and could simplify understanding of results with respect to first units and additional units in a generation.

The largest time requirement (by a factor of over 100) in the operation of the merged model of satellite acquisitions involves the orbital propagator (placing satellites in orbits and examining their coverage over time). The technique for the control module (constructing a level order memory tree) was written with parallelization in mind as a method of combating this computational requirement. Even so, the orbit was fixed to existing known orbits for both the GPS and Weather mission areas as a way of saving computational time. Future work could examine optimal ways of using coverage models in conjunction with such a technique. If better utilization of coverage models can be realized, the design spaces being examined can be expanded. It is highly possible that current generation graphics cards (graphical processing units, GPUs) provide better hardware on which to run an orbital propagator (as opposed to CPUs), as they quickly solve many problems in parallel and mathematically perform computations (floating point matrix multiplication) that GPUs are optimized for. The arrangement of secondary processing hardware and the emergence of race conditions (where code needs to execute in a specific sequence) would need to be interfaced with the construction of the memory tree's construction.

Once more detailed coverage (orbital-propagator-driven) models are available, the addition of agent-based modeling would enable even more detailed examination of system level performance under context (e.g., unexpected events such as loss of satellites, or temporary disturbances such as solar storms). As the pipeline abstracts the production of a finite quantity of satellites, each individual satellite could be classified as an agent. This would present several opportunities to improve the capabilities of this modeling approach. First, this would permit the testing of probability laws on specific satellites or groups of satellites (e.g., what happens if some satellites are lost prematurely or lose partial capability). This would enable examination of the model's reaction to the loss of on-orbit capability and provide superior modeling of the level and duration of service disruption. This could be conducted deliberately or through a Monte-Carlo approach. Second, this would interface with an improved orbital propagator to provide insight into the replenishment plan of satellites. As a constellation of satellites requires positioning in specific orbits, using an agent-based approach would interface well with the physics modeling in standard TSE practice (e.g., orbital propagator and associated coverage computations). It would enable detection of emergent gaps in capability. It would also allow testing under a wide variety of "what if" situations and possible resolution options to loss of on-orbit capability. Most importantly, the results of such analysis would provide the resolution time associated with each policy. This would enable policy makers to understand the level and length of capability degradation under various scenarios.

10.5.1   Possible use of Discrete-Event Simulations and Techniques

One alternative to the approach taken in this thesis is discrete-event simulation. In a discrete-event simulation, unlike the continuous SD model implemented in this thesis, events occur over a time period and the occurrence of an event marks the change of state in the system (Matloff, 2008). For example, Wirthlin breaks several stages of the Air Force acquisitions pipeline into components, where each component is the office responsible for a process in the acquisition pipeline (Wirthlin, 2009).To understand the time and variance associated with the completion of each task, he conducted interviews with personnel in each of the offices involved in the acquisitions process. Using this information, he simulated the Air Force acquisition process as a discrete-event simulation. His simulation highlights the capability of discrete-event simulation to model a system with multiple paths and calculate the average times associated with completing the acquisition process. It also enables the testing of the impact of policies on changing either times or pathways through the system and testing for positive or negative outcomes associated with implementation of these policies. The SD model implemented in this thesis abstracts all of acquisition into a high-level, top-down examination of an acquisitions pipeline. Wirthlin's work is, in contrast, a bottom-up analysis based on estimates of each component derived from interviews with acquisitions personnel.

Another example of discrete event simulation being used to model the performance of a DoD system was seen on the DARPA F-6 program. Modeling of the fractionated satellite constellation in a discrete-event simulation was conducted to analyze the constellations performance on orbit across time and multiple operational scenarios as a way to evaluate performance under context (Dubos & Cornford, 2012). This work did not use a discrete-event simulation to track the acquisitions system producing the potential f-6 spacecraft.

Implementing a discrete-event simulation of the acquisition and fielding of GPS satellites would enable policy testing for the production pipeline and might be an alternative method of answering the policy questions of this thesis. It would be possible to gather data about historical times associated with satellite bus and payload creation and construct an end-to-end contract signing to expiration on orbit, discrete-event simulation of the GPS satellite production pipeline. Each element of such a simulation would be assigned its own probability distribution; through a Monte Carlo approach the expected time to create and field space assets could be evaluated. This approach would enable an additional benefit: as discrete-event simulation comes with "native" support for stochastic modeling, the impact of random events on constellation performance (on-orbit) could easily be examined. Ultimately, a discrete-event simulation could function in place of the SD model for tracking the production of GPS satellites and their on-orbit operations. While the discrete-event simulation can keep track of satellites in production and on orbit, like the SD model in this work, it must still invoke external physics models to validate the performance of the satellites on orbit.

A draw back to a discrete-event simulation would be the loss of the learning model present in this work. The efficiency metric, which functioned as the flow control to the production pipeline, varied heavily as a function of, experience, technology age and the time constants assorted with technology and process cycle time. As the probability distributions (confidence intervals) associated with each stage in the discrete-event simulation model would be based on historical fact, it might be difficult to predict a future that looks different than the past using fixed probabilities. For a discrete-event simulation to predict anything other than the expected

average of historical performance (when run through many iterations), assumptions about future probability distributions would need to be changed. For example, the process cycle time which is directly linked in the present work to the rate at which satellites are produced, in a discrete-event simulation might always be the same as the historical satellite production times making it unable to track changes across generations. This would require an external body of work to validate the assumptions about why future results would differ from historical results if such a generation across generation evaluation was performed. Still, within the discrete-event simulation, the concept of reinforcing or balancing loops could be implemented, and the state of the model could iterate upon the previous acquisition (or satellite production), driving variables such as experience or process cycle time. However, as noted, the degree to and rate at which these changes over time would occur must somehow be determined. In effect, to capture the generation-across-generation changes the simulation would need to be encoded to function much like a SD model. Which poses a greater threat to such an approach, discrete-event simulations require predetermined starting and ending points. As one change in efficiency is a changing of beginning and ending points of acquisitions, it is possible that this would preclude such a modeling approach from capturing the appropriate termination points of acquisitions. Beyond this, a question of validity would also need to be addressed. In this thesis, validity was handled through the matching of reference modes for both historical and holdback time periods and finding prediction error to be comparable to current mass- and cost-modeling approaches. In short, implementing a discrete-event simulation to tackle some of the policy questions in this thesis is a possible alternative implementation. Yet this approach provides no obvious method of statistical validation and would require its own body of work and justification.

10.5.2   Possible use of Epoch-Era Analysis

In this work, maintaining lower costs while improving acquisitions is the major focus of "performance." Traditional TSE often uses utility theory and employs multi-objective utility functions aggregating different metrics to derive a utility function representing value delivery. For this work, performance was fixed inside a generation for all cross-architectural comparisons. Future work adapting utility functions to this modeling effort would enable cross comparison of architectures which vary not only in cost but also performance as represented in coverage metrics (e.g., number of signals or sensors, performance under context, coverage levels, and other measures of satellite performance). Such a technique will be important for comparing large data sets involving tens of thousands to millions of design points. The difficulty in across-generation implementation of utility functions revolves around the problem of generation completion. If acquisition generations complete at different times, then neither satellite constellation performance nor cost can be equivalent and direct comparison is not possible.

Typically, in TSE, the modeler or analyst examines the resulting design points or solutions close to the Pareto front when plotting cost against utility. These are said to stochastically dominate the other points from either a cost or performance perspective, and as such are the designs of greatest interest; this cannot be achieved if the utility or cost is not constant over the time period of examination. Thus, a multi-dimensional analysis become necessary to evaluate such a Tradespace in the event of different performances or costs over time. However, it is also possible that if performance is abstracted into utility at each discrete time-step (eight per year in this work) and as cost per operational year is already computed for each time step, it is possible that utility against cost per operational time-step would be possible. Then an average utility against an average cost could be plotted for any time region. Moreover, this would give

appropriate benefit to programs which complete faster than others as they would deliver higher performance (and thus higher utility) for longer. Thus, utility functions may serve as a way to solve the difficulty in comparing capability and cost changes across time with more research.

Epoch-Era Analysis includes temporal calculations in the evaluation of candidate systems. It first defines a set of systems (as in MATE), then computes the performance of candidate systems relative to the exogenous context variables. A time period with fixed context and needs is referred to as an "Epoch." If these same design points are tested against different context (or assumption) variables, this creates a different Epoch, and it is expected that performance of the various systems will change. Era-level analysis arises from an ordering of Epochs (each with their own durations) and an examination of the performance of candidate solutions across a sequence of Epochs. This approach provides another alternative to answering the policy questions of this thesis. The advantage in Epoch-Era Analysis lies in the simplicity and ease of examining performance under context or sequences of expected contexts. In this thesis, upgrade paths for perceived performance increases were constructed. These upgrade paths are nearly identical to setting the context in requirements for a sequence of four Epochs. Also in this thesis, context variables such as reduction in launch costs were investigated. Again Epoch-Era Analysis well handles such an analysis, as the upgrade path proposed in this thesis would be then aligned with Epochs representing reductions in launch costs.

It is also possible for Epoch-Era Analysis to include both satellites and satellite production inside a utility function; performing analysis on a system of systems. If Epochs are pre-computed they are inherently not linked and the sequence of epochs does not influence the performance of the system being evaluated from one epoch to the next. However, in Era level analysis epoch can be linked enabling the transfer of memory or state from one Epoch to the next which could align with the required upgrades in performance for the analysis of the policy questions in this thesis. The concern relative to the SD model implemented in this thesis is that the time period of an Epoch would need to be set equal to the time period for which learning would occur. This would require dynamically changing time intervals on future epochs based on the time of satellite construction as it changes across time. If this was the case then an analysis of ~30 years could require up to ~500 epochs in a sequence. In fact one could claim that the SD model implemented in this thesis was generating a new Epoch with each 'dt' or time-step and was the mechanism that dynamically determining future Epoch lengths and then computing the utility of the architecture under investigation after all execution was completed.

10.5.3 Additional Causal Loops in the SD model

While many iterations of the SD model and its causal loop were produced before obtaining the final representative model, there are several causal loops which could be added which would either enhance the modeling capability or extend its ability to answer specific questions. The first would be a unified approach across TSE and SD to handle the concept of complexity and how it shifts across architectural implementations. In this thesis, complexity is assumed to be constant for the GPS constellation, and for Weather and Climate Sensing it is modified based on a very specific set of rules tied to specific capabilities and sensors. A more robust model would better incorporate such modeling of complexity across the entire merged model, extending the complexity modification into a SD causal loop. Complexity must also address the distribution of complexity, not only for satellites but also for launch and operations. This might involve adding two loops to the SD model: one for launch and one for on-orbit operations. By adding causal

loops linking the production rate of satellites to their impact on launch and operations, the model boundary might better encompass the total perspective and life-cycle of satellite acquisitions. The SD model might also be expanded by including the impact of technology from the private sector and the leadership role it may assume over the next few decades in space technology. Substantial research and work would be required to incorporate the proper relationships of such elements and inductively tune them. If, however, this and the other improvements were made, a substantial acquisitions tool would come into existence, capable of answering a wide range of questions about pipeline acquisitions.

11 References

Gibbons Media & Research LLC. (2015, 6 1). *GPS III*. Retrieved from Inside GNSS: http://www.insidegnss.com/node/2746

A. Ross, N. D. (2003). Multi-Attribute Tradespace Exploration with Concurrent Design for Space System Conceptual Design. *41 Aerospace Sciences Meeting and Exhibit.* Reno, Nevada.

A.Golkar, A. (2013). *Federated Satellite Systems (FSS): A Vision Towards an Innovation in Space Systems Design.* Skolkovo, Odintsovsky district, Moscow Region: Skolkovo Institute of Science and Technology.

Abbott, A. D. (2004). *Methods of Discovery: Heuristics for the Social Sciences.* New York: W.W. Norton & Co.

Adcock, R., & Collier, D. (2001). Measurement Validity: A Shared Standard for Qualitative and Quantitative Research. *American Political Science Review*, 529-546.

Aerospace Corperation. (2015, 06 02). *SSCM DATABASE*. Retrieved from Aerospace: http://www.aerospace.org/research/space-systems-infrastructure/small-satellite-cost-model/

Air Force Space Command. (2013). *Resiliency and Disaggregated Space Architectures.* Washington, D.C.: Air Force Space Command.

Air Force Space Command. (2013). *Resiliency and Disaggregated Space Architectures.* Los Angeles: Air Force Space Command.

AirBus Defence and Space. (2015, 6 25). *Press Release: Airbus Defence and Space Selected to Partner in Production of OneWeb Satellite Constellation.* Retrieved from Airbud Defence & Space: http://airbusdefenceandspace.com/wp-content/uploads/2015/06/press-release-space-15062015-eng.pdf

Airforce Technology. (2015, 06 01). *Global Positioning System III (GPS III) Military Satellite, United States of America*. Retrieved from Airforce Technology: http://www.airforce-technology.com/projects/gps-iii-military-satellite/

Akcam, B. K., Guney, S., & Cresswell, A. M. (2011). Major Issues in Mixed Use of Grounded Theory and System Dynamics Approaches in Qualitative Secondary Data. *The 29th International Conference of the System Dynamics Society.* Washington, DC.

Akhtar, M. K., Simonovic, S. P., Wibe, J., MacGee, J., & Davies, J. (2011). *Water Resources Research Report: An Integrated System Dynamics Model for Analyzing Behaviour of the Social-Energy-Economic-Climatic System.* UNIVERSITY OF WESTERN ONTARIO.

Albin, S., & Forrester, J. W. (1997). *Building a System Dynamics Model.* Cambridge: Massachusetts Institute of Technology. Retrieved from http://ocw.mit.edu/courses/sloan-school-of-management/15-988-system-dynamics-self-study-fall-1998-spring-1999/readings/building.pdf

Alibay, F. (February 2014). *EVALUATION OF MULTI-VEHICLE ARCHITECTURES FOR THE EXPLORATION OF PLANETARY BODIES IN THE SOLAR SYSTEM.* Cambridge, MA: Massachusetts Institute of Technology.

Alibay, F., & Strange, N. (2013). Trade Space Evaluation of Multi-Mission Architectures for the Exploration of Europa. *IEEE.* Cambridge, MA: Massachusetts Institute of Technology.

Andersen, D. F., & Richardson, G. P. (1997). Scripts for group model building. *System Dynamics Review*, 107-129.

Ashish, S., & Tellis, G. (2005). The S-Curve of Technological Change: Strategic Law or Self-Fulfilling Prophecy. *Marketing Science Institute*.

Babbie, E. R. (2009). *The Practice of Social Research 12th Edition.* Belmont, CA: Wadsworth Cengage.

Badiru, A. B. (2012, July). *Half-Life Learning Curves in the Defense Acquisition Life Cycle.* Retrieved from Defence Acquistion University: www.dau.mil

Bartolomei, J. E. (2007). *Qualitative Knowledge Construction for Engineering Systems: Extending the Design Structure Matrix Methodology in Scope and Procedure.* Cambridge, MA: Massachusetts Institute of Technology.

Bertseakas, D., & Tsitsiklis, J. (2009). *Introduction to Probability 2nd edition.* Belmont, Massachusetts: Athena Scientific.

Black, L. J., Carlile, P. R., & Repenning, N. P. (2004). A Dynamic Theory of Expertise and Occupational Boundaries in New Technology Implementation: Building on Barley's Study of CT Scanning. *Administrative Science Quarterly, 49*(4), 572-607.

Blackwell, W. J., Cull, C. F., Czerwinski, R. N., Leslie, R. V., & Osaretin, I. (2012, 1 24). The Advanced Technology Microwave Sounder (ATMS): New Capabilities for Atmospheric Sensing. New Orleans, LA.

Boeing. (2015, 5 21). *702 Satellite Historical Snapshot*. Retrieved from Beoing Products: http://www.boeing.com/history/products/702-satellite.page

Brantley, M., McFadden, W., & Davis, M. (2002). *Expanding the Trade Space: An Analysis of Requirements Tradeoffs Affecting System Design.* DOD.

Brinton, T. (2010, 2 2). *White House Dissolves NPOESS Partnership in Blow to Northrop*. Retrieved from Space News: spacenews.com/white-house-dissolves-npoess-partnership-blow-northrop/

Bureau of Industry and Security. (February 2014). *U.S. Space Industry 'Deep Dive' Final Dataset Findings: Impact of U.S. Export Contols on the Space Industrial Base.* Washington, D.C.: U.S. Department of Commerce.

Bureau of Industry and Security. (September 2014). *U.S. Space Industry 'Deep Dive' Final Dataset Findings: Employment in the U.S. Space Industrial Base.* Washington, D.C.: U.S. Department of Commerce.

Campbell, D., & Stanley, J. (1963). *Experimental and Quasi-Experimental Designs for Research.* Cengage Learning.

Carter, A. B., & Mueller, J. (October 2011). *Should Cost Management: Why? How?* Washington D.C.: Defense AT&L.

Chang, D. D., & Weck, O. L. (2004). Basic capacity calculation methods and benchmarking for MF-TDMA and MF-CDMA communication satellites. *Int. J. Satell. Commun* (pp. 100:1–999). John Wiley & Sons, Ltd.

Chauhan, N. (2003). NPOESS Conical Microwave Imager/Sounder: issues and progress. *Geoscience and Remote Sensing Symposium. 1.* IEEE. Retrieved from http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=1293779

Collins, B. (2013, September). *Space Universal Modular Architecture (SUMO).* Retrieved from Goddard Contractors Association: http://www.goddard-contractors-association.org/presentations/SUMO%20for%20NASA%20GCA%20130918.pptx

Collins-Williams, T., & Salembier, G. (1996). nternational Discipline on Subsidies: The GATT, the WTO, and the Future Agenda. *Journal of World Trade*, 5-17.

Commitee on Science, House of Representatives. (2007). *The Future of NPOESS: Results of the Nunn-McCurdy Review of NOAA's Weather Satellite Program.* Washington D.C.: U.S. Government Printing Office. Retrieved from www.house.gov/science

Corbin, B. A. (2015). *The Value Proposition of Distributed Satellite Systems for Space Science Missions.* Cambridge: MIT.

Coyle, G., & Exelby, D. (2000). The validation of commercial system dynamics models. *System Dynamics Review, 16*(1), 27-41.

Coyle, R. (1977). *Managment System Dynamics.* Chichester: Wiley.

Curiel, A. D. (2015, 5 17). *Rapid Development of Navigation Payloads for Galileo Full Operational Capability.* Retrieved from United Nations Office for Outer Space Affairs: http://www.unoosa.org/pdf/sap/2011/UAE/Presentations/05.pdf

Curley, S., Yates, J., & Abrams, R. (1986). Psychological Sources of Ambiguity Avoidance. *Organizational Behavior and Human Decision Processes, 38*, 230-256.

