Air Traffic Control Resource Management Strategies and the Small Aircraft Transportation System: A System Dynamics Perspective

by

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(ABSTRACT)

The National Aeronautics and Space Administration (NASA) is leading a research effort to develop a Small Aircraft Transportation System (SATS) that will expand air transportation capabilities to hundreds of underutilized airports in the United States. Most of the research effort addresses the technological development of the small aircraft as well as the systems to manage airspace usage and surface activities at airports. The Federal Aviation Administration (FAA) will also play a major role in the successful implementation of SATS, however, the administration is reluctant to embrace the unproven concept.

The purpose of the research presented in this dissertation is to determine if the FAA can pursue a resource management strategy that will support the current radar-based Air Traffic Control (ATC) system as well as a Global Positioning Satellite (GPS)-based ATC system required by the SATS. The research centered around the use of the System Dynamics modeling methodology to determine the future behavior of the principle components of the ATC system over time.

The research included a model of the ATC system consisting of people, facilities, equipment, airports, aircraft, the FAA budget, and the Airport and Airways Trust Fund. The model generated system performance behavior used to evaluate three scenarios. The first scenario depicted the base case behavior of the system if the FAA continued its current resource management practices. The second scenario depicted the behavior of the system if the FAA emphasized development of GPS-based ATC systems. The third scenario depicted a combined resource management strategy that supplemented radar systems with GPS systems.

The findings of the research were that the FAA must pursue a resource management strategy that primarily funds a radar-based ATC system and directs lesser funding toward a GPS-based supplemental ATC system. The most significant contribution of this research was the insight and understanding gained of how several resource management strategies and the presence of SATS aircraft may impact the future US Air Traffic Control system.

Dedication

I dedicate this work to my wife and daughters, three special people who accompanied me throughout the dissertation journey. Their love, support and understanding served as an endless source of energy that inspired me to persevere.

Regina, Shelby and Olivia – you are a blessing. Thank you.

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Chapter 1: Introduction

1.1 Challenges for Air Traffic Control

There is worldwide interest among operators and researchers in the aviation community to pursue four goals related to air traffic control: first, to increase the capacity of airspace available to aircraft; second, to make airspace more accessible to aircraft; third, to provide more flexibility to aircraft utilizing airspace; and fourth, to increase the safety of aircraft operations (Federal Aviation Administration, 1999). In the United States (US), the Federal Aviation Administration's (FAA) proposed "Free Flight" airspace management system addresses the four goals primarily from the perspective of commercial airliners. Meanwhile, the National Aeronautics and Space Administration (NASA) is developing the concept of a Small Aircraft Transportation System (SATS) to provide a fast, safe, and affordable means of airborne transportation (NASA, 2000a) that will also support the four goals of access, capacity, flexibility, and safety improvement. However, when operational, SATS may place significant demands on the future air traffic control (ATC) system for aircraft in the US. Current research on ATC related issues for Free Flight primarily addresses a system comprised of commercial airline aircraft and focuses on the physical interactions among aircraft competing for the same airspace. There is little research that addresses the introduction of SATS aircraft into the National Airspace System (NAS) and the subsequent behavior of the ATC system under various future configurations.

The existing approach to ATC emphasizes safety through centralized control of aircraft flying along a routing system defined by ground based navigation aids, constrained by vertical or horizontal separation criteria, and enforced by air traffic controllers. Currently, aircraft flying in "controlled" airspace under instrument flight rules (IFR) must maintain 1000 feet vertical and 5 miles horizontal separation. The most common vision of the future NAS centers on the use of Global Positioning Satellites (GPS) as the primary means of air traffic control under the Free Flight concept, which should result in reduced separation criteria. However, the FAA's interpretation of the implementation of Free Flight as anything that eliminates flight restrictions (FAA, 1999) indicates that resource constraints may limit the system to a hybrid combination of

GPS and radar, as opposed to a complete transition to GPS. Thus, the implementation of some level of GPS-based air traffic control systems combined with the need to maintain radar-based ATC processes is likely to be a future challenge for air traffic controllers.

Besides the resource and implementation challenges of replacing radar with GPS, the FAA may face the problem of integrating two complex systems – the ATC system and SATS. One particular problem the administration must address is how the introduction of SATS aircraft into the NAS will impact the FAA's ability to conduct ATC under various combinations of GPS and radar-based technology. Additionally, the introduction of SATS aircraft may adversely influence the revenue collected to fund the ATC system through the Airport and Airways Trust Fund (AATF). The development of SATS is currently in the concept development stage. Research related to the integration of SATS and ATC at the macro system level is minimal. Thus, there are opportunities to investigate potential scenarios to determine ATC system behavior under various combinations of ATC and aircraft technologies.

1.2 Research Purpose

NASA is spending $69M on research to determine the feasibility of the SATS concept by 2005 (NASA, 2000). The Nimbus Corporation recently placed an order for 1,000 Eclipse 500 aircraft, which have operational characteristics similar to those of the SATS aircraft envisioned by NASA (Eclipse Aviation, 2001). There is a great deal of industry and government momentum to advance the use of small aircraft within the national transportation system. However, there is limited research to determine how the introduction of SATS aircraft may influence the FAA's ATC system and how SATS may impact upon the flow of excise taxes under future radar or GPS-based configurations. NASA proponents of SATS may argue that SATS aircraft will be able to navigate entirely with their onboard systems and have little influence on the ATC system. The SATS program objectives highlight capabilities such as self-separation among aircraft through the use of advanced software and an airborne internet (NASA, 2000). However, it is highly likely that SATS aircraft will transit through airspace along with less technologically capable aircraft, and, SATS aircraft will need to fly in airspace controlled by human air traffic controllers.

Given the aforementioned developments and the fact that the FAA's budget for 2001 was approximately $12.5B (FAA, 2002a), of which more than $11B emanated from the AATF, during the upcoming years government decision-makers will make important policy decisions regarding the use of human and financial resources that will have long-term effects on the NAS. The results of the research proposed in this document may offer new insights into the development of policies related to the integration of SATS aircraft into the NAS by exposing the feedback, causation, and implications of various ATC resource management policies.

It is infeasible to use real aircraft and an assortment of radar or GPS-based configurations of an operating ATC system to conduct research on the macro-level behavior of the system over time. Therefore, there is a need for an approach that uses a reasonable amount of resources, yet remains a valid representation of the system under study. Computer simulation modeling of the dynamic feedback within potential ATC system architectures offers an approach that meets these criteria. In particular, the System Dynamics approach offers a combination of methodology and tools to create and build a valid model of the principle components of an ATC system: people, aircraft, facilities, equipment, airports, and their associated financial resources.

1.3 Research Objective

The objectives of the research outlined in this document are fourfold. The first goal of the research is to determine how many SATS aircraft will be able to operate within the ATC system under radar and GPS-based configurations. The second goal of the research is to gain understanding of the dynamic behavior of the air traffic control system over time. The third goal of the research is to contribute to a higher-level transportation system model of SATS being developed at Virginia Tech. The fourth goal of the research is to contribute to the body of knowledge used by FAA, NASA, and other SATS stakeholders and decision-makers.

The steps to achieve the objective are twofold: first, to create and validate a System Dynamics computer simulation model of the ATC system; and second, to use the model to evaluate three future scenarios under which SATS aircraft may operate within the NAS.

1.4 Research Questions

The following questions stem from the fundamental research question: what air traffic control resource management strategy will support the future needs of the Small Aircraft Transportation System and create adequate tax revenue to fund the Federal Aviation Administration?

- Given the continuation of the current ground and radar-based ATC system, what level of SATS flights will the system be able to support?
- Given a future transition period toward a GPS-based ATC system, what level of SATS flights will the system be able to support?
- Given a future radar-based ATC system supplemented by a transition period to GPS, what level of SATS flights will the system be able to support?

1.5 Hypothesized System Behavior Over Time

System Dynamics modeling will be useful to help interested parties understand the behavior of the US ATC system as it evolves over time and attempts to accommodate SATS aircraft. System Dynamics is an approach that addresses the relationships among the structure and variables in a system. System Dynamics modeling is a process and a tool that shows how a system continually adjusts itself over time to accommodate the policy alternatives decision-makers may wish to implement. Researchers express System Dynamics "hypotheses" in terms of "behavior over time" diagrams or "reference modes" to determine if a system may support growth, decay, or some oscillating combination of the two (Ford, 1999; Sterman 2000). The behavior over time diagram in Figure 1-1 shows how the introduction of SATS flights into the ATC system may cause a drop in the revenue created by the Airport and Airways Trust Fund.

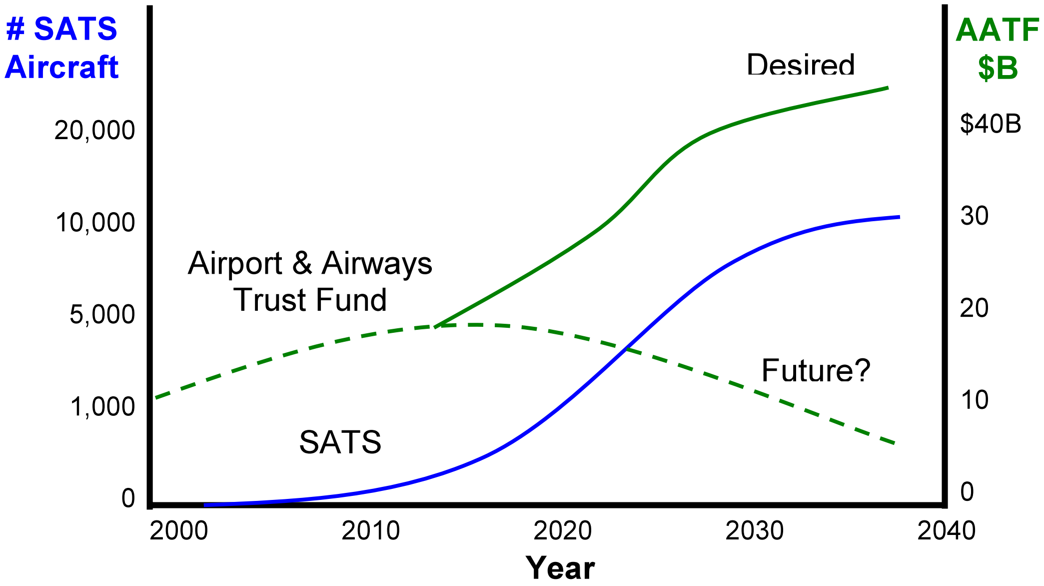

Figure 1-1: Alternative policies implemented by resource managers will influence the number of SATS aircraft the ATC system will support.

Historically, the aviation industry in the US has shown continuous growth. The aircraft inventory in the US grew from 76,549 in 1960 to 204,710 in 1998 (Bureau of Transportation Statistics, 2002). Thus, the notional shape of the curve representing the number of SATS flights over time in Figure 1-1 shows general patterns of growth. The challenge for ATC managers is to support the growth of SATS flights, meet the demands of non-SATS aircraft, operate within the resource constraints of the ATC system, and generate revenue for the AATF. The resource constraints include the number of controllers, maintainers, facilities, airports, equipment, and money available in the system. Resource managers of the ATC system should determine what policies might cause the undesirable system behavior and what policies and strategies they may use to create the desired system behavior. In this manner the System Dynamics approach serves as a tool for learning and understanding the general behavior of systems (Ford, 1999).

1.6 Research Contribution

A rigorous investigation of the behavior of the ATC system under several radar and GPS-based architectures will help to determine the potential level of participation of SATS aircraft in the system. The research will address questions that remain unanswered in the academic literature and are solely at the level of speculation and opinion within the practitioner literature. The research may contribute to policy decision-making, further policy analysis, and continued debate within the aviation community. The National Airspace System Architecture Version 4.0 (FAA, 1999) offers detailed plans for future air traffic control; however, it does not even address the SATS. Meanwhile, the SATS Program Plan focuses on the vehicle technologies and does not fully address the larger ATC infrastructure implications of SATS aircraft operating in the NAS and potentially influencing the AATF. The research in this dissertation will serve as a bridge between the FAA and NASA to show how the actions of the two administrations will dynamically interact within the larger framework of the NAS. The results of the research may provide findings that help the FAA to manage its resources to create the conditions that provide an ATC system capable of meeting all of the demands of SATS and non-SATS aircraft.

The research expands the application of System Dynamics to government policy issues. The System Dynamics approach is a valid methodology to offer insight into the potential impact of SATS upon the ATC system. The approach will contribute to an ongoing System Dynamics project at Virginia Tech. The application of the System Dynamics approach to issues important to the aviation resource management community may encourage further use of System Dynamics to address other pressing concerns in that community. The basic modeling approach will serve as a framework to generalize the System Dynamics approach to further ATC studies and to the widespread and diverse domain of government resource allocation problems in general.

1.7 Outline of Document

The remainder of the document consists of the following:

Chapter 2: The literature review includes the plans and objectives of NASA and the FAA, a national-level overview of the current air traffic control system, a summary of related modeling efforts, and a discussion of the System Dynamics modeling process: what it is, how to do it, how to make it valid, how the approach is relevant for the research topic, and specific step-by-step procedures to conduct the research.

Chapter 3: The research design stems from the System Dynamics model development and refinement effort discussion presented in chapter 2. The nine-step methodology guides the research effort through model development, validation, and application for policy analysis.

Chapter 4: The development of the model includes justification for all components of the model, initial conditions, and the rational used to create various parameters used in model equations.

Chapter 5: A variety of tests and procedures aid in verification and validation of the model.

Chapter 6: The evaluation of the three basic scenarios provides results and information useful to answer the research questions.

Chapter 7: The results and conclusions provide insight into the future of Air Traffic Control and the Small Aircraft Transportation System as well as opportunities for further research.

Chapter 2: Literature Review

2.1 The Vision of a Small Aircraft Transportation System

In 2001 researchers at the National Aeronautics and Space Administration (NASA) Langley Research Center began formal development of the concept of a Small Aircraft Transportation System (SATS). They intend to demonstrate by 2005 whether or not the concept works. They claim that, for distances of 800 miles or less, SATS will provide a faster, safer, and more affordable means of airborne transportation than the current airline hub and spoke system. They envision SATS aircraft operating out of the 5,400 public-use airports located throughout the US as shown in Figure 2-1. The anticipated all-weather landing capabilities of SATS aircraft represent a marked expansion in the accessibility of air travel throughout the US. Figure 2-2 depicts the approximately 700 airports with precision instrument landing systems that guide aircraft to safe landings during periods of low ceilings or low visibility. Together the two figures illustrate aspects of the vision statement articulated by the SATS program director, Dr. Bruce Holmes, to guide researchers and developers associated with the SATS program: *The small aircraft transportation vision is a safe travel alternative freeing people and products from transportation system delays, by creating access to more communities in less time* (NASA, 2000a).

The SATS vision statement emphasizes safety, speed, and access. Clearly, Figure 2-1 and Figure 2-2 demonstrate the potential increased geographic access SATS may provide. Additionally, SATS may fill the gap projected in 2009 between the availability and demand for hub and spoke flights indicated in Figure 2-3, thereby providing access simply by meeting passenger demand. A NASA study of transportation system speed concluded that SATS has the potential to greatly increase the average travel speed from doorstep to destination compared to other forms of transportation (Holmes, 2000b). Figure 2-4 shows the results of the study and indicates that SATS may provide far superior travel times. However, the safety of SATS remains indeterminate until research shows the system's feasibility as a safe form of air transportation.

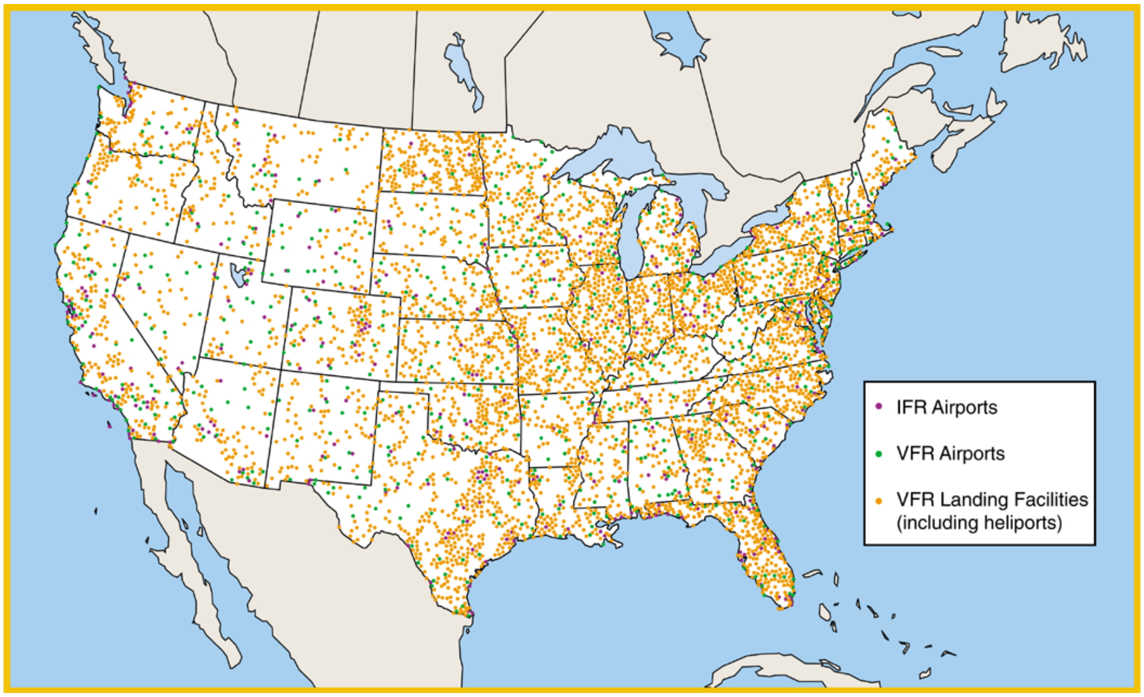

Figure 2-1. Approximately 5,400 public use airports can support SATS precision landings (Adapted from Holmes, 2000a).

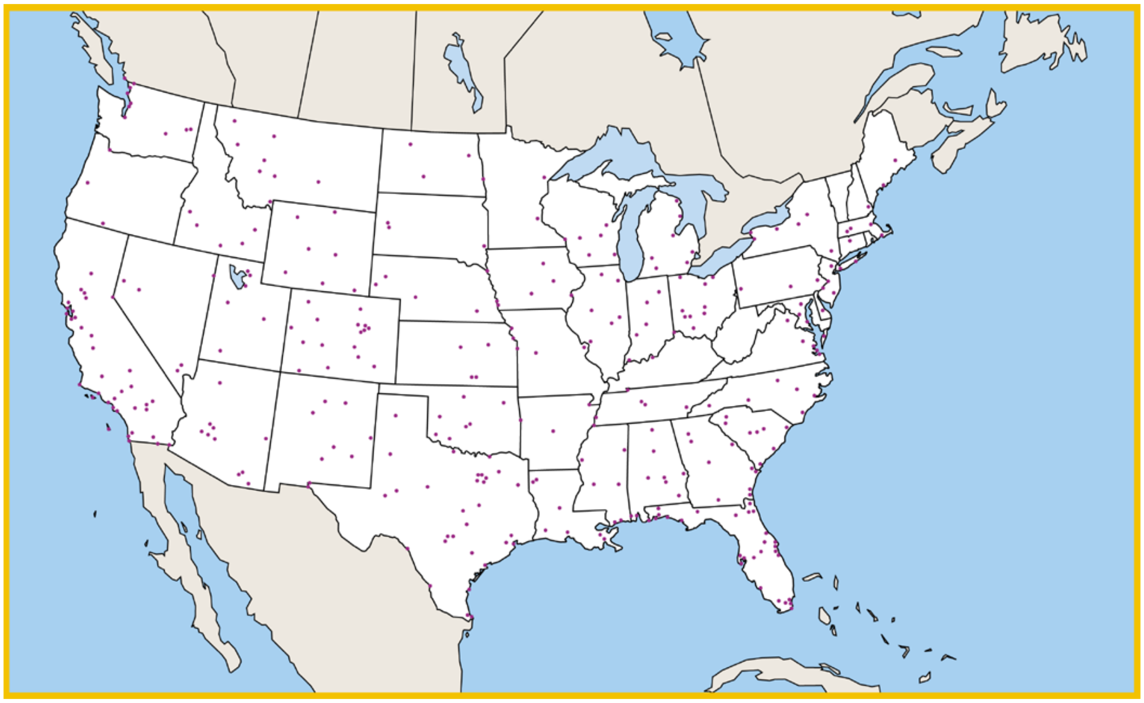

Figure 2-2. A constraint to the current airspace system is that there are approximately 700 airports suitable for precision instrument landings (Adapted from Holmes, 2000a).

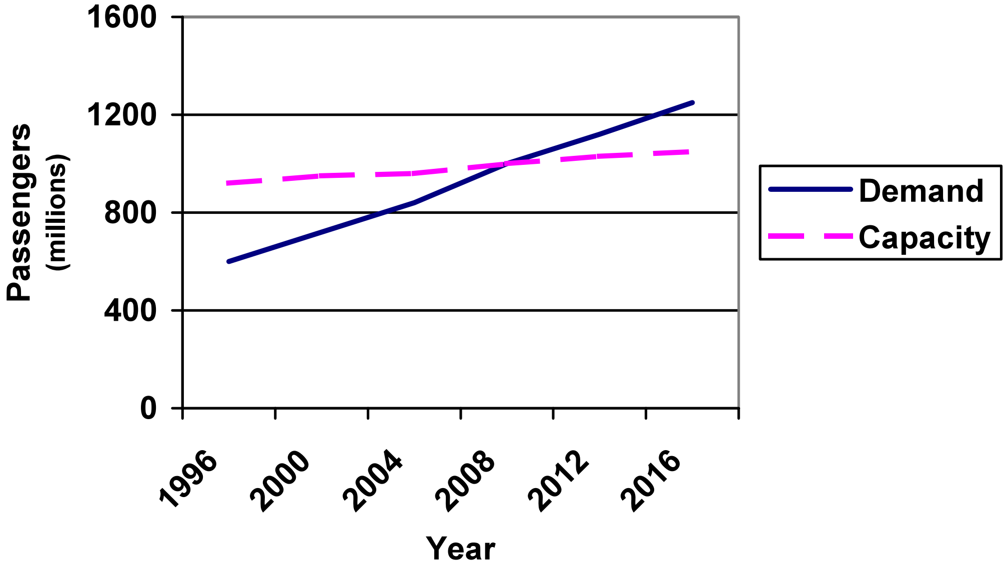

Figure 2-3. Beginning in approximately 2009 the capacity of the hub and spoke system will not meet demand (Holmes, 2000a).

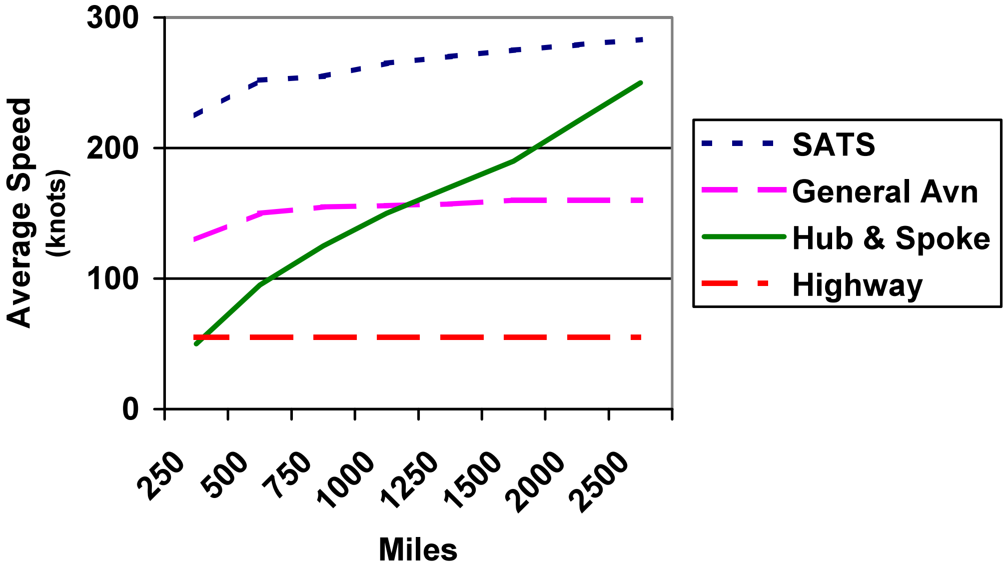

Figure 2-4. In a comparison of average speed of travel from doorstep to destination, SATS may have significant speed advantages over other forms of transportation (Holmes, 2000a).