Curry, M. (2014). Personal Communication. *OREOS.*

Davis, F. (1989). Perceived usefulness, perceived ease of use, and user accpetance. *MIS Quart*, 319-340.

de Weck, O. (2001, Spring). *16-851-satellite-engineering*. Retrieved from MIT Open Courseware: http://ocw.mit.edu/courses/aeronautics-and-astronautics/16-851-satellite-engineering-fall-2003/lecture-notes/l9_acs.pdf

Dubos, G., & Cornford, S. (2012). Modeling Temporal Processes in Early Spacecraft Design: Application of Discrete-Event Simulations for Darpa's F6 Program. *AIAA SPACE 2012 Conference & Exposition.* Pasadena, CA: AIAA.

Dwyer, M. M. (2015). *The Cost of Jointness: Insights from Environmental Monitoring Systems in Low Earth Orbit.* Cambridge, MA: Massachusetts Institute of Technology.

Dwyer, M. M. (Feburary 2015). *The Cost of Jointness: Insights from Environmental Monitoring Systems in Low Earth Orbit .* Cambridge, MA: Massachusetts Institute of Technology.

Ellis, R. E. (2001). *The Use of System Dynamics in a Large-Scale System Engineering Effort: Case Study of the Deepwater Project.* McLean, VA: JAYCOR, INC.

ESA. (2016, 04 02). *JPSS (Joint Polar Satellite System)*. Retrieved from Sharing Earth Observation Resources: https://directory.eoportal.org/web/eoportal/satellite-missions/j/jpss

European Space Agency. (2016, 04 05). *JPSS (Joint Polar Satellite System)*. Retrieved from eoPortal: https://directory.eoportal.org/web/eoportal/satellite-missions/j/jpss

Federal Aviation Administration. (2011). 2011 Commercial Space Transportation Forecasts. Washington , D.C.: Office of Commercial Space Transportation.

Ferster, W. (2013, 5 17). *DARPA Cancels Formation-flying Satellite Demo*. Retrieved from Space News: http://spacenews.com/35375darpa-cancels-formation-flying-satellite-demo/

Fisher, R., & Ury, W. (1981). *Getting to Yes: Negotiating Without Giving In.* New York, N.Y.: Penguin Group.

Forrester, J. (1961). *Industrial Dynamics.* Pegasus Communications.

Franke, R. H., & Kaul, J. D. (1978). The Hawthorne Experiments: First Statistical Interpretation. *American Sociological Review*, 623.

Freeman, R. E. (1984). *Strategic Management: A Stakeholder Approach.* Harpercollins College.

Geddes, B. (1990). How the cases you choose affect the answers you get: Selection bias in comparative politics. *Political Analysis*, 131-150.

George, A., & Bennett, A. (2005). *Case Studies and Theory Development in the Social Sciences.* Cambridge, MA: The MIT Press; Fourth Printing edition.

Gerst, K. J. (2011). *Evaluating the Impact of Government Energy R&D Investments through a Multi-Attribute Utility-based Decision Tool.* Cambridge, MA: Massachusetts Institute of Technology.

Glaser, B. (1998). *Doing grouded theory: Issues and discussions.* Mill Valley, CA: Sociology Press.

Glaser, B. G., & Strauss, A. L. (1967). *The Discovery of Grounded Theory: Strategies for Qualitative Research.* Chicago: Aldine.

Glasser, B. (1998). *Doing grouded theory: Issues and discussions.* Mill Valley, CA: Sociology Press.

Global Positioning Systems Directorate. (2014). *GPS Systems Engineering & Integration Interface Specification IS-GPS-200.* Los Angeles: US Air Force.

Globalsecurity.org. (2011, 7 7). *F-117A Nighthawk.* Retrieved from Global Security: http://www.globalsecurity.org/military/systems/aircraft/f-117.htm

GlobalSecurity.Org. (2011, 07 21). *GPS Block II F.* Retrieved from Global Security: http://www.globalsecurity.org/space/systems/gps_2f.htm

GPS.GOV. (2015, 06 31). *Control Segment.* Retrieved from GPS.GOV: http://www.gps.gov/systems/gps/control/

Gruss, M. (2014, 11 5). *GAO: Air Force Needs More Info Before Committing to Disaggregation.* Retrieved from http://spacenews.com/42464gao-us-air-force-needs-more-info-before-committing-to-disaggregation/

Gurfil, P. P. (2015, 6 11). *Distributed Space Systems Laboratory.* Retrieved from Distributed Space System: http://dssl.technion.ac.il/

Hamaker, J. (2011). QuickCost: Suite of Space Project Cost Estimation Models. Albuquerque, NM.

Hastings, D., La Tour, P., & Putbrese, B. (2015). Value-Based Analysis of a Low-Earth Orbit Communications and Data Relay Infrastructure. *2015 IEEE Aerospace Conference.* Big Sky, Montana: IEEE.

Henttu, H., Izaret, J.-M., & Potere, D. (2012). *Geospatial Services: A $1.6 Trillion Growth Enginer for the U.S. Economy.* Boston: Boston Consulting Group (BCG).

Hines, J. (2005). *Molecules of Strucure.* Cambridge.

Holt, N., & Walker, I. (2009). *Research with People: Theory, Plans and Practicals.* Palgrave Macmillan.

Homer, J. B. (1997 (winter)). Structure, Data, and Compelling Conclusions: Notes from the Field. *System Dynamics Review*, 293-309.

Homer, J. B. (1997, Winter). Structure, Data, and Compelling Conclusions: Notes from the Field. *System Dynamics Review*, 293-309.

Intel. (2015, 5 20). *Intel Tick-Tock Model.* Retrieved from Intel: http://www.intel.com/content/www/us/en/silicon-innovations/intel-tick-tock-model-general.html

Intel. (2015, 03 15). *Intel Tick-Tock Model.* Retrieved from Intel: http://www.intel.com/content/www/us/en/silicon-innovations/intel-tick-tock-model-general.html

Jilla, C. D. (2002). *A Multiobjective, Multidisciplinary Design Optimization Methodology for the Conceptual Design of Distributed Satellite Systems.* Cambridge, MA: Massachusetts Institute of Technology.

Jilla, C. D. (2002). *A Multiobjective, Multidisciplinary Design Optimization Methodology for the Conceptual Design of Distributed Satellite Systems.* Cambridge, MA: Massachusetts Institute of Technology.

Kapmeier, F. (2006). Research Based on Two Pillars: Combining Qualitative Empirical Social Research and Simulation in Strategic Management., (p. Listed on page 77 accessed through website). Nijmegen.

Kasper, J., & Balle, O. (2014, 10 28). *About the GPS Program.* Retrieved from Aerospace & Defense Intelligence Report : http://bga-aeroweb.com/Defense/Global-Positioning-System.html

Keeney, R., & Raiffa, H. (1993). *Decisions with multiple objectives–preferences and value tradeoffs.* Cambridge: Cambridge University Press.

Kitts, C., Pranajaya, F., Townsend, J., & Twiggs, R. (1999). Emerald: An Experimental Mission in Robust Distributed Space Systems. *13th Annual AIAA/USU Conference on Small Satellites*, (pp. SSC99-VI-5).

Kopainsky, B., & Luna-Reyes, L. F. (2008). Closing the loop: promoting synergies with other theory building approaches to improve system dynamic practice. *Systems Research and Behavioral Science*, 471-486.

La Tour, P. A., Frazier, A. B., Sondecker, G., & Abramowitz, L. (2011). U.S. Air Force's SMC/XR SENSE NanoSat Program. *AIAA SPACE 2001 Conference & Exposition.* Long Beach, CA: AIAA.

Lamberson, P. J., & Page, S. E. (2012, 02 02). Tipping Points. SANTA FE. Retrieved from http://www.santafe.edu/media/workingpapers/12-02-002.pdf

Lane, D. (1994). Social Theory and System Dynamics Practice. *International System Dynamics Conference*, (pp. 53-66).

Lane, D., & Oliva, R. (1998). The greater whole: Towards a synthesis of system dynamics and soft systems methodology. *European Journal of Operations Research, 107*, 214-235.

Lankford, J. (2003). Measuring system and software architecture compelxity. *IEEE Aerospace Conference.*

Lave, C. A., & March, J. (1992). *An Introduction to Models in the Social Sciences.* University Press of America.

Laws, K., & McLeod, R. (2004). Case study and grouded theory: Sharing some alternative qualitative research methodologies with system professionals. *22nd International Conference of the System Dynamics Society.* Oxford, England.

Legge, R. S. (2014). *Optimization and Valuation of Reconfigurable Satellite Constellations Under Uncertainty.* Cambridge: MIT.

Leone, D. (2014, 6 9). *NASA Official: A Landsat 8 Clone Would Cost More Than $650 Million.* Retrieved from Space News: http://spacenews.com/40841nasa-official-a-landsat-8-clone-would-cost-more-than-650-million/

Lijphard, A. (1971). Comparative politics and the comparative method. *The American Political Science Review*, 682.

Lockheed Martin. (2005, 5 17). *GPS III The Next Generation Global Positioning System.* Retrieved from GPS III Fact Sheed FINAL 1: http://www.lockheedmartin.com/content/dam/lockheed/data/space/documents/gps/GPSIII_FactSheetFINAL1.pdf

Lockheed Martin. (2014). *GPS III: The Next Generation Flobal Positioning System.* Retrieved from Lockheed Martin:

http://www.lockheedmartin.com/content/dam/lockheed/data/space/documents/gps/GPS-III-Fact-Sheet-2014.pdf

Lockheed Martin. (2015, 5 17). *Global Positioning System (GPS)*. Retrieved from http://www.lockheedmartin.com/us/products/gps.html

Los Angeles Air Force Base. (2015, 5 17). *GLOBAL POSITIONING SYSTEM (GPS) IIF SATELLITE.* Retrieved from Los Angeles Air Force Base: http://www.losangeles.af.mil/library/factsheets/factsheet.asp?id=18670

Luna-Reyes, L. F., & Andersen, D. L. (2004). Collecting and analyzing qualitative data for system dynamics: methods and models. *System Dynamics Review, 19*(4), 271-296.

Lyneis, J. M. (1999 (spring)). System dynamics for business strategy: a phased approach. *System Dynamics Review*, 37-70.

Mathworks. (2015, 05 07). *Matlab*. Retrieved from Mathworks Matlab: http://www.mathworks.com/products/matlab/index-b.html

Matloff, N. (2008). Introduction to Discrete-Event Simulation and the SimPy Language. UC Davis. Retrieved from http://heather.cs.ucdavis.edu/~matloff/156/PLN/DESimIntro.pdf

Mehaffey, J., Yeazel, J., Penrod, S., & Deiss, A. (2015, 6 31). *GPS Information*. Retrieved from GPS Information: http://gpsinformation.net/main/gpspower.htm

Mehmet, S., & Yasarcan, H. (2015). *Block Diagrams of Generic System Dynamics Models.* Istanbul, Turkey: System Dynamics Society.

Mekdeci, B. (2013). *MANAGING THE IMPACT OF CHANGE THROUGH SURVIVABILITY AND PLIABILITY TO ACHIEVE VIABLE SYSTEMS OF SYSTEMS.* Cambridge, MA: Massachusetts Institute of Technology.

Memorandium from the Under Secretary of Defense: Acquisition Technology and Logistics. (2013, Apr 24). Implementation Directive for Better Buying Power 2.0 -- Achieving Greater Efficiency and Productivity in Defense Spending. Washington, D.C.

Memorandum from the Under Secretary of Defense: Acquisition Technology and Logistics. (2013, Apr 24). Implementation Directive for Better Buying Power 2.0 -- Achieving Greater Efficiency and Productivity in Defense Spending. Washington, D.C.

Mingers, J. (2000). Variety is the spice of life: combining soft and hard OR/MS methods. *International Transactions in Operational Research, 7*, 673-691.

Mingers, J., & Brocklesby, J. (1997). Multimethodology: Towards a framework for mixing methodologies. *Omega, International Journal of Management Science, 25*(5), 489-509.

Morrison, J. B. (2008). *Implementation as Learning: An Extension of Learning Curve Theory.* Brandeis University International Business School.

Morrison, J. B. (2011). *Process Improvement Dynamics Under Constrained Resources: Managing the Work Harder versus Work Smarter Balance.* Waltham, MA : Brandeis International Business School.

Morrison, J. B., Rudolph, J. W., & Carroll, J. S. (2008). THE DYNAMICS OF DIAGNOSING: Virtuous and Vicious Cycles in the Operating Room. *The 26th International Conference of the System Dynamics Society.* Athens, Greece.

NASA. (2010). *Cost Estimating Handbook (CEH).* Washingtion: NASA.

NASA. (2016, 4 19). *Advanced Technology Microwave Sounder (ATMS)*. Retrieved from National Aeronautics and Space Administration Goddard Space Flight Center: http://npp.gsfc.nasa.gov/ATMS.html

NASA. (2016, 3 28). *Cross-track Infrared Sounder (CrIS)*. Retrieved from NASA Goddard Space Flight Center: http://npp.gsfc.nasa.gov/cris.html

NASA. (2016, 04 01). *NASA Space Science Data Coordinated Archive*. Retrieved from NASA: http://nssdc.gsfc.nasa.gov/nmc/spacecraftSearch.do

NASA. (2016, 3 28). *Visible Infrared Imaging Radiometer Suite (VIIRS)*. Retrieved from NASA Goddard Space Flight Center: http://npp.gsfc.nasa.gov/viirs.html

National Security Space Office. (2007). *Defense Industrial Base Assessment: U.S. Space Industry FINAL REPORT.* Dayton, Ohio: U.S. Air Force.

National Snow & Ice Data Center. (2016, 04 02). *Defense Meteorological Satellite Program (DMSP)* . Retrieved from NSIDC.org: https://nsidc.org/data/docs/daac/f17_platform.gd.html

NOAA. (2016, 04 05). *Clouds and the Earth's Radiant Energy System (CERES)*. Retrieved from Joint Polar Satellite System: http://www.jpss.noaa.gov/ceres.html

NOAA. (2016, 04 05). *Ozone Mapping and Profiler Suite (OMPS)*. Retrieved from Joint Polar Satellite System: http://www.jpss.noaa.gov/omps.html

O. de Weck, D. R. (2011). *Engineering Systems: Meeting Human Needs in a Complex Technological World.* Cambridge, MA: The MIT Press.

Office of the Federal Coordinator for Meteorological Services and Supporting Research National Space Weather Program Council Joint Action Group for Space Environmental Gap Analysis. (2014, 4). *Space Weather 2013 Report.* Retrieved from Whitehouse.gov: https://www.whitehouse.gov/sites/default/files/microsites/ostp/spaceweather_2013_report.pdf

Office of the Under Secretary of Defense. (November 2012). *Better Buying Power 2.0.* Washington D.C.: Department of Defense Acquisitions, Technology, and Logistics.

Oliva, R. (1995). *A Vensim® Module to Calculate Summary Statistics for Historical Fit.* Cambridge, MA: System Dynamics Group, MIT. Retrieved from http://sigs.systemdynamics.org/wp/wp-content/userup/BehHistFit_Manual.pdf

Olivier, R. (1995). *A Vensim® Module to Calculate Summary Statistics for Historical Fit.* Cambridge, MA: System Dynamics Group, MIT. Retrieved from http://sigs.systemdynamics.org/wp/wp-content/userup/BehHistFit_Manual.pdf

ORBCOMM. (2015, 1 1). *Networks: Satellite*. Retrieved from Orbcomm: http://www.orbcomm.com/en/networks/satellite/orbcomm-og2

OSCAR. (2016, 04 02). *Instrument: OMPS-nadir* . Retrieved from Observing Systems Capability Analysis and Review Tool: http://www.wmo-sat.info/oscar/instruments/view/379

Perry, W. (1994, June 29). Specifications & Standards - A New Way of Doing Business. Washington , DC: Secretary of Defense.

Petter. (2009, Jan 26). *0-1 Knapsack.* Retrieved from Matlab Central: http://www.mathworks.com/matlabcentral/fileexchange/22783-0-1-knapsack/content/knapsack.m

Pruyt, E. (2006). *What is System Dynamics? A Paradigmatic Inquiry.* Vrije Universiteit Brussel, Business School Solvay, .

Putbrese, B. (2015). *Exploring Design and Policy Options for Orbital Infrastructure Projects.* Cambridge, MA: Massachusetts Institute of Technology.

Randers, J. (1980). *Elements of the System Dynamics Model.* Portland, OR: Productivity Press.

Richards, M. G. (2007). Defining Survivability for Engineering Systems. *The 5th Conference on Systems Engineering Research.* Hoboken, NJ.

Richards, M. G. (2009). *MULTI-ATTRIBUTE TRADESPACE EXPLORATION FOR SURVIVABILITY.* Cambridge, MA: MASSACHUSETTS INSTITUTE OF TECHNOLOGY.

Ronald K. Mitchell, B. R. (1997). Theory of Stakeholder Identification and Salience. *The Academy of Management Review*, 853-854.

Ross, A. M., & Hastings, D. E. (2005). The tradespace exploration paradigm. *2005 INCOSE Int Symp.* Rochester, NY.

Ross, A. M., Diller, N., & Hastings, D. (2003). *MULTI-ATTRIBUTE TRADESPACE EXPLORATION WITH CONCURRENT DESIGN AS A VALUE-CENTRIC FRAMEWORK FOR SPACE SYSTEM ARCHITECTURE AND DESIGN.* Cambridge: MIT.

Ross, A. M., McManus, H. L., Rhodes, D. H., & Hastings, D. E. (2010). Revisiting the tradespace exploratoin paradigm: structuring the exploration process. *AIAA SPACE 2010 Conference & Explosition.* Anaheim, CA.

Ross, A. M., McManus, H. L., Rhodes, D. H., Hastings, D. E., & Long, A. (2009). Responsive Systems Comparison Method: Dynamic Insights into Designing a Satellite Radar System. *AIAA Space.* Pasadena, CA.

Ross, A., & Rhodes, D. (2008). Using Natural Value-Centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis. *INCOSE 2008.*

Ross, A., Hastings, D., Warmkessel, J., & Diller, N. (2004). Multi-Attribute Tradespace Exploration as a Front End for Effective Space System Design. *Journal of Spacecraft and Rockets, 41*.

Rudolph, J. W., & Repenning, N. P. (2002). Disaster Dynamics: Understanding the Role of Quantity in Organizational Collapse. *Administrative Science Quarterly, 47*, 1-30.