The congressionally mandated research program for SATS includes four key operating capabilities that NASA and the Federal Aviation Administration (FAA) must address. First, they must demonstrate the feasibility of multiple aircraft operating in airspace around small airports without control towers or radar surveillance. Second, they must demonstrate that aircraft can conduct pinpoint landings in adverse weather without the use of ground based navigation aids. Third, they must demonstrate that SATS aircraft can integrate with the en route airspace system and with other aircraft. Fourth, they must demonstrate that single pilots of SATS aircraft can function safely and competently in complex airspace (NASA, 2000b). However, due to budgetary constraints, the NASA program managers have insufficient resources to fund research for the third operating capability - integrating SATS into the en route airspace.

Despite the lack of funding for en route research, there remains a need to identify and demonstrate the feasibility of ATC techniques using future technological capabilities available to SATS aircraft and the managers of the NAS. Future technologies may allow a shift in control from the centralized ATC system currently operated by the FAA to a decentralized system of interacting aircraft conducting collaborative decision making to dynamically generate safe flight paths (NASA, 2000a). Conceptually, SATS aircraft will communicate via an “airborne internet” and will navigate using GPS to gain access to thousands of suburban, rural, and remote airfields. The NASA proponents envision SATS aircraft using the airborne internet and GPS to operate within the NAS under a concept called “Free Flight” (Federal Aviation Administration, 1999).

2.2 The FAA Goal of Free Flight

In the late 1990s the FAA, in concert with the aviation community, recognized four goals related to airspace in order to increase the capacity, accessibility, and flexibility of airspace available to aircraft while also contributing to the increased safety of aircraft operations (Federal Aviation Administration, 1999). The proposed method of meeting the goals is through a concept called “Free Flight.” The FAA accepts the definition of Free Flight advocated by the Radio Technical Commission for Aeronautics (RTCA), a consortium of government and industry organizations established in 1935 to build consensus among all members of the aviation community regarding issues of mutual concern. The RTCA describes Free Flight as, “…a safe and efficient operating capability under instrument flight rules in which the operators have the freedom to select their path and speed in real time. Air traffic restrictions are imposed only to ensure separation, to preclude exceeding airport capability, to prevent unauthorized flight through special use airspace, and to ensure safety of flight. Restrictions are limited in extent and duration to correct the identified problem. Any activity which removes restrictions represents a move toward Free Flight" (Federal Aviation Administration, 1999, p. 2-6). The Free Flight description depicts the concept as an objective, not a specific system design. Additionally, the description indicates that an incremental approach to Free Flight implementation is acceptable to the aviation community. Among the reasons for adopting new approaches to air traffic management, such as Free Flight, are to increase throughput at airports without building new runways (Sastry, 1995) and to improve fuel consumption by making aircraft routing more efficient (Chiang, 1997).

The FAA's (1999) National Airspace Architecture Version 4.0 outlines the administration's approach to Free Flight. The FAA envisions a series of technological innovations to incrementally modernize the ATC system. The FAA anticipates aircraft navigation shifting from today's ground and radar-based system of navigational aids, such as radio beacons and transmitters, to satellite-based navigation and landing procedures. Aircraft communications systems should transition from analogue to digital. Automated systems may provide interactive flight planning to adjust flight routes prior to departure, they may monitor and advise aircraft in flight, and they may create the conditions for a steady flow of air traffic throughout the system. The FAA is devoting significant effort to transition to the systems it envisions for the future. Currently, over 19,000 air traffic controllers use thousands of pieces of equipment at hundreds of locations to manage the air traffic system. However, the infrastructure is old, rapidly deteriorating, and in need of modernization (FAA, 1999, p. 2-3). Thus, the FAA's move to Free Flight involves a complex transition in personnel, technology, and procedures.

The changes associated with the use of airspace may entail a dramatic shift from a philosophy of firm control to that of loose management. Figure 2-5 and Figure 2-6 graphically show the physical and conceptual changes the FAA must undergo to transition from the current radar-based system of air traffic control to the satellite-based Free Flight system of air traffic management. Currently, aircraft flying under IFR rely on voice transmissions from ground-based controllers using radar and radio transmissions from ground-based navigation aids to move through airspace as depicted in Figure 2-5. Under the FAA's proposed Free Flight system portrayed in Figure 2-6, technological innovations such as advanced cockpit displays and conflict avoidance software may allow aircraft to fly freely using satellite based navigation and procedures that integrate aircraft flight paths and ATC systems (FAA, 1999). The desired end result is a system that gives pilots the freedom of flying under visual flight rules (VFR) while providing the safe separation of aircraft similar to that of aircraft flying IFR.

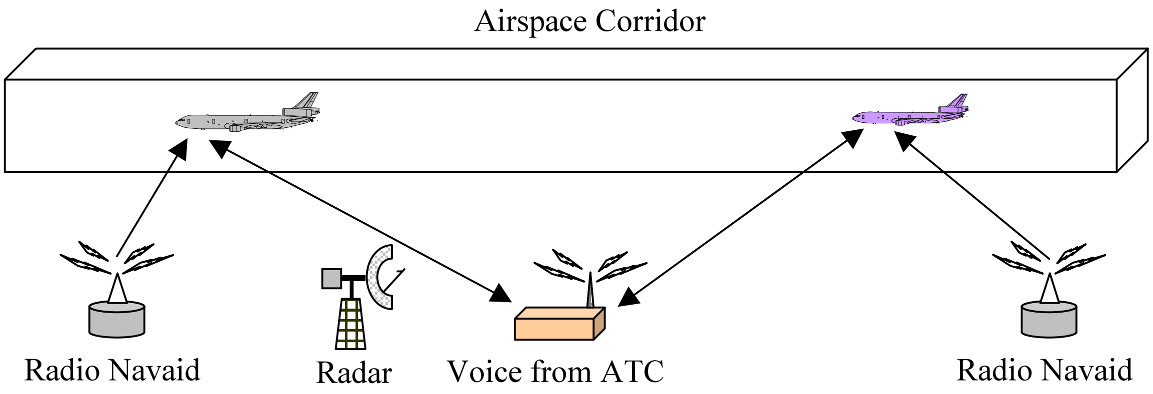

Figure 2-5. In the current air traffic control system voice commands and transmissions from ground-based navigation aids provide the primary means of navigation and conflict avoidance in predefined air corridors.

Although the Free Flight concept does not specifically address SATS, the intentions of Free Flight advocates are similar to those of the SATS proponents. A premise of Free Flight is that precision approaches based on satellite navigation will open more airports to IFR operations. The Free Flight concept includes the assumption that pilots will have the technological capability to assume much more responsibility in adjusting their route, altitude, and airspeed to maintain separation from other aircraft. The Free Flight concept primarily addresses high altitude airliners operating above 29,000 feet. However, regional, business, or general aviation aircraft that fly below 18,000 feet may also be able to operate in a Free Flight mode. The SATS concept takes the Free Flight goal and stretches it to the point where control towers and radar surveillance become unnecessary.

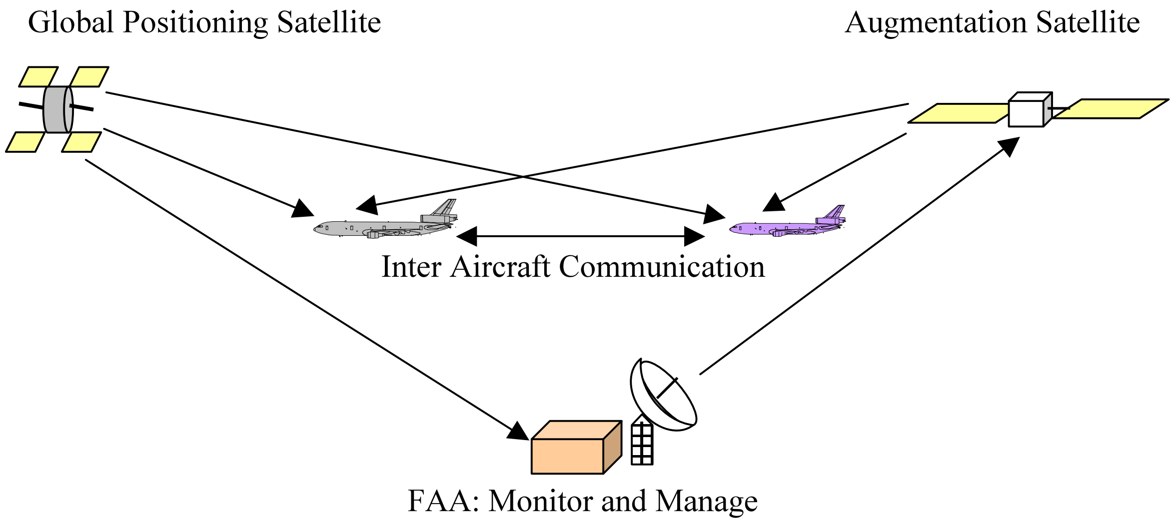

Figure 2-6. In the future, the FAA anticipates monitoring and managing airspace via ground and cockpit displays that show aircraft, obstacles, and terrain by linking electronically to satellites and other aircraft (FAA, 1999).

However, despite Free Flight, there will be restrictions that limit aircraft in the vicinity of airports, other areas of high-density air traffic, or around facilities designated as national security sites. Existing ground-based navigational aids may continue to work in high-density areas as well as in areas where aircraft must avoid terrain obstacles, maneuver around special use airspace, or transition between airspace with different separation standards. Due to the terrorist hijackings and attacks of September 11th, 2001, air traffic managers will maintain positive control of aircraft in areas with large populations or vital national security facilities. Thus, the application of Free Flight may occur primarily within the en route portion of most flights.

The FAA appears to be taking a systems approach to the migration of Air traffic control to air traffic management under the Free Flight concept. The Free Flight vision for the future includes two principle human/technological components. First, air traffic controllers will have decision support tools to assist them in both strategic and tactical airspace planning. Air traffic controllers conduct strategic airspace planning to ensure efficient system wide flow of all flights. Tactical planning addresses the safe passage of each flight as it physically travels through the national airspace system. Second, pilots will have improved avionics, satellite based navigation, and a dynamic collaborative flight planning process (FAA, 1999). However, the FAA summarizes its Free Flight goal by restating the last line of the RTCA definition, "Any activity that removes operational restrictions is a move towards Free Flight" (FAA, 1999, p. 6-1). In effect, the administration recognizes that its plans are subject to resource constraints that may limit a vast modernization effort to a few activities that reduce or remove operational restrictions. Subsequently, the FAA uses the preponderance of its resources to maintain safe current operations and relies to a great extent on outside research related to Free Flight.

Most Free Flight research promotes the development of an interactive system of pilots, airspace managers, and airline operations centers using advanced telecommunications and intensive computational algorithms to manage air traffic. Examples of such research efforts include methodologies and algorithms to maintain separation (Hu, Prandini, & Sastry, 2000; Jardin, 2000; Barrer, 1999; Devasia & Meyer, 1999; Eby & Kelly, 1999; Tomlin, Pappas, & Sastry, 1998; Ball, 1997; and, Chiang, Klosowski, Lee, & Mitchell, 1997). The principal focus of these research efforts relates to conflict avoidance among two or more aircraft operating on the same two-dimensional plane. Significantly more effort will expand the research to three dimensions and involve higher fidelity models that replicate the real system.

Other Free Flight researchers use more systems oriented approaches to address a variety of airspace management issues such as pilot behavior (Hoekstra, van Gent, & Ruigrok, 1998), cockpit functions and air traffic management control functions (Jackson & Green, 1998), hybrid hierarchical decision-making systems (Pappas, Tomlin, Lygeros, Godbole, & Sastry, 1997), and information access and sharing (Smith, Billings, Woods, & McCoy, 1998). Most research addresses specific applications of technology and the general role of people in a Free Flight environment. However, little research addresses the higher-level issues of how the ATC system will behave on a national level in light of the transition from radar to GPS and the introduction of hundreds or thousands of SATS aircraft into the system. A first step in understanding the potential behavior of the system is to observe how it behaved in the past.

2.3 A Brief History of Air Traffic Control

The history of Air Traffic Control (ATC) consists of proactive and reactive applications of technology and procedures to address aviation operational initiatives, aircraft performance improvements, and Congressional reactions to aircraft accidents and incidents. An early technological and procedural illustration of ATC addressing aviation operational initiatives was the use of lighted towers to illuminate over 18,000 miles of cross-country airways in the 1920s and 1930s, which enabled pilots to fly at night. An example of ATC aligning with aircraft performance improvements was the first landing in a blinding snowstorm of a passenger-carrying Boeing 247-D airliner traveling from Washington, DC to Pittsburgh in January of 1938, which was successful because of a ground-based instrument landing system that complemented the aircraft's navigation system. Examples of ATC responding to Congressional reaction to accidents and incidents, such as the first crash of an airliner that killed 27 people in 1946 and the midair collision of two airliners over New York City that killed 136 people in 1960, include accelerated installation of new equipment and the initiation of studies to improve the capabilities of the ATC system (Illman, 1999; Nolan, 1999).

Despite the applications of new technology and procedures, the ATC system also has a history of poor funding and mediocre management practices creating performance shortfalls in the application of technology and the use of new procedures. Civil aviation activities began in the US following World War I when the Post Office Department used a succession of Army aircraft, Post Office aircraft, and contract aircraft to transport airmail from 1918 until 1933. Since air traffic was sparse, the attention of air traffic managers was in two areas: first, they developed control towers at airports in large cities such as New York, Chicago, and San Francisco; and second, they installed simple radio-based mechanisms to establish airways among the big cities. Air traffic controllers provided advisories to pilots, however they were not legally obligated to follow them. Due to the growth of passenger carrying airlines and instrument flight, Congress established the Bureau of Air Commerce in 1934 to oversee aviation activities. Yet, the Copeland Commission of the House Commerce Committee issued a negative report on the Bureau of Air Commerce two years later citing poor management of the airways and problems with congestion at major airports. The Bureau had little authority. The airlines had been directing their own flights along airways, and military and private aircraft did not have to comply with the airlines' control stations. Subsequently, Congress replaced the Bureau of Air Commerce with the Civil Aeronautics Authority in 1938 (Illman, 1999; Nolan, 1999).

After some initial growing pains, the unwieldy Civil Aeronautics Authority became the Civil Aeronautics Administration (CAA) in 1940. The CAA centralized and standardized aviation procedures. Additionally, the administration implemented air traffic management practices using up to date instrument flight technology and approach control and interstate airway communication procedures. Congress provided adequate funding to the CAA in response to the problems of congestion, near misses, and unsafe mixing of air traffic operating under instrument and visual flight rules. The federal government also increased CAA's budget to support World War II related flight operations during a time when the US aviation industry became the largest in the world. Unfortunately, by the mid 1950s the CAA's budget shrank. Disgruntled air traffic controllers left their underpaid profession. In 1957 two midair collisions between military jets operating under visual flight rules and civilian airliners operating under instrument flight rules prompted Congress to establish the Federal Aviation Agency in 1958 and give the director cabinet rank (Illman, 1999; Nolan, 1999).

The creation of the Federal Aviation Agency clearly indicated the national importance of the US aviation system, yet it did not address all of the system's needs. The Agency experienced a short-lived independence. It became part of the Department of Transportation in 1967 and was renamed the Federal Aviation Administration (FAA). Like its predecessor organizations, the FAA experienced funding constraints in the late 1960s that precluded modernization in order to maintain day-to-day operations. The deregulation of the airline industry in 1978 overwhelmed the air traffic control system due to the creation of the hub and spoke networks by the airlines. Three years later frustrated controllers went on strike and President Reagan directed the FAA to fire over 10,000 controllers who left their jobs. Poor management and changing technology caused the billion-dollar air traffic control modernization project of the late 1980s to falter (Illman, 1999; Nolan, 1999). Today the ATC system remains as an interim modernization effort that faces challenges of congestion, resource constraints, and security issues stemming from the terrorist attacks of September 11, 2001.

2.4 Anticipated Air Traffic Control Requirements and Initiatives

Despite the historically tenuous health of the ATC system, forecasters anticipate an air traffic growth rate of 10 percent per year during the first decade of the 21st century. Currently, as more aircraft attempt to use the air traffic system, system managers must impose restrictions on flight routes in order to prevent conflicts and to reduce the number of aircraft each controller monitors. The subsequent rerouting of aircraft increases fuel consumption, flight time, and delays. Less airspace becomes available for air traffic and more airspace remains empty. It appears that the primary constraint on the system is the controller's ability to coordinate clearances and anticipate conflicts. Therefore, the FAA envisions increasing productivity by providing controllers with computer systems that monitor air traffic, anticipate conflicts, and then recommend courses of action to prevent potential problems (Nolan, 1999). An alternative to increasing each controller's productivity is to utilize more controllers in order to reduce each controller's share of responsibility. However, the marginal increases in the capacity of the system would likely be offset by higher amounts of coordination among a larger number of controllers handing off aircraft control responsibilities across airspace boundaries.

The FAA is undertaking two initiatives to address the crowding of the national airspace system: ATC modernization and the Free Flight concept. Modernization efforts include systems to monitor and calculate traffic flow throughout the airspace system. Three programs involved in the traffic flow calculations are departure delay, en route metering, and en route sector loading. The departure delay program attempts to hold aircraft on the ground prior to departure if the destination airport forecast shows that the airport will exceed its flight acceptance rate. Controllers use the en route metering program to delay aircraft in the air when the system indicates that the destination airport acceptance rate would be too high. Controllers reroute aircraft or adjust their airspeed in an attempt to prevent holding prior to landing. The en route sector loading program provides computer predictions of upcoming traffic in an en route sector in order to allow controllers to manually reroute traffic if a sector overload condition appears imminent (Nolan, 1999).

The FAA has a goal to have the bulk of air traffic management conducted under the concept of Free Fight by 2010. The concept of Free Flight is to allow pilots operating under IFR to choose their route, speed, and altitude as they fly. Controllers will only monitor operations unless positive aircraft separation may not occur. As each aircraft travels, two zones surrounding it will move with the aircraft to provide separation from other aircraft. The alert zone is a large volume of space around each aircraft which, when it overlaps with another aircraft's alert zone, alerts the pilots, controllers, and decision support software that the two aircraft may have conflicting routes. Pilots can fly at their own discretion until their alert zones intersect. Inside each alert zone is a smaller volume of space called the protected zone. The goal of the Free Flight system is to never have overlap among protected zones (Nolan, 1999). However, the attacks of September 11, 2001 may cause modifications to the Free Flight goal, causing a need to maintain more positive control in sensitive airspace.

The implementation of Free Flight will cause the FAA and the aviation community to undergo a major philosophical change by transitioning from the practice of air traffic control to the concept of air traffic management. Pilots and airlines will become the principal decision-makers in determining air routes, altitudes, and airspeed. Airspace managers will only intervene to ensure safe operations (Nolan, 1999). The transition from air traffic control to air traffic management will require many changes. Recently, the FAA began expanding the number of national route program flights that allow pilots flying at the higher altitudes above 29,000 feet to choose their own route. The FAA anticipates reducing its reliance on analogue voice radio communications and migrating to a digital means of communication. Similarly, the FAA plans on evolving to satellite-based navigation systems for use as both en route and approach navigation aids. Finally, the FAA intends to make surveillance system improvements that will help air traffic managers locate and track aircraft while simultaneously reducing separation standards to increase the volume of flow throughout the system. The FAA is upgrading the existing radar system, which is the primary means of air traffic surveillance, while also transitioning to a satellite-based position broadcasting system that may eventually replace radar (Nolan, 1999). The process of changing the air traffic control system will be complex and multi-faceted. An important aspect of the change will be to consider how the culture of the organization will respond to the proposals.

Barrett and Beck (2001) argue that changes in air traffic control systems should be evolutionary, not revolutionary. Due to the initial selection process and their subsequent training, air traffic controllers are "conservative people" who are "resistant to what they may see as unnecessary change" (p. 27). Accordingly, changes made in air traffic control systems should be done one piece at a time by changing either a process or the technology, but not both simultaneously. The SATS program appears to be what Barret and Beck (2001) describe as a "big bang project;" a project that historically does not work well because of conflicts with the culture of ATC. The ATC culture is one which prefers step-by-step change that is well planned, tested, and communicated. Communicating with ATC stakeholders may be crucial to the success of change efforts like SATS. To appreciate the perspective of the controllers, it is useful to understand their duties and the environment in which they operate.

2.5 Air Traffic Controller Functions and Tools

Air traffic controllers serve in a variety of functions to provide safe passage to aircraft operating within the NAS. The phases of a commercial airline flight provides a good framework to best understand the roles fulfilled by air traffic controllers. The following sequential phases of flight – preflight, takeoff, departure, enroute, approach, and landing - correspond with air traffic controller activities of tracking, monitoring, and directing aircraft.

2.5.1 Preflight

The "clearance delivery controller" works in a control tower and issues a flight plan clearance to the pilot of each flight. He or she then creates a flight progress strip, which is a piece of paper that contains information about each flight. After radioing a clearance to the pilot, the clearance delivery controller gives the flight progress strip to a "ground controller," another member of the control tower. The ground controller directs aircraft from the departure gate by providing taxi instructions to the pilot. The ground controllers in the tower rely primarily on visual observation and radio communication to direct aircraft on the ground. They also use computer databases to manage information and Airport Surface Detection Equipment (ASDE) or "surface radar" to monitor aircraft and ground vehicular activity during reduced visibility (FAA, 2000).

2.5.2 Takeoff

Approximately 15 minutes after leaving the gate, the average commercial aircraft is in position to enter the active runway. At that time the ground controller physically passes the flight progress strip to the "local controller," who issues the clearance for takeoff to the pilot. The local controller is responsible for maintaining appropriate spacing during takeoff, depending on the size and type of aircraft. The local controller visually monitors aircraft from the vantage point of the control tower and observes radar displays showing the progress of the flight on the ground and in the air. When the aircraft is approximately five miles from the airport, the local controller instructs the pilot to change radio frequency and contact the "departure controller" (FAA, 2000).

2.5.3 Departure

The departure controller sits in front of a radar display in one of the 184 Terminal Radar Approach Control (TRACON) facilities in the US. The departure controller identifies each aircraft by an electronic tag on the radar display. The departure controller directs the aircraft from the airport to the en route airspace by giving pilots heading, altitude, and speed instructions to safely guide each aircraft to its cruise altitude via an air corridor. After directing the aircraft to a point near the boundary of the TRACON, the departure controller electronically hands-off the aircraft to a "center controller" at one of the 21 Air Route Traffic Control Centers (ARTCC) in the US. The departure controller instructs the pilot to change radio frequency and contact the center controller (FAA, 2000).

2.5.4 Enroute

Center controllers monitor flights on a radar display during the cruise phase by providing spacing and weather advisories to the pilots. Each center consists of approximately 20 sectors each monitored by two center controllers. As each flight passes through the center controller's sector, he or she hands-off the flights to either another center controller or to a TRACON "approach controller" if the aircraft needs to descend towards a final destination. Center controllers use computer based prediction tools, such as the Traffic Management Advisor (TMA), to determine when congestion may occur at an airport due to too many simultaneous arrivals. The TMA provides recommended flight adjustments that controllers may issue in order to adjust aircraft arrivals to remain within the capacity of the airport (FAA, 2000).

2.5.5 Approach

Like the departure controller, the approach controller observes a radar display in the TRACON. The approach controller simultaneously separates aircraft and sequences them into a smooth flow of arrivals at the destination airport by instructing pilots to change heading, speed, and altitude. The approach controller instructs the pilot to change radio frequency to contact the local controller when the aircraft is approximately 10 miles from the destination airport. In addition to the radar display, some TRACONs have the Final Approach Spacing Tool (FAST) to help approach controllers determine how to best sequence arriving aircraft according to their size and capabilities (FAA, 2000).

2.5.6 Landing

Similar to takeoff, but in the opposite order, the controllers in the tower control the arriving aircraft from about 10 miles away from the airport until the aircraft parks at a gate. The local controller issues a landing clearance and directs the aircraft off of the runway onto a taxiway. The ground controller provides taxi instructions to safely direct the aircraft to an arrival gate.

Table 2-1 summarizes the different types of controllers, their functions, and their tools (FAA, 2000).

Table 2-1: Air Traffic Controllers perform several important functions from multiple locations.

Controller	Location	Function	Tools
Clearance Delivery	Tower	Clears flight plan, Creates flight progress strip	Radio, Database
Ground	Tower	Taxi instructions, Ground separation	Radio, Surface Radar
Local	Tower	Takeoff separation, Landing clearance	Radio, Surface Radar, Airport Radar
Departure	TRACON	Separation, Route to cruise altitude in center	Radio, Radar
Center	ARTCC	Enroute separation, Route to approach control	Radio, Radar, TMA
Approach	TRACON	Separation, Sequence arrivals to final destination	Radio, Radar, FAST

The six functions performed by the 19,000 air traffic controllers in the US involve approximately 64,000 daily flight plans and a constant presence of approximately 5,000 airborne aircraft over the US between 7:00am and 7:00pm daily. Although the intent of NASA proponents of SATS is to create aircraft that self-separate, the magnitude of the current system suggests that there will be a large presence of human air traffic controllers for many years into the future. Therefore, it is prudent for government managers to use tools to determine what may be the best policies that support the technological advancements of SATS, while respecting the needs of the present system.

2.6 SATS Modeling at Virginia Tech

The objective of a research effort at Virginia Polytechnic Institute and State University is to develop a high level tool to investigate the impact of SATS as a transportation system. The effort consists of the ongoing development of a System Dynamics model of the entire SATS in order to better understand how the system will behave over time. The nineteen components of the System Dynamics model address the following aspects of SATS (Trani, 2002):

- Aircraft Production
- Airport Infrastructure
- Airspace

- Air Traffic Controllers
- Communications
- Economics
- Energy
- Measures of Effectiveness
- Modal Split
- Air Transportation Network Assignment
- Noise
- Pilot Training
- Population
- Safety
- SATS Vehicle Technology
- Service Provider Operations
- Transportation Cost
- Trip Distribution
- Trip Generation

Researchers are making progress in several areas of the above model: trip generation, trip distribution, noise, and the air transportation network assignment submodels. The other submodels still require study and refinement. The research effort in this document will relate to the air traffic controllers submodel.

2.7 The FAA Strategic Decision Support System Model

Also using the System Dynamics approach, developers of a strategic decision support system for the FAA (Suiter & Peterson, 2001) created a submodel on Air Traffic Control Capacity that includes three major ATC system constraints: infrastructure, communication bandwidth, and air traffic control personnel. The developers defined infrastructure as the combination of radars, computers, buildings, and repair facilities. Their submodel contains variables to replicate infrastructure details such as budgets, equipment age, and deterioration. However, the developers considered bandwidth and the number or air traffic controllers as constants in the system. The rationale for the use of a constant to represent bandwidth is that the amount available cannot change without the introduction of new technology to use it and negotiation to obtain it from another user. The rationale for the use of a constant number of air traffic controllers is that, "Historical trends have shown that the capacity of the system is not strongly tied to the mere number of air traffic controllers" (Suiter & Peterson, 2001, p. 15). The developers point out that air traffic controllers were able to surge operations and operate with greater than normal collaboration during events such as the Gulf War in 1991.

The developers base their claims regarding the capabilities of air traffic control personnel on interviews made with subject matter experts in the FAA. Many of the interviewees indicated that controller "ingenuity and ability to adapt as a primary factor in system performance (keeping out of gridlock)" (Suiter & Peterson, 2001, p. 42). Yet the developers chose to model the controllers with a constant instead of looking deeper into the role of the controllers to determine how other variables may account for aspects such as ingenuity and adaptability. Interviewees also indicated that the National Air Traffic Controllers Association (NATCA) impedes the introduction of new equipment to aid controllers as a negotiating bargaining chip. Interviewees pointed out three issues involving controller pay and incentives: first, controller pay is a function of the volume and complexity of the air traffic they control; second, controller pay lacks incentives for inter-controller cooperation; and third, current policies dictate individual punishment for violating rules such as not adhering to minimum aircraft separation standards. Interviewees claim some controllers act on biases, such as increasing separation distances when they hear a female pilot's voice or stubbornly delaying an aircraft to show dominance over a pilot. Interviewees expressed concern that the high number of controllers taking a summer vacation caused excessive overtime and understaffing. Although the developers of the ATC submodel chose not to consider the effects of NATCA, pay, punishment, bias, and vacation policies, further research into the implications of these issues may improve understanding of the performance of the air traffic control system.

2.8 European Shortages of Air Traffic Controllers

A study done by Eurocontrol, the European organization for the safety of air navigation, includes several reasons for a shortage of air traffic controllers in Europe. First, the population pool from which controllers emanate also provides employees to other competing industries, so there is a recruiting challenge. Second, the volume of air traffic has increased faster than the abilities of the controller base. Third, insufficient long-term manpower management has been weak. It does not adequately take into account changes in the airspace, volume of traffic, new technology, working conditions, leaves, and administrative job requirements assigned to controllers. Fourth, planners did not adequately considered early retirement or burnout that causes controllers to leave the system sooner than they might otherwise. Fifth, although it helps improve performance and reduce workload, new technology has not yet replaced the need for human controllers, nor will it do so under current plans for the future. Sixth, there is a 25% failure rate among new controllers in either initial training or on the job training, and, due to lack of instructors the controller training capacity operates at 80% of its capability (Skoniezki, 2001). The US system may face similar problems soon as the majority of controllers currently in the system began their careers as replacements for the controllers fired in the 1981 strike.

2.9 Preview: A System Dynamics Approach to Air Traffic Control Manpower and Infrastructure Modeling

The history and anticipated requirements of ATC provide insight into the underlying causes of the events that influenced the development of ATC capabilities in the past and the future impacts of demand and modernization upon ATC. Many of the past events and future conditions that influence ATC are expressible in terms of quantities and equations such as numbers of aircraft, aircraft performance capabilities, safety records, capital equipment, and numbers of controllers. The quantities and equations provide the input that is useful for developing mathematical models of ATC.

A significant portion of the research effort outlined in this document will involve the search for valid descriptions of the quantities and equations associated with the variables in an ATC manpower and infrastructure resource management model. Measurements of the activities in the ATC system in terms of flows of people, aircraft, ATC capital equipment, money, and information will provide a basis upon which to evaluate how structure, delays, and decision-making shape system behavior to create stability, growth, or decay (Forrester, 1961). For example, Figure 2-7 depicts the flow of air traffic controllers through a system involving training, controlling, and retirement. Expanding the structure of the model may include the various functions of air traffic control at towers, TRACONS, or centers as well as administrators and retirees as depicted in Figure 2-8. Decision-making activities may occur to determine when or how many controllers to train or move from one function to another. Delays may occur when attempting to recruit and train new hires or transition experienced controllers from one job to another.

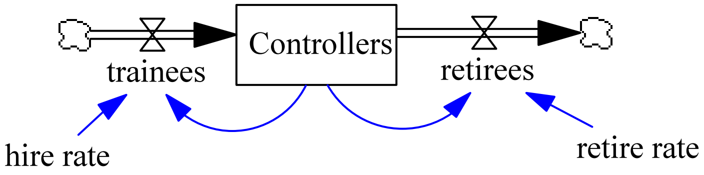

Figure 2-7. A simple model of the flow of air traffic controllers.

Figure 2-7 is a simple "stock and flow" diagram expressed in the language of the field of System Dynamics. Sections 2.12 below contains a detailed discussion of System Dynamics. The box around controllers in Figure 2-7 indicates that an accumulation occurs at that point similar to water filling a bathtub. The amount of controllers increases as trainees flow into the controller box, as indicated by the valve on the arrow flowing into controllers. The rate of flow of the trainees depends on the hire rate and the number of controllers in the system, both indicated by the influence arrows connected to trainees. Similarly, the flow of retirees out of controllers indicates a reduction in the number of controllers in a manner similar to water draining from a bathtub. The clouds on either end indicate unlimited sources and sinks. System Dynamics models consist of combinations of accumulations, causal influences, and delays that cause feedback and dynamic behavior within systems.

Understanding the impacts of other key variables, such as the number of aircraft flights and ATC capital equipment, requires an expanded model that integrates all the relevant system structure. The nature of the ATC system is such that changes in one variable, such as the number of flights, causes feedback that influences other variables such as the required number of air traffic controllers. The dynamic feedback characteristics of the ATC manpower and infrastructure requirements problem makes the use of the System Dynamics process and computer simulation approach quite suitable as a means of understanding the behavior of the

ATC system. The application of System Dynamics to ATC may help to avoid phenomena such as the "improvement paradox" described by Keating et al (1999), where improvements in production rates in some companies resulted in excess capacity which led to layoffs and subsequently drove down employee commitment to improvement programs. Thus, a systems perspective is a relevant approach to the challenges of managing ATC system resources.

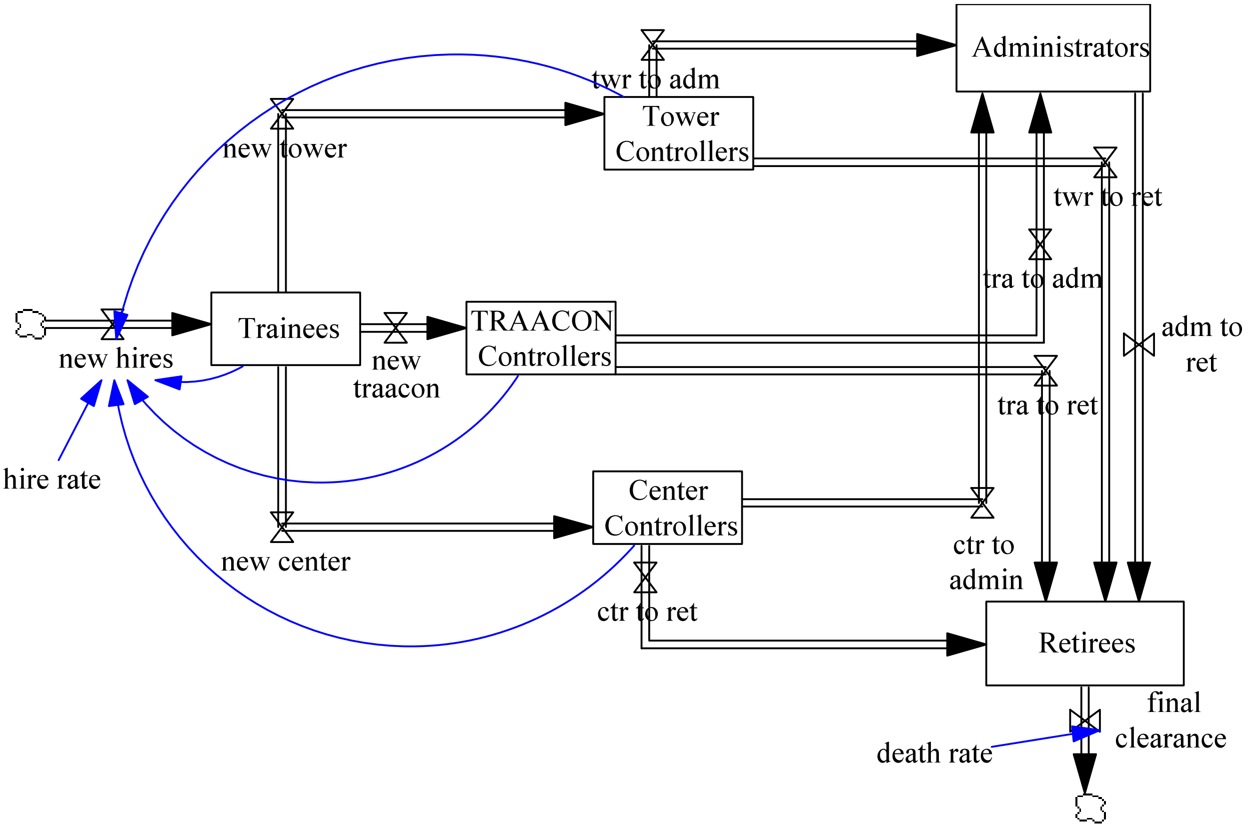

Figure 2-8. An expanded depiction of Figure 2-7 where the controller stock consists of tower, TRACON, and center controllers and administrators.

2.10 Systems Thinking and the Systems Approach

The systems literature offers insights that may be helpful in dealing with the challenges faced by government air traffic control administrators who must make decisions that have ramifications throughout the large complex systems within which they operate. Senge (1990) offered systems oriented insights for managers of large complex systems by popularizing the notion of "systems thinking," which he defined as "a conceptual framework, a body of knowledge and the tools that has been developed over the past fifty years…" (p. 7). Senge intended to shift the mindset that managers controlled isolated organizations to the mindset that many interrelated forces influenced organizational behavior. He advocated the use of systems thinking as the foundation upon which managers could create a "learning organization – an organization that is continually expanding its capacity to create its future" (p. 14), by designing structure into organizations to shape growth, thinking, and communication. Senge's approach sets the stage for the search to identify and understand the concepts, knowledge, and tools of systems thinking that may help managers of complex organizations improve their decision-making abilities.

Blanchard and Fabrycky (1998) address the basic concepts of systems thinking by defining a system as "a set of interrelated components working together toward some common objective or purpose" (p. 2). They claim that the world is transitioning from thinking dominated by reductionism and mechanism to a new thinking dominated by expansionism. Reductionism breaks things down into small pieces; mechanism assigns a specific cause to each event. Expansionism attributes behavior to the interrelationships of many parts. The significance of the transition in human thinking from breaking things down to putting things together is twofold. First, people recognize that they can combine the three concepts of reductionism, mechanism, and expansionism by focusing on how the interrelationships of many parts influence the behavior of the whole. Second, people realize that trying to make each part perform optimally often causes the system to perform less than optimally. Blanchard and Fabrycky describe the new thinking as the "systems approach" (p. 12).

Churchman (1968), a pioneering systems thinker in the 1960s, described the systems approach as "simply a way of thinking about these total systems and their components" (1968, p. 11). He claimed "every system is embedded in a larger system" (p. 48) and presented the idea that the "larger system" may actually be the world in the future - thus connecting the aspect of time with systems thinking. He alluded to the direct relationship between structure and behavior by stating; "The management scientist sees the nature of the whole system as a determinant of individual behavior" (p.200). Although Churchman believed few managers understood how they determined what important variables to monitor in their systems, he believed it was possible to provide managers with a systems approach that would help them understand what to attend to and why.

Churchman advocated a scientifically oriented systems approach centered on the use of mathematical or behavioral models to describe systems. He defined a model as "a way in which the human thought process can be amplified" (p. 61). He believed that modelers should consider five aspects of systems: 1) the objective of the system and system performance metrics; 2) the environment of the system – those things which effect the system but which the system cannot influence very much; 3) the resources inside the system that it uses to accomplish the objective; 4) the system's components, their activities and performance; and 5) the management of the system. Churchman recognized that one would truly know they were viewing the system as a whole when they could see the system intentionally sacrifice lesser goals in the pursuit of it's true objective. Such an approach was somewhat radical in its time and still may prove challenging for government managers battling among each other for constrained resources. The approach would require one agency or department to intentionally shortchange its own efforts in order to provide another agency or department with the resources that increase the performance of the larger system.

To operate at such a challenging, benevolent, and sacrificial level of thinking, Richmond (1993) proposed seven "systems thinking skills" that individuals should develop separately and use simultaneously in order to be effective systems thinkers. He recommended learning the following skills separately in order to prevent the "cognitive overload" experienced by people trying to learn them all at once:

1. Dynamic thinking: the ability to focus on patterns of behavior over time rather than on specific events.
2. Closed-loop Thinking: observing a system as an interdependent spider web of components rather than as an organizational chart of singular cause and effect relationships.
3. Generic thinking: attributing events to the structure of the system, not to specific individuals.
4. Structural thinking: recognizing and appreciating the dimensions of the stocks and flows in a system. Note: section 2.12.1 below contains definitions of stocks and flows.

5. Operational thinking: realistically integrating the essential elements required to make a system operate.
6. Continuum thinking: replacing the polarizing if-then-else approach to decision-making with acceptance of multiple possibilities along a continuum of alternatives.
7. Scientific thinking: quantifying variables and using them to test hypotheses.

The above skills provide not only a framework for understanding system thinking, but also recognition of the depth and diversity of thought and talent required to address the dynamic nature of problems within systems. Clearly, an effective systems approach involves thoroughness, openness, and the abilities to research and communicate. As O'Connor & McDermott (1997) see it, "Systems thinking is the way we can discern some rules, some sense of patterns and events, so we can prepare for the future and gain some influence over it" (p. xiv).

The concepts and frameworks by Senge, Blanchard & Fabrycky, Churchman, Richmond and O'Connor & McDermontt provide a foundation for the application of systems thinking toward the challenges of managing manpower and infrastructure in the US ATC system. In particular, the above perspectives allude to or directly advocate the usage of the tools and procedures associated with the computer modeling of the System Dynamics process. They advocate the sort of systems thinking that goes beyond observing, thinking, diagramming and talking about systems. Forrester cautioned that such superficial systems thinking (Forrester, 1994) lacks the rigor of the "quantitative and dynamic analysis that constitutes real System Dynamics" (Koegh & Doman, 1992, p. 10), which leads people to an understanding of how management policies shape decision-making within a system. A further investigation of the concepts, processes, and tools of System Dynamics will clarify how researchers may apply it to increase understanding of the dynamic interactions among air traffic controllers, flights, capital equipment, and other resources in order to determine the potential behavior of the ATC system under various resource management scenarios and with the introduction of SATS aircraft into the system.

2.11 System Dynamics

Coyle (1996) defines System Dynamics as a qualitative and quantitative approach to describe, model, and design structure for managed systems in order to understand how delays, feedback, and interrelationships among variables influence the behavior of the system over time.

Coyle claims that managers can use System Dynamics to model the effects of manipulating policies governing the system in order to create more desired system behavior. Sterman (2000, 1994) describes System Dynamics as an aid to learning and understanding complex systems. He emphasizes how the System Dynamics modeling process consists of tools to elicit mental models of systems, procedures to create formal models based on the mental models, computer simulations of the formal models, and applications of the findings of the simulations to improve understanding of the system. Lyneis (1999) highlights the business application of System Dynamics as an approach that combines a client's decision-making processes and computer simulation models to develop decision-making tools. The definition from the System Dynamics Society website defines System Dynamics as "a methodology for studying and managing complex feedback systems" (System Dynamics Society, 2001). Mathematically, System Dynamics models consist of nonlinear ordinary differential equations (Sterman, 2000). The fundamental insights from the above definitions of some of the leading researchers and practitioners in the field of System Dynamics are:

- System Dynamics is qualitative and quantitative.
- System Dynamics is a process involving elicitation, modeling, and simulation tools.
- System Dynamics is useful as a learning process and a means to create tools to aid understanding.
- System Dynamics describes systems in terms of interactions with delays and feedback.

The System Dynamics concepts listed above provide a framework for researchers who seek to understand complex systems. The System Dynamics approach will be useful to investigate the impact of SATS upon the complex NAS.

The roots of Coyle and Sterman's descriptions of System Dynamics lie in Forrester's seminal work that originally introduced the concept of System Dynamics, initially with the term "industrial dynamics." Forrester (1961) claimed in his preface to *Industrial Dynamics* that, "Industrial dynamics is a way of studying the behavior of industrial systems to show how policies, decisions, structure, and delays are interrelated to influence growth and stability. It integrates the separate functional areas of management – marketing, investment, research, personnel, production, and accounting. Each of these functions is reduced to a common basis by recognizing that any economic or corporate activity consists of flows of money, orders, materials, personnel, and capital equipment" (p. vii). Since Forrester conducted his initial work, researchers have applied System Dynamics to a variety of business, medical, environmental, economic, military, and social issues. The approach appears well suited for the ATC resource management and SATS/NAS integration issues as the system consists of functional areas and flows of personnel (air traffic controllers), investment (government appropriations), production (flights), accounting (performance measures), capital equipment (radar or satellite navigation systems), and material (aircraft) in the system.

2.12 System Dynamics Terminology and Tools

The System Dynamics literature is replete with descriptions of concepts and tools useful for modeling. However, the still maturing field does not have a formal standard of definitions. Subsequently, practitioners and theorists offer their descriptions of terms in their work. There is much commonality, yet there is also diversity of opinion, in cases such as the use of system archetypes. The following definitions incorporate the perspectives of several leaders in the field of System Dynamics, such as Forrester, Sterman, Ford, Coyle, Senge, and others. In general their views reflect the fundamental concept of System Dynamics that feedback structures of interconnected stocks and flows govern system behavior (Forrester,1961; Coyle, 1996; Ford, 1999; Sterman, 2000). Thus, the definitions and tools below relate to those aspects of system behavior.

2.12.1 Fundamental Concepts of System Dynamics

Stock: Stocks are the most important variables in a model. Stocks represent accumulations of some measurable entity (Ford, 1999). According to Sterman (2000), stocks "characterize the state of the system and generate the information upon which decisions and actions are based" (p. 192). Stocks may be people, parts, money, or even intangibles such as happiness. In Figure 2-7, the box around "controllers" identifies it as a stock. Table 2-2 provides a variety of interpretations of stocks under the heading "accumulation."

Flow: Flows are the physical or conceptual entities in systems that move over time. Examples of flows include people, material, or subjective concepts such as satisfaction. Flows into or out of stocks cause them to change. Sources and sinks are infinite capacities from which flows may originate or into which flows may depart. In Figure 2-7, the valve symbol above "trainees" identifies it as a flow. Table 2-2 provides a variety of interpretations of flows under the heading "action."

Auxiliaries: Sterman (2000) describes auxiliary variables as "intermediate concepts added to the model to aid clarity" (p. 205). Similarly, Coyle (1996) describes auxiliaries as "intermediate stages by which the levels determine the rates" (p. 86). Ford (1999) also claims that they help to "describe the flow" (p. 19) and serve as a tool to calculate system performance metrics. In Figure 2-7, "hire rate" is an auxiliary variable. Table 2-2 provides a variety of interpretations of auxiliary variables under the heading "auxiliary."

Table 2-2: Many different terms describe the concepts of stocks, flows, and auxiliary variables.