SAIC. (2010). *NASA -- Air Force Cost Model*. Retrieved from NAFCOM Website: http://www.nasa.gov/offices/ooe/CAD/Models_Tools.html#.VLK9kivF9AA

Saleh, H. (2008). test123. *test1*.

Saleh, J. H. (2008, January). Flawed Metrics: Satellite Cost per Transponder and Cost per Day. *IEEE Transactions on Aerospace and Electronic Systems, 44*(1), 147-156.

Saleh, J. H., Hastings, D. E., & Newman, D. J. (2002). Spacecraft Design Lifetime. *Journal of Spacecraft and Rockets*, 244-257.

Schaffner, M. A., Ross, A. M., & Rhodes, D. H. (2014). A Method for Selecting Affordable System Concepts: A Case Application to Naval Ship Design. *Conference on Systems Engineering Research.* Redondo Beach, CA: Elsevier.

Schaffner, M. A., Wu, M. S., Ross, A. M., & Rhodes, D. H. (2013). Enabling Design for Affordability: An Epoch-Era Analysis Approach. *Tenth Annual Acquisition Research Symposium* (pp. 262-279). Monterey, CA: Naval Postgraduate School.

Schwartz, S. (1977). Normative Influences on altruism. *Adcance in experimental social psychology*, 221-279.

Scott, M. (2014, Sept 4). *Tech Giante Embrace the Smart Home, but Consumers Remain Skeptical*. Retrieved from The New York Times: http://bits.blogs.nytimes.com

Selva, D. (2012). *Rule-Based System Architecting of Earth Observation Satellite Systems.* Cambridge, MA: MIT.

SEMTECH. (2007). *Calculating Radiated Power and Field Strength for Conducted Power Measurements* . Retrieved from Semtech: https://www.semtech.com/images/promo/Semtech_ACS_Rad_Pwr_Field_Strength.pdf

Shah, N. B. (2004). *Modularity as an Enabler for Evolutionary Acquisition.* Cambridge: MIT.

Smith, M. W. (June 2014). *Model-Based Requirement Definition for Instrument Systems.* Cambridge, MA: Massachusetts Institute of Technology.

Space Daily. (2016, 3 5). *SpaceX launches SES-9 satellite to GEO; but booster landing fails*. Retrieved from Space Daily: http://www.spacedaily.com/reports/SpaceX_launches_SES_9_satellite_to_GEO_999.html

SpaceX. (2014, 10 22). *SPACEX COMPLETES 100TH MERLIN 1D ENGINE*. Retrieved from SpaceX Updates.

SpaceX. (2015, 5 21). *Falcon 9*. Retrieved from SpaceX: http://www.spacex.com/falcon9

SpaceX. (2015, 12 21). *ORBCOMM-2 Mission*. Retrieved from Space X: http://www.spacex.com/sites/spacex/files/spacex_orbcomm_press_kit_final2.pdf

Spaulding, T. J. (2003). *TOOLS FOR EVOLUTIONARY ACQUISITION: A STUDY OF MULTI-ATTRIBUTE TRADESPACE EXPLORATION (MATE) APPLIED TO THE SPACE BASED RADAR (SBR).* Cambridge: MIT.

Sterman, J. (1994, Summer-Fall). Learning in and about complex systems. *System Dynamics Review, 10*(2-3), 291-330.

Sutherland, T. A. (2009). *Stakeholder Value Network Analysis for Space-Based Earth Observations.* Cambridge, MA: Massachusetts Institute of Technology.

Swanborn, P. (2010). *Case Study Research: What, Why and How?* Los Angeles: SAGE.

System Dynamics for Academia. (2014). Retrieved from System Dynamics Society: http://www.systemdynamics.org/sd-for-academia/

Tedeschi, B. (2015, Jan 21). *How Pink is Your Floyd?* Retrieved from The New York Times: https://nyti.ms/1CR7HKB

THE UNIVERSITY OF TEXAS AT DALLAS. (2016, 04 02). *DMSP*. Retrieved from THE UNIVERSITY OF TEXAS AT DALLAS: http://cssxp1000.utdallas.edu/DMSP/spacecraft.htm

Toft, M. B., Schuitema, G., & Thogersen, J. (2014). Responsibile technology acceptance: Model Development and application to consumer acceptance of Smart Grid technology. *Applied Energy*, 392-400.

Tversky, A., & Kahneman, D. (1979, March). Prospect Theory: An Analysis of Decision Under Risk. *Econometrica, 47*(2), 263-291.

Under Secretary of Defense Acquistion Technology and Logistics. (2015, 4 19). Implemenetation Directive for Better Buying Power 3.0. Washington, DC.

Union of Concerned Scientists. (2014, August 1). *UCS Satellite Database.* Retrieved from http://www.ucsusa.org/nuclear_weapons_and_global_security/solutions/space-weapons/ucs-satellite-database.html#.VF03kSJ4pKA

United States Department of Transportation. (1997). TRENDS IN SATELLITE MASS AND HEAVY LIFT LAUNCH VEHICLES. Washington, D.C.: Federal Aviation Administration.

United States Government Accountability Office. (2012). *SPACE ACQUISITIONS DOD Faces Challenges in Fully Realizing Benefits of Satellite Acquisition Improvements.* Washington, DC: GAO. Retrieved from http://www.gao.gov/assets/590/589487.pdf

Universal Space Network. (2002). *Universal Space Network Commercial Antenna Network Evaulation (CANE) Overview.* Universal Space Network.

University of Colorado Boulder. (2016, 04 02). *Quick Facts: Total and Spectral Solar Irradiance Sensor (TSIS)*. Retrieved from University of Colorado Boulder: http://lasp.colorado.edu/home/missions-projects/quick-facts-tsis/

Ury, R. F. (1981). *Getting to Yes: Negotiating Without Giving In.* New York: Penguin Books.

Ury, W., & Fisher, R. (1981). *Getting to Yes: Negotiating Without Giving In.* New York, N.Y.: Penguin Group.

Valero, D. S. (June 2012). *Rule-Based System Architecting of Earth Observation Satellite Systems.* Cambridge, MA: Massachusetts Institute of Technology.

Vascik, P. D., Ross, A. M., & Rhodes, D. H. (2014). A Method for Exploring Program and Portfolio Affordability Tradeoffs Under Uncertainty Using Epoch-Era Analysis: A Case Application to Carrier Strike Group Design. *12th Annual Acquisition Research Symposium.* Monterey.

Vennixa, J. A. (1999). Group model-building: tackling messy. *System Dynamics Review*, 379-401.

Ventana Systems Inc. (2015, 12 12). *DLL Venapp and Command Changes*. Retrieved from Vensim:

https://www.vensim.com/documentation/index.html?dll_venapp_and_command_changes.htm

Ventana Systems Inc. (2015, 17 5). *Vensim Software*. Retrieved from Vensim: http://vensim.com/vensim-software/

Wayana Software. (2016, 01 04). *TrackingSat GPS*. Retrieved from GEOSATS: http://www.geosats.com/antennas.html

Weck, O. L., Rhodes, D. H., & Ross, A. M. (2012). *Investigating Relationships and Semantic Sets amongst System Lifecycle Properties (Ilities).* Cambridge, MA: Third International Engineering Systems Symposium.

Wertz, J. (2011). Introduction. In J. Wertz, D. Everett, & J. Puschell (Eds.), *Space Mission Engineering: The New SMAD* (pp. 1-28). Hawthorne, CA: Microcosm Press.

Wertz, J. (2011). Reducing Space Mission Cost and Schedule. In J. Wertz, D. Everett, & J. Puschell (Eds.), *Space Mission Engineering: The New SMAD* (pp. 355-398). Hawthorne, CA: Microcosm Press.

Wertz, J. (2013). *Reinventing Space: Dramatically Reducing Space Mission Cost — Reducing Launch Cost.* SpaceNews.com.

Wertz, J., Everett, D., & Puschell, J. (2011). *Space Mission Engineering: The New SMAD.* Hawthore, CA: Space Technology Library.

Wikipedia. (2015, 01 29). *Subsidy*. Retrieved from Knowledge Encyclopedia: http://www.referenceforbusiness.com/knowledge/Subsidy.html

Wilson, J. (1998). Iridium: a COTS technology success story. *Military and Aerospace Electronics, 9*(8).

Wirthlin, J. R. (2009). *Identifying Enterprise Leverage Points in Defense Acquisition Program Performance.* Cambridge: MIT.

Wolstenholme, E. (1983, Winter). System Dynamics: A System Methodology or a System Modelling Technique. *DYNAMICA, 9*(II), 84-90.

Yin, R. (2009). *Case study research: Design and methods. 4th edition.* Los Angeles: SAGE.

Yin, R. K. (2014). *Case Study Research: Design and Methods (5th Edition).* Thousand Oaks, CA: SAGE Publications Ltd.

12 Appendix A Variables and Definitions in TSE model

- **The Downlink Rate**: The rate of communication from the GPS satellite to ground stations for C&C operations. This rate is a critical requirement.
- **Percent Contact Time with Ground Stations**: Percent of the time that a GPS satellite is able to be in contact with a ground station. This can be considered a performance metric for calculating how often a satellite is in contact with a ground station. The time between contacts and the longest time between contacts are also variables of interest. These variables change only if the orbit of the satellite is changed, or the number and location of ground station changes.
- **Cross-link**: Add a cross-link payload to satellites. This element is added within the design vector under the Payload Alignment variable. In traditional TSE the design vector could have implemented the capability as a new design variable (e.g., [Crosslink]). However, as the code was implemented an object-oriented design, where a model represented architecture is composed of satellites and in turn satellites are comprised of payloads, creating this as a separate payload object becomes the correct implementation.
- **Cross-link Data Rate**: Speed of communication among satellites. This variable is set as an assumption about how much data would need to be fed through a GPS network and is required for link-closure calculations.
- **Cross-link Range**: Computes the range between GPS Satellites, assuming 25% of the GPS constellation is missing. This range is dynamically computed based upon the number of satellites in a constellation assuming an even spacing; implying that constellations with more satellites require less range.
- **Cross-link Transmission Power**: The power required to support the crosslink capability. This variable requires assumptions about duty cycle. This value is added to the power requirements for the overall satellite power budget.
- **Cross-link Mass**: Mass of the cross-link based on performance requirements. This value will be added to the total mass of the payloads placed on the satellite.
- **Inter-link**: This is a legacy capability to add a payload to the satellite which would enable communication with non-GPS satellites. This capability changes a GPS constellation into a MEO communications relay. Initial modeling does not make use of this capability; however, the code possesses the capability to examine this configuration (from the previous code-base and the on-orbit communications relay work). Computations similar to the cross-link payload are required. Based on the amount of data the inter-link will provide to other non-GPS satellites, the requirements on the GPS cross-link payload will increase, and in turn this will increase the requirements of the downlink to ground stations to ensure all data can be offloaded from the satellite.
- **Structure Mass**: Satellite bus mas required to affix subsystems and payloads, also required for rigidity and dampening to survive the launch to orbit.
- **Thermal Mass:** Satellite bus mass required for thermal management, primarily convective cooling and thermal dissipation from solar panels and transmitters throughout the larger structure's mass as these are the sources of high temperatures. As satellites in MEO typically reach a constant steady-state temperature and they are rarely in an eclipse condition, little mass is required for heating elements in contrast to LEO satellites which may spend up to 30% of their time in eclipse. This does not include payload-specific cooling requirements. If activated, the model possesses an eclipse calculator (built into the

orbital propagator) which is able to compute the number of minutes a satellite is in eclipse versus sunlight during a 1,440 minute day.

- **TTC_ Mass:** Mass required for telemetry, transmitting and receiving equipment for C&C functions to ground stations.
- **CDH Process Mass:** Mass attributed to Command and Data Handling (CDH), the "brains" of the satellite: its internal CPU as well as software and control of all other subsystems.
- **ADCS Mass:** Attitude Determination and Control (ADCS), mass varies based on size of satellite and pointing accuracy and pointing knowledge required. In this model, ADCS Mass is computed using a regression model. A higher fidelity model could improve the resolution—see (de Weck, 2001). Mass of star-cameras, reaction wheels, and associated support hardware is included in this variable.
- **Closeout Mass:** Mass attributed to "close-out" or surroundings around the frame; typically made of aluminum or carbon-loaded kapton.
- **Power Mass:** The total mass of the power subsystem needed for the satellite to provide power to the bus and payloads.
- **Payload Mass:** The total mass of all payloads to be hosted by the satellite under development. This mass is derived based on the design vector of Payload Alignment and the various configurations selected for a satellite.
- **Thermal Power:** Power used for thermal management of the spacecraft.
- **ADCS Power:** Power required for attitude determination and control of spacecraft.
- **Processing Power:** Power required for CDH and logic.
- **Transmission Power:** Power required for communication with ground stations.
- **Average Transmission Power:** Average power required by telemetry transmitting and control system. Computed as transmission power time's average daily duty cycle. (e.g., 100 watts needed ten percent of the time is 10 watts average power consumption, buffering is made possible by battery mass).
- **Propulsion Power**: The power required for on-orbit station-keeping activities. Batteries are sized with a margin in the event additional maneuvering power is required.
- **Bus Power:** Average power consumed by bus.
- **Payload Power**: Power required by all payloads.
- **Total Power:** Total power required by the satellite, bus and payloads.
- **Solar Mass:** The mass of the solar panels and associated support hardware.
- **Power Distribution and Regulation Mass:** The mass of the power regulation, discharge and recharge system, part of the total power mass.
- **Battery Mass:** The mass of batteries on the satellite. The performance of available batteries has changed over time increasing the discharge level of batteries as well as the number of cycles possible and decreasing the associated mass per watt hour that can be stored per kilogram of battery. This variable selects a set of mass and efficiency values from a lookup table; this can be used as assumption for future performance if desired.
- **Solar Type:** The performance of solar cells has changed over time. The model default is lithium-ion batteries. If desired, higher-performance theoretical designs could be implemented and unlocked as assumptions based on the Year value passed to the TSE computation.
- **Average Cosine Loss:** The average cosine loss of energy from solar arrays not pointing directly at the sun.

- **Solar Surface Area:** Size of the solar array in square meters.
- **Propulsion:** All GPS satellites are currently sized with propulsion systems. The model possesses this variable in the event a satellite is desired without propulsion, or a substantially different propulsion scheme is to be added.
- **Delta V Lost to Drag:** Delta-V or the change in velocity required for orbital change maneuvers. In MEO this is considered to be close to zero; however, in LEO atmospheric drag must be accounted for. For MEO-based spacecraft this variable refers only to degradation of the orbit due to gravitational forces and alignment with the rest of the constellation. This variable is not used for the GPS examination but is required for the space-weather example.
- **Delta V for Maneuvers:** The amount of Delta V or total impulse available to accelerate the spacecraft for maneuvers outside of normal station-keeping activities. This includes any propulsion required for end-of-life activities. In the model, this value and the Delta V lost to drag/magnetic effects are extrapolated from fuel mass or "wet mass" requirements provided to existing GPS designs, as there is no published source or requirement.
- **Propulsion Mass:** The mass of the hardware required for maneuvers and station keeping.
- **Fuel Mass:** The mass of propellant required for station-keeping and maneuvers.
- **Apogee Kick Motor:** Current GPS satellites launched on Delta IV rockets do not require an additional kick motor, however, it is possible that different constellations in different orbits may require such capability. The model allows for the addition of such a device.
- **Kick Motor Mass**: In the event a kick motor is required, its required mass is stored here. This variable is not used in the GPS BATNA examination but is required for examination of space-weather constellations.
- **Dry Mass:** Total mass of the satellite excluding fuel, kick motor, and any orbital insertion apparatus.
- **Wet Mass:** Total mass to be placed on launch vehicle. Includes fuel, kick-motor and additional hardware required for orbital insertion.
- **Launch Vehicle:** The name of the rocket to be used e.g., Atlas V_500.
- **Number of Launch Vehicles:** Number of launch vehicles required to place all satellites in this block buy into orbit.
- **Maximum Space Vehicles per Launch Vehicle Allowed:** Maximum number of satellites allowed to be placed on a single launch vehicle. Currently, one GPS satellite is launched per rocket. One future option may be to dual-launch GPS satellites, placing two satellites in orbit using one large launch vehicle. In the event of disaggregation and smaller satellites, a cost-affordable solution would almost invariably mandate the ability to launch multiple satellites on a single launch vehicle. SpaceX placed 11, 173 kg satellites and one mass simulator into LEO on a single rocket and Iridium was placed into LEO with between six and eight satellites per launch vehicle as early as 1996; however, no such launches have been performed for MEO. (ORBCOMM, 2015)
- **Maximum Space Vehicles per Launch Vehicle:** Largest number of satellites placed on any launch vehicle based on knapsack alignment.
- **Excess Launch Capacity**: Extra capacity available on the selected launch vehicle after manifesting of satellites. Typically one would seek to minimize this value, yet some excess is unavoidable.
-

13 Appendix B Variables and Definitions of TSE Model Outputs

1. **Program Start (year)**: When was this set of satellites procured?
2. **First Production SV Launched (year)**: When was the First Production Vehicle Ready/Launched? The time between this and Year of design represents the time required to spend the NRE and produce the Theoretical First Unit. In this TSE model this time must be an assumption based on other satellite programs. In the merged model this variable can be represented as the time through a process and the variable will gain greater fidelity and meaning.
3. **Gen Number**: The generation in sequence of this particular design, will become even more useful in the merged model when looking at sequences of generations across longer time periods.
4. **Design Life**: How long were the satellites built in this generation designed to last?
5. **NRE This Generation**: How much non-reoccurring engineering must be spent to fulfill the needs of this procurement? Computed as outlined in Theoretical First Unit.
6. **Cost First Production:** What is the expected cost of the first production unit? Computed as outlined in First Production Unit.
7. **Replication Costs (TSE):** This variable is the TSE's estimate of replication costs when picking an 's' value as described in the section Total Cost and Cost per Operational Year
8. **Replication Costs (SD)**: This variable represents the System Dynamics Model's computation of the Replication Costs for this generation. This variable and its computation is explained in Chapters 2 and 3.
9. **Launch Costs:** Launch costs for this generation as outlined in Launcher Select.
10. **Ops Costs:** Operations costs for this generation as outline in Cost Models.
11. **Cost per Year Total (all generations):** The life-cycle cost of this effort and all previous efforts since model inception (2008), including payload, satellite, launch vehicle, and operations and maintenance costs for the entire history of this system, through the end of this buy's capability, divided by the design life.
12. **Cost per Year (This Generation):** The life-cycle cost of just this acquisition since this program's start date, including payload, satellite, launch vehicle, and operations and maintenance costs for the entire history of this system through the end of this buy's capability, divided by the design life of this generation.
13. **SVs Ordered this Generation:** The number of physical satellites built this generation.
14. **Equivalent Capability as BATNA Dry Mass (Kg):** Dry mass required to achieve equivalent performance as the BATNA in this generation; computed as outlined in Mass Model.
15. **Equivalent Capability as BATNA Wet Mass (Kg):** Wet Mass required to achieve equivalent performance as the BATNA in this generation, computed as outlined in Mass Model.