Source	Accumulation	Action	Auxiliary
Forrester	Levels	Rates	Multiplier
Sterman (2000)	Stock	Flow	Auxiliary
Ford (1999)	Stock	Flow	Converter
Mathematics	Integration	Differentiation	Parameter
Grammatical Analogue	Noun	Verb	Adverb
Assembly line	Buffer	Machine and Conveyor throughput	Machine and conveyor speed
Bank Analogy	Bank Account Balance	Interest added	Interest rate

Bounded Rationality: The concept that the unaided human mind cannot intuitively solve dynamically complex problems. From his studies of people working with simulations, Sterman (2000) believes people "misperceive feedback" because "the mental models people use to guide their decisions are dynamically deficient" (p. 27). System Dynamics is a tool to overcome the normal responses to bounded rationality, such as habits or rules of thumb (Sterman, 2000).

Delay: Stocks create delays in a system when the flow into the stock is greater than the flow out of the stock (Sterman, 2000).

Detail Complexity: Systems or decision-making situations characterized by many components or alternatives from which to choose have detail complexity due to the large numbers of combinations they present (Sterman, 2000).

Dynamic Complexity: Dynamic complexity occurs in systems characterized by large numbers of interactions over time where feedback and delays make it impossible to intuitively determine the behavior of even simply structured systems (Sterman, 2000).

Endogenous variables: Model variables that lie within the boundary of a model where the structure and policies within the modeled system influence the variables' behavior (Sterman, 2000).

Exogenous variables: Variables outside the model boundary that have no causal connection from the endogenous variables within the model boundary, but have causal connections to the endogenous variables in the model. Ideally, exogenous variables remain constant throughout the time horizon of the model (Sterman, 2000; Ford, 1999).

Feedback: Feedback occurs in a system when its own past activity influences its future. Negative feedback in a system causes the system to seek a goal such as when a thermostat starts and stops heating and cooling systems. In System Dynamics models, negative feedback loops are called balancing loops. Positive feedback generates continuous growth or decay, such as when a bank account accrues compound interest. In System Dynamics models, positive feedback loops are called reinforcing loops (Forrester, 1971; Sterman, 2000).

Graphical System Behavior: Graphs of the behavior of key variables in a system are an important product of System Dynamics models. Typical patterns on System Dynamics graphs show growth, decay, goal setting, and oscillation.

Intended Rationality: The concept that people make decisions according to their mental model of the outcome of their decisions within their perceived environment. The challenge for System Dynamics modelers is to represent the decision-making, the mental models, and the environment in a computer model of a system (Sterman, 2000).

Level of Aggregation: Sterman (2000) claims that most clients desire at least twice as much detail in a System Dynamics model than is needed to appreciate system behavior, however, client satisfaction requires the modeler to include enough detail to make the client use the model as a basis for action. Modelers should keep in mind the purpose of the model and seek to aggregate those parts of the system that occur close enough in time, accumulate in similar stocks, or reside in stocks for a similar amount of time.

Mental models: Senge et al (1994) describes mental models as "internal pictures of the world" (p. 6). Doyle and Ford (1998) found that definitions of "mental models" varied greatly within

System Dynamics and among practitioners in other fields. Therefore, Doyle and Ford proposed a definition for "mental models of dynamic systems" (p. 17) as a long lasting, easily recallable, and generally accurate cognitive structure of a system.

Model boundary: The line separating endogenous variables from exogenous variables. All components within the boundary of the model, such as stocks, flows, and auxiliary variables, are influenced by the policies and structure governing the system (Sterman, 2000; Ford, 1999).

Policy: The rules that govern organizational strategy, organizational structure, and how and when decisions should be made in an organization. Modelers use System Dynamics models to evaluate how changes to policies and interactions among policies affect system behavior over time (Sterman, 2000). According to Coyle (1996), policies consist of structure, represented by descriptive equations and causal links, and parameters, represented by adjustable quantities in a system. Maani and Cavana (2000) describe policies as individual variables or specific structural relationships among variables.

Social System: According to Forrester (1998), "The idea of a social system implies that the relationship between its parts strongly influence human behavior" (p.1). Examples of social systems include organizations, communities, and teams. Social systems influence peoples' behavior because they respond to the circumstances created by the structure and feedback of the system.

System: Blanchard and Fabrycky (1998) define a system as "a set of interrelated components working together toward some common objective or purpose" (p. 2). Similarly, Forrester (1971) defines a system as "a grouping of parts that operate together for a common purpose" (p.1-1).

Systems thinking: The mindset that many interrelated forces influence organizational behavior (Senge, 1990) coupled with the abilities to focus on patterns of behavior over time, to see how system structure influences behavior, to think in terms of stocks and flows, and to accept multiple possibilities along a continuum of alternatives (Richmond, 1993).

Units: It is important to maintain unit integrity throughout a System Dynamics model. Ford (1999) points out that the units of a flow variable are the same as the stock it flows into or out of divided by time.

2.12.2 System Dynamics Modeling Tools

Boundary Chart: A listing of endogenous, exogenous, and excluded variables of a model that define the domain of the problem to which the model applies (Sterman, 2000). Ford (1999) uses a "bull's-eye diagram" to communicate the same concept and information.

Causal Loop Diagram: A picture of the endogenous and exogenous variables in a system connected by arrows that depict cause and effect relationships among them in order to illuminate the feedback structure, or feedback loops of the system (Sterman, 2000; Ford, 1999). Causal loop diagrams are also know as "influence diagrams."

Dynamic Hypothesis: Sterman defines a dynamic hypothesis as "a working theory of how the problem arose" (2000, p. 95) in terms of stocks, flows, and feedback. Ford (1999) describes the initial System Dynamics model as the "dynamic hypothesis for the system behavior" (p. 172). Thus, the dynamic hypothesis is a modeler's early conjecture, which usually evolves through the System Dynamics modeling process, of how a problem arose from the structure and relationships among the components of a system.

Equilibrium diagrams: Equilibrium occurs in a model when the inflow and outflow from each stock are equal. Ford (1999) creates an equilibrium diagram by writing the value and units of each variable on a stock and flow diagram. He uses equilibrium diagrams to highlight potential inconsistencies in a model, illuminate incorrect use of units, and set the conditions to determine the relative stability of the system.

Partial Model Test: The action of isolating a portion of a model where decision-making occurs to ensure that the decision making process reflects the mental model of the decision-maker by changing exogenous inputs and observing the behavior of the isolated system. The partial model test allows modelers to ensure the model captures people's intended rationality (Sterman, 2000).

Policy Structure Diagram: Maps of the information streams that prompt managers to make decisions to adjust the rates of flow of the endogenous variables they can control (Sterman, 2000).

Proxy variable: A proxy variable is a variable in a model that takes the place of a variable or condition that is too complex to replicate in a computer model. For example, in a System Dynamics model of Mono Lake in California, Ford (1999) uses the variable "elevation" of the surface of a lake as a proxy for the state of the lake's ecosystem, which is difficult to model, but corresponds closely with the elevation of the surface of the lake.

Reference modes: Ford (1999) describes reference modes as a modeler's initial expectation of how the model will graphically depict the behavior of a selected variable in the system being modeled. The modeler draws the reference mode based on expected growth, decay, or oscillation. The horizontal axis represents the time period under consideration and the vertical axis represents the particular variable being modeled. The shape of the reference mode is relative to the vertical axis, yet does not have exact values as the structure of the model should reproduce the shape, while the parameter values move the shape relative to the range of values on the axes. Sterman (2000) describes reference modes as sets of graphs that show how a problem evolved in the past and how it may go forward into the future. Modelers also identify key variables and their time horizons while developing reference modes. Figure 1-1 is an example of a reference mode. Reference modes often reflect patterns of growth, decay, goal seeking, or oscillation.

Stock and Flow Diagram: A depiction of the physical configuration of the system and the relationships among system variables (Sterman, 2000). Figure 2-7 and Figure 2-8 are examples of stock and flow diagrams.

Subsystem Diagram: A high-level overview or a series of hierarchical views of the system and problem the modeler will address (Sterman, 2000). Subsystem diagrams depict the general structure, flows, and interconnections among the major components of a system.

System Archetypes: Senge (1990) describes "system archetypes" as common structures that create consistent patterns of behavior in a wide range of systems in fields as diverse as biology, psychology, politics, economics, and management. He claims that archetypes are useful to identify where to influence systems in order to change behavior.

Time Horizon: Sterman (2000) describes the time horizon as the span of time that includes the period when a problem emerged and the future impact of alternative policies. The time horizon is the horizontal axis of a reference mode graph. Sterman cautions modelers to select a sufficiently long time horizon to capture the effects of delays. He recommends establishing a time horizon "several times" (p. 94) longer than the biggest delay in the system. If large oscillations are present, Ford (1999) advocates a time horizon long enough to see "two or three oscillations" (p. 172) to determine if they dampen.

Time step: Ford (1999) offers a rule of thumb for setting the time delta or time step in a simulation; set the DT to less than half of the smallest time constant in the model. He also recommends keeping simulations under 1000 time step iterations when running the model by using an appropriate DT and a reasonable time horizon. Sterman (2000) makes several recommendations regarding the time step in a model. First, he recommends setting the time step "between one-fourth and one-tenth the size of the smallest time constant in your model" (p. 907). Second, he recommends checking the time step by cutting it in half until the model is no longer sensitive to the size of the time step. Third, he recommends selecting a base-2 time step, such as 4, 2, 1, 0.5, 0.25, 0.125, to minimize rounding error caused by truncation of numbers in a computer, which uses the binary system. Fourth, when mixing years and months between the model and historical data, he recommends expressing 1/12 with as many digits as possible (0.833333…), or use months as the time step and divide all numbers expressed in years by twelve.

2.13 Why Use System Dynamics

Sterman (1994) advocates the use of System Dynamics because managers, decision-makers, and citizens in general do not have sufficient time to learn from feedback in the form of outcomes within the systems in which they operate over the natural course of time. The delays between action and feedback are too long to allow for timely learning or the maturation of decision-rules. Due to "bounded rationality," Sterman (2000) claims that the unaided human mind is unable to cognitively map and process the dynamic relationships within systems of complex causal relationships. The history of air traffic control, characterized by delays in the implementation of systems and by feedback in the form of accidents or controller strikes, supports Sterman's perspective that the natural learning process is too long and too complex for the human mind to comprehend.

Ford (1999) uses System Dynamics to create clear, simple models of environmental systems; such as reservoir water levels, deer herds, or global warming because the approach emphasizes the type of feedback and nonlinear relationships that are prevalent in natural systems. He sites four views of equilibrium in natural systems, shown in Figure 2-9, and claims that the "homeostatic plateau" (Odum, 1971) depicted in the lower right shows the concept of a "span of control" within which a perturbed system will return to equilibrium, up to a point. If pushed too far beyond the span of control, the forces creating positive feedback in such a system will become dominant and change the fundamental nature of the system. He advocates the use of

System Dynamics for both analysis of the stability of systems and for training managers to better understand the potential behavior of systems. Ford's natural environment perspective for training and analysis, applied to the air traffic control system, may shed light on the effects of events such as the terrorist attacks of September 11, 2001, by providing natural analogues to the extremes of observed and modeled system behavior.

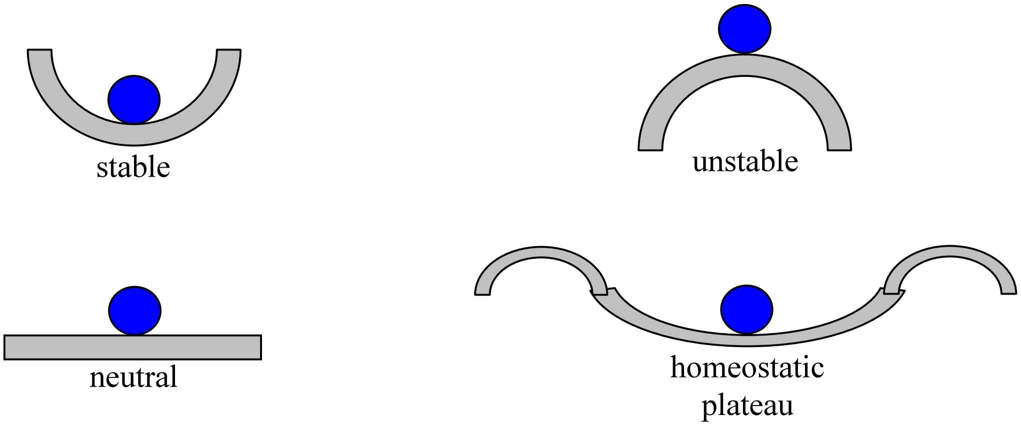

Figure 2-9. Four views of equilibrium (Ford, 1999).

From a practical business perspective, Lyneis (2000) recommends the use of System Dynamics models to "forecast" the behavior of markets. He claims that the structural orientation of System Dynamics models provides more accurate depictions of short and mid-term behavior than statistical models, which often become skewed by "noise" in the system. He claims that the use of System Dynamics models not only aids decision-making, but also identifies what variables in a system have the greatest impact on decision-making and deserve the most attention over time. In the domain of air traffic control, Lyneis' market perspective of System Dynamics makes it a useful tool for administrators responsible for making resource allocation decisions based on their interpretation of the past and present behavior of the system. As an alternative approach, System Dynamics offers a more comprehensive and rigorous view of a system than the inadequate mental models usually used by decision-makers. System Dynamics tools can help government air traffic control resource managers identify key variables to monitor, such as the number of aircraft registered in the US or the average age of capital equipment, and then forecast potential system behavior based on manipulations of the key variables or other variables related to them.

Over the past forty years, Forrester described a number of reasons to use the System Dynamics approach. In his seminal work, Forrester (1961) claimed that management was transitioning from an art to a science, thus allowing the approach to management based on principle rather than just experience. Forrester advocated the principle of viewing an organization as an information-feedback system. Accordingly, he developed the concept of "industrial dynamics," the precursor to System Dynamics, to create organizational models that showed how the structure, policies, decisions, and delays in organizational systems influenced the growth and stability of the organization. In the early 1990s he advocated the use of System Dynamics as a tool for CEOs to design their organizations (Koegh & Doman, 1992). He claimed that CEOs should reduce their participation in operations and instead undertake the role of designer who determines the structure of the organization, the flow of information, and the policies governing where decision-making occurs and who makes the decisions. He claimed that there was an abundance of "information pollution" in organizations that diverted limited managerial time away from the important information that managers needed to make decisions. In the late 1990s, Forrester reflected on the usefulness of System Dynamics as an alternative to designing an organization by "committee and intuition" (1998). He emphasized decisions as present moment actions, policies as guides to decision-making, and System Dynamics as a means of determining organizational policy to experiment with alternatives in order to elicit the desired organizational behavior.

2.14 The System Dynamics Modeling Process

Forrester (1994) acknowledged both the growing interest in System Dynamics and the lack of guidance for developing System Dynamics simulation models. He described a six-step System Dynamics process depicted in Figure 2-10. Currently available System Dynamics software, such as Stella or Vensim, makes it possible for modelers to transition smoothly through the mechanical aspects of diagramming and equation writing in steps one, two, and three. The software serves as a tool for modelers to 1) visually describe the system through computerized stock and flow diagrams, 2) embed equations while building the model, and 3) rapidly simulate system behavior. Nevertheless, the feedback arrows in Figure 2-10 indicate that Forrester's approach is iterative regardless of the advances in computer software. Furthermore, the discussion below illuminates the challenging process of discerning the structure of the system that causes dynamic behavior, converting it to a model, and then testing the model for validity.

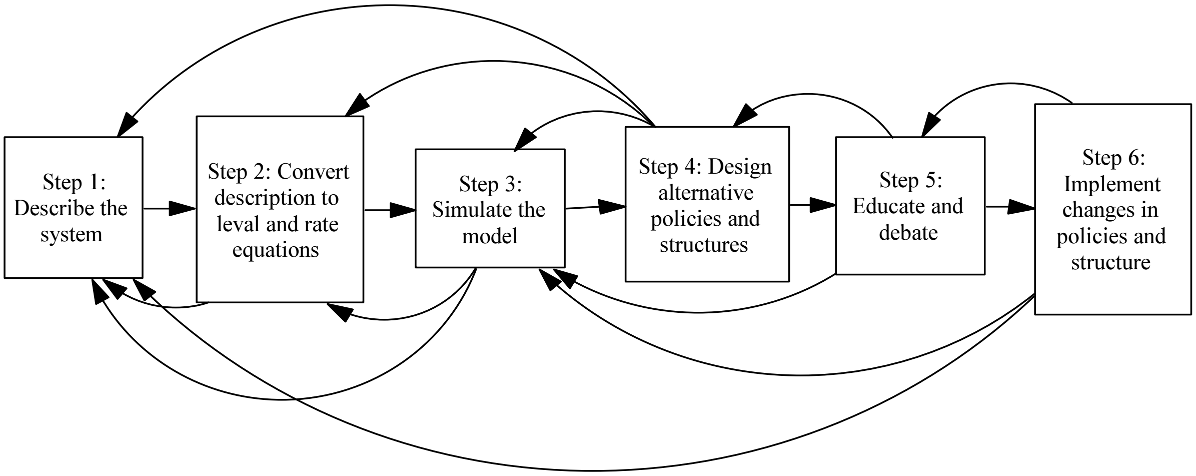

Figure 2-10. Forrester's 6-step model of the System Dynamics process shows the role of feedback and indicates the need for frequent iteration of the process (Forrester, 1994).

2.14.1 Ford's Eight-step System Dynamics Modeling Process

Ford's (1999) eight-step modeling process also emphasizes iteration and highlights the importance of starting with a simple model and building increased complexity during the iterative model development process. His process, listed in Table 2-3, includes activities to create and test System Dynamics models. Initially, in step 1, he recommends getting to know the individual or group with the dynamic problem in order to determine how the client likes to communicate, how the client is addressing the problem, other computer models the client may be using, and who within the client's organization has the power to accept and implement findings from the modeling effort. The second and most important step is to determine if there is a dynamic problem. Ford recommends graphically depicting the problem as a variable that shows undesirable behavior over time – a reference mode that the client will immediately recognize as a depiction of the problem. The reference mode should show the variable on the vertical axis and a timeline along the horizontal axis. Figure 1-1 is an example of a reference mode graph for the "number of SATS flights" variable in the ATC system. The horizontal axis of a reference mode should encompass enough time to show the behavior of the variable within the system. Ford points out that the shape of the reference mode graph often shows an underlying pattern of growth, decay, oscillation, or a combination of these patterns. If a modeler cannot create a reference mode, then the System Dynamics approach may not be suitable for the problem. Finally, after creating a reference mode, a modeler should also be able to draw an additional curve on the graph that shows improved behavior.

Table 2-3: Ford's (1999) Eight-step System Dynamics Modeling Process.

STEP	PNEUMONIC	ACTION
1	A is for Acquainted	Get Acquainted with the system
2	B is for Be specific	Be specific about the dynamic problem
3	C is for Construct	Construct the stock and flow diagram
4	D is for Draw	Draw the causal loop diagram
5	E is for Estimate	Estimate the parameter values
6	R is for Run	Run the model to get the reference mode
7	S is for Sensitivity	Conduct Sensitivity analysis
8	T is for Test	Test the impact of policies

Ford points out that the third step, creating a stock and flow diagram, is interchangeable with step four, drawing causal loop diagrams. The stock and flow diagram identifies the key variables and relationships within a system. Causal loop diagrams help modelers to identify the important feedback loops in a system. Ford recommends identifying the stocks first, then determining the flows, and finally adding the auxiliary variables.

Forrester (1991) emphasized the need to obtain and use a wide range of information from the three primary sources depicted in Figure 2-11: the mental database, the written database, and the numerical database. Forrester's guidance provides modelers with direction to help find the information needed to construct stock and flow and causal loop diagrams. He highlighted the value of the mental database in knowing where and how information flows, where decision-making occurs, and the roles of people in a system. The written database is valuable to the System Dynamics modeler because of its wide availability. According to Forrester, the current press is more useful to System Dynamics modeling than professional journals because the current press provides the relevant dynamic context surrounding decision-making in a system. Conversely, academic and professional writing generally prescribes how to make decisions to attain equilibrium. The numerical database is useful to System Dynamics modeling as a source of information about inventory levels, account balances, averages, ratios and other such data. Many systems have large compilations of numerical data that is useful to create models as well as verify and validate the output of System Dynamics models.

The three sources of data advocated by Forrester are sources of information also useful for the fifth step of Ford's modeling process: estimating the parameter values. He identifies several considerations during step 5: first, use a range of information from scientific constants, results of experiments, statistical analysis of databases, case studies, expert knowledge, and modelers intuition; second, it may be necessary to guess parameter values rather than to ignore them and subsequently assign them the value of zero; third, expect a large amount of uncertainty in the accuracy of parameter estimates; and lastly, the degree of accuracy required for each estimate varies according to how sensitive the final policy recommendations are to the particular estimate. The iterative nature of the System Dynamics modeling process allows modelers to continue to revise and refine their parameter values.

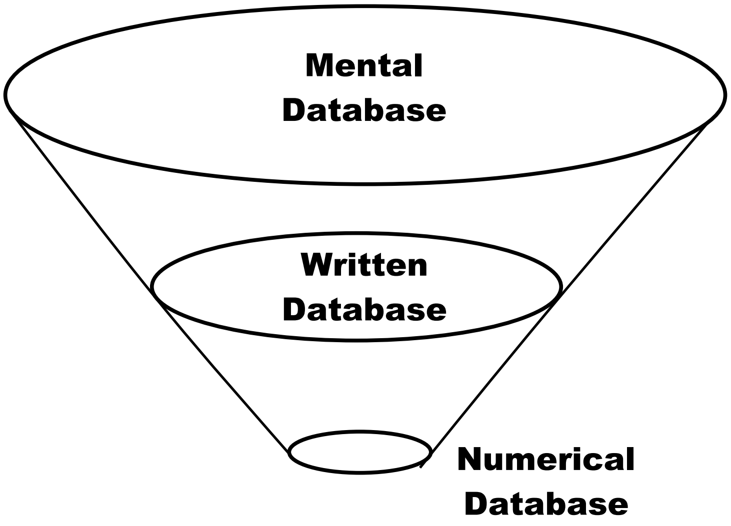

Figure 2-11. Of the three sources of data for the System Dynamics process, the greatest source of the most useful information comes from the mental database (Forrester, 1991).

An important determinant of the need to iterate occurs at Ford's sixth step: running the model. If the simulation appears to represent the anticipated pattern recorded in the reference mode, then the modeler should move on to step 7. Otherwise, the modeler should return to steps 1-3 to gain better understanding of the system, rethink the reference mode diagram, or reconstruct the stock and flow diagram. Ford's seventh step, conduct sensitivity analysis, involves formal or informal tests of the parameters of the model across their full ranges. The objective of step 7 is to ensure that the underlying feedback structure creates model behavior; parameter values should not be the driving force behind model behavior. The modeler should return to step 5 to reconsider parameter estimation if the model behavior pattern changes as individual parameters vary.

Campbell (2001) described the lessons she learned at Hewlett-Packard while facilitating a System Dynamics modeling process through the equivalent of Ford's first six steps. Campbell recognized the importance of initially accepting detail complexity in her team's System Dynamics model in order to develop a sense of ownership and understanding among the model development team. Contributors to the model initially expected it to reflect their detailed understanding of system processes. Eventually, during the team and model maturation process, the detail complexity would give way to a higher-level model with appropriate dynamic complexity. Campbell described an unexpected, frustrating, but necessary period of confusion among the model development team as the members transitioned through a period of realigning their mental models of the system with the behavior depicted by the System Dynamics model of the system. Campbell played a key role by reassuring her clients that the challenging transition was a normal part of the process. Finally, she highlighted the value to the client of two other aspects of the System Dynamics modeling process: first, the development of a common language of describing systems with influence diagrams and stock and flow diagrams, and second, the compilation of model data into a single document. Campbell's insight provides a realistic perspective on the modeling process that enhances understanding of the process flows advocated above by Forrester and Ford.