14 Appendix C Example RF Configuration File (Class and Variables)

```matlab
%%The following variables are ones which will be actively changed
%%throughout.

RF_comm.downlink_antenna_gain = 8; %3 is a low end %dB
RF_comm.downlink_freq = 2.1; %GHz

%constant
RF_comm.modem_implementation_loss = -1.20; %dB
RF_comm.required_Eb_No = 3.89; %dB
RF_comm.link_margin = 3.1; %dB
RF_comm.code_rate = 9/10;
RF_comm.channel_bandwidth = 36; %MHz
RF_comm.downlink_range = 500; %km
RF_comm.ground_diameter = 2; %m
%RF_down_pwr_from_data.downlink_power = 150; %W
RF_comm.downlink_coverage_area = 13.30; %degrees^2
RF_comm.required_power_dBW = 0;


%calculated
RF_comm.bandwidth = 0; %MHz

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%satellite downlink characteristics

%user defined
RF_comm.downlink_efficiency = 0.70; %percentage
RF_comm.downlink_backoff_and_line_loss = -4.5; %dB
%calculated
%RF_down_pwr_from_data.downlink_antenna_gain = 0; %dBi
%RF_down_pwr_from_data.downlink_eirp = 0; %dBW

%%downlink propagation losses

%user defined
RF_comm.downlink_atmospheric_loss = -7.0; %dB
%calculated
RF_comm.downlink_space_loss = 0; %dB
RF_comm.downlink_net_path_loss = 0; %dB

%%ground receiver characteristics
%user defined
RF_comm.ground_efficiency = 0.55; %percentage
RF_comm.ground_line_loss = -2.0; %dB
RF_comm.ground_system_noise_temp = 27.0; %dB
%calculated
RF_comm.ground_beamwidth = 0; %degrees
RF_comm.ground_gain = 0; %dBi
RF_comm.ground_receiver_carrier_power = 0; %dBW
RF_comm.ground_G_T = 0; %dB/K
RF_comm.ground_receiver_C_No = 0; %dBW
```

```matlab
RF_comm.ground_data_rate = 0; %dB-Hz
RF_comm.ground_available_Eb_No = 0; %dB-Hz
```

15 Appendix D RF Link Closure Code

```
%Data needed for required power calculation:
RF_down_pwr_from_data.downlink_space_loss          =        -(92.45        +
20*log10(RF_down_pwr_from_data.downlink_range)                             +
20*log10(RF_down_pwr_from_data.downlink_freq)); %dB
RF_down_pwr_from_data.downlink_net_path_loss                              =
RF_down_pwr_from_data.downlink_space_loss                                 +
RF_down_pwr_from_data.downlink_atmospheric_loss; %dB
RF_down_pwr_from_data.ground_beamwidth                                    =
21/(RF_down_pwr_from_data.downlink_freq*RF_down_pwr_from_data.ground_diameter
); %degrees
RF_down_pwr_from_data.ground_gain          =          20.4          +
20*log10(RF_down_pwr_from_data.downlink_freq)                             +
20*log10(RF_down_pwr_from_data.ground_diameter)                          +
10*log10(RF_down_pwr_from_data.ground_efficiency); %dBi
RF_down_pwr_from_data.ground_data_rate                                    =
10*log10(RF_down_pwr_from_data.data_rate*10^6); %dB-Hz
RF_down_pwr_from_data.bandwidth                                           =
1.34*RF_down_pwr_from_data.data_rate/RF_down_pwr_from_data.code_rate/2; %MHz


%Required power calculation
RF_down_pwr_from_data.required_power_dBW                                  =
RF_down_pwr_from_data.required_Eb_No  +  RF_down_pwr_from_data.link_margin  +
RF_down_pwr_from_data.ground_data_rate                                    +
RF_down_pwr_from_data.ground_system_noise_temp        -        228.6      -
RF_down_pwr_from_data.ground_gain                                         -
RF_down_pwr_from_data.downlink_net_path_loss                              -
RF_down_pwr_from_data.ground_line_loss                                    -
RF_down_pwr_from_data.downlink_antenna_gain                              -
RF_down_pwr_from_data.downlink_backoff_and_line_loss;


%EIRP, based on above calculation
RF_down_pwr_from_data.downlink_eirp = RF_down_pwr_from_data.required_power_dBW
+            RF_down_pwr_from_data.downlink_antenna_gain            +
RF_down_pwr_from_data.downlink_backoff_and_line_loss; %dBW


%Performance on ground, based on calculated satellite power
RF_down_pwr_from_data.ground_receiver_carrier_power                       =
RF_down_pwr_from_data.required_power_dBW + RF_down_pwr_from_data.ground_gain +
RF_down_pwr_from_data.downlink_net_path_loss                              +
RF_down_pwr_from_data.ground_line_loss; %dBW
RF_down_pwr_from_data.ground_G_T   =   RF_down_pwr_from_data.ground_gain   -
RF_down_pwr_from_data.ground_system_noise_temp; %dB/K
RF_down_pwr_from_data.ground_receiver_C_No                                =
RF_down_pwr_from_data.ground_receiver_carrier_power                       -
RF_down_pwr_from_data.ground_system_noise_temp + 228.6; %dBW
RF_down_pwr_from_data.ground_available_Eb_No                              =
RF_down_pwr_from_data.ground_receiver_C_No                                -
RF_down_pwr_from_data.ground_data_rate; %dB-Hz


Data_rate_Mbps = RF_down_pwr_from_data.data_rate
Required_transmit_power_dBW = RF_down_pwr_from_data.required_power_dBW;
Received_carrier_power_dB                                                 =
RF_down_pwr_from_data.ground_receiver_carrier_power
Bandwidth_possible_MHz = RF_down_pwr_from_data.bandwidth;
```

```
Required_power_Watts = 10^(RF_down_pwr_from_data.required_power_dBW/10)
```

16 Appendix E Launch Vehicle Database Delta IV

```matlab
veh{i}.family = 'Delta';
veh{i}.class = 'Delta IV';
veh{i}.country = 'USA';
veh{i}.provider = 'Boeing';
veh{i}.success_flight = 0; %# of flights%
veh{i}.total_flights = 0;
veh{i}.stddwntime = 0.3; %years
veh{i}.surge = 1.15; %percentage
veh{i}.max_axial_accel = 6.5; %g
veh{i}.max_lat_accel = 2.5; %g
veh{i}.min_lat_freq = 27; %Hz
veh{i}.min_long_freq = 30; %Hz
veh{i}.shock = 4000; %g
veh{i}.acoustic = 133; %dB
veh{i}.fairing_press = 4.14; %kPa/s
veh{i}.max_aeroheating = 1135; %W/m^2
veh{i}.air_clean = 100000; %ppm
veh{i}.orbital_accu_alt = 8.6; %km
veh{i}.orbital_accu_incl = 0.06; %km
veh{i}.rate = 15; %# per year


veh{i}.site{1}.name = 'KSC';
veh{i}.site{1}.min_incl = 28.5; %deg
veh{i}.site{1}.max_incl = 51; %deg


veh{i}.site{2}.name = 'Vandenberg';
veh{i}.site{2}.min_incl = 63; %deg
veh{i}.site{2}.max_incl = 120; %deg


 %-- Variants / Upper Stages --
 j=1;
  veh{i}.upper_stage{j}.var_name = 'DIV M';
  veh{i}.upper_stage{j}.mass2leo = 8600; %kg
  veh{i}.upper_stage{j}.mass2polar = 6870; %kg
  veh{i}.upper_stage{j}.mass2sunsync = 6300; %kg
  veh{i}.upper_stage{j}.mass2gto = 3900; %kg
  veh{i}.upper_stage{j}.mass2geo = 0; %kg
  veh{i}.upper_stage{j}.cost = 90; %million dollars
  veh{i}.upper_stage{j}.fairingheight = 5.3; %m
  veh{i}.upper_stage{j}.fairingdiameter = 3.8; %m

 j=j+1;
  veh{i}.upper_stage{j}.var_name = 'DIV M+';
  veh{i}.upper_stage{j}.mass2leo = 13600; %kg
  veh{i}.upper_stage{j}.mass2polar = 10400; %kg
  veh{i}.upper_stage{j}.mass2SS = 11800; %kg
  veh{i}.upper_stage{j}.mass2sunsync = 9600; %kg
  veh{i}.upper_stage{j}.mass2gto = 6120; %kg
  veh{i}.upper_stage{j}.mass2geo = 2100; %kg
  veh{i}.upper_stage{j}.cost = 110; %million dollars
  veh{i}.upper_stage{j}.fairingheight = 5.3; %m
  veh{i}.upper_stage{j}.fairingdiameter = 3.8; %m

 j=j+1;
```

```
veh{i}.upper_stage{j}.var_name = 'DIV H';
veh{i}.upper_stage{j}.mass2leo = 25800; %kg
veh{i}.upper_stage{j}.mass2polar = 20800; %kg
veh{i}.upper_stage{j}.mass2SS = 23250; %kg
veh{i}.upper_stage{j}.mass2sunsync = 13200; %kg
veh{i}.upper_stage{j}.mass2gto = 10843; %kg
veh{i}.upper_stage{j}.mass2geo = 6100; %kg
veh{i}.upper_stage{j}.cost = 170; %million dollars
veh{i}.upper_stage{j}.fairingheight = 7.2; %m
veh{i}.upper_stage{j}.fairingdiameter = 4.6; %m
```

17 Appendix F Implementation of Subscripts in Vensim

Figure 17-1 depicts all elements within the Learning flow seen in
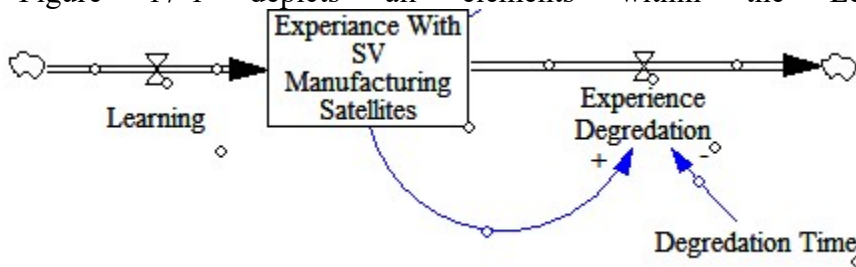
Figure 17-2. This is how Vensim physically implements a subscript. Each of the Elements SV1 through SV8 represent flows through the same structure but may contain different levels.
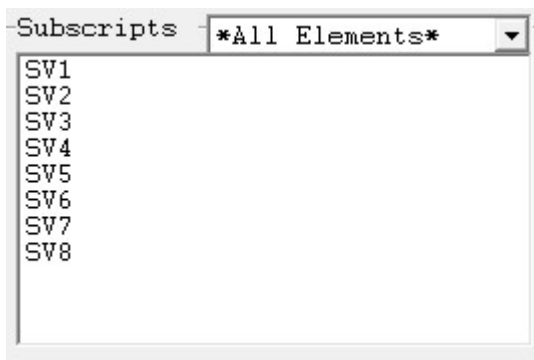
Figure 17-1: Creating Subscripts in Vensim
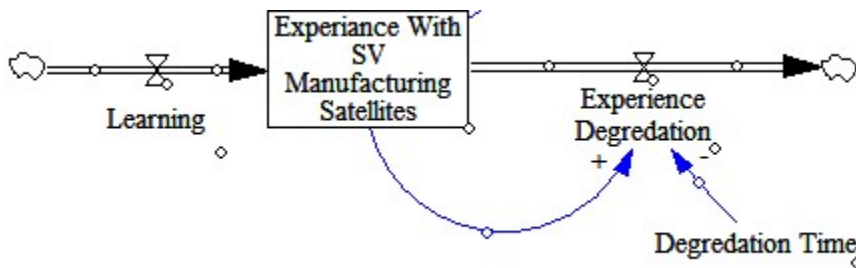
Figure 17-2: Experience Stock with Subscripts Enabled

Having activated subscrpts for the inflow of Learning, and by extension all stocks and flows which are connected to this flow different equations or logic is implemented for each subscript. Figure 17-3 and Figure 17-4 show the respective equations for subscript SV1 and subscript SV8. In Subscript one only the inputs from all other subscript [SV1] present in the model are added to the

Learning   inflow.
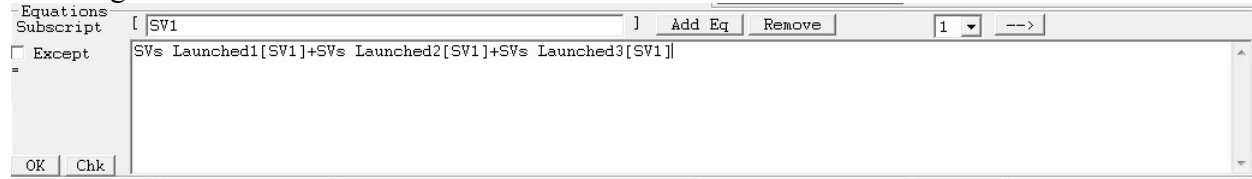
Figure 17-3: Learning Flow, Subscript 1

In [SV8] all subscripts 1 through 8 are summed. This equation physically states that whatever activity is present in the GPS constellation is also part of the industry as a whole. As experience is translated into learning effects within the model, learning effects are computed individually for each subscript; representing specific learning for that subscript or satellite program. The eighth subscript which is now the sum of the context variable for the industry dealing with activity levels is summed with the activity respective to subscripts 1 through 7 as well; which in this case represents activity in the GPS constellation. This translates into learning within the GPS industry extends to learning in the industry as a whole.

Figure 17-4: Learning Flow, Subscript 8

This adds to model validity because any SD model once deductively assembled should be inductively tuned through historical data. In this case, running historical data for the entire space industry through subscript [SV8] variables in the model should reach levels seen in the real world, or at least the trends and inflection of curves should match real world data. If other behavior is seen, one might suggest that a loop or structure is missing from this model and further investigation is required.

18 Appendix G GPS Program of Record Command Script

:Time=1983
Change Performance Demands[Gen1]=1660
Change Performance Demands[Gen2]=1816
Change Performance Demands[Gen3]=2030
Change Performance Demands[Gen4]=1650
Change Performance Demands[Gen5]=3680
Change Performance Demands[Gen6]=3680
Change Performance Demands[Gen7]=3680
Change Performance Demands[Gen8]=3680
Change Performance Demands[Gen9]=3680
Difficulty Reduction Under Disaggregation[Gen1]=1
Difficulty Reduction Under Disaggregation[Gen2]=1
Difficulty Reduction Under Disaggregation[Gen3]=1
Difficulty Reduction Under Disaggregation[Gen4]=1
Difficulty Reduction Under Disaggregation[Gen5]=1
Difficulty Reduction Under Disaggregation[Gen6]=1
Difficulty Reduction Under Disaggregation[Gen7]=1
Difficulty Reduction Under Disaggregation[Gen8]=1
Difficulty Reduction Under Disaggregation[Gen9]=1
Disaggregate[Gen1]=1
Disaggregate[Gen2]=1
Disaggregate[Gen3]=1
Disaggregate[Gen4]=1
Disaggregate[Gen5]=1
Disaggregate[Gen6]=1
Disaggregate[Gen7]=1
Disaggregate[Gen8]=1
Disaggregate[Gen9]=1
Equilibrium Tuning Constant=0.015
Error Factor=0.9
Firefighting Correct Level=1
Matlab Pulse Gen=0
Matlab Pulse NRE=0
Max Error Fraction=0.9
Mitigate Firefighting=1
Program Funding Override[Gen5]=450
Program Funding Override[Gen6]=450
Program Funding Override[Gen7]=450
Program Funding Override[Gen8]=450
Program Funding Override[Gen9]=450
Set Design Life[Gen1]=0
Set Design Life[Gen2]=0
Set Design Life[Gen3]=0
Set Design Life[Gen4]=0

Set Design Life[Gen5]=15
Set Design Life[Gen6]=20
Set Design Life[Gen7]=24
Set Design Life[Gen8]=24
Set Design Life[Gen9]=24
Tech Halflife Context=4.5
Tune Design Life=1
:Time=2008
Change Performance Demands[Gen5]=3547
Matlab Pulse Gen=1
Matlab Pulse NRE=1
Program Funding Override[Gen5]=518
Set Design Life[Gen5]=10
:Time=2008.13
Matlab Pulse Gen=0
Matlab Pulse NRE=0
:Time=2018.75
Change Performance Demands[Gen6]=3515
Matlab Pulse Gen=1
Matlab Pulse NRE=1
Program Funding Override[Gen6]=516
Set Design Life[Gen6]=10
:Time=2018.88
Matlab Pulse Gen=0
Matlab Pulse NRE=0
:Time=2029.5
Change Performance Demands[Gen7]=3515
Matlab Pulse Gen=1
Matlab Pulse NRE=1
Program Funding Override[Gen7]=516
Set Design Life[Gen7]=10
:Time=2029.63
Matlab Pulse Gen=0
Matlab Pulse NRE=0
:Time=2040.25
Change Performance Demands[Gen8]=3515
Matlab Pulse Gen=1
Matlab Pulse NRE=1
Program Funding Override[Gen8]=516
Set Design Life[Gen8]=10
:Time=2040.38
Matlab Pulse Gen=0
Matlab Pulse NRE=0
:Time=2051
Change Performance Demands[Gen9]=3515
Matlab Pulse Gen=1

Matlab Pulse NRE=1
Program Funding Override[Gen9]=500
Set Design Life[Gen9]=10
:Time=2051.13
Matlab Pulse Gen=0
Matlab Pulse NRE=0
:Time=2068.13

19 Appendix H Interfaces from SD to TSE and TSE to SD

From SD to TSE

- Request for Satellites (TSE trigger)
- Satellites on Orbit; represents the amount of capability on orbit at any given time. Checks against minimum performance requirement.
- Stock of Capability (in operational years) on orbit; used to trigger the procurement when capability runs out.
- Stock of Capability (In operational years) in production; a proxy metric for the health of the Industrial base, it is also used to trigger procurement.
- Efficiency Metric; used to adjust and compute the production cost.
- Production Time of Satellites (year)
- Funding Delta to Calculate over or under run Relative to Program Baseline/Initial Estimate
- Technology Half-life; used to adjust the theoretical first unit (and NRE) cost in a new generation.
- The Current Year in Execution; responsible for synchronizing context variables with time.

From TSE to SD
- Quantity of Satellites to Produce
- Design Life of Satellites
- Mass of Satellites; Serves as the proxy for work in the production pipeline
  - Sum Total Mass if Disaggregated
- Program Baseline ($M FY 2010 dollars); How much money per year will be sent to production.
- NRE Events; Will production be a clone or a technology update)
- Number of Launch Vehicles (quantity) and cost of Launch Vehicles Required ($M FY 2010 dollars); This may be modified based upon the context of the SD model.

20 Appendix I Control Module Execution Sequence
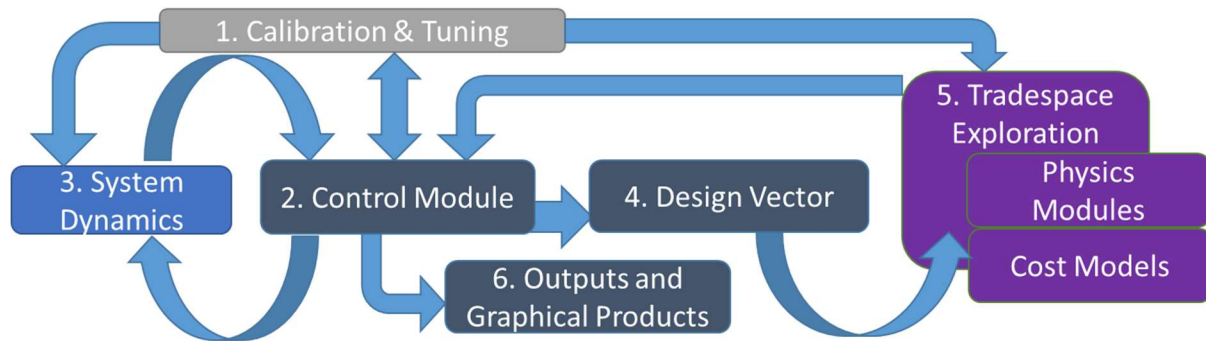
Figure 20-1: Execution Flow Control

1. Calibration and Tuning runs the SD model on historical data until the time point where analysis is to begin; this trains the model based on tuning data.
   a. For TSE this tuning involves the adjustment of cost models to match historical GPS systems for weight and cost of payload, bus development, and production.
   b. For SD this is the tuning routine or "command script" developed in the last chapter and listed in Appendix G GPS Program of Record Command Script
   c. Calibration and Tuning starts in 1988 and stops in 2008 at the decision point for the GPS III constellation. As previously noted, this enables GPS III to function as a hold-back set of data, as well as allow comparison of the outcomes of decisions made in 2008 against potential policy alternatives.
2. The Control Module takes over when the model represents the Space Industry in 2008. This state is saved and associated with Level 1 Node 1 seen in Figure 5-4. Visually, this can be seen as the blue circle in Figure 5-7.
   a. If there is a desire to compare a policy or constellation design different than the GPS III Program of Record in 2008, it would be instantiated and saved as Level 1 Node 2. Such a node is not shown in Figure 5-4.
3. The Control Module reads the context variables in the SD Model and the policies selected for examination.
   a. The model calibration was such that in 2008 a new acquisition would be required to start in 2008 to match historical data.
   b. Future acquisitions will start when the Control Module detects a gap in performance will occur if a new acquisition is not created.
      i. This replaces the SD model's pipeline structure for triggering procurement seen in Chapter 3 Figure 3-11: Generic Pipeline with Correction to Changing Outflow specifically the variable "Replacement Starts"
      ii. This is why in Figure 3-40: Vensim GPS Production Model there is no equivalent to "Replacement Starts" as it has now been pulled out of the SD model into the control code.
   c. This new acquisition is not guaranteed to protect against performance gaps as it is based on the historical performance of the acquisition system depicted in the SD model. If development of the next generation takes longer or production of the next generation is slower than expected, capability gaps can emerge and this would be handled as failing to meet a constraint in analysis. The model may be able to correct

over time through natural occurrence or through program re-baselining; in either case the result is captured and can be analyzed.

4. The Design Vector is created. This creates $2^{(n-1)} +1$ possible implementations where n is the number of design parameters to change in TSE, assuming a full factorial expansion. The Design Vector Module performs tree-pruning, saving computational time by deleting illogical design choices through implementation of three rules:
   a. Architectures are not "re-aggregated" after a disaggregated approach has been selected.
   b. The option to clone the last generation can occur only if no changes are made to the design. This is the reason for the "+1" and the "n-1" in the size of the Design Vector. This requires pruning the Design Vector of impossible implementations. This also means the design vector must possess an NRE pulse if any change occurs to the architecture design.
   c. Performance once added, is never subtracted. If capabilities such as crosslinks, spot-beams, and new signals are added in the future, once added they are not removed.

5. The TSE module receives the Design Vector and computes the associated payloads, satellites, architectures, operations costs and rockets required to deliver the specified design points.
   a. The TSE module returns the cost and performance results to the Control Module.
   b. The Control Module saves the results in the Memory Tree. This is represented in Figure 5-4 as Level 2 Nodes 1, 2 and 3.
   c. The return of all three design points, not just the optimal design, is stored in the Memory Tree. Highlighted in green in Figure 5-3, this step exchanges memory and computational time to get around myopic optimization by carrying forward clearly sub-optimal designs; as opposed to more efficient point optimization techniques and a single best solution. This enables testing of policies with larger up-front costs that may take years (decades) to realize their potential.
   d. Generation-over-generation results can be seen in Figure 5-20: where the change in the cost per operational year for various policies is shown by the change from the first node (generation) to the fourth node (generation).

6. This completes the first execution of the model.
   a. At this point the three, Level 2 nodes could be spawned into individual threads to enable parallel executions.
   b. This will hold true at every node in the Memory Tree on future execution cycles. Once level order execution has been selected, each node is no longer dependent on other nodes' results and out-of-order execution is possible.

7. The Control Module now resets the SD Model to the Vensim command script stored at Level 2 Node 1.
   a. The Control Module allows the SD model to step time forward until a new acquisition is required.
   b. This is visually represented in Figure 5-4 by the lines connecting nodes to each other.
   c. A copy of the command script for the GPS Program of Record is included in Appendix G GPS Program of Record Command Script.

8. After the Control Module execution completes, all remaining computations are identical to steps 3 to 7, and the Control Module completes them in a loop.
    a. The Control Module processes all the Level 2 nodes then in sequence, all the Level 3, 4 and finally, Level 5 nodes.
    b. Execution continues until all nodes in the tree arrive at a terminal condition, either time beyond the range of examination or a tree depth of four GPS generations.
    c. This form of execution is known as Level-Order Execution and is illustrated in Figure 5-5.
9. After the memory tree is constructed data processing can be conducted on the tree.
    a. The nodes of the memory tree contain the results of TSE runs.
    b. The connections between the nodes are the commands scripts produced for the TSE model across the time between acquisition decisions; their names are stored with respect to the nodes they link.

21 Appendix J Upgrade Path for GPS BATNA

21.1 Generation 1

```
architecture.num_sats_to_complete = [1];

architecture.payloads_sat_1 =
[all_L1,all_L2,Nudet_stuff,saftey,mil1,mil2,Atomic_Clock];

architecture.satellites = satellite;

architecture.satellites.payload = all_L1;
architecture.satellites.payload(2) = all_L2;
architecture.satellites.payload(3) = Nudet_stuff;
architecture.satellites.payload(4) = saftey;
architecture.satellites.payload(5) = mil1;
architecture.satellites.payload(6) = mil2;
architecture.satellites.payload(7) = Atomic_Clock;
```

21.2 Generation 2,3 and 4

```
architecture.num_sats_to_complete = [1];
architecture.payloads_sat_1 =
[all_L1,all_L2,Nudet_stuff,saftey,mil1,mil2,Atomic_Clock,new_sig_L4,CL1];

architecture.satellites = satellite;

architecture.satellites.payload = all_L1;
architecture.satellites.payload(2) = all_L2;
architecture.satellites.payload(3) = Nudet_stuff;
architecture.satellites.payload(8) = new_sig_L4;
architecture.satellites.payload(4) = saftey;
architecture.satellites.payload(5) = mil1;
architecture.satellites.payload(6) = mil2;
architecture.satellites.payload(7) = Atomic_Clock;
architecture.satellites.payload(9) = CL1;
```

22 Appendix K Upgrade Path for 2x Disaggregation (Military and Civilian)

22.1 Generation 1

```
architecture.num_sats_to_complete = [2];
architecture.payloads_sat_1 = [all_L1,all_L2,saftey,Atomic_Clock];
architecture.payloads_sat_2 = [Nudet_stuff,mil1,mil2,Atomic_Clock];

architecture.satellites = satellite;
architecture.satellites(2) = satellite;

architecture.satellites(1).payload = all_L1;
architecture.satellites(1).payload(2) = all_L2;
architecture.satellites(1).payload(3) = saftey;
architecture.satellites(1).payload(4) = Atomic_Clock;

architecture.satellites(2).payload = Nudet_stuff;
architecture.satellites(2).payload(2) = mil1;
architecture.satellites(2).payload(3) = mil2;
architecture.satellites(2).payload(4) = Atomic_Clock;
```

22.2 Generation 2, 3 and 4

```
architecture.num_sats_to_complete = [2];
architecture.payloads_sat_1 = [all_L1,all_L2,saftey, new_sig_L4,
Atomic_Clock,CL4];
architecture.payloads_sat_2 = [Nudet_stuff,mil1,mil2,Atomic_Clock,CL4];

architecture.satellites = satellite;
architecture.satellites(2) = satellite;

architecture.satellites(1).payload = all_L1;
architecture.satellites(1).payload(2) = all_L2;
architecture.satellites(1).payload(3) = saftey;
architecture.satellites(1).payload(4) = new_sig_L4;
architecture.satellites(1).payload(5) = Atomic_Clock;
architecture.satellites(1).payload(6) = CL1;

architecture.satellites(2).payload = Nudet_stuff;
architecture.satellites(2).payload(2) = mil1;
architecture.satellites(2).payload(3) = mil2;
architecture.satellites(2).payload(4) = Atomic_Clock;
architecture.satellites(2).payload(5) = CL1;
```

23 Appendix L Upgrade Path for 3x Disaggregation (Galileo Implementation)

23.1 Generation 1

```
architecture.num_sats_to_complete = [3];
architecture.payloads_sat_1 = [all_L1,all_L2,Atomic_Clock];
architecture.payloads_sat_2 = [saftey,Nudet_stuff,Atomic_Clock];
architecture.payloads_sat_3 = [mil1,mil2,Atomic_Clock];

architecture.satellites = satellite;
architecture.satellites(2) = satellite;
architecture.satellites(3) = satellite;

architecture.satellites(1).payload = all_L1;
architecture.satellites(1).payload(2) = all_L2;
architecture.satellites(1).payload(3) = Atomic_Clock;



architecture.satellites(2).payload = saftey;
architecture.satellites(2).payload(2) = Nudet_stuff;
architecture.satellites(2).payload(3) = Atomic_Clock;



architecture.satellites(3).payload = mil1;
architecture.satellites(3).payload(2) = mil2;
architecture.satellites(3).payload(3) = Atomic_Clock;
```

23.2 Generation 2, 3 and 4 (Option 1, New Signal)

```
architecture.num_sats_to_complete = [3];
architecture.payloads_sat_1 = [all_L1,all_L2,Atomic_Clock,new_sig_L4];
architecture.payloads_sat_2 = [saftey,Nudet_stuff,Atomic_Clock];
architecture.payloads_sat_3 = [mil1,mil2,Atomic_Clock];

architecture.satellites = satellite;
architecture.satellites(2) = satellite;
architecture.satellites(3) = satellite;
architecture.satellites(1).payload = all_L1;
architecture.satellites(1).payload(2) = all_L2;
architecture.satellites(1).payload(3) = new_sig_L4;
architecture.satellites(1).payload(4) = Atomic_Clock;



architecture.satellites(2).payload = saftey;
architecture.satellites(2).payload(2) = Nudet_stuff;
architecture.satellites(2).payload(3) = Atomic_Clock;



architecture.satellites(3).payload = mil1;
architecture.satellites(3).payload(2) = mil2;
architecture.satellites(3).payload(3) = Atomic_Clock;
```

23.3 Generation 2, 3 and 4 (Option 2, New Signal and Crosslink)

```
architecture.num_sats_to_complete = [3];
architecture.payloads_sat_1 = [all_L1,all_L2,Atomic_Clock,new_sig_L4,CL3];
architecture.payloads_sat_2 = [saftey,Nudet_stuff,Atomic_Clock,CL3];
architecture.payloads_sat_3 = [mil1,mil2,Atomic_Clock,CL3];

architecture.satellites = satellite;
architecture.satellites(2) = satellite;
architecture.satellites(3) = satellite;
architecture.satellites(1).payload = all_L1;
architecture.satellites(1).payload(2) = all_L2;
architecture.satellites(1).payload(3) = new_sig_L4;
architecture.satellites(1).payload(4) = Atomic_Clock;
architecture.satellites(1).payload(5) = CL3;

architecture.satellites(2).payload = saftey;
architecture.satellites(2).payload(2) = Nudet_stuff;
architecture.satellites(2).payload(3) = Atomic_Clock;
architecture.satellites(2).payload(4) = CL3;


architecture.satellites(3).payload = mil1;
architecture.satellites(3).payload(2) = mil2;
architecture.satellites(3).payload(3) = Atomic_Clock;
architecture.satellites(3).payload(4) = CL3;
```

24 Appendix M Upgrade Path for 7x Disaggregation (Full Disaggregation)

24.1 Generation 1

```
architecture.num_sats_to_complete = [6];
architecture.payloads_sat_1 = [all_L1,Atomic_Clock];
architecture.payloads_sat_2 = [all_L2,Atomic_Clock];
%architecture.payloads_sat_3 = [new_sig_L4];
architecture.payloads_sat_3 = [saftey,Atomic_Clock];
architecture.payloads_sat_4 = [Nudet_stuff,Atomic_Clock];
architecture.payloads_sat_5 = [mil1,Atomic_Clock];
architecture.payloads_sat_6 = [mil2,Atomic_Clock];


architecture.satellites = satellite;
architecture.satellites(2) = satellite;
architecture.satellites(3) = satellite;
architecture.satellites(4) = satellite;
architecture.satellites(5) = satellite;
architecture.satellites(6) = satellite;
%architecture.satellites(7) = satellite;

architecture.satellites(1).payload = all_L1;
architecture.satellites(1).payload(2) = Atomic_Clock;
architecture.satellites(2).payload = all_L2;
architecture.satellites(2).payload(2) = Atomic_Clock;
%architecture.satellites(3).payload = new_sig_L4;
architecture.satellites(3).payload = saftey;
architecture.satellites(3).payload(2) = Atomic_Clock;
architecture.satellites(4).payload = Nudet_stuff;
architecture.satellites(4).payload(2) = Atomic_Clock;
architecture.satellites(5).payload = mil1;
architecture.satellites(5).payload(2) = Atomic_Clock;
architecture.satellites(6).payload = mil2;
architecture.satellites(6).payload(2) = Atomic_Clock;
```

24.2 Generation 2, 3 and 4 (Option 1 New Signal)

```
architecture.num_sats_to_complete = [7];
architecture.payloads_sat_1 = [all_L1,Atomic_Clock];
architecture.payloads_sat_2 = [all_L2,Atomic_Clock];
architecture.payloads_sat_7 = [new_sig_L4,Atomic_Clock];
architecture.payloads_sat_3 = [saftey,Atomic_Clock];
architecture.payloads_sat_4 = [Nudet_stuff,Atomic_Clock];
architecture.payloads_sat_5 = [mil1,Atomic_Clock];
architecture.payloads_sat_6 = [mil2,Atomic_Clock];


architecture.satellites = satellite;
architecture.satellites(2) = satellite;
architecture.satellites(3) = satellite;
architecture.satellites(4) = satellite;
architecture.satellites(5) = satellite;
```

```
architecture.satellites(6) = satellite;
architecture.satellites(7) = satellite;

architecture.satellites(1).payload = all_L1;
architecture.satellites(1).payload(2) = Atomic_Clock;
architecture.satellites(2).payload = all_L2;
architecture.satellites(2).payload(2) = Atomic_Clock;
architecture.satellites(7).payload = new_sig_L4;
architecture.satellites(7).payload(2) = Atomic_Clock;
architecture.satellites(3).payload = saftey;
architecture.satellites(3).payload(2) = Atomic_Clock;
architecture.satellites(4).payload = Nudet_stuff;
architecture.satellites(4).payload(2) = Atomic_Clock;
architecture.satellites(5).payload = mil1;
architecture.satellites(5).payload(2) = Atomic_Clock;
architecture.satellites(6).payload = mil2;
architecture.satellites(6).payload(2) = Atomic_Clock;
```

24.3 Generation 2, 3 and 4 (Option 1 New Signal and Crosslink)

```
architecture.num_sats_to_complete = [7];
architecture.payloads_sat_1 = [all_L1,Atomic_Clock,CL7];
architecture.payloads_sat_2 = [all_L2,Atomic_Clock,CL7];
architecture.payloads_sat_3 = [saftey,Atomic_Clock,CL7];
architecture.payloads_sat_4 = [Nudet_stuff,Atomic_Clock,CL7];
architecture.payloads_sat_5 = [mil1,Atomic_Clock,CL7];
architecture.payloads_sat_6 = [mil2,Atomic_Clock,CL7];
architecture.payloads_sat_7 = [new_sig_L4,Atomic_Clock,CL7];

architecture.satellites = satellite;
architecture.satellites(2) = satellite;
architecture.satellites(3) = satellite;
architecture.satellites(4) = satellite;
architecture.satellites(5) = satellite;
architecture.satellites(6) = satellite;
architecture.satellites(7) = satellite;

architecture.satellites(1).payload = all_L1;
architecture.satellites(1).payload(2) = Atomic_Clock;
architecture.satellites(1).payload(3) = CL7;

architecture.satellites(2).payload = all_L2;
architecture.satellites(2).payload(2) = Atomic_Clock;
architecture.satellites(2).payload(3) = CL7;

architecture.satellites(3).payload = saftey;
architecture.satellites(3).payload(2) = Atomic_Clock;
architecture.satellites(3).payload(3) = CL7;

architecture.satellites(4).payload = Nudet_stuff;
architecture.satellites(4).payload(2) = Atomic_Clock;
architecture.satellites(4).payload(3) = CL7;

architecture.satellites(5).payload = mil1;
```

```
architecture.satellites(5).payload(2) = Atomic_Clock;
architecture.satellites(5).payload(3) = CL7;


architecture.satellites(6).payload = mil2;
architecture.satellites(6).payload(2) = Atomic_Clock;
architecture.satellites(6).payload(3) = CL7;


architecture.satellites(7).payload = new_sig_L4;
architecture.satellites(7).payload(2) = Atomic_Clock;
architecture.satellites(7).payload(3) = CL7;
```