Ford's final step is to test the various policy options managers may pursue by changing the values of model variables they can control through policy adjustments. Once a desired policy emerges, Ford recommends several more actions: first, conduct a sensitivity test of the values of the parameters managers cannot control while using the values associated with the new policy variables that the managers can control; second, introduce randomness into the system and observe the effects; and lastly, consider revising the stock and flow diagram from step 3 to include more detail in the new policy model.

2.14.2 Sterman's Five-step System Dynamics Modeling Process

Like Ford, Sterman (2000) offers a detailed description of the System Dynamics modeling process; he reinforces many of Ford's perspectives and he offers his own insights. Sterman points out that modeling is a creative process in which each modeler approaches a problem differently. However, Sterman claims that there are five essential steps to modeling that are characteristics of all successful modeling efforts. Table 2-4 lists the five steps and includes activities and tools used in each step. Supporting Ford's claim that modeling is an iterative process, Sterman states that the modeler gets feedback from the real world, adjusts the model, and then provides additional model feedback to the real world. Sterman also agrees with Ford that defining the problem is the most important step in the process. Sterman emphasizes the need to ensure that the purpose of the model is to solve a problem, not simply to model a system. The model must simplify the system to a point where the model replicates a specific problem. Sterman advises modelers to be aware of clients who seek validation of their preconceived notions about system behavior. If the model claims otherwise, then the modeler should challenge the client's point of view, stand firmly on the side of truth, and maintain the responsibility to be ethical and forthright. Otherwise, the modeler should move on to another problem and another client.

Table 2-4: Sterman's (2000) Five-step System Dynamics Modeling Process.

STEP	ACTION	ACTIVITIES
1	Problem Articulation	Define what the problem is and why it is a problem, identify key variables, determine the time horizon, and develop reference modes.
2	Formulation of Dynamic Hypothesis	Develop a dynamic hypothesis that describes the problem as a result of the relationship among the variables and internal structure of the system. Use mapping techniques such as model boundary diagrams, subsystem diagrams, causal loop diagrams, stock and flow diagrams, and policy structure diagrams.
3	Formulation of a Simulation Model	Create a computer model by specifying units, relationships, and equations. Clarify concepts from steps 1 and 2.

4	Testing	Check the usefulness of the model by using reference modes, extreme values, sensitivity testing, integration error testing, behavior reproduction testing, behavior anomaly testing, surprise behavior testing, and system improvement testing. Return to previous steps as needed to refine the model.
5	Policy Design and Evaluation	Identify situations and policies to conduct “what if” analysis, then determine the sensitivity and interactions of policies.

Sterman’s second step involves the process of determining what caused the problem by focusing on structures within the system. The dynamic hypothesis emerges from the process of selecting primarily endogenous variables, conservatively including few exogenous variables, and using mapping tools to determine the structure of the relationships among the variables. The model boundary chart helps modelers to categorize variables as endogenous, exogenous, or excluded, and, the chart also limits the purpose of the model by defining the boundary of its domain. Ford (1999) uses a “bull’s-eye diagram” (p. 97) to visually depict the elements of a boundary diagram. Subsystem diagrams provide an overview of the system architecture within the domain of the problem under investigation. Causal loop diagrams capture the feedback loops within the system while stock and flow diagrams provide a description of the structure of the system. Policy structure diagrams highlight how information prompts decision-making within a system (Sterman, 2000). Sterman’s emphasis on diagramming tools helps modelers to portray the problem within a structured system comprised of essential interrelated components, while capturing the flow of people, material, and information, and at the same time recognizing the influence of other key elements inside and outside of the system.

In steps three and four of the System Dynamics modeling process, Sterman creates an operational model that includes “equations, parameters, and initial conditions” (2000, p. 103) and then tests it. The creation of the first formal computer model requires the modeler to conform to the unforgiving specificity of the computer. The computer software forces the modeler to clearly state units, equations, and relationships. In the testing phase, the modeler must ensure that the model has “dimensional consistency” – the relationships among the units in the stocks, flows, and auxiliary variables and constants must make sense. The modeler also seeks correlation between the model and the real world system. Furthermore, modelers should test the model with extreme values to ensure the behavior of the model conforms to physical laws, such as not creating a negative population. Several other tests to determine the utility of the model include sensitivity testing, integration error testing, behavior reproduction testing, behavior anomaly testing, surprise behavior testing, and system improvement testing.

Sterman (2000) advocates thorough and continuous testing to build confidence in the model and gain insight into the system. He encourages modelers to ensure that the model conforms to the original purpose of the modeling effort; in particular the model should adhere to physical laws of nature and includes all relevant feedbacks. Additionally, the modeler should keep clients informed and keep all stakeholders involved. Sterman's realistic approach to the development and refinement of a model highlights the need for modelers to be both scientific and artistic in their efforts. Homer (1996) advocates "scientific modeling" (p. 3) that relies on thorough validation of the model through iterative experimentation by comparing the behavior of the model with the behavior of the real system. Fundamentally, to create a good model, researchers must continually seek feedback from stakeholders, the real world, and through comparisons with the original model development plan.

The final step in Sterman's System Dynamics modeling process is to use the model to design policies and evaluate their potential impact. The range of policy design activities extends from simply changing parameter values to restructuring a system and its processes. Modelers work with the client to determine what scenarios may develop and what policies managers of the system would invoke. The modeler's challenge is to represent the alternatives within the model in order to determine system behavior under the new conditions. Additionally, the modeler must evaluate the sensitivity of the system under the new conditions and determine how policy alternatives may interact positively or negatively. The final step in Sterman's approach again emphasizes the need for System Dynamics modelers with the skills to communicate with people, understand their needs, and conduct the hands-on modeling process. The modeler's ability to think as both engineer and artist leads directly to a valid model.

2.15 Model Validity

Forrester (1994) claims that modelers cannot validate System Dynamics models. He advocates establishing a level of confidence where researchers can accept the model as an adequate depiction of the system it represents. Forrester's view is that modelers face resource constraints that influence the amount of time or money available for model development. He states that most System Dynamics models only compete with the mental models people use for decision-making and policy development within a system. Thus, from his experience, clients readily accept System Dynamics models as "valid" because they offer far greater clarity and insight than what was previously available.

Sterman (2000) claims that "all models are wrong" (p. 846) and that people conditionally accept a formal or mental model if it is useful for a specific decision-making purpose and if it meets each individual's standards. However, Sterman (2000) also recommends the following twelve procedures to evaluate the shortcomings and limitations of System Dynamics models in order to provide a framework by which individuals can evaluate the acceptability of a model:

1. Boundary Adequacy: Use model boundary charts, subsystem diagrams, causal diagrams, stock and flow diagrams, and study model equations to identify the boundary and ensure the model captures all the appropriate endogenous variables. Use experts and personal knowledge of the system to evaluate model behavior after making boundary adjustments; determine if the model has sufficient structure to include all appropriate feedbacks in the system. Evaluate the sensitivity of the model to extensions of the boundary by making exogenous variables and constants into endogenous parts of the model.
2. Structure Assessment: Use policy structure diagrams, stock and flow diagrams, causal diagrams, and study the model equations to evaluate the level of analysis of the model. Break down the model into lower level components that contain more detail than the higher-level aggregation. Compare the behavior of the separate components of the model to the higher-level combined model to determine the appropriate level of "disaggregation" (p. 864); use the simplest model that accurately represents the system. Ensure the model adheres to physical laws and the decision-making procedures of the real system.
3. Dimensional Consistency: Inspect equations and use analysis routines built into System Dynamics software to ensure the units associated with model variables are consistent within equations and do not rely on "fudge factors."
4. Parameter Assessment: Use statistical tests, partial model tests, expert opinion, and disaggregated submodels to ensure that the values of model parameters match the available numerical data and known information about the system. Each model parameter should have meaning in the real world, whether derived from historical

numerical data, from interviews and reviews of expert opinion, or from a combination of numbers and opinion.

5. Extreme Conditions: Use extreme values in each model equation and combinations of equations to determine if the equations and the model behave reasonably and adhere to physical laws, such as not creating negative people. An indication that the balancing and reinforcing loops in the model are working occurs when modeled system behavior eventually returns to normal conditions (Maani & Cavana, 2000).
6. Integration Error: First, keep cutting the time step in half until the model is no longer sensitive to the size of the time step. Second, although Euler integration, which assumes rates remain constant during each time interval dt, is usually suitable for models of social systems, modelers should test their models with other integration methods, such as Runge-Kutta, to ensure the Euler method is sufficient.
7. Behavior Reproduction Tests: Plot the output of simulated data along with actual data and use summary statistics to evaluate how well a model reflects actual system behavior. Although behavior reproduction tests cannot prove that a model is correct, statistical analysis of the fit of the model data to the real world data, such as the correlation coefficient, the mean absolute error, or Theil's Inequality statistic, help modelers identify the sources and sizes of error.
8. Behavior Anomaly Tests: Remove a portion of the structure of a model, such as an entire feedback loop, to determine how important the eliminated structure is to the behavior of the entire model. If the model's behavior changes significantly in the absence of the loop, then that portion of the model is important and must remain in the model.
9. Family Member Tests: Apply the model to other systems similar to the system being modeled; the plotted output of the model should have similar characteristics to that of the output of the original model. For instance, models of government resource management should generate similar results for different departments.
10. Surprise Behavior Tests: Observe closely the behavior of all variables in a model and look for unusual output that the real world system also exhibits, but which experts in the real world system have not yet recognized. Often a model will help identify where to look for counterintuitive behavior in a system.

11. Sensitivity Analysis: Test the model for numerical, behavior mode, and policy sensitivity. Testing for numerical sensitivity involves determining how changes in assumptions causes changes in the numerical output of the model. As a general rule, test numerical assumptions over a range twice as wide as expert opinion or statistical analysis anticipate values to vary. Testing for behavior mode sensitivity is done to determine how changes in assumptions cause changes in the shape of the graphical output of the model, such as an output change from s-shaped growth to exponential growth. Testing for policy sensitivity is done to determine if changes in assumptions cause the proposed policy alternative to backfire. For models of social systems, behavior mode sensitivity and policy sensitivity matter most. Methods of testing for sensitivity include comparing the best versus the worst-case scenarios, conducting Monte Carlo analysis, and Miller's (1998) Automated Nonlinear Test.
12. System Improvement Tests: Determine if the modeling process resulted in the adoption of policy alternatives that caused the system being modeled to improve. From the outset of a modeling effort, modelers should determine how they will evaluate the results of their efforts and create the conditions, ideally as an experimental design, to properly assess the impact of the effort.

Sterman's (2000) above twelve procedures for evaluating the utility of System Dynamics models outlines many of the responsibilities modelers must attend to throughout the model development and application process. Additionally, Sterman highlights the importance of thorough documentation so that another System Dynamics modeler can replicate the model.

Ford (1999) advocates five "concrete tests" to determine the validity of a model and he echoes Sterman's concerns about evaluating a model based on the purpose of the model and how the model compares to the alternative means of achieving the same purpose. First, Ford recommends having an independent party run the model on a different computer to verify that the model operates according to the claims made by the model developers. Regardless of whether or not one agrees with the model output, verification ensures that the model documentation and programming are sound. Second, Ford recommends using personal judgment and understanding of the system the model replicates to determine if the model structure and parameters have face validity. If a model is a complex black box, then Ford recommends not using the model. Third, like Sterman's "behavior reproduction test," Ford also recommends comparing model output with real world data. He points out that the quality of the comparison relates directly to the percent of endogenous versus exogenous variables in the model. The more the model uses internal structure to accurately reproduce historical behavior, the higher is its validity. Fourth, like Sterman's "extreme conditions" test, Ford also recommends using extreme values to check for unacceptable model behavior. He cautions that "cosmetic features" (p. 287) that make the model more acceptable under normal conditions may cause unreasonable behavior during unusual conditions. Fifth, if other more detailed models of subsystems are available, Ford recommends comparing them to the higher-level model of the system. Besides the above five procedures, Ford claims that the "ultimate test" occurs when an organization uses the model to create and implement new policies.

Peterson and Eberlein (1994) describe an approach that surpasses the face validity acceptable to a client. They claim that the key to good System Dynamics modeling is the development of the questions to ask of a model in order to determine its validity. The validity questions become a focal point around which to discuss and evaluate the model output. They recommend several tests that are expressible as validity questions for a model: simulation of reference modes, behavior under extreme conditions, correlation with real data, sensitivity over wide ranges, and adherence to "thought experiments." They believe that "thought experiments," where researchers use mental models to determine how the real world system does or would behave, offer the best basis upon which to validate the behavior of the computer simulation model. Thus, in the case of SATS and its impact upon air traffic control, validity issues may involve mental models of surges of flights within the system, correlation of the surges with real past data, and the sensitivity of the model throughout a variety of scenarios.

Combining the admonitions of Forrester, Sterman, Peterson and Eberlein, and Ford elicits a variety of validation questions to apply to the output of a System Dynamics simulation of SATS and its impact on the ATC system. The following are potential model validation questions:

- If there are zero flights, does the system require zero manpower and zero infrastructure?
- If the number of flights surges, does the system require a surge in manpower and infrastructure?

- If the system manpower is zero, does the system greatly restrict the number of flights?
- Does the output of the simulation correlate with past real world data?
- When isolated, do the components of the model provide realistic output?
- Do sudden spikes in one variable cause significant behavior changes in other variables?
- What is the effect of a small change in a variable upon the rest of the system?
- Are the dimensions of the model consistent throughout?

2.15.1 Maani and Cavana's Policy, Strategy, and Scenario Approach

Like Ford and Sterman, Maani and Cavana (2000) advocate a System Dynamics modeling process involving problem definition, diagramming, and computer modeling to create a base case model of a system. Additionally, they include several interesting and useful steps that guide the researcher from the development and validation of the base case model, to identification and sensitivity analysis of key variables, to the development of system performance metrics, to policy design and testing, to strategy development and testing, and finally to scenario planning and modeling. The following discussion outlines the process advocated by Maani and Cavana.

1. Use sensitivity tests to determine which model variables have the greatest impact on system behavior. First, adjust all values of the base case as depicted in Table 2-5. Next, hold all variables constant except for one test variable and run the model to determine if the increase or decrease in the variable value influences the behavior of the model output. Repeat the sensitivity test for each variable.

Table 2-5: Adjusting parameters and values (notional) for model sensitivity testing is the first step in determining which variables have significant influence on system behavior.

Model Input Variables	Base Case Values	20% Increase	20% Decrease
Manpower Submodel			
Controllers	20,000	24,000	16,000
Maintainers	10,000	12,000	8,000
Aircraft Submodel			
SATS	10,000	12,000	8,000
Non-SATS	400,000	480,000	320,000

2. Create system performance metrics based on the original purpose of the model. In the case of the ATC resource management model, the original purpose was to determine the behavior of the ATC system under various architectures and the system's ability to support SATS flights. Therefore, the following performance metrics may provide a basis for evaluating the behavior of the modeled system:
    a. Aircraft
        i. Number of SATS flights
        ii. Number of non-SATS flights
    b. Manpower
        i. Number of controllers
        ii. Number of maintenance technicians
    c. Equipment
        i. Number of radar-based equipment
        ii. Number of approved GPS-based equipment
        iii. Number of aircraft with GPS capability
    d. Facilities
        i. Number of SATS airports
        ii. Numbers of control towers by type
3. Researchers often use metrics similar to those above to compare the performance of the system to a benchmark, such as a market. For a monopolistic organization like the air traffic control system, the benchmark would be a base case of performance at a point in the system's history. Therefore, researchers should use the metrics to evaluate the relative performance of the various model sectors of the system by comparing how new structure or parameter values shape system behavior relative to the original structure and parameter values of the base case. Performance metrics frequently include measures involving ratios of the new case compared to the base case or quantities of components of the new system.
4. Summarize the results of steps 1 and 2 above by creating a matrix that compares the performance of each model variable against the base case to highlight the sensitivity of the model to the particular variable. The comparisons, as depicted in Table 2-6 indicate the percent change in the system performance metrics in the top row compared to the

model variables in the first column. For example, Table 2-6 shows that within a submodel of controllers, the number of trainees may have a significant impact on the behavior of the system, but the number of experienced controllers who switch from the tower to administrative positions may be irrelevant. Thus, managers would want to focus on their ability to influence the number of trainees over time. The number of trainees would be a key variable, but the number of experienced controllers changing from the control tower to administrative jobs would not.

Table 2-6: The results of the sensitivity tests (notional) provide an indicator of which variables have significant influence on system behavior and warrant management attention

Model Input Variables	Controller Washout	# SATS Aircraft	SATS Airports
Base Case	5%	5,000	500
20% increase in parameter input values			
	(%) (% change)	(#) (% change)	(#) (% change)
Manpower Submodel			
Controllers	6% (20%)	5,000 (0%)	500 (0%)
Maintainers	5% (0%)	5,200 (4%)	550 (10%)
Aircraft Submodel			
SATS	5% (0%)	23,000 (15%)	1,100 (10%)
Non-SATS	5% (0%)	30,000 (50%)	1,200 (20%)

5. Use the matrix developed in step 4 to identify the endogenous parameters management should influence and the exogenous parameters management should monitor.
6. Conduct policy experiments. Maani and Cavana refer to policy as “single or localized changes to the policy parameters in the model or structural changes to the policy relationships” (p. 236). Accordingly, policy design involves changing parameter values or the causal structure of the model. If the resultant system behavior is acceptable, then they describe the policy as “robust.” Because a model with many variables has many possible policies, Maani and Cavana recommend first, reviewing the purpose for creating the model to guide the policy analysis process and second, addressing only the policies that management can influence. Each change in a parameter value or structural relationship in the model is a policy experiment that creates output for comparison with the output from the base case model. The collection of robust policies will serve as

possible input for strategy development. The process of conducting policy experiments is much like conducting additional sensitivity analysis on the most influential variables.

7. Conduct strategy experiments. Maani and Cavana (2000) refer to strategies as "multiple changes to policy parameters and structures to achieve the strategic objectives set by management" (p. 236). In the strategy base case, the model incorporates the new or redesigned system structure, however, the model parameters remain the same as in the original base case model. Other strategy models also include the new model structure as well as changes to the parameters that reflect particular strategies, such as shortening delays or expanding capabilities. Table 2-7 is an example of possible parameters the managers of the air traffic system may adjust under various strategies. Graphic output and tabular comparisons of strategy versus system performance metrics helps decision-makers determine which strategy to employ.

Table 2-7: Notional strategy alternatives using parameters that managers control, such as the number of trainees in the system, the allocation of funds, and the threshold for goals.

Endogenous Policy Parameters	Strategy 1: Base Case	Strategy 2: Radar Only Control	Strategy 3: GPS only Control
Controller Trainees	5%	2%	12%
Funding for GPS	20%	12%	55%
Max Delay Goal	4%	5%	2%

8. Conduct scenario analysis. Ultimately, Maani and Cavana (2000) advocate the use of scenario analysis to investigate how "what-if" changes in exogenous variables may affect the system behavior. Table 2-8 is an example of external values that interact with the air traffic control system. Scenarios are likely sets of conditions that the system may encounter in the future. Scenarios capture the decisions and strategies that move a system toward the future conditions depicted in the scenario. Scenarios are useful to experiment with policy and strategy alternatives, to create policies and strategies to avoid undesirable future conditions, and to provide common frameworks for organization-wide planning. If there are a relatively small number of adjustable external parameters, the theme of the analysis may be to contrast optimistic scenarios against pessimistic scenarios. Otherwise, if there are many variables, it may be better to focus on either

optimistic or pessimistic scenarios. As a benchmark against the optimistic or pessimistic scenarios, researchers should also create a "surprise free" scenario that includes a description of the future based on assumptions acceptable to all system stakeholders (Maani & Cavana, 2000).

Table 2-8: Notional scenario input values for external variables that interact with the air traffic control system.

Exogenous Parameter	Base Case Scenario	Worst Case Scenario	Best Case Scenario
SATS % of IFR Flights	5%	2%	8%
Pool of Controller Candidates	50,000	15,000	300,000
% GPS equipped aircraft	25%	12%	60%

Scenario analysis adds three more steps to the System Dynamics modeling process. First, researchers should list and categorize the uncertain aspects of the future that may impact upon the system, such as available population, market prices, demand for services, and working capital. Candidates for the list will emanate from the exogenous variables in the System Dynamics model. To focus the list, researchers should chose variables linked to those aspects of the system that are most likely to occur or those that may have the largest potential impact. Second, researchers should investigate two to four scenarios consisting of a base case "surprise free" scenario described above, and at least two extreme cases. The extreme cases may be a combination of the worst of the worst, the best of the worst, the worst of the best, and the best of the best. The worst and best policy and strategy experiments provide the input for the worst and best scenarios. The mental, written, and numerical databases contain information researchers may use to ensure the parameter values are within reason. Validity tests described above in section 2.15 are tools to aid researchers in shaping the scenarios. Third, researchers should compile the results of the scenario analysis in a manner similar to that depicted in Table 2-9 to summarize and compare the outcomes of the scenarios. Interpretation of the results should incorporate the original strategic objectives of the managers of the system.

Table 2-9: Results of the notional scenarios contain information comparing the optimistic, pessimistic, or no surprises scenarios with ATC strategies managers may pursue.

ATC Strategy	Base Case Scenario	Worst Case Scenario	Best Case Scenario
	Relative Trainee to Controller Ratio		
1. Base Case	X	X+	X-
2. Radar Only	Y	Y+	Y-
3. 50% GPS	Z	Z++	Z+
	Relative GPS Funding		
1. Base Case	A	A-	A+
2. Radar Only	B	B--	B-
3. 50% GPS	C	C	C++
	Relative on-time performance		
1. Base Case	D	D-	D
2. Radar Only	E	E-	E
3. 50% GPS	F	F	F+

2.16 System Archetypes

The process of developing a System Dynamics model and using it for experiments and analysis helps researchers to gain greater understanding of the structure and behavior of systems. Senge (1990) describes “system archetypes” as common structures that create consistent patterns of behavior in a wide range of systems in fields as diverse as biology, psychology, politics, economics, and management. He claims that archetypes are useful to identify where to influence systems in order to change behavior. Senge (1990) and Senge et al (1994) illustrate a handful of system archetypes by using simple combinations of balancing loops, reinforcing loops, and delays to show how simple structure creates universal behavior under certain circumstances.

Sterman (Senge et al, 1994) cautions against relying solely on the archetypes to understand systems and predict behavior. He sees a danger in fitting archetypes to situations based on apparent preexisting conditions and then using the archetype as the only tool for diagnosis and intervention. Forrester (1994) implies that an archetype-only approach is a “superficial” form of systems thinking that does not lead to true understanding of the dynamic behavior of systems. Sterman advocates the use of formal models created through a rigorous modeling process for two reasons. First, people who rely solely on archetypes approach problems as if there is a “multiple-choice” solution, and second, they would have to intuitively solve high order differential equations to predict system behavior. Rather, Sterman recommends using causal loop diagrams and stock and flow diagrams to capture all of the important causality, feedback, and delays in systems that archetypes may fail to include. Additionally, he describes maps of the system created by diagrams or archetypes as hypotheses that require testing by means of computer simulation. Thus, relying exclusively on archetypes can create the conditions that cause people to "jump to conclusions" (Senge et al, 1994, p. 183). Accordingly, the usefulness of archetypes appears twofold: first, to initially illustrate the possible causes of system behavior during the early model application process, and second, to communicate research findings at the end of the System Dynamics modeling process.

The following section describes some of the archetypes in terms of their structure and the behavior they produce. Some archetypes involve growth through reinforcing loops; others address problem solving by orienting on balancing loops. The illustrative examples are issues relevant to managers of the ATC system and are concerns that those planning to use the NAS may consider.

2.16.1 The Limits to Growth Archetype

Limits to growth occur when an activity that produces a desired effect becomes offset by a constrained counterbalancing activity (Senge, 1990; Senge et al, 1994). Figure 2-12 below is an example of the limits to growth archetype. The reinforcing loop on the left links passenger flow to revenue then back to passenger flow. Airlines initiatives, such as advertising or expansion, could attract more passengers and increase revenue. However, limited runway capacity eventually may cause delays that result in passenger dissatisfaction resulting in fewer airline passengers because people opt for another mode of transportation or substitute a teleconference for a business trip.

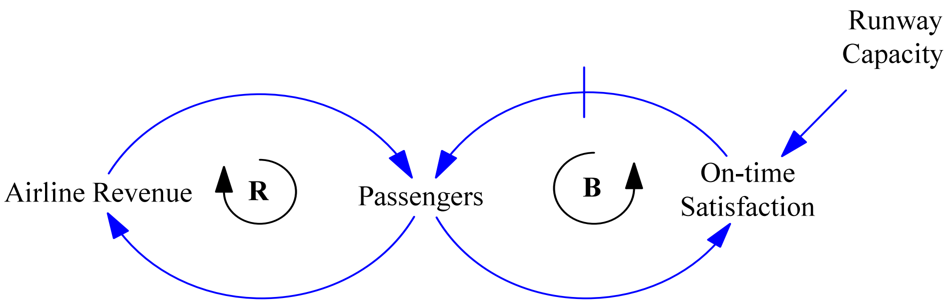

Figure 2-12. The limits to growth archetype consist of growth through the reinforcing loop on the left counteracted by the balancing loop on the right, which has a vertical mark indicating a delay.

The structure of the system characterized by the limits to growth archetype causes key variables to initially improve as desired and then plateau or deteriorate. Figure 2-13 is an example of the typical pattern of behavior.

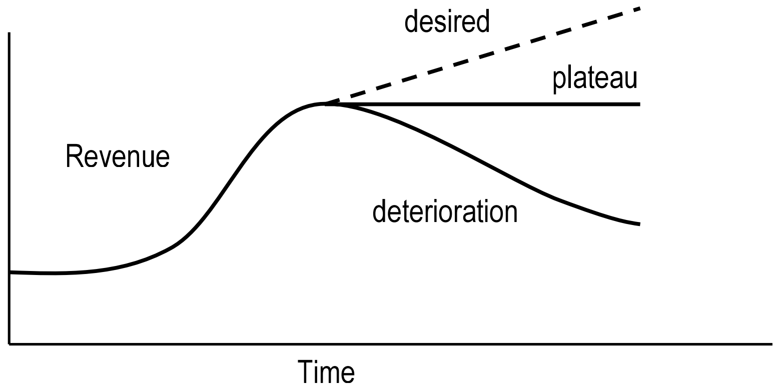

Figure 2-13. The typical pattern of behavior caused by the limits to growth system archetype includes a period of favorable behavior followed by a plateau or deterioration.

Senge (1990) and Senge et al (1994) recommend several strategies to overcome the limits to growth. First, address the limiting condition in the system, such as the runway capacity above, to change the system behavior. Second, refrain from the natural tendency to push harder on the reinforcing loop activities, such as increasing advertising or expanding airline operations, because they will only cause the balancing loop to strengthen as well. Third, after removing a limit to growth, attempt to determine what other limits to growth may also reside in the system and address them. Finally, look for other reinforcing loops that may provide new opportunities for growth.

2.16.2 The Tragedy of the Commons Archetype

The tragedy of the commons occurs when many individuals initially benefit from an easily accessible common resource until it becomes overused, less beneficial, and eventually depleted (Senge, 1990; Senge et al, 1994). Figure 2-14 is an example of the tragedy of the commons archetype. The upper and lower reinforcing loops represent growing airlines that are adding more flights to their schedule. Eventually, they may use up the limited airspace available in the NAS.

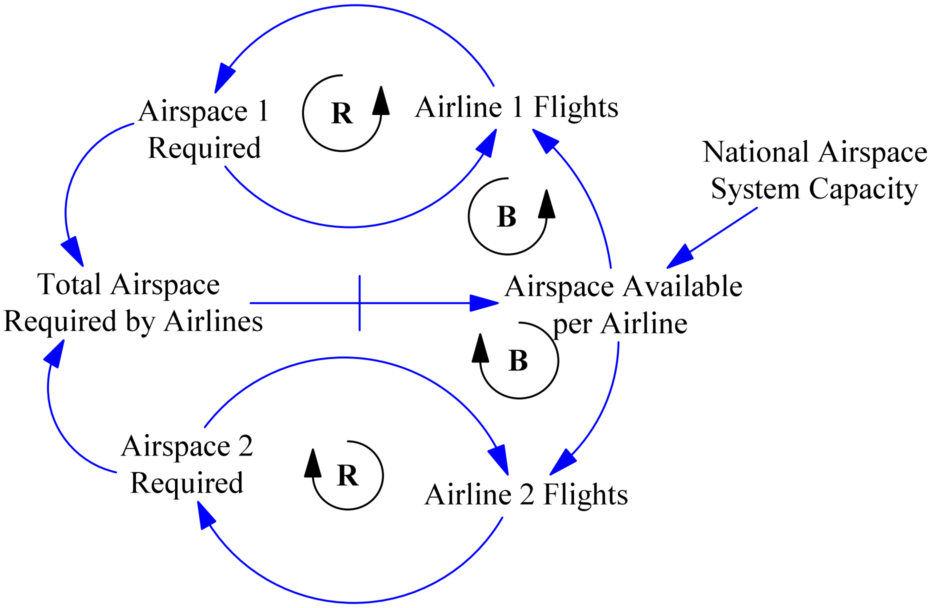

Figure 2-14. The tragedy of the commons archetype consists of growing individual airlines, depicted in the upper and lower reinforcing loops, constrained by the common resource of airspace available in the national system.

The structure of the system characterized by the tragedy of the commons archetype includes a period of favorable behavior followed by a decline as more individuals compete for the same limited resource. Figure 2-15 is an example of the typical pattern of behavior.

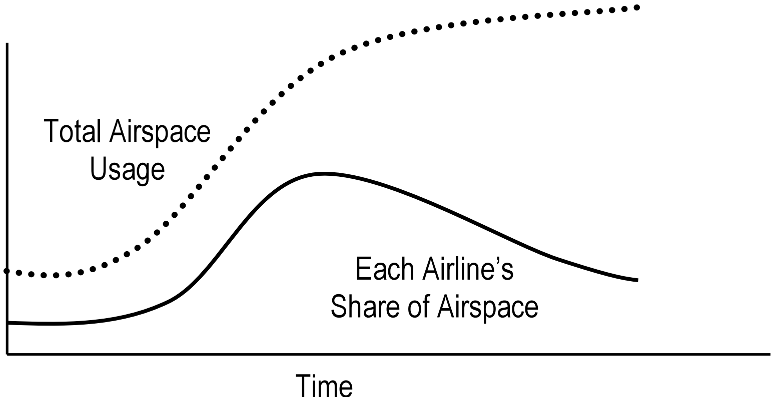

Figure 2-15. The typical pattern of behavior caused by the tragedy of the commons system archetype includes a period of favorable behavior followed by a decline as more individual airlines compete for the same limited resource.

Senge (1990) and Senge et al (1994) recommend strategies to overcome the tragedy of the commons. The best approach to managing the common resource is through participation by all individuals in awareness and regulation efforts in order to replenish, preserve, or expand the common resource. If common agreement is not possible, it may be necessary to seek legislation from a higher authority that advocates a common vision for all. In the case of the NAS, takeoff and landing rights, arrival and departure gates, and clearance delays are among the resources managed by the FAA in order to avoid the tragedy of the commons.

2.16.3 The Success to the Successful Archetype

The success to the successful archetype occurs when two individuals vie for a common resource and the dominant individual grows and becomes more dominant due to growth feeding more growth (Senge, 1990). Figure 2-16 below is an example of the success to the successful archetype. The initially dominant airlines continue to grow and growth feeds on growth as they receive ever increasing preferential use of the NAS.

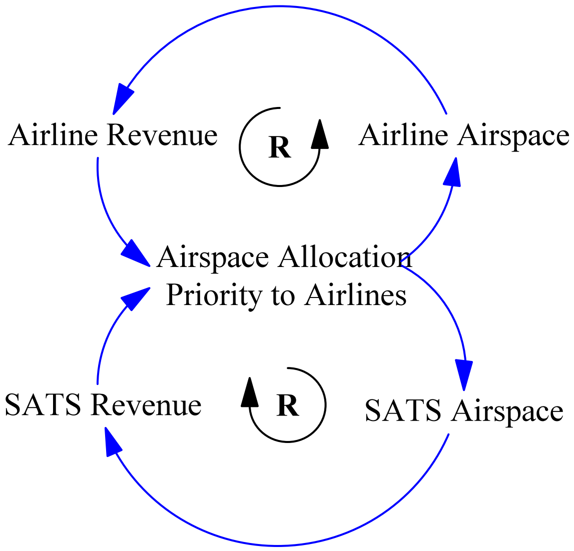

Figure 2-16. Since the airlines initially dominate, as depicted in the upper reinforcing loop, they continue to grow while the competing SATS declines.

The behavior of the system characterized by the success to the successful archetype shows increased growth by the initially dominant individual and decline by the other competing individual. Figure 2-17 is an example of the typical pattern of behavior.

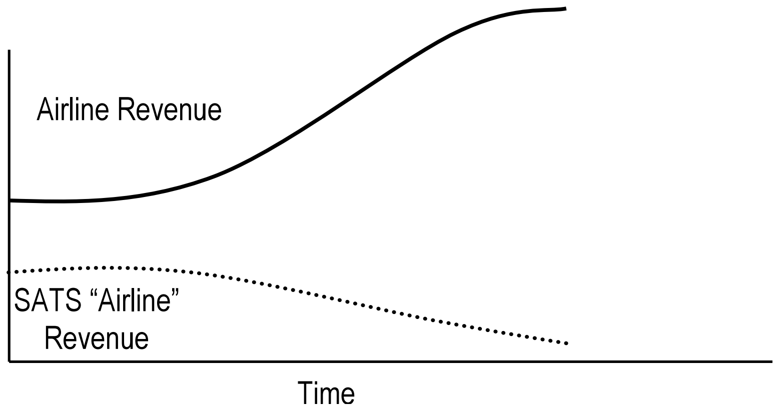

Figure 2-17. The typical pattern of behavior caused by the success to the successful system archetype involves a divergence of performance as the airlines' initial dominance feeds growth.

Senge (1990) recommends strategies to overcome the success to the successful challenge. He recommends seeking a higher goal that the competing individuals may both pursue with mutual advantage. An agreement to complement each other with connecting flights may be one such solution. Otherwise, an opposite strategy is to reduce the competition for the common resource by reorienting one on another resource, such as providing separate airspace or airfields for SATS and the airlines.

Archetypes may be useful to guide the development of the model as well as interpret the model output. Archetypes, used in concert with system diagrams, help explain system behavior during model development and application. Graphically oriented System Dynamics software packages include symbols for illustrating archetypes as well as causal mapping capabilities to trace the flows of influence through models. Further exploration of System Dynamics software will help to determine which software may best suit the overall modeling and system analysis effort.

2.17 System Dynamics Software

Ford (1999) discusses four commercial software packages designed specifically for System Dynamics modeling. The software packages Stella, Vensim, and Powersim all use icon-based graphical interfaces to make the model building process visual and intuitively simpler than the equation-based approach of DYNAMO. The DYNAMO software evolved form mainframe computers as the original System Dynamics modeling language in the 1960s. The Ventanna consulting firm developed Vensim to support their consulting efforts and to use it as a tool to communicate with clients. Stella and Vensim are compatible on both MacIntosh and personal computers, however, Powersim will not run on a MacIntosh computer. Powersim interfaces well with other windows applications through dynamic data exchange, object linking and embedding, and application programmer's interfaces. Ford prefers Stella and he uses it to demonstrate modeling throughout his text. He appears to favor the ease of creating modeling diagrams and interfaces with Stella, although he praises the unique capabilities of Vensim and the interconnectivity of Powersim with other windows programs.

Coyle's (1996) remarks about System Dynamics software, although dated in terms of software capabilities, provide worthwhile insight regarding not only the features one should seek, but also pitfalls to avoid in using the software. He claims that it is more important to use the software properly than to worry about which package one chooses to use. Accordingly, he focuses on the factors that relate to sound System Dynamics modeling: proper equations, appropriate units, thorough documentation, debugging capabilities, and the ability to experiment. In his view, the software packages break down into two camps, the first being text-based software such as Dynamo, COSMIC, and DYSMAP2. The second camp consists of the graphics-based software: Stella, Powersim, and Vensim. Although he highlights the advantages and clarity of creating graphic displays of models, he strongly cautions modelers not to be too quick to create a model without thoroughly ensuring that the equations and units accurately represent the system being modeled. Thus, his concerns lie primarily in the area of model validation because he fears the graphical approach makes it too easy to build bad models. He makes two recommendations, first, modelers should consider using more than one software package, and second, modelers should patiently learn how to use the software before using it in a "serious model."

Although Sterman (2000) does not discuss System Dynamics software packages, a compact disc containing ithink, Powersim, and Vensim accompanies his text. As one of the leading System Dynamics theorists, his tacit endorsement of the three packages places them high in the hierarchy of software and adds considerable credibility to the use of the graphically oriented approach. Sterman's thorough treatment of model validity and proper model development addresses Coyle's admonitions regarding the possibility of building visually attractive, but flawed models. Thus, the graphic approach is here to stay and it is the model builder's responsibility to attend to the nuances of equation writing and unit integrity to create a good product.

The above discussion combined with prior experience and software availability makes Vensim the software of choice for the modeling of future ATC system behavior. The Vensim software offers the ability to create causal loop diagrams, stock and flow diagrams, and simulation experiments. The software has built in checks to ensure consistency of units, proper equation structure, and user definable "reality checks" to address model validity. Nevertheless, despite the functionality of the software, the software is a tool and the essence of the System Dynamics modeling effort consists of how well the modeler can apply the process of representing a real world system as a model.

2.18 Summary

The literature review provides the context for the impact of SATS on the air traffic control system. The FAA and NASA have ambitious plans for the future of aviation. NASA is advocating revolutionary technological advances, while the FAA seeks a more evolutionary approach that emphasizes the need for safety in current operations. The history of air traffic control is one of irregular resource management, reactionary approaches to crises, and initially marginal success with new technology.

The literature review also addresses the activities involved in air traffic control, modeling efforts related to this study, and problems experienced by the European ATC system. The background, issues, and related research leads to the conclusion that the systems approach is a valid and feasible manner of addressing the issue of how managers can influence future ATC systems, support the needs of SATS and non-SATS aircraft, and generate revenue to fund the ATC system.

The systems approach leads to the application of System Dynamics as a model development process to investigate the future behavior of the ATC system under various scenarios. As a maturing field, the body of knowledge that guides researchers in the proper application of the System Dynamics approach is scattered among the works of theorists and practitioners. An overview of their work sets the stage for sound modeling practices that will lead to insight for managers to adapt policies that will create desirable results. The next chapter will provide the blueprint to create a System Dynamics model.

Chapter 3: Research Design

3.1 Research Design Overview

The research design is a plan consisting of the step-by-step procedures to apply a methodology to interpret the meaning of data (Leedy, 2001). The methodology will combine the System Dynamics modeling process along with computer simulation experiments. The mental, written, and numerical databases will provide the information needed to build and validate the model (Forrester, 1991). Users of the model will be able to create data representing the future behavior of the ATC system under a predominantly radar or GPS-based NAS to determine the number of SATS aircraft the system may support. The output of the model will be useful to evaluate various policy and strategy alternatives. The model will also be useful as a management tool to understand the conditions associated with possible future scenarios. Figure 3-1 provides an overview of the research design.

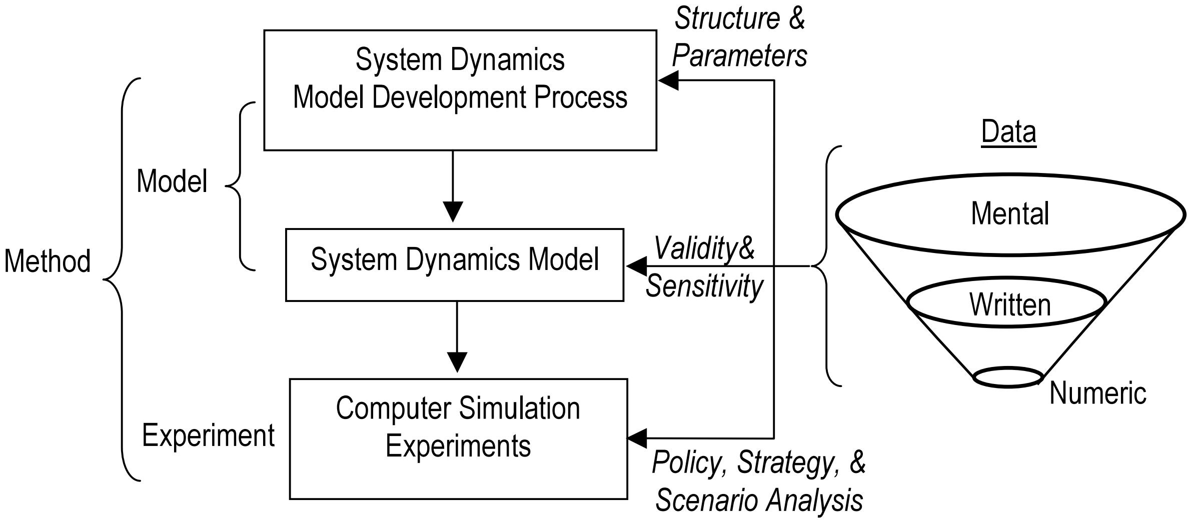

Figure 3-1. The research design is a plan to develop the model, test the model, use the model for policy and strategy experimentation, and conduct scenario analysis.

3.2 The System Dynamics Modeling Process

The System Dynamics modeling process described in Chapter 2 and outlined below includes the steps needed to create and validate a computer simulation model of air traffic control in a future radar or GPS-based NAS with or without a SATS presence. The mental, written, and numeric databases associated with air traffic control will serve as a source of information to develop and validate a System Dynamics model. The mental models of stakeholders and subject matter experts will help to reveal how the air traffic control system operates and how they understand decision-making to occur within the system. Accordingly, interviews using a procedure similar to that advocated by Ford & Sterman (1998) will supply a portion of the data to construct the model. The written database will also serve as a source of information to capture important nuances in the design of the system. The numeric database will contain evidence to support parameter development and serve as a benchmark for evaluating model output. Fundamentally, the role of the researcher will be to manage the System Dynamics modeling process in order to develop insights and encourage innovation in the use of policies related to manning the nation's air traffic control system (Schrage, 2000).

The following discussion outlines the step-by-step process of developing a good model. It is important to recognize that the process is iterative. The researcher's goal is to use the process to ultimately generate numeric and graphic output showing cause and effect relationships among key variables in the NAS that influence the behavior of the ATC system. The procedures stem from the discussion in Chapter 2 above and reflect the concepts espoused by Forrester, Sterman, Ford, Campbell, Homer, and others.

3.2.1 Step 1: Problem Definition

Like all scientific research endeavors, the System Dynamics modeling process begins with a definition of the dynamic problem. To be dynamic, the problem must change over time. If the problem is not dynamic, another approach such as linear programming may be appropriate.

1. Identify the individual or group with the dynamic problem.
    a. Determine how the client likes to communicate.
    b. Determine how the client is addressing the problem.
    c. Identify other computer models the client may be using.

    d. Identify who within the client's organization has the power to accept and implement findings from the modeling effort.
2. Define the dynamic problem and why it is a problem.
    a. Identify key variables in the system.
    b. Determine the time horizon over which the problem influences the system.
3. Develop a dynamic hypothesis that describes the problem as a result of the relationship among the variables and internal structure of the system.
    a. Develop reference modes to graphically depict the undesirable behavior over time.
    b. Draw an additional curve on the reference mode graphs that show improved behavior.
4. Develop performance measurement metrics that will help to determine the effectiveness of the System Dynamics approach to the problem.

3.2.2 Step 2: System Description

Researchers use mapping tools to determine the structure of the system and to identify endogenous, exogenous and excluded variables. Modelers may revise the system description as they gain more insight from subsequent steps in the modeling process.

1. Interview stakeholders and subject matter experts.
    a. Determine where and how information flows through the system.
    b. Determine where decision-making occurs.
    c. Describe the roles of people in the system.
2. Conduct a literature review.
    a. Seek information from the mainstream media as well as academic journals.
    b. Incorporate information from relevant case studies.
3. Assemble numerical data.
    a. Obtain data that will be useful to estimate parameters, describe stocks, or provide past averages or ratios of system variables.
    b. Include data derived from scientific constants, results of experiments, or statistical analysis of databases.

4. Create diagrams of the system using commercially available System Dynamics modeling software.
    a. Develop stock and flow diagrams of the whole system and its subsystems to describe the key variables, relationships, and structure in the system.
        i. Identify the stocks.
        ii. Determine the flows.
        iii. Add the auxiliary variables.
    b. Develop causal loop diagrams of the whole system and its subsystems to highlight the feedback loops in the system.
    c. Use a model boundary chart to categorize variables as endogenous, exogenous, or excluded.
    d. Create policy structure diagrams to determine how information prompts decision-making within the system.
5. Present the results of the above diagramming efforts to stakeholders and subject matter experts.
    a. Receive feedback on the conceptual descriptions of the system.
    b. Make adjustments as necessary.

3.2.3 Step 3: Build a Simulation Model

To build a System Dynamics model, the modeler seeks the appropriate level of dynamic complexity while trying to avoid getting too wrapped up with detail complexity. Model building is both an art and a science. The modeler should start with a simple model then add more complexity until the model replicates the system.

1. Use the stock and flow diagrams developed above and the System Dynamics software as the basis for the simulation model.
    a. Determine mathematical relationships among the variables in the model by interpreting the results of the inquiries into the mental, written, and numeric databases. Convert verbal, written, and numeric descriptions of the system to mathematical relationships.
    b. Use statistical tests to determine model parameters when numeric data is available.

   c. Create proxy variables to represent aspects of the system that are too difficult to model.
   d. Identify variables that represent policy levers managers may adjust to influence the system by changing policy or structure.
   e. It is better to guess at parameter values rather than excluding them from the model; by omitting the parameter values the modeler assigns them the value of zero.
   f. Determine the initial conditions of variables in the model.
   g. Check for unit integrity among the variables and equations.
   h. Determine the appropriate time step to use in the simulation.
   i. Run the model to get the reference mode.
      i. If the model output resembles the reference mode, move on to model validation.
      ii. If the model output does not resemble the reference mode, return to the system description to gain better understanding of the system, rethink the reference mode diagram, or reconstruct the stock and flow diagram.
2. Create an equilibrium diagram to highlight potential inconsistencies in the model, to illuminate incorrect use of units, and to set the conditions to determine the relative stability of the system.
3. Select measures of performance to evaluate how the model depicts system behavior under various policies and strategies.

3.2.4 Step 4: Validate the Model

Establishing model validity involves many tests of the entire model or portions of the model. The effort to establish validity is iterative, detailed, and prolonged. Modelers must carefully navigate their way through the tests despite challenges such as missing data. Researchers should document their validation efforts and note findings that shed light on the nature of the system.