25 Appendix N Upgrade Path for Survivable Disaggregated Architecture

25.1 Generation 1

```
architecture.num_sats_to_complete = [4];
architecture.payloads_sat_1 = [all_L1,all_L2,Atomic_Clock];
architecture.payloads_sat_2 = [all_L2, mil1, Nudet_stuff,Atomic_Clock];
architecture.payloads_sat_3 = [mil1,mil2, Nudet_stuff,Atomic_Clock];
architecture.payloads_sat_4 = [mil2,all_L1,Atomic_Clock];

architecture.satellites = satellite;
architecture.satellites(2) = satellite;
architecture.satellites(3) = satellite;
architecture.satellites(4) = satellite;

architecture.satellites(1).payload = all_L1;
architecture.satellites(1).payload(2) = all_L2;
architecture.satellites(1).payload(3) = Nudet_stuff;
architecture.satellites(1).payload(4) = Atomic_Clock;

architecture.satellites(2).payload = all_L2;
architecture.satellites(2).payload(2) = mil1;
architecture.satellites(2).payload(3) = Nudet_stuff;
architecture.satellites(2).payload(4) = Atomic_Clock;

architecture.satellites(3).payload = mil1;
architecture.satellites(3).payload(2) = mil2;
architecture.satellites(3).payload(3) = Atomic_Clock;

architecture.satellites(4).payload = mil2;
architecture.satellites(4).payload(2) = all_L1;
architecture.satellites(4).payload(3) = Atomic_Clock;
```

25.2 Generation 2

```
architecture.num_sats_to_complete = [5];
architecture.payloads_sat_1 = [all_L1,all_L2,Atomic_Clock];
architecture.payloads_sat_2 = [all_L2, mil1, Nudet_stuff,Atomic_Clock];
architecture.payloads_sat_3 = [mil1,mil2, Nudet_stuff,Atomic_Clock];
architecture.payloads_sat_4 = [mil2,saftey,Atomic_Clock];
architecture.payloads_sat_5 = [saftey,all_L1,Atomic_Clock];

architecture.satellites = satellite;
architecture.satellites(2) = satellite;
architecture.satellites(3) = satellite;
architecture.satellites(4) = satellite;
architecture.satellites(5) = satellite;

architecture.satellites(1).payload = all_L1;
architecture.satellites(1).payload(2) = all_L2;
architecture.satellites(1).payload(3) = Nudet_stuff;
architecture.satellites(1).payload(4) = Atomic_Clock;
```

```
architecture.satellites(2).payload = all_L2;
architecture.satellites(2).payload(2) = mil1;
architecture.satellites(2).payload(3) = Nudet_stuff;
architecture.satellites(2).payload(4) = Atomic_Clock;


architecture.satellites(3).payload = mil1;
architecture.satellites(3).payload(2) = mil2;
architecture.satellites(3).payload(3) = Atomic_Clock;


architecture.satellites(4).payload = mil2;
architecture.satellites(4).payload(2) = saftey;
architecture.satellites(4).payload(3) = Atomic_Clock;


architecture.satellites(5).payload = saftey;
architecture.satellites(5).payload(2) = all_L1;
architecture.satellites(5).payload(3) = Atomic_Clock;
```

25.3 Generation 3

```
architecture.num_sats_to_complete = [6];
architecture.payloads_sat_1 = [all_L1,all_L2,Atomic_Clock];
architecture.payloads_sat_2 = [all_L2, mil1, Nudet_stuff,Atomic_Clock];
architecture.payloads_sat_3 = [mil1,mil2, Nudet_stuff,Atomic_Clock];
architecture.payloads_sat_4 = [mil2,saftey,Atomic_Clock];
architecture.payloads_sat_5 = [saftey,new_sig_L4,Atomic_Clock];
architecture.payloads_sat_6 = [new_sig_L4,all_L1,Atomic_Clock];

architecture.satellites = satellite;
architecture.satellites(2) = satellite;
architecture.satellites(3) = satellite;
architecture.satellites(4) = satellite;
architecture.satellites(5) = satellite;
architecture.satellites(6) = satellite;

architecture.satellites(1).payload = all_L1;
architecture.satellites(1).payload(2) = all_L2;
architecture.satellites(1).payload(3) = Atomic_Clock;

architecture.satellites(2).payload = all_L2;
architecture.satellites(2).payload(2) = mil1;
architecture.satellites(2).payload(3) = Atomic_Clock;

architecture.satellites(3).payload = mil1;
architecture.satellites(3).payload(2) = mil2;
architecture.satellites(3).payload(3) = Atomic_Clock;

architecture.satellites(4).payload = mil2;
architecture.satellites(4).payload(2) = saftey;
architecture.satellites(4).payload(3) = Atomic_Clock;

architecture.satellites(5).payload = saftey;
architecture.satellites(5).payload(2) = new_sig_L4;
```

381

```
architecture.satellites(5).payload(3) = Nudet_stuff;
architecture.satellites(5).payload(4) = Atomic_Clock;

architecture.satellites(6).payload = new_sig_L4;
architecture.satellites(6).payload(2) = all_L1;
architecture.satellites(6).payload(3) = Nudet_stuff;
architecture.satellites(6).payload(4) = Atomic_Clock;
```

25.4 Generation 4

```
architecture.num_sats_to_complete = [6];
architecture.payloads_sat_1 = [all_L1,all_L2,Atomic_Clock,CL7];
architecture.payloads_sat_2 = [all_L2, mil1,Nudet_stuff,Atomic_Clock,CL7];
architecture.payloads_sat_3 = [mil1,mil2, Nudet_stuff,Atomic_Clock,CL7];
architecture.payloads_sat_4 = [mil2,saftey,Atomic_Clock];
architecture.payloads_sat_5 = [saftey,new_sig_L4,Atomic_Clock,CL7];
architecture.payloads_sat_6 = [new_sig_L4,all_L1,Atomic_Clock,CL7];

architecture.satellites = satellite;
architecture.satellites(2) = satellite;
architecture.satellites(3) = satellite;
architecture.satellites(4) = satellite;
architecture.satellites(5) = satellite;
architecture.satellites(6) = satellite;

architecture.satellites(1).payload = all_L1;
architecture.satellites(1).payload(2) = all_L2;
architecture.satellites(1).payload(3) = Atomic_Clock;
architecture.satellites(1).payload(4) = CL7;

architecture.satellites(2).payload = all_L2;
architecture.satellites(2).payload(2) = mil1;
architecture.satellites(2).payload(3) = Atomic_Clock;
architecture.satellites(2).payload(4) = CL7;

architecture.satellites(3).payload = mil1;
architecture.satellites(3).payload(2) = mil2;
architecture.satellites(3).payload(3) = Atomic_Clock;
architecture.satellites(3).payload(4) = CL7;

architecture.satellites(4).payload = mil2;
architecture.satellites(4).payload(2) = saftey;
architecture.satellites(4).payload(3) = Atomic_Clock;
architecture.satellites(4).payload(4) = CL7;

architecture.satellites(5).payload = saftey;
architecture.satellites(5).payload(2) = new_sig_L4;
architecture.satellites(5).payload(3) = Nudet_stuff;
architecture.satellites(5).payload(4) = Atomic_Clock;
architecture.satellites(5).payload(5) = CL7;

architecture.satellites(6).payload = new_sig_L4;
architecture.satellites(6).payload(2) = all_L1;
architecture.satellites(6).payload(3) = Nudet_stuff;
architecture.satellites(6).payload(4) = Atomic_Clock;
```

```
architecture.satellites(6).payload(5) = CL7;
```

Appendix O: Change Quantity Produced and Design Life
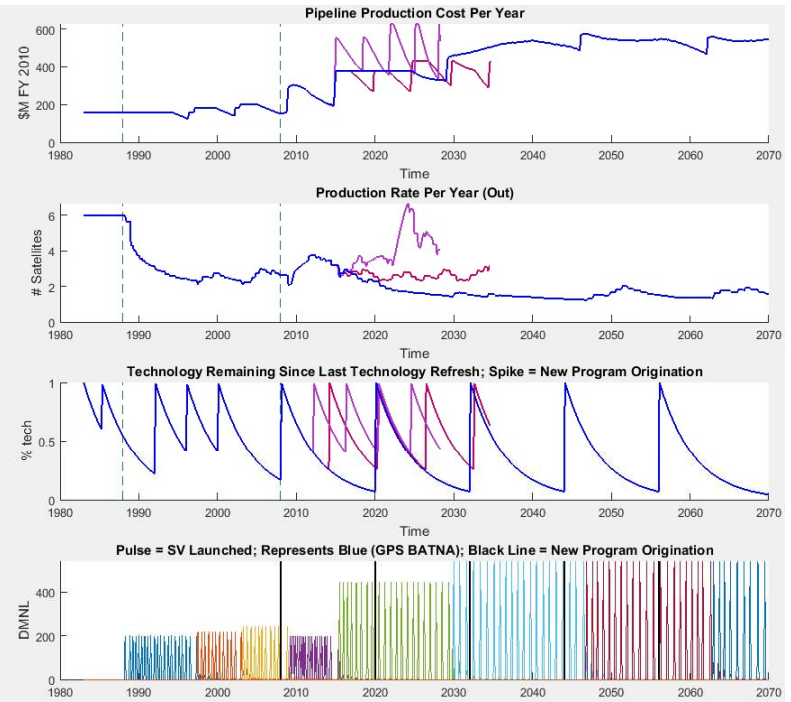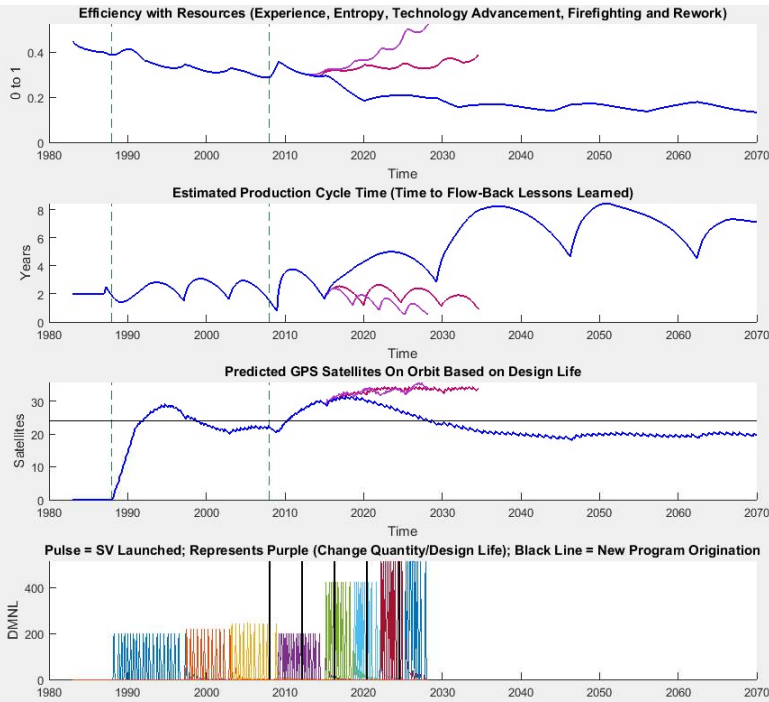
	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 10 vs 15	1	Gen 2, 10 vs 15	1	Gen 3, 10 vs 15	1	Gen 4, 10 vs 15
2	Number Satellites Produced	2	12 vs 24	2	12 vs 24	2	12 vs 24	2	12 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	183.02%	3	155.21%	3	161.18%	3	167.89%
4	Cost to Acquire a Year of Operational Capability	4	139.67%	4	92.44%	4	97.46%	4	91.57%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	183.02% in 2019	5	175.30% in 2022	5	191.45% in 2025	5	199.19% in 2028
6	Compensate for Difference of Production Rate (Time & Performance)	6	139.67% in 2019	6	104.41% in 2022	6	115.76% in 2025	6	108.65% in 2028

385

28 Appendix P: GPS BATNA Versus Tick-Tock

28.1 Tick Bus Update (12) → Tock Payload Update (12)

	Variable	vs BATNA
1	Generation Number(s), Design Life of Satellite (years)	Gen 1 & 2,15
2	Number Satellites Produced	12 + 12 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	99.41%
4	Cost to Acquire a Year of Operational Capability	93.38%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	99.06% in 2030
6	Compensate for Difference of Production Rate (Time & Performance)	92.98% in 2030

	Variable	vs BATNA
1	Generation Number(s), Design Life of Satellite (years)	Gen 3 & 4, 15
2	Number Satellites Produced	12 + 12 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	96.14%
4	Cost to Acquire a Year of Operational Capability	82.10%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	96.19% in 2044
6	Compensate for Difference of Production Rate (Time & Performance)	82.04% in 2044

386

28.2 GPS BATNA Versus Tick-Tock extra NRE in Gen 1 for Block IIIA (jump start)

	Variable	vs BATNA
1	Generation Number(s), Design Life of Satellite (years)	Gen 1 & 2,15
2	Number Satellites Produced	12 + 12 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	111.95%
4	Cost to Acquire a Year of Operational Capability	87.49%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	111.96% in 2026
6	Compensate for Difference of Production Rate (Time & Performance)	87.40% in 2026

	Variable	vs BATNA
1	Generation Number(s), Design Life of Satellite (years)	Gen 3 & 4, 15
2	Number Satellites Produced	12 + 12 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	97.39%
4	Cost to Acquire a Year of Operational Capability	76.74%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	100.34% in 2040
6	Compensate for Difference of Production Rate (Time & Performance)	78.95% in 2040

387

29 Appendix Q: Flavors of Disaggregation

29.1 Military/Civilian Implementation (2x Disaggregation)

Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1 Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2 Number Satellites Produced	2	48 vs 24	2	48 vs 24	2	48 vs 24	2	48 vs 24
3 Avg Cost Per Production Year Gen vs. Gen	3	115.17%	3	116.45%	3	121.15%	3	99.72%
4 Avg Cost Per Production Year Gen vs. Gen Ex Ops	4	113.99%	4	107.34%	4	111.00%	4	92.64%
5 Avg Cost Per Production Year Gen vs. Gen Ex Launch	5	107.01%	5	96.99%	5	90.30%	5	76.87%
6 Cost to Acquire a Year of Operational Capability	6	94.96%	6	65.93%	6	69.50%	6	72.53%
7 Cost at End of Production, Policy Cost per year Relative to BATNA	7	115.17% in 2027	7	119.92% in 2036	7	127.89% in 2046	7	99.99% in 2058
8 Compensate for Difference of Production Rate (Time & Performance)	8	94.96% in 2027	8	67.89% in 2036	8	73.36% in 2046	8	72.72% in 2058

29.2 Galileo-Size Implementation (3x Disaggregation)

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	72 vs 24	2	72 vs 24	2	72 vs 24	2	72 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	138.87%	3	142.45%	3	111.85%	3	111.06%
4	Cost to Acquire a Year of Operational Capability	4	101.11%	4	72.27%	4	83.24%	4	80.77%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	138.87% in 2025	5	149.92% in 2034	5	118.47% in 2046	5	110.93% in 2058
6	Compensate for Difference of Production Rate (Time & Performance)	6	101.11% in 2025	6	76.06% in 2034	6	88.16% in 2046	6	80.68% in 2058

389

29.3 Full Disaggregation (5x-6x-7x)

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	168 vs 24	2	168 vs 24	2	168 vs 24	2	168 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	178.23%	3	137.44%	3	127.27%	3	138.31%
4	Cost to Acquire a Year of Operational Capability	4	111.00%	4	86.91%	4	95.70%	4	100.59%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	178.23% in 2024	5	146.04% in 2035	5	134.23% in 2047	5	137.80% in 2059
6	Compensate for Difference of Production Rate (Time & Performance)	6	111.00% in 2024	6	92.35% in 2035	6	100.93% in 2047	6	100.22% in 2059

390

29.4 Survivable Disaggregated

Efficiency with Resources (Experience, Entropy, Technology Advancement, Firefighting and Rework)

Pipeline Production Cost Per Year

Estimated Production Cycle Time (Time to Flow-Back Lessons Learned)

Production Rate Per Year (Out)

Predicted GPS Satellites On Orbit Based on Design Life

Technology Remaining Since Last Technology Refresh; Spike = New Program Origination

Pulse = SV Launched; Represents Purple (Survivable Disaggregated); Black Line = New Program Origination

Pulse = SV Launched; Represents Blue (GPS BATNA); Black Line = New Program Origination

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	96 vs 24	2	120 vs 24	2	144 vs 24	2	144 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	186.08%	3	186.77%	3	158.99%	3	163.06%
4	Avg Cost Per Production Year Gen vs. Gen Ex Ops	4	192.72%	4	176.75%	4	150.62%	4	154.60%
5	Avg Cost Per Production Year Gen vs. Gen Ex Launch	5	157.64%	5	135.52%	5	120.85%	5	124.30%
6	Cost to Acquire a Year of Operational Capability	6	135.48%	6	100.25%	6	119.55%	6	118.59%
7	Cost at End of Production, Policy Cost per year Relative to BATNA	7	186.08% in 2025	7	196.06% in 2035	7	167.94% in 2047	7	162.55% in 2059
8	Compensate for Difference of Production Rate (Time & Performance)	8	135.48% in 2025	8	105.24% in 2035	8	126.28% in 2047	8	118.21% in 2059

29.5 Survivable Disaggregated: Extend Design Life to 20 years

	Variable		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 20 vs 15	1	Gen 2, 20 vs 15	1	Gen 3, 20 vs 15
2	Number Satellites Produced	2	144 vs 24	2	144 vs 24	2	144 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	163.38%	3	161.39%	3	144.46%
4	Cost to Acquire a Year of Operational Capability	4	113.94%	4	105.91%	4	107.51%
5	Cost at End of Production, Policy Cost per year Relative to BA	5	163.38% in 2028	5	161.87% in 2042	5	147.56% in 2058
6	Compensate for Difference of Production Rate (Time & Perform	6	113.94% in 2028	6	106.22% in 2042	6	109.82% in 2058

29.6 Survivable Disaggregated: Build Capability of 32 Versus 24

Variable		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15
2	Number Satellites Produced	2	192 vs 24	2	192 vs 24	2	192 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	199.94%	3	193.94%	3	173.47%
4	Cost to Acquire a Year of Operational Capability	4	140.74%	4	128.41%	4	129.10%
5	Cost at End of Production, Policy Cost per year Relative to BAT	5	199.94% in 2028	5	194.47% in 2043	5	176.89% in 2059
6	Compensate for Difference of Production Rate (Time & Perfor	6	140.74% in 2028	6	128.76% in 2043	6	131.64% in 2059

393

29.7 Survivable Disaggregated: Tick-Tock

	Variable	vs BATNA
1	Generation Number(s), Design Life of Satellite (years)	Gen 1 & 2,15
2	Year of Production Completion & Number Satellites Produced	72 + 72 vs 144
3	Non-Reoccurring Engineering (Technology Refresh Costs) this Generation	110.67%
4	Cost of First Production Unit	97.97%
5	Replication Costs of Production Units (Sum of Production Costs)	100.60%
6	Launch Costs	106.25%
7	Cost Per Operational Year, Gen vs. Gen (Compares Performance Not Time)	99.65%
8	Total Cost Cost Per Acquisition (Compares Performance Not Time)	103.37%
9	Cost at End of Production Policy Relative to BATNA (Compares Time Not Performance)	97.93% in 2026
10	Compensate for Difference of Production Rate	102.65% in 2026

	Variable	vs BATNA
1	Generation Number(s), Design Life of Satellite (years)	Gen 3 & 4, 15
2	Year of Production Completion & Number Satellites Produced	72 + 72 vs 144
3	Non-Reoccurring Engineering (Technology Refresh Costs) this Generation	108.22%
4	Cost of First Production Unit	111.98%
5	Replication Costs of Production Units (Sum of Production Costs)	126.83%
6	Launch Costs	111.11%
7	Cost Per Operational Year, Gen vs. Gen (Compares Performance Not Time)	108.27%
8	Total Cost Cost Per Acquisition (Compares Performance Not Time)	115.69%
9	Cost at End of Production Policy Relative to BATNA (Compares Time Not Performance)	109.23% in 2036
10	Compensate for Difference of Production Rate	116.71% in 2036

394

30 Appendix R: Disaggregation under Expectation of Budget Cuts and Longer On Orbit Service Life

30.1 GPS BATNA

Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1 Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2 Number Satellites Produced	2	24 vs 24	2	24 vs 24	2	24 vs 24	2	24 vs 24
3 Avg Cost Per Production Year Gen vs. Gen	3	91.33%	3	96.23%	3	95.49%	3	95.48%
4 Cost to Acquire a Year of Operational Capability	4	100.94%	4	100.74%	4	100.63%	4	105.76%
5 Cost at End of Production, Policy Cost per year Relative to BATNA	5	90.97% in 2031	5	94.63% in 2048	5	95.15% in 2065	5	95.47% in 2083
6 Compensate for Difference of Production Rate (Time & Performance)	6	100.55% in 2031	6	99.07% in 2048	6	100.27% in 2065	6	105.75% in 2083

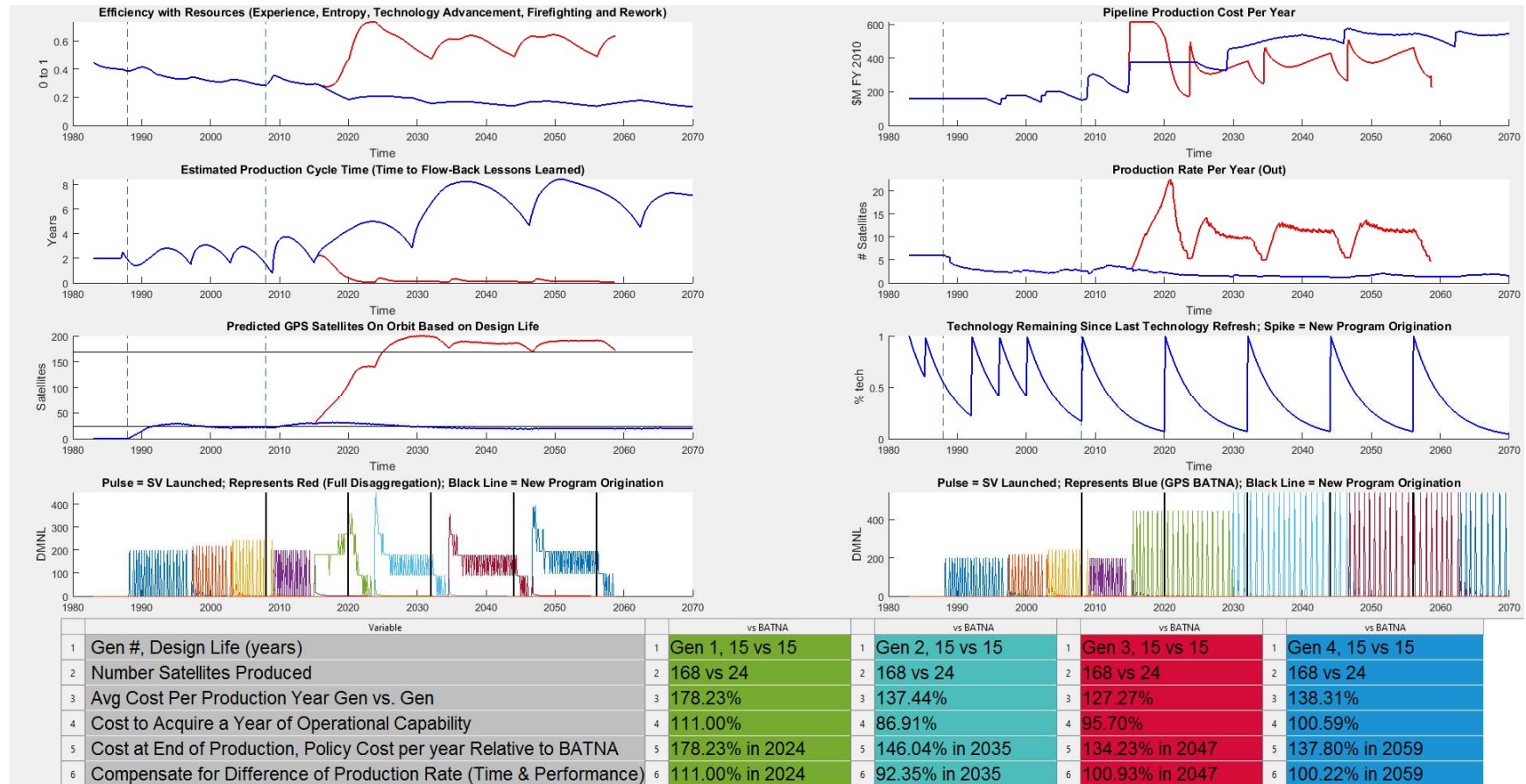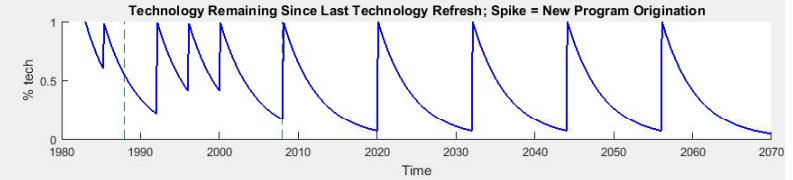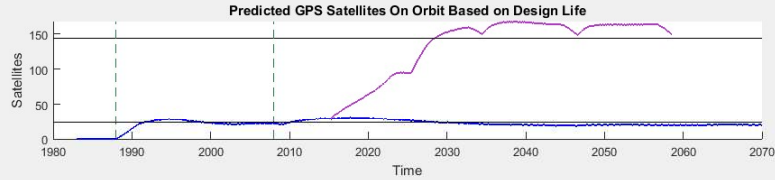## 30.2 Military/Civilian Implementation (2x Disaggregation)

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	48 vs 24	2	48 vs 24	2	48 vs 24	2	48 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	103.02%	3	95.76%	3	86.83%	3	83.42%
4	Cost to Acquire a Year of Operational Capability	4	96.69%	4	84.49%	4	92.89%	4	94.80%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	103.02% in 2028	5	96.45% in 2043	5	87.67% in 2061	5	83.42% in 2079
6	Compensate for Difference of Production Rate (Time & Performance)	6	96.69% in 2028	6	85.10% in 2043	6	93.79% in 2061	6	94.80% in 2079

30.3 Galileo-Size Implementation (3x Disaggregation)

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	72 vs 24	2	72 vs 24	2	72 vs 24	2	72 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	104.60%	3	98.09%	3	97.74%	3	95.89%
4	Cost to Acquire a Year of Operational Capability	4	95.43%	4	72.12%	4	81.82%	4	81.36%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	104.60% in 2028	5	99.26% in 2041	5	100.01% in 2054	5	95.74% in 2068
6	Compensate for Difference of Production Rate (Time & Performance)	6	95.43% in 2028	6	72.99% in 2041	6	83.73% in 2054	6	81.23% in 2068

397

30.4 Full Disaggregation (5x-6x-7x)

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	144 vs 24	2	168 vs 24	2	168 vs 24	2	168 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	133.16%	3	132.32%	3	120.17%	3	103.55%
4	Cost to Acquire a Year of Operational Capability	4	106.29%	4	78.81%	4	88.50%	4	86.30%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	133.16% in 2026	5	136.67% in 2037	5	125.80% in 2048	5	103.41% in 2062
6	Compensate for Difference of Production Rate (Time & Performance)	6	106.29% in 2026	6	81.40% in 2037	6	92.65% in 2048	6	86.17% in 2062

398

30.4.1 Full Disaggregation (5x-6x-7x) Extreme Budget Cuts

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	168 vs 24	2	168 vs 24	2	168 vs 24	2	168 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	113.47%	3	118.56%	3	109.09%	3	102.86%
4	Cost to Acquire a Year of Operational Capability	4	102.52%	4	74.97%	4	84.56%	4	84.94%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	113.47% in 2028	5	120.23% in 2039	5	112.85% in 2051	5	102.67% in 2065
6	Compensate for Difference of Production Rate (Time & Performance)	6	102.52% in 2028	6	76.03% in 2039	6	87.48% in 2051	6	84.78% in 2065

30.5 Survivable Disaggregated

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	96 vs 24	2	120 vs 24	2	144 vs 24	2	144 vs 24
3	Avg Cost Per Production Year Gen vs. Gen	3	141.75%	3	142.27%	3	129.31%	3	111.84%
4	Cost to Acquire a Year of Operational Capability	4	141.75%	4	110.89%	4	124.29%	4	122.01%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	141.75% in 2029	5	142.27% in 2043	5	131.10% in 2058	5	111.88% in 2076
6	Compensate for Difference of Production Rate (Time & Performance)	6	141.75% in 2029	6	110.89% in 2043	6	126.02% in 2058	6	122.05% in 2076

30.5.1 Survivable Disaggregated and Tick-Tock

	Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 15 vs 15	1	Gen 2, 15 vs 15	1	Gen 3, 15 vs 15	1	Gen 4, 15 vs 15
2	Number Satellites Produced	2	48 vs 96	2	60 vs 120	2	72 vs 144	2	72 vs 144
3	Avg Cost Per Production Year Gen vs. Gen	3	93.56%	3	95.92%	3	97.36%	3	86.03%
4	Cost to Acquire a Year of Operational Capability	4	96.85%	4	94.11%	4	91.08%	4	106.43%
5	Cost at End of Production, Policy Cost per year Relative to BATNA	5	93.56% in 2022	5	108.27% in 2029	5	94.31% in 2036	5	98.21% in 2044
6	Compensate for Difference of Production Rate (Time & Performance)	6	96.85% in 2022	6	106.23% in 2029	6	88.23% in 2036	6	121.50% in 2044

30.5.2 Survivable Disaggregated and Tick-Tock Versus GPS BATNA

	Variable	vs BATNA
1	Generation Number(s), Design Life of Satellite (years)	Gen 1 & 2,15
2	Year of Production Completion & Number Satellites Produced	72 + 72 vs 24
3	Non-Reoccurring Engineering (Technology Refresh Costs) this Generation	95.33%
4	Cost of First Production Unit	203.18%
5	Replication Costs of Production Units (Sum of Production Costs)	124.19%
6	Launch Costs	212.50%
7	Cost Per Operational Year, Gen vs. Gen (Compares Performance Not Time)	143.25%
8	Total Cost Cost Per Acquisition (Compares Performance Not Time)	138.83%
9	Cost at End of Production Policy Relative to BATNA (Compares Time Not Performance)	142.50% in 2029
10	Compensate for Difference of Production Rate	138.75% in 2029

	Variable	vs BATNA
1	Generation Number(s), Design Life of Satellite (years)	Gen 3 & 4, 15
2	Year of Production Completion & Number Satellites Produced	72 + 72 vs 24
3	Non-Reoccurring Engineering (Technology Refresh Costs) this Generation	96.81%
4	Cost of First Production Unit	100.21%
5	Replication Costs of Production Units (Sum of Production Costs)	79.30%
6	Launch Costs	250.00%
7	Cost Per Operational Year, Gen vs. Gen (Compares Performance Not Time)	136.08%
8	Total Cost Cost Per Acquisition (Compares Performance Not Time)	118.11%
9	Cost at End of Production Policy Relative to BATNA (Compares Time Not Performance)	136.63% in 2044
10	Compensate for Difference of Production Rate	118.55% in 2044

31 Appendix S: Weather Command Script for Vensim Initialization

:Time=1983
Change Performance Demands[Gen1]=800
Change Performance Demands[Gen2]=1220
Change Performance Demands[Gen3]=2400
Change Performance Demands[Gen4]=1900
Change Performance Demands[Gen5]=1
Change Performance Demands[Gen6]=1
Change Performance Demands[Gen7]=1
Change Performance Demands[Gen8]=1
Change Performance Demands[Gen9]=1
Complexity Metric[Gen1]=1
Complexity Metric[Gen2]=1
Complexity Metric[Gen3]=1
Complexity Metric[Gen4]=1
Complexity Metric[Gen5]=1
Complexity Metric[Gen6]=1
Complexity Metric[Gen7]=1
Complexity Metric[Gen8]=1
Complexity Metric[Gen9]=1
Difficulty Reduction Under Disaggregation[Gen1]=1
Difficulty Reduction Under Disaggregation[Gen2]=1
Difficulty Reduction Under Disaggregation[Gen3]=1
Difficulty Reduction Under Disaggregation[Gen4]=1
Difficulty Reduction Under Disaggregation[Gen5]=1
Difficulty Reduction Under Disaggregation[Gen6]=1
Difficulty Reduction Under Disaggregation[Gen7]=1
Difficulty Reduction Under Disaggregation[Gen8]=1
Difficulty Reduction Under Disaggregation[Gen9]=1
Disaggregate[Gen1]=1
Disaggregate[Gen2]=1
Disaggregate[Gen3]=1
Disaggregate[Gen4]=1

Disaggregate[Gen6]=1
Disaggregate[Gen7]=1
Disaggregate[Gen8]=1
Disaggregate[Gen9]=1
Error Factor=0.9
Extra Life=1.25
Extra Life Post 2010=1.25
Firefighting Correct Level=1
Matlab Pulse Gen=0
Matlab Pulse NRE=0
Matlab Pulse NRE2=0
Max Error Fraction=0.9
Mitigate Firefighting=1
Program Funding Override[Gen1]=140
Program Funding Override[Gen2]=200
Program Funding Override[Gen3]=0
Program Funding Override[Gen4]=0
Program Funding Override[Gen5]=0
Program Funding Override[Gen6]=0
Program Funding Override[Gen7]=0
Program Funding Override[Gen8]=0
Program Funding Override[Gen9]=0
Set Design Life[Gen1]=5
Set Design Life[Gen2]=7
Set Design Life[Gen3]=7
Set Design Life[Gen4]=0
Set Design Life[Gen5]=0
Set Design Life[Gen6]=0
Set Design Life[Gen7]=0
Set Design Life[Gen8]=0
Set Design Life[Gen9]=0
Tech Halflife Context=4.5
Tick Tock Active=0

Tune Design Life=2
:Time=2002
Change Performance Demands[Gen3]=2425
Matlab Pulse Gen=1
Matlab Pulse NRE=1
Matlab Pulse NRE2=1
Program Funding Override[Gen3]=349
Set Design Life[Gen3]=7
:Time=2002.13
Matlab Pulse Gen=0
Matlab Pulse NRE=0
Matlab Pulse NRE2=0
:Time=2009.25

32 Appendix T: Flavors of Disaggregation for Weather and Climate Sensing Missions

32.1 Weather and Atmospheric Measurement Split; 2x Disaggregation + CMIS Free Flyer in 3rd Generation
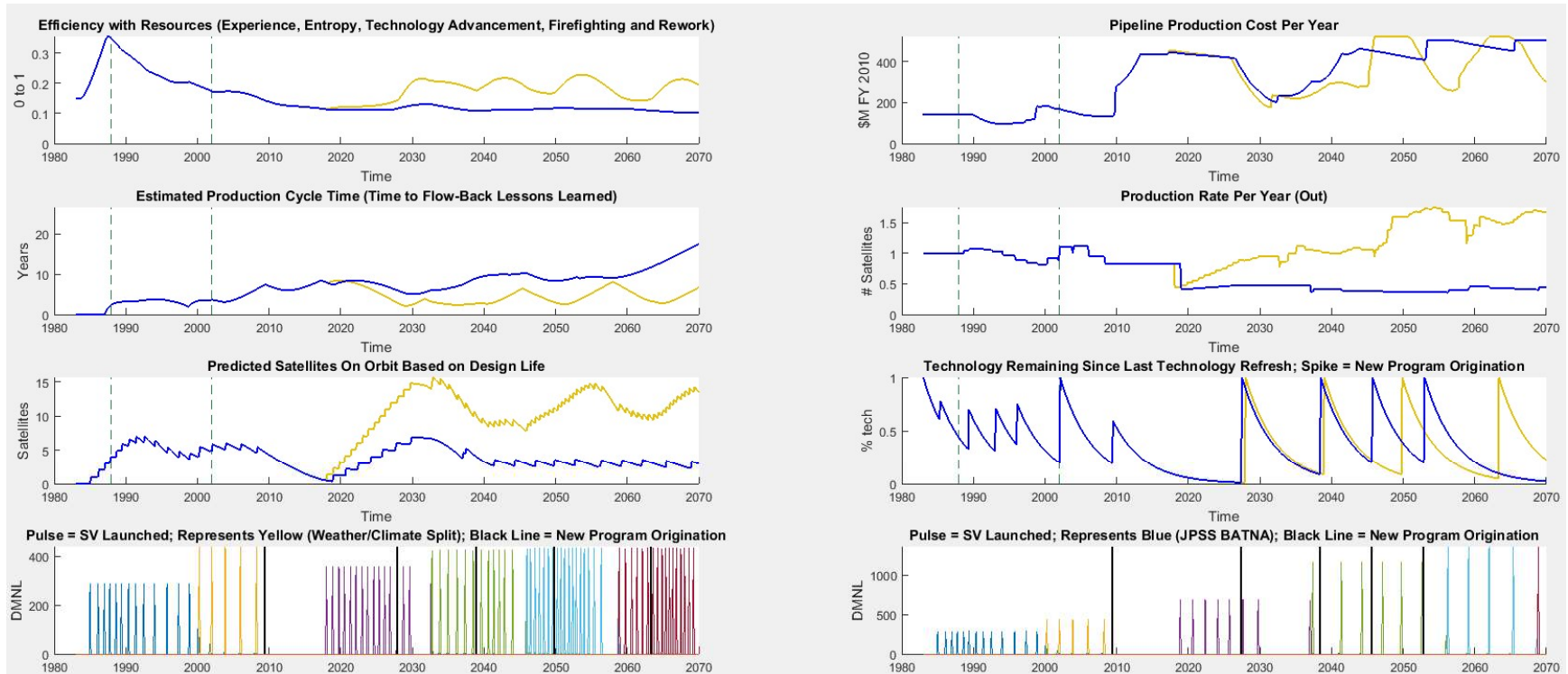
Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1 Gen #, Design Life (years)	1	Gen 1, 7 vs 7	1	Gen 2, 7 vs 7	1	Gen 3, 7 vs 7	1	Gen 4, 7 vs 7
2 Number Satellites Produced	2	16 vs 8	2	12 vs 6	2	18 vs 4	2	18 vs 4
3 Avg Cost Per Production Year Gen vs. Gen	3	103.72%	3	100.72%	3	99.60%	3	105.45%
4 Avg Cost Per Production Year Gen vs. Gen Ex Ops	4	101.04%	4	91.07%	4	93.55%	4	95.89%
5 Cost to Acquire a Year of Operational Capability	5	65.21%	5	44.09%	5	67.74%	5	74.82%
6 Cost at End of Production, Relative to BATNA	6	103.72% in 2032	6	100.31% in 2045	6	119.96% in 2058	6	100.38% in 2073
7 Compensate for Quantity Placed on Orbit	7	65.21% in 2032	7	43.91% in 2045	7	81.59% in 2058	7	71.22% in 2073