1. Evaluate the sensitivity of the model to extensions of the boundary by making exogenous variables and constants into endogenous parts of the model.
2. Break down the model into lower level components that contain more detail than the higher-level aggregation. Compare the behavior of the separate components of the model

to the higher-level combined model to identify the simplest model that accurately represents the system.

3. Ensure the model adheres to physical laws and the decision-making procedures of the real system.
4. Use the built in dimension checking routines in the modeling software to check for consistency among the units in the model.
5. Ensure that there are no “fudge factors” in the model to adjust dimensions in order to obtain unit consistency.
6. Check all model parameters:
    a. Ensure the model parameters have meaning in the real world.
    b. Ask experts knowledgeable of the system to confirm the accuracy of the parameters.
    c. Use partial model tests to isolate and evaluate parameters.
    d. Keep in mind that the required accuracy of parameter estimates depends on how sensitive the final policy recommendations are to the particular estimate
7. Conduct extreme values testing.
8. Ensure the model is not sensitive to the time step.
9. Conduct behavior reproduction testing.
10. Conduct behavior anomaly testing.
11. Conduct family member tests if there are similar systems to the system being modeled.
12. Compare the output of the model to other models of the same system if they exist.
13. Conduct surprise behavior testing.
14. Conduct sensitivity analysis:
    a. Determine how changes in assumptions cause changes in the numerical output of the model.
    b. Conduct behavior mode sensitivity testing to determine how changes in assumptions cause changes in the shape of the graphical output of the model.
    c. Test for policy sensitivity to determine if changes in assumptions cause the proposed policy alternative to backfire.
    d. Determine which model variables have the greatest impact on system behavior.

15. Ask an independent party to run the model on a different computer to verify that the model operates as intended.
    a. Ask them to check the programming.
    b. Ask them to check the documentation.
16. Ask experts to review the model to verify that the model structure, parameters and behavior replicate the system being modeled.
    a. Expect some experts to transition through a period of realigning their mental models of the system with the behavior depicted by the System Dynamics model of the system.
    b. Reassure those associated with the model that the challenging transition of realigning mental models is a normal part of the process.
17. Be aware of stakeholders who desire to use the model to validate their preconceived notions of how they believe the system behaves.
18. Determine if the application of the model resulted in improved system performance according to the process effectiveness metrics developed above in the problem definition outlined in section 3.2.1.

3.3 Computer Simulation Experimentation

In this phase of the process the researcher moves beyond just creating and handling data. The researcher uses insights gained from the modeling effort to begin thinking about new ways of addressing the problem.

3.3.1 Step 5: Establish a Base Case

The base case is the result of the iterative model development efforts and it is a reproduction of the reference mode.

1. Define the base case in terms of specific values for all of the key variables in the model.
2. Identify whether variables are endogenous or exogenous. Indicate the degree of influence management has on each variable.
3. Define the benchmark or base case of performance against which to compare other runs of the model after making structural or parameter value adjustments to it.
4. Create system performance metrics based on the original purpose of the model.

3.3.2 Step 6: Conduct Policy Experiments

Policy changes occur when modelers change individual endogenous parameter values or the structure of a model to create new behavior.

1. Review the purpose for creating the model to guide the policy analysis process.
2. Address only the policies that management can influence.
3. Change parameter values and compare the output with the base case of the model.
4. Change model structure and compare the output with the base case of the model.
5. Conduct visual inspection of output and statistical tests to determine if there is a significant difference in the behavior of the system under the various policies. Record the results of the experiments and identify the policies that are robust.

3.3.3 Step 7: Conduct Strategy Experiments

Strategy changes occur when modelers change combinations of endogenous parameter values or make multiple changes to the structure of a model to create new behavior.

1. Update the model base case to include the structural changes made as a result of policy experiments.
2. Keep model parameters the same as in the original base case.
3. Make combinations of parameter and structural adjustments to the new base case and compare them to the base case.
4. Evaluate the strategy against the system performance metrics.
5. Conduct visual inspection of output and statistical tests to determine if there is a significant difference in the behavior of the system under the various strategies. Record the results of the experiments and identify the strategies that are most beneficial.

3.3.4 Step 8: Conduct Scenario Analysis

Use scenario analysis to investigate how “what-if” changes in exogenous variables may affect the system behavior.

1. Identify the exogenous variables in the system.
2. Determine if the theme of the scenario analysis will be optimistic versus pessimistic or consist of varying degrees of either optimism or pessimism.
3. Create a surprise free scenario.

4. List and categorize the uncertain aspects of the future that may impact upon the system. Consider the aspects most likely to occur or those that may have the greatest impact.
5. Identify two to four scenarios to investigate.
6. Compile the results of the scenario analysis to summarize and compare the outcomes.
7. Interpret the results in accordance with the original strategic objectives of the managers of the system.

3.3.5 Additional Considerations for Policy, Strategy, and Scenario Alternatives

Throughout the steps above, researchers should consider other activities that may enhance their efforts.

1. Look for system archetypes, described above in section 2.16, that may be useful to identify where to influence systems in order to change behavior.
2. Ask stakeholders and system experts what new scenarios may emerge and what policies they would recommend. Use the model to test their suggestions.
3. Conduct a sensitivity test of the values of the parameters managers cannot control while using the values associated with the new policy variables that the managers can control.
4. Introduce randomness into the system and observe the effects.
5. Consider revising the stock and flow diagram from the system description in section 3.2.2 above to include more detail in the new policy model.

3.3.6 Step 9: Implement New Policies and Structure

The ultimate result of the System Dynamics modeling process is to implement new policies or change the structure of the system based on the insights gained by using the model. The culmination of the researchers' efforts consists of recommendations to the managers of the system. The managers' response will correlate directly with the thoroughness of the modeling effort.

3.4 Treatment of the Data

The purpose of building the model is to generate data about future possible ATC scenarios and how potential management policies will impact upon the behavior of the ATC system. Thus, there is a requirement to use numerical data and relationships among the components of the system to build and validate the model. Additionally, the model will be a source of data. The literature review in chapter 2 addressed both the data for building and the data for policy development. The following discussion contains a summary of the data requirements, data management procedures, and data analysis procedures in order to determine how much support future radar or GPS-based ATC systems will provide to SATS aircraft.

3.4.1 Data Requirements

The data requirements emanate from the main components of the air traffic control system replicated in the System Dynamics model. As model development progresses, data requirements will evolve. Data requirements will be both relational, such as how many controllers work in a control tower, and longitudinal, such as the annual number of controllers in the FAA over time. Anticipated data requirements to support the model development are as follows:

1. Personnel submodel
    1) Numbers and types of air traffic controllers and maintenance technicians over time
    2) Controllers and maintainers required for each type of facility or piece of equipment
    3) Controller training data
2. Budget Submodel
    1) FAA budgets
    2) Airport and Airways Trust Fund
    3) Revenue per type of aircraft
    4) Controller costs over time
    5) ATC equipment costs of time
    6) Airport costs over time
3. Aircraft submodel
    1) Numbers and types of aircraft over time
    2) SATS aircraft fielding projections
4. Equipment submodel
    1) Numbers and types of radar-based equipment

    2) Numbers and types of GPS equipment
    3) ATC equipment capabilities and fielding schedule
    4) Aircraft navigation equipment capabilities

5. Facilities submodel
    1) Numbers and types of facilities
    2) Controllers required per type of facility
    3) Equipment required per type of facility

Section 3.3 above describes the development and treatment of the data for the policy experiments, strategy experiments, and scenario analysis.

3.4.2 Data Management

The data to build and validate the model comes from the mental, written, and numerical databases. Ultimately, the compilation of the data resides in the mathematical relationships embedded in the software of the System Dynamics model. For explanatory purposes, the data used in the model is in the discussion in Chapter 4 or in a summary appendix to the research documentation in either spreadsheet format or as mathematical expressions showing relationships among components of the model. Otherwise, the capabilities of the System Dynamics software allow modelers to use graphic user interfaces to easily insert and access the data in the model.

3.4.3 Data Analysis

Data analysis falls into two primary categories: 1) analysis of data to build the model; and 2) analysis of data generated by the model. Since the type and format of the data is similar in both categories, the analysis procedures will also be similar. The data analysis procedures will involve analysis of tabular data, visual graphical analysis, statistical techniques such as regression, and the use of output from other studies and models. Additionally, the System Dynamics software includes the capability to conduct various forms of output analysis.

3.5 Expected Results

At a minimum, the products of the research effort will include a System Dynamics model of the components of the air traffic control system that demonstrates how the system may behave under various resource management strategies. Additionally, the research will result in a compilation of the salient mental models, written perspectives, and numerical data that describe the flow of resources and revenue through the ATC system. Finally, the research will produce knowledge of the potential ramifications of changes to policies associated with the ATC system and its ability to support SATS aircraft and generate sufficient revenue for the Airport and Airways Trust Fund.

The impact of the results will provide new insight for decision-makers at the FAA and NASA regarding the introduction of the small aircraft transportation system under various ATC resource management strategies. The insights may serve as a bridge between the aggressive, revolutionary vision proposed by NASA and the cautious, evolutionary perspective practiced by the FAA. Although, both government agencies share the goal of improving the use of the NAS, they choose to pursue the goal in fundamentally different ways. Subsequently, neither agency is taking a hard look at the relationships among SATS and the behavior of future ATC systems. The NASA SATS advocates assume that technology will solve any ATC problems and the FAA administrators see no ATC requirement because SATS is merely conceptual. The research proposed in this document will objectively highlight the emerging issues and identify potential problems that may lie ahead. The development of the System Dynamics model in the next chapter is the first step toward obtaining research results.

Chapter 4: The ATC Resource Management Model

4.1 System Dynamics Model Development Process

The NASA advocates of SATS proposed the system as an intervention to alleviate the delays incurred by travelers who use the hub and spoke system. However, from a systems thinking perspective, one realizes that interventions often have desired effects and undesired side effects. The undesired side effects usually emanate from "policy resistance, the tendency for interventions to be defeated by the response of the system to the intervention itself" (Sterman, 2001, p.8). The response of the large and complex air traffic control system to architectural changes and the influx of SATS aircraft may result in unanticipated side effects due to the inherent feedback structure of the ATC system and delayed responses caused by changes to the flow of resources and revenue through the system. Accordingly, the System Dynamics modeling process offers an approach that can capture the behavior of the ATC system by means of a computer model that replicates the system structure and the entities that flow through it.

The flowchart in Figure 4-1 depicts nine steps modelers use to define a problem, create a model, and apply the model to recommend actions that may improve system behavior. The modeling process involves iteration, particularly among the first three steps, to refine the effort as feedback from the real world invokes the need to make changes. The art of modeling requires the modeler to discern the nature of the system through study, discussion, and numerical analysis. The science of modeling requires the modeler to develop parameters for the model, validate the model, and apply it to investigate system behavior. An important aspect of the art and science of the modeling effort is to determine the appropriate level of aggregation and analysis of the components of the system in order to create a valid and useful replication of the real world.

4.2 Levels of analysis

The concept of "levels of analysis" is a relevant issue for any modeling effort and is an important concern in the development of a System Dynamics model. A survey of the simulation modeling literature indicated that the inclination of most modelers was to use the broadest scope and greatest level of detail when creating models (Chwif, Barretto, & Paul, 2000). However, Law and Kelton (2000) discourage replicating every element of a system in a model prior to defining the purpose of the study, determining the modeled performance metrics to evaluate, and fully consulting with managers and subject matter experts associated with the study. Klein, Dansereau, and Hall (1994) describe how conclusions drawn about a variety of organizational research issues; in areas such as personnel management, technology, and organizational performance; resulted in findings that varied according to the level of analysis.

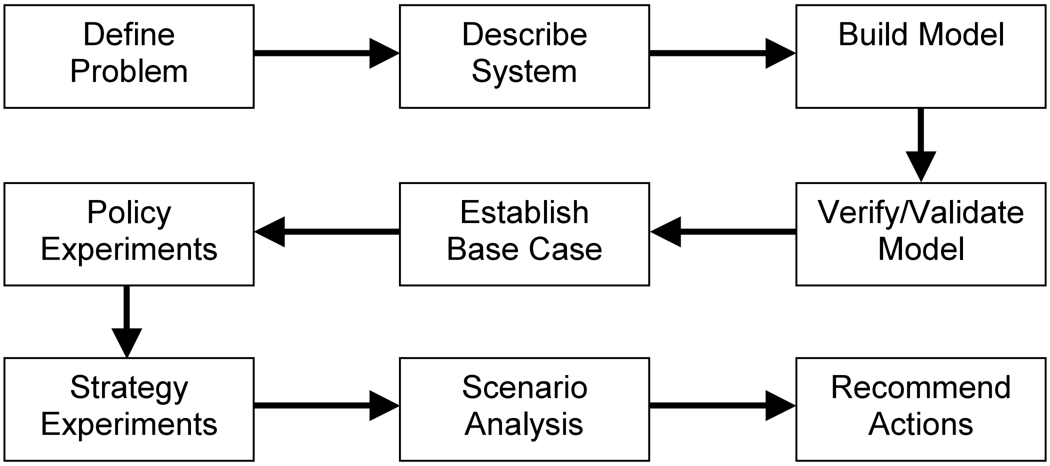

Figure 4-1: Steps of the System Dynamics Modeling Process lead modelers from problems to solutions (Maani and Cavana, 2000).

The "levels of analysis" framework proposed by Klein, Dansereau, and Hall (1994) describes the "levels of analysis" concept and highlights why it is important to organizational research and modeling. They define the "level of theory" as the intended person, team, or organization that a modeler seeks to replicate and elucidate; the "level of measurement" as the point at which the data originated; and the "level of statistical analysis" as the point at which the researcher aggregates data for analysis. The word "point" means the level of aggregation of people, such as the individual, dyad, team, group, organization, community, or beyond, which Klein et al. refer to as an "entity." Thus, an entity is not just an individual person. An entity may be any collection of people provided it represents a particular level at which a researcher may apply theory, collect data, or conduct statistical analysis. Dansereau, Alutto, and

Yammarino (1984) describe entities as, “specific objects of interest to a researcher” (p. 9). For the domain of air traffic control, entities may consist of individual controllers, facilities such as airport control towers, or entire air traffic control regions.

4.2.1 The Level of Theory

It is important for researchers to clearly describe the object to which a level of theory applies; either to the level of the individual, to some group level, or to the level of an individual within a group. If the entity is at the level of the individual, then the implication is that the individual’s behavior is independent of the group behavior. For example, at the independent individual level of theory, researchers would investigate the performance of each individual air traffic control tower within the National Airspace System. If the entity is at the level of the group, then the implication is that every member of the group is similar enough to consider the group homogeneous. For example, at the group level of theory, all air traffic control towers would operate identically within the NAS. Finally, if the entity is at the level of the individual within the heterogeneous group, then the implication is that the evaluation of an individual’s performance is relative to the performance of the group as a whole. For example, the performance characteristics of the control tower at O’Hare International Airport in Chicago would differ from those of all towers combined (Klein et al., 1994). Therefore, some stocks, such as control towers, may require disaggregating to lower levels.

4.2.2 Entities and Variables

In addition to identifying the level of theory for an object or “entity”, researchers should also differentiate between “entities” and “variables” during the model development process. The two terms are important aspects of the “levels of analysis” concept as they distinguish between the people in an organization, the entities; and the characteristics or attributes of the individual or groups of people, the variables (Markham, 1998). The individual, facility, and regional entities of the air traffic control system consist of people and their performance as air traffic controllers. The variables associated with these entities are attributes such as number of operations, operational errors, or aircraft delayed. To blend the concept of entities and variables with the System Dynamics methodology, modelers should describe all stocks within a system as entities. In the air traffic control system, other entities may include individual aircraft or groups of computer navigation equipment. Additionally, modelers should describe the flows and auxiliary variables as the variables that describe the characteristics of the stocks, for example, training time for new controllers, aircraft navigation equipment capabilities, or time to deploy a new computer system. The System Dynamics process facilitates the identification of entities and variables. It is important to discern the difference between entities and variables in order to apply theory, make measurements, and conduct statistical analysis at the appropriate entity level.

The discussion above identifies several issues to deal with in the model development effort. First, what level of theory will the model address: individual controller, facility, region, or the entire system? Second, from what level in the system do the data emanate? Third, at what level will the modeler aggregate the data to conduct analysis? Fourth, are entities within the system independent, homogenous, or heterogeneous? And fifth, what are the variables associated with the entities? Since the System Dynamics model of the air traffic control system will center on the homogeneity of entities within the system, it is important to determine at what level the entities are indeed homogeneous. The overview of the system in the next section provides the bounds within which to identify ATC entities and the levels of analysis best suited for them.

4.3 Model Overview

The purpose of the model is to determine what air traffic control resource management strategy will support the future needs of the Small Aircraft Transportation System and create adequate tax revenue to fund the Federal Aviation Administration. The model should replicate the behavior of the system to determine how it behaves with or without the presence of SATS aircraft. Thus, the components of the model must reflect both the current ATC system with non-SATS aircraft and the likely ATC system of the future with both SATS and non-SATS aircraft. Additionally, to be useful to those who develop policies for the ATC system, the model should contain the capability to include exogenous variables, such as the amount of funding for GPS equipment, in the system that managers can influence to ascertain the response of the system to manipulations that reflect resource management strategies. The researcher attempted to include all of these characteristics through a series of iterations and embellishments that resulted in the system level model depicted in Figure 4-2.

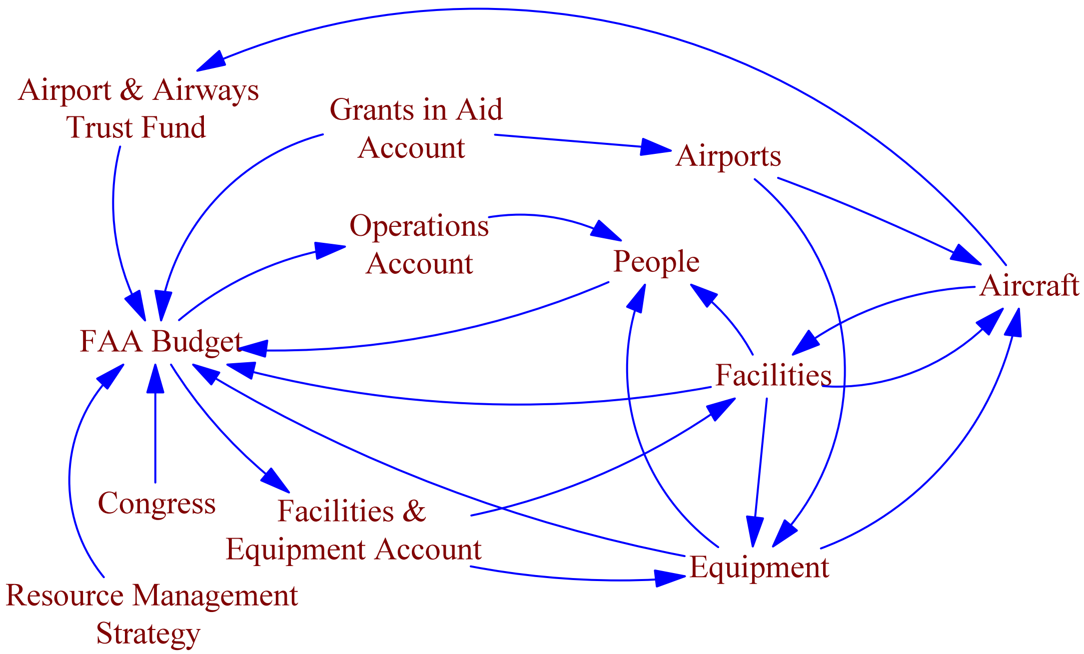

Figure 4-2: The ATC manpower and infrastructure policy planning model includes aspects of the ATC system that SATS may influence.

Fundamentally, the model depicts a system governed by supply and demand. The ATC system supplies airports, facilities, equipment, and people to the aircraft that demand ATC services. The internal decision-making mechanisms within several feedback loops influence the level of participation of aircraft in the system. The amount and distribution of the money in the FAA budget determines the numbers of controllers, maintainers, facilities, equipment, and airports in the ATC system. The number of aircraft that may operate in the ATC system depends on the numbers of controllers, maintainers, facilities, equipment, and airports in the ATC system. The number of aircraft operating in the system influences the amount of revenue for the Airport and Airways Trust Fund. The revenue generated by the Airport and Airways Trust Fund constrains or enhances the FAA budget in a reinforcing feedback loop. Additionally, the people employed by the FAA, particularly the numbers of controllers and field maintenance personnel required by the amount and type of ATC infrastructure and equipment, also serve as a balancing feedback for the FAA budget. Thus, the feedback within the system creates the conditions for adjustments in the quantity of manpower and infrastructure available to supply ATC services. Similarly, the feedback structure of the system also influences the number of aircraft that conduct operations that may demand ATC services, which impacts on the amount of revenue collected in the Airport and Airways Trust Fund.

Managers of the ATC system make adjustments to policy variables in order to elicit desired system behavior. The model includes the policy variable input interface depicted on the left side of Figure 4-3 to conduct scenario analysis of various combinations of ATC resource management policies. The input interface allows a model user to adjust system variables linked to the resource management strategies, such as the percent of resources devoted to GPS funding, across a range of values. The computer software processes the input values through the modeled closed-loop feedback system to generate the behavior of the ATC system over time. The model generates numeric and graphic output. The right side of Figure 4-3 represents a typical output graph of a system performance metric.

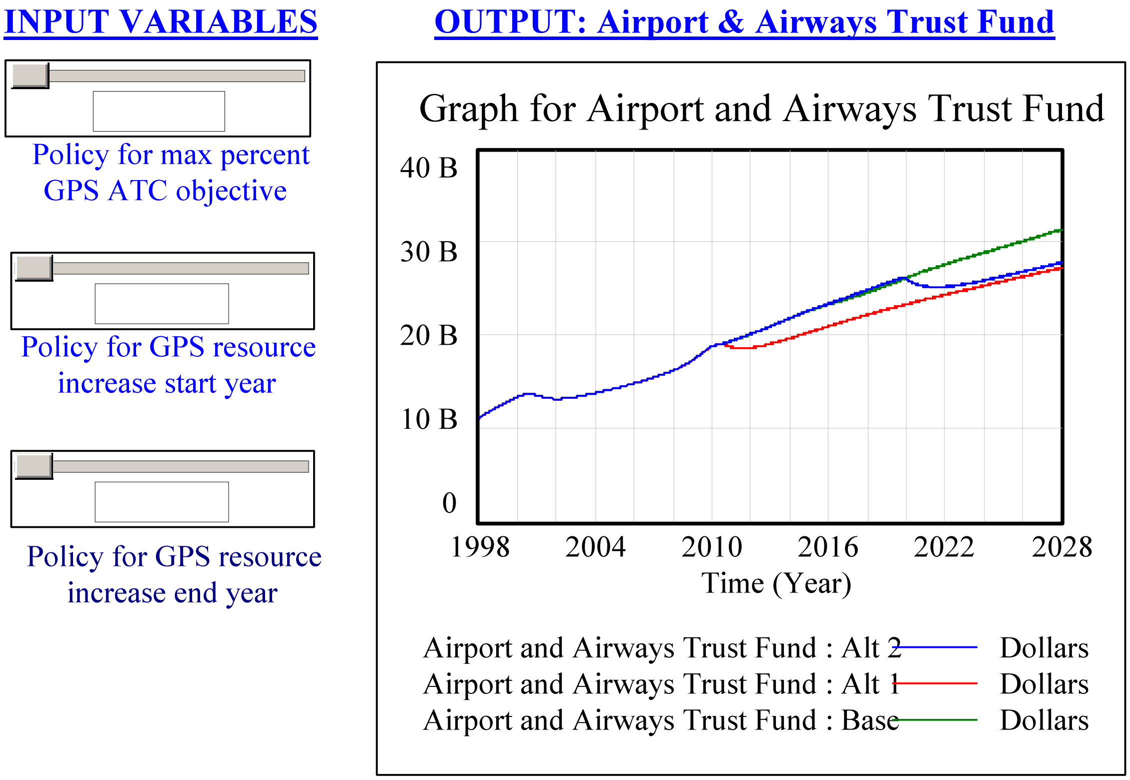

Figure 4-3: Model input variable "sliders" and graphic output

4.3.1 Model Conceptualization

The model structure consists of five interconnected subsystems and a strategy input control panel. The control panel allows model users to adjust endogenous variables that managers use to implement resource management strategies and observe system behavior. The model attempts to replicate the ATC infrastructure through the Airports, Facilities, and Equipment submodels. The People submodel addresses the ATC manpower requirements for air traffic controllers and system maintenance technicians. The Aircraft submodel includes several categories of aircraft that place demands on the ATC system, including SATS aircraft. The last submodel, the Budget submodel, captures the flow of money for salaries, operating costs, new construction and procurement. Additionally, the Budget submodel includes revenue generated through the Airport and Airways Trust Fund. Figure 4-4 illustrates the general flow of feedback through the system.