32.2 Three common satellites each hosting 300 kg of Payload + CMIS Free Flyer in 3rd Generation
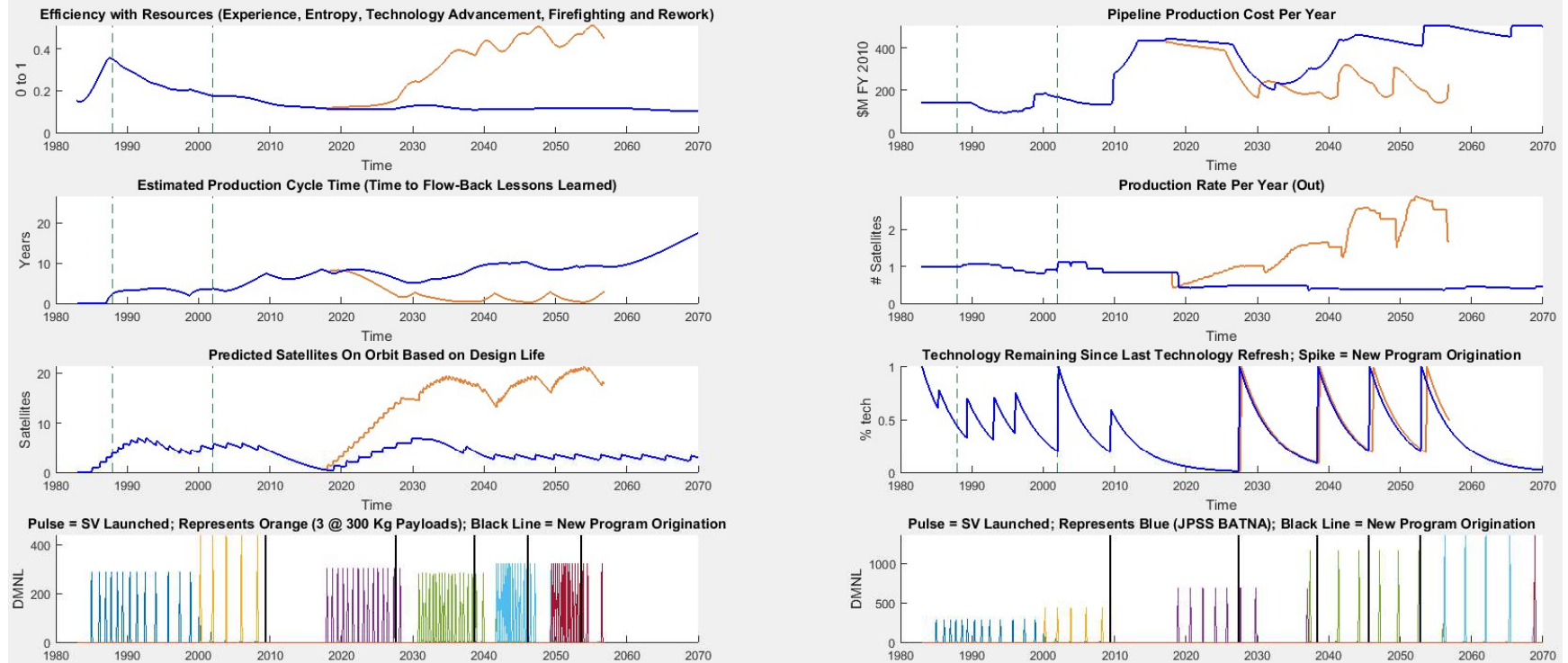
Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1 Gen #, Design Life (years)	1	Gen 1, 7 vs 7	1	Gen 2, 7 vs 7	1	Gen 3, 7 vs 7	1	Gen 4, 7 vs 7
2 Number Satellites Produced	2	16 vs 8	2	18 vs 6	2	16 vs 4	2	16 vs 4
3 Avg Cost Per Production Year Gen vs. Gen	3	106.14%	3	108.52%	3	110.84%	3	112.36%
4 Avg Cost Per Production Year Gen vs. Gen Ex Ops	4	101.31%	4	92.97%	4	100.96%	4	99.34%
5 Cost to Acquire a Year of Operational Capability	5	90.61%	5	58.18%	5	69.42%	5	62.88%
6 Cost at End of Production, Relative to BATNA	6	106.14% in 2030	6	107.03% in 2042	6	151.09% in 2049	6	121.08% in 2057
7 Compensate for Quantity Placed on Orbit	7	90.61% in 2030	7	57.38% in 2042	7	94.62% in 2049	7	67.76% in 2057

407

32.3 Five Satellites,
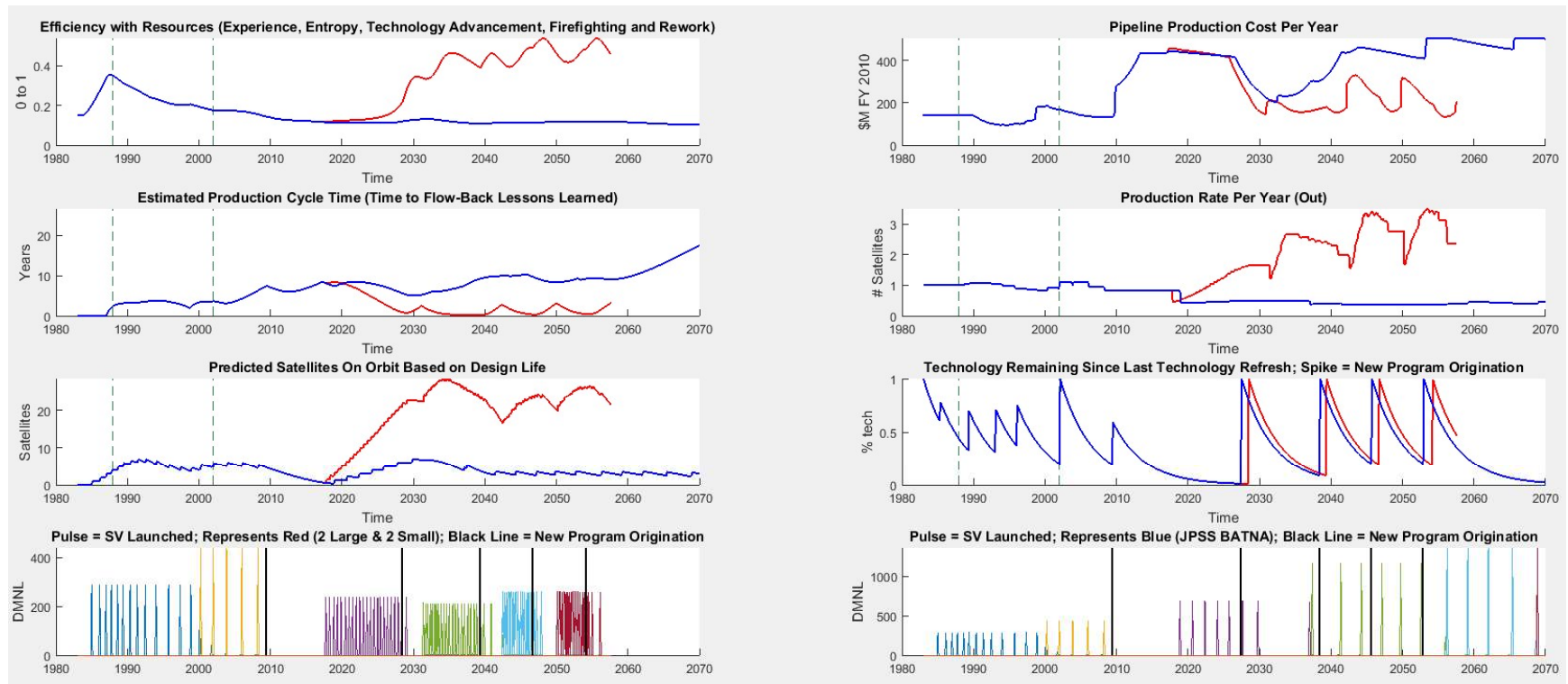
Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 7 vs 7	1	Gen 2, 7 vs 7	1	Gen 3, 7 vs 7	1	Gen 4, 7 vs 7
2	Number Satellites Produced	2	24 vs 8	2	24 vs 6	2	20 vs 4	2	20 vs 4
3	Avg Cost Per Production Year Gen vs. Gen	3	105.98%	3	105.12%	3	110.68%	3	111.82%
4	Avg Cost Per Production Year Gen vs. Gen Ex Ops	4	99.66%	4	85.10%	4	99.02%	4	96.62%
5	Cost to Acquire a Year of Operational Capability	5	95.64%	5	56.99%	5	68.20%	5	62.58%
6	Cost at End of Production, Relative to BATNA	6	105.98% in 2031	6	104.19% in 2042	6	150.80% in 2050	6	116.86% in 2058
7	Compensate for Quantity Placed on Orbit	7	95.64% in 2031	7	56.49% in 2042	7	92.92% in 2050	7	65.40% in 2058

32.4 Full Disaggregation
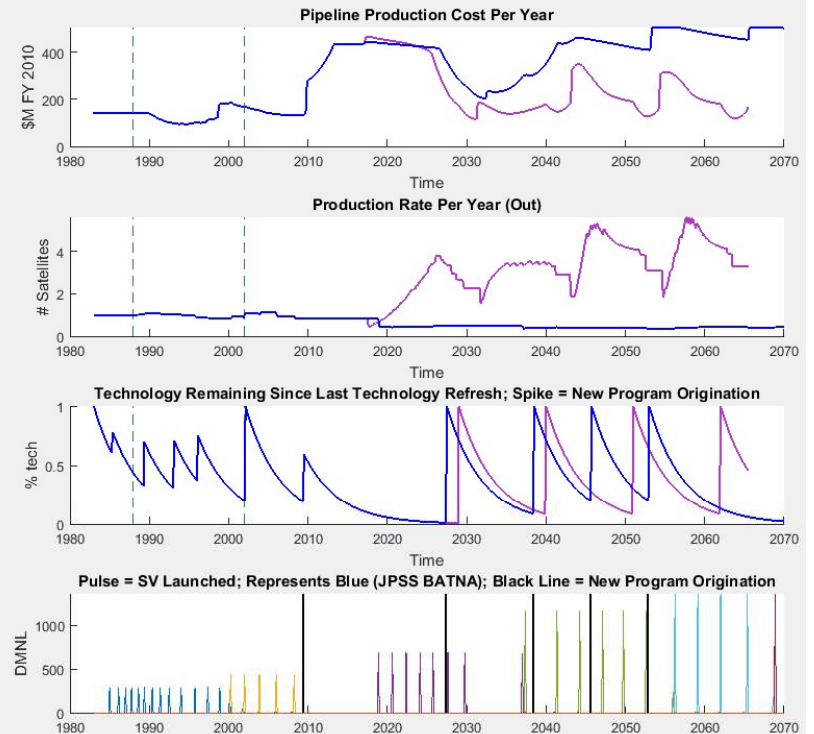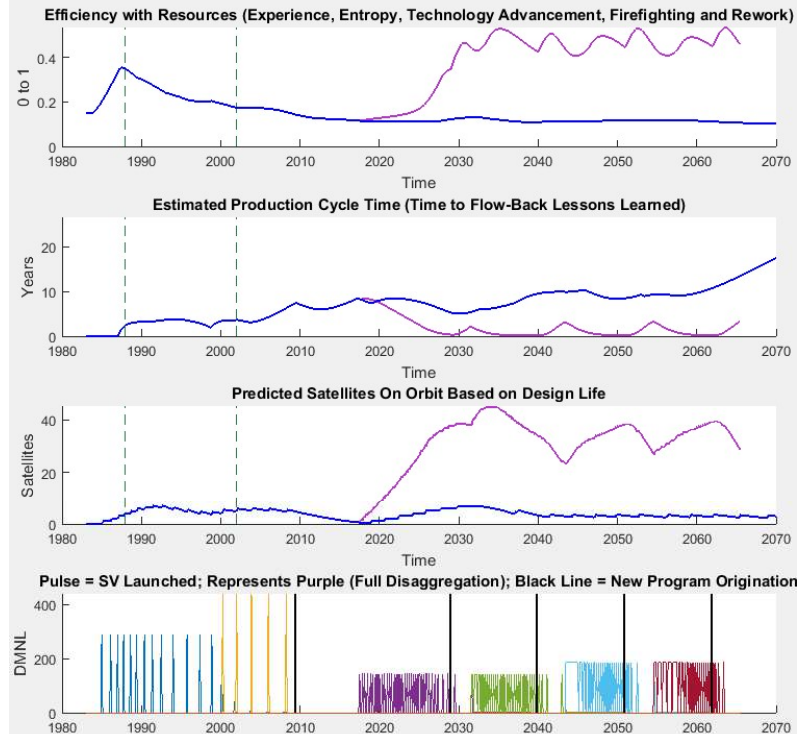
Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 7 vs 7	1	Gen 2, 7 vs 7	1	Gen 3, 7 vs 7	1	Gen 4, 7 vs 7
2	Number Satellites Produced	2	40 vs 8	2	36 vs 6	2	42 vs 4	2	42 vs 4
3	Avg Cost Per Production Year Gen vs. Gen	3	105.93%	3	100.11%	3	90.89%	3	99.62%
4	Avg Cost Per Production Year Gen vs. Gen Ex Ops	4	94.87%	4	72.89%	4	72.68%	4	78.19%
5	Cost to Acquire a Year of Operational Capability	5	65.45%	5	38.20%	5	54.47%	5	53.62%
6	Cost at End of Production, Relative to BATNA	6	105.93% in 2032	6	99.54% in 2043	6	119.76% in 2055	6	91.10% in 2066
7	Compensate for Quantity Placed on Orbit	7	65.45% in 2032	7	37.98% in 2043	7	71.78% in 2055	7	49.03% in 2066

409

32.5 Failed Disaggregation

Efficiency with Resources (Experience, Entropy, Technology Advancement, Firefighting and Rework)

Pipeline Production Cost Per Year

Estimated Production Cycle Time (Time to Flow-Back Lessons Learned)

Production Rate Per Year (Out)

Predicted Satellites On Orbit Based on Design Life

Technology Remaining Since Last Technology Refresh; Spike = New Program Origination

Pulse = SV Launched; Represents Purple (Full Disaggregation); Black Line = New Program Origination

Pulse = SV Launched; Represents Blue (JPSS BATNA); Black Line = New Program Origination

Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 7 vs 7	1	Gen 2, 7 vs 7	1	Gen 3, 7 vs 7	1	Gen 4, 7 vs 7
2	Number Satellites Produced	2	20 vs 6	2	24 vs 6	2	28 vs 6	2	28 vs 6
3	Avg Cost Per Production Year Gen vs. Gen	3	99.57%	3	130.59%	3	103.05%	3	116.43%
4	Avg Cost Per Production Year Gen vs. Gen Ex Ops	4	103.42%	4	122.11%	4	93.37%	4	105.79%
5	Cost to Acquire a Year of Operational Capability	5	117.06%	5	75.87%	5	104.80%	5	100.81%
6	Cost at End of Production, Relative to BATNA	6	99.57% in 2025	6	119.89% in 2031	6	133.30% in 2041	6	123.91% in 2050
7	Compensate for Quantity Placed on Orbit	7	117.06% in 2025	7	69.66% in 2031	7	135.56% in 2041	7	107.29% in 2050

32.6 Faster Tech Advancement

Variable		vs BATNA		vs BATNA		vs BATNA		vs BATNA
1	Gen #, Design Life (years)	1	Gen 1, 7 vs 7	1	Gen 2, 7 vs 7	1	Gen 3, 7 vs 7	1	Gen 4, 7 vs 7
2	Number Satellites Produced	2	40 vs 8	2	36 vs 6	2	42 vs 6	2	42 vs 4
3	Avg Cost Per Production Year Gen vs. Gen	3	98.67%	3	101.85%	3	97.18%	3	79.91%
4	Avg Cost Per Production Year Gen vs. Gen Ex Ops	4	88.11%	4	73.99%	4	78.14%	4	67.64%
5	Cost to Acquire a Year of Operational Capability	5	68.92%	5	44.18%	5	46.13%	5	51.52%
6	Cost at End of Production, Relative to BATNA	6	99.30% in 2031	6	101.98% in 2043	6	109.71% in 2054	6	96.01% in 2065
7	Compensate for Quantity Placed on Orbit	7	69.35% in 2031	7	44.24% in 2043	7	52.08% in 2054	7	61.90% in 2065

411