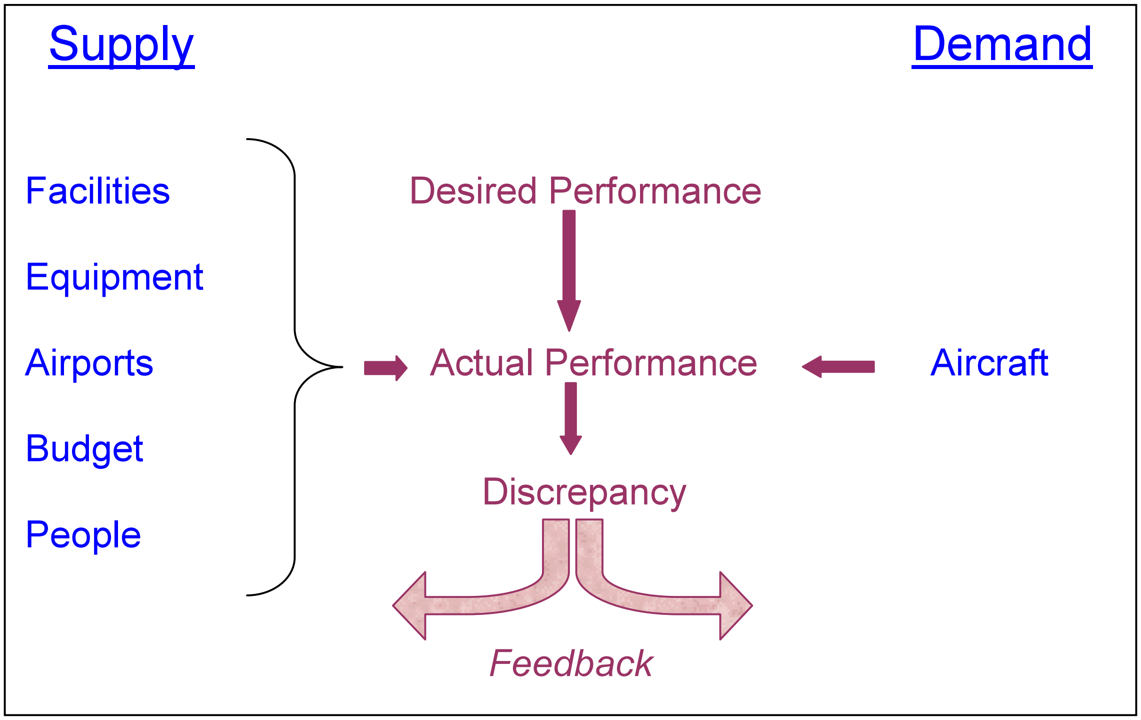

Figure 4-4: Feedback loops create dynamic behavior in the model of the ATC system.

4.3.2 Delays and Feedback loops

Several feedback loops and inherent delays within them cause dynamic behavior over time within the ATC system. The first feedback loop links the Airports and Airways Trust Fund, the FAA budget, the infrastructure of the system created and supported by the budget, and the aircraft the system can support. Ultimately, the number of aircraft supported generates revenue that feeds into the trust fund to reinforce the operation of the ATC system. Several feedback loops connect the submodels and cause internal adjustments among the stocks in the submodels. Delays occur in some loops, such as the requirement to train controllers and maintainers before they can become fully qualified. The interaction of the feedback loops and the delays causes growth, decay, or oscillations in the system performance metrics.

4.3.3 Modeling Assumptions

The following assumptions simplify and shape the model structure, while still capturing the essential aspects of the real world system.

1. The core of the current national airspace system will evolve with technology, but remain fundamentally the same. Thus, the air carrier aircraft will continue to function in a system primarily controlled by human controllers in a system of control towers, TRACONs, and ARTCCs.
2. The peripheral parts of the national airspace system will be the areas subject to the most change. The thousands of small airports around the country that do not connect to the hub and spoke system will provide the most opportunity to support SATS aircraft through the application of new GPS-based technology.
3. Two Air Route Traffic Control Centers will consolidate into one center in 2010. ARTCCs will perform monitoring roles under GPS-based ATC architectures in addition to their radar-based ATC responsibilities.
4. All Flight Service Stations will also perform monitoring roles under GPS-based ATC architectures.
5. The ATC community will resolve future airspace issues that may interfere with SATS operations.
6. The FAA will continue to experience budget trends like those of the past. However, the model will capture dynamic system feedback through the Airport and Airways Trust Fund.
7. Projections from the FAA regarding aircraft growth rates will serve as a basis for similar parameters in the model, which are listed in Table 5-2.

8. The ATC system will not allow for mixed modes of traffic operating within the same airspace. Aircraft will fly according to IFR, VFR, or in accordance with "SATS flight rules."
9. Military aircraft will adjust their use of Public Use Airports to accommodate the growth of SATS airports.

4.3.4 Modeling Objectives

The objective of the modeling effort is to present a top-level System Dynamics model of the ATC system that shows the cause and effect relationships among the "supply" of ATC services provided by facilities, equipment, manpower, airports and the budget; and the "demand" for ATC services from aircraft. Additionally, the modeling effort should replicate the current ATC system and project its behavior into the future based upon various resource management strategies that may change the system structure. Finally, the model should demonstrate the potential support the ATC system may provide to the future SATS and subsequent behavior of the system under the influence of SATS aircraft. Users of the model will see how the various resource management strategies of the ATC system will dynamically behave over time.

4.4 Modeling ATC Resource Management Strategies

The model is useful to investigate three strategies FAA managers may pursue. The three strategies involve policies to meet the demand for ATC instrument operations from conventional aircraft and to expand the growth of systems to support GPS-based ATC. The GPS-based ATC will be the primary means by which SATS aircraft will navigate and maintain separation from other aircraft. The model will also provide an indication of the amount of SATS flights the ATC system will support under the various resource management strategies and the revenue produced by the system.

4.4.1 Strategy 1: Maintain the Radar-based System

The first strategy is to maintain the current ATC system by investing in people, airports, facilities, and equipment to meet the demands of aircraft operating under radar-based ATC. The primary objective of resource managers using the first strategy is to continue to expand and modernize the radar-based ATC system. Most resources will go to achieving that goal.

However, some resources will support a low level of GPS-based ATC growth as part of the system modernization effort.

4.4.2 Strategy 2: Reduce the Radar-based System

The second strategy is to aggressively reduce the radar-based ATC system by maintaining a high rate of investment in GPS-based ATC equipment and airports while accepting shortfalls in the radar-based ATC system during the transition period. Conceptually, the strategy would induce delays in the radar-based system and cause aircraft owners to invest in on-board systems to operate in the GPS-based environment.

4.4.3 Strategy 3: Supplement the Radar-based System

The third strategy is to supplement the radar-based ATC system with a GPS-based ATC system growing at a rate that is constrained somewhat by the requirements of the radar-based ATC system. Managers would provide resources to meet the demand for radar-based ATC while using all additional funding to expand the GPS-based system.

4.4.4 ATC Resource Management Policies

Strategies are combinations of policies. The above three strategies consist of combinations of two FAA resource management policies. The first policy determines the desired level of support the FAA should attempt to give to aircraft that demand radar-based ATC services. The amount of money devoted to the accounts that pay for the radar-based ATC services is a surrogate measure of the level of support. Since resource management is a zero sum game, managers would direct the money not devoted to radar-based ATC toward GPS-based ATC requirements. The second policy determines the timeframe over which resource managers should implement the first policy. The timeframe consists of a period of years bounded by a start year, a period of adjustment, and a target year in which the first policy would be in full effect. The combination of policies one and two create three exogenous decision variables for the system: a target level of radar-based ATC funding, a year to begin transitioning to the desired new funding level, and an end year to fully meet the funding objective.

4.4.5 Exogenous Input into the System and the Model

The model boundary diagram in Figure 4-5 distinguishes between endogenous and exogenous components of the system and the outside world excluded from the model. The endogenous components include the stocks and flows within the system that, if unperturbed by outside forces, create normal system behavior. The exogenous components include the aspects of the system that generally remain constant over time and influence the endogenous parts of the system. Resource managers will utilize funding levels for radar-based or GPS-based airports, equipment, and facilities to influence the behavior of the ATC system. It is desirable to minimize the impact of other potential exogenous inputs into the model to limit the behavior of the model to the internal structure of the system and those management controlled external variables. The excluded aspects of the outside world provide a sense of the domain represented by the model.

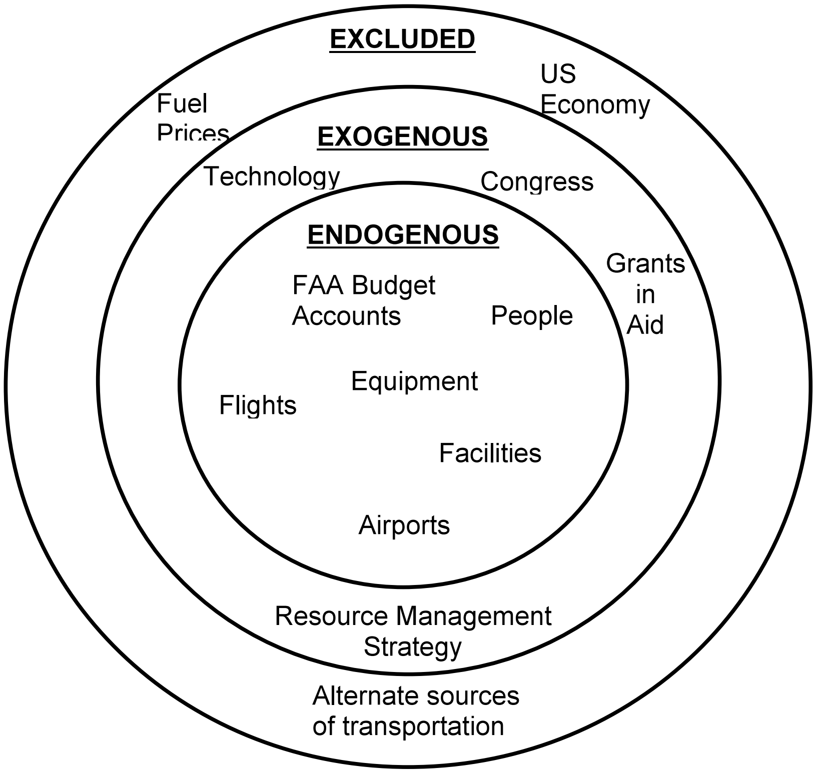

Figure 4-5: The model boundary diagram conveys the domain of the modeling effort.

4.5 Model subsystems

The model consists of six subsystems that work together to replicate the flow of resources through the ATC system in the US. The People Subsystem includes air traffic controllers and field maintenance personnel. The Budget Subsystem includes the FAA annual budget as well as the Airport and Airways Trust Fund. The Facilities Subsystem includes Air Route Traffic Control Centers, Terminal Area Controls, Air Traffic Control Towers, and Flight Service Stations. The Equipment Subsystem includes equipment that supports radar-based or GPS-based ATC. The Airports Subsystem includes non-SATS and SATS airports. The Aircraft Subsystem includes commercial airliners, air taxi, general aviation, and SATS aircraft. Decision-making occurs when stocks change. The decisions create dynamic endogenous feedback in the system that causes further changes in the stocks and flows. The exogenous input in the form of resource management strategies generates dynamic behavior that provides insight into the potential system performance generated by the interaction of the subsystems.

The remainder of Chapter 4 provides the details of the subsystems that combine to create the ATC manpower and infrastructure resource management model. Each subsystem includes a written description, additional diagrams, equations, tables, and explanations regarding the development of model parameters.

4.6 The People Subsystem

The people subsystem consists of the 50,000 employees of the FAA. Table 4-1 below shows the distribution of employees throughout the FAA. Over 85% of the people in the FAA work in two main areas: Air Traffic Services, and, Regulation and Certification. Within Air Traffic Services there are approximately 17,500 air traffic controllers, 8,500 field maintenance personnel, 3,000 Flight Service Station employees, and 6,000 employees involved in telecommunications, logistics, or system requirements. Within Regulation and Certification there are approximately 4,000 inspectors, engineers, and pilots; 1,000 technical and field support personnel and 700 employees involved in certification administration, aviation safety education, and research (FAA, 2001b). The Civil Aviation Security organization, which consisted of about 1,200 FAA employees, transferred to the newly formed Transportation Security Administration in the wake of the events of September 11, 2001.

The number of people in the ATC system influences the amount of money Congress must provide for the FAA budget. Historically, the AATF provided from 34% to 100% of the money needed for employee salaries and benefits. Primarily, the AATF provides money for improvements to airports and modernization of facilities and equipment. In the FAA budget and in the model, Congress must make up for shortfalls in the budget not provided for by the AATF.

The challenge in modeling the people subsystem lies in the determination of how future technology will impact upon the need for people in the system. The people subsystem model uses aircraft, facilities and equipment, and ATC technology growth rates combined with manpower requirements from policy decisions to determine how the behavior of the system will influence the need for FAA employees.

Table 4-1: The FAA employs approximately 50,000 people.

FAA Employees	1996	1997	1998	1999	2000	2001	2002 (est)
Air Traffic Services	34,929	35,019	35,789	35,732	35,425	36,349	36,216
Regulation and Certification	5,132	5,766	5,721	6,030	5,864	6,195	6,122
Civil Aviation Security	755	1,015	1,175	1,156	1,153	1,221	0
Airports	463	472	483	490	446	472	464
Research and Acquisitions	777	770	1,899	1,902	1,898	1,858	1,850
Comm Space Transportation	28	34	28	30	25	44	60
Staff Offices & Other	5,211	5,190	3,704	3,728	3,652	3,762	3,794
Total	47,295	48,266	48,799	49,068	48,463	49,901	48,506

Source: FAA, 2002a

Table 4-2 provides a breakdown of the distribution of employees among the Air Traffic Services and Regulation and Certification components of the FAA, where the majority of FAA employees work.

Table 4-2: Approximately 85% of FAA employees work in either Air Traffic Services or Regulation and Certification.

ATS and R&C Employees	1998	1999	2000	2001	2002 (est)
Air Traffic Controllers	17,756	17,639	17,547	17,510	17,464
Field Maintenance	8,338	8,070	7,830	8,188	8,493
Flight Service Stations	3,100	3,017	2,976	2,934	2,872
Other ATS	6,595	7,006	7,072	7,717	7,387
Inspectors, Engineers, Pilots (Flt Standards)	4,506	4,357	4,206	4,476	4,407

Technical and Field Support (Acft Cert)	1,024	980	992	1,025	1,034
Other R&C	191	693	666	694	681
Total	41,510	41,762	41,289	42,544	42,338
Total FAA	48,799	49,068	48,463	49,901	48,506
Percent ATS and R&C	85%	85%	85%	85%	87%

Source: FAA, 2002a

Table 4-3 shows that 60% of the FAA employees are air traffic controllers or system maintenance technicians, implying that FAA employees classified in the model as "all others" includes approximately 40% of the people in the FAA.

Table 4-3: Approximately 60% of FAA employees are either air traffic controllers or maintenance technicians.

Controllers & Maintainers	1998	1999	2000	2001	2002 (est)
Air Traffic Controllers	17,756	17,639	17,547	17,510	17,464
Field Maintenance	8,338	8,070	7,830	8,188	8,493
Flight Service Stations	3,100	3,017	2,976	2,934	2,872
Total:	29,194	28,726	28,353	28,632	28,829
Total FAA	48,799	49,068	48,463	49,901	48,506
Percent Controller and Maintainer	60%	59%	59%	57%	59%

4.6.1 FAA Employee Job Descriptions

The majority of the employees of the FAA serve as air traffic controllers, maintenance technicians, or inspectors. Currently, controllers comprise approximately 35% of the manpower in the FAA. Controllers perform the following types of duties:

1) **Center Controllers**: Center controllers "provide air traffic control service to aircraft operating on an IFR flight plan within controlled airspace and principally during the en route phase of flight. When equipment capabilities and controller workload permit, certain advisory/assistance service may be provided to VFR aircraft" (FAA, 2002, Glossary).
2) **Tower Controllers**: Tower controllers "use air/ground communications, visual signaling, and other devices, to provide air traffic control services to airborne aircraft operating in the vicinity of an airport and to aircraft operating on the movement area (surface)" (FAA, 2002, Glossary).

3) **Approach Controllers**: Approach controllers "use radar and air/ground communications to provide approach control services to aircraft arriving, departing, or transiting the airspace controlled by the facility" (FAA, 2002, Glossary).
4) **Automated Flight Service Stations and Flight Service Station Controllers**: Controllers at FSSs and AFSSs, "provide preflight pilot briefings and en route communications with VFR flights, assist lost aircraft, assist aircraft having emergencies, relay air traffic control clearances, originate, classify, and disseminate Notices to Airmen, broadcast aviation weather and national airspace system information, receive and close flight plans, monitor radio navigational aids, notify search and rescue units of missing VFR aircraft and operate the national weather teletypewriter systems. In addition, at selected locations, FSS controllers take weather observations, issue airport advisories, administer airmen written examinations, and advise Customs & Immigration of transborder flights" (FAA, 2002, Glossary).

Many FAA employees serve as maintainers and inspectors:

1) **Airway Transportation Systems Specialists and Electronics Technicians**: The FAA employs Airway Transportation Systems Specialists and Electronics Technicians to design, develop, install, certify, inspect, and repair thousands of pieces of equipment in or near airports and at remote sites to support the ATC mission. The maintenance specialists and technicians work with equipment such as radar, computers, communications, navigational aids, lighting aids, and the mechanical and electrical components of FAA facilities.
2) **Aviation Safety Inspectors**: The FAA employs Aviation Safety Inspectors to ensure that those who produce, maintain, operate, and modify civil aircraft comply with all applicable standards and regulations.

4.6.2 Modeling the People Subsystem

The model treats FAA employees as entities in the system and places them into three categories: controllers, maintainers, or all others. Both the controllers and maintainers occupy two stocks each. The model treats all other employees as a function of the number of controllers and maintainers. Over time, employees flow into the stocks as new hires and eventually leave the system as retirees. Several assumptions underlie the people subsystem model:

1. On average, the FAA hired 430 people annually to become Air Traffic Controllers from 1997 to 2001 (GAO, 2002). Based on the numbers of controllers in the system during those years, the model incorporates an average controller-hiring rate of 0.021, based on the data presented in Table 4-4.

Table 4-4: The recent average hiring rate for Air Traffic Controllers was 2.1% of the controller pool.

Controllers	1998	1999	2000	2001
Air Traffic Controllers	20,856	20,656	20,523	20,444
Hirees	430	430	430	430
Annual Hire Rate	0.021	0.021	0.021	0.021

2. If there is a shortage of controllers or maintainers, the system can surge hiring to twice the normal rate and three times the normal rate for extreme conditions.
3. If there is an overage of controllers or maintainers, the system slows down the hiring rate to 25% of the normal rate.
4. Controller training time to become fully proficient takes two to four years (GAO, 2002).
5. Controller trainees have a 10% wash out rate.
6. Controllers and maintainers depart the system annually based on a retirement rate of (Controllers/average controller career) and an early departure rate of 100 controllers per year. Additionally, the model includes the air traffic controller retirement surge expected from 2003 through 2008 (GAO, 2002).
7. The data in Table 4-5 supports the claim that 60% of the employees are controllers or maintainers and the other 40% are primarily inspectors and administrators.

Table 4-5: Controllers and Maintainers account for 60% of the FAA employees.

Controllers & Maintainers	1998	1999	2000	2001	2002 (est)
Air Traffic Controllers	20,856	20,656	20,523	20,444	20,336
Field Maintenance	8,338	8,070	7,830	8,188	8,493
Total:	29,194	28,726	28,353	28,632	28,829
Total FAA Employees	48,799	49,068	48,463	49,901	48,506
Percent ATC & Maint	60%	59%	59%	57%	59%

(Source: FAA Fact Book)

8. Table 4-6 contains a breakdown of Air Traffic Controllers in Towers, Centers, and TRACONs and controllers who work in flight service stations.

Table 4-6: Approximately 42% of all FAA employees are air traffic controllers.

Controllers	1998	1999	2000	2001	2002 (est)
Air Traffic Controllers	17,756	17,639	17,547	17,510	17,464
Flight Service Stations	3,100	3,017	2,976	2,934	2,872
Total:	20,856	20,656	20,523	20,444	20,336
Total FAA	48,799	49,068	48,463	49,901	48,506
Percent	43%	42%	42%	41%	42%

(Source: FAA Fact Book)

9. The number of facilities in the system determines the total number of controllers, as depicted in Table 4-7.

Table 4-7: Estimates of the number of controllers per facility.

Type Facility	1998	Avg # Controllers	Total Controllers
Centers	21	375	7,875
Core AC Towers	170	18	3,060
Core AT Towers	135	8	1,080
Core GA Towers	157	5	785
Approach Controls	190	25	4,750
FSS/AFSS	137	22	2,992
Total:			20,542

(Source: FAA Fact Book)

10. The amount of equipment in the system and the number of controllers determines how many maintainers are in the system. Table 4-8 shows that there are approximately 1.09 maintainers per piece of radar-based equipment in the ATC system. The model includes assumptions that the same maintainer to equipment ratio will apply to GPS-based ATC equipment. Table 4-9 contains data to support the assumption that the average ratio of 0.40 field maintenance personnel to air traffic controllers provides an estimation of how many maintainers work in the ATC system.

Table 4-8: There are approximately 1.09 maintainers for each piece of equipment in the ATC system.

Maintainers	1998	1999
Field Maintenance	8,338	8,070
Radar-based Eqpt	7,460	7,685
Ratio	1.12	1.05

(Source: FAA Budget in Brief, 2001)

Table 4-9: There are approximately 0.4 maintainers for each controller in the ATC system.

Controllers to Maintainers Ratio	1998	1999	2000	2001	2002 (est)
Field Maintenance	8,338	8,070	7,830	8,188	8,493
Air Traffic Controllers	20,856	20,656	20,523	20,444	20,336
Ratio	0.40	0.39	0.38	0.40	0.42

(Source: FAA Fact Book)

11. Model calculations determine the required number of maintainers by taking the average of 0.4*(controllers) and 1.09*(radar-based equipment + GPS-based equipment).
12. The number of controllers and maintainers determines the number of "all other" employees in the system. As suggested in Table 4-5 above, all other employees account for 40% of the FAA workforce.

4.6.3 People Subsystem Stock & Flow Diagrams

The controller and maintainer stock and flow diagrams in Figure 4-6 and Figure 4-7 include the assumptions and descriptions discussed above.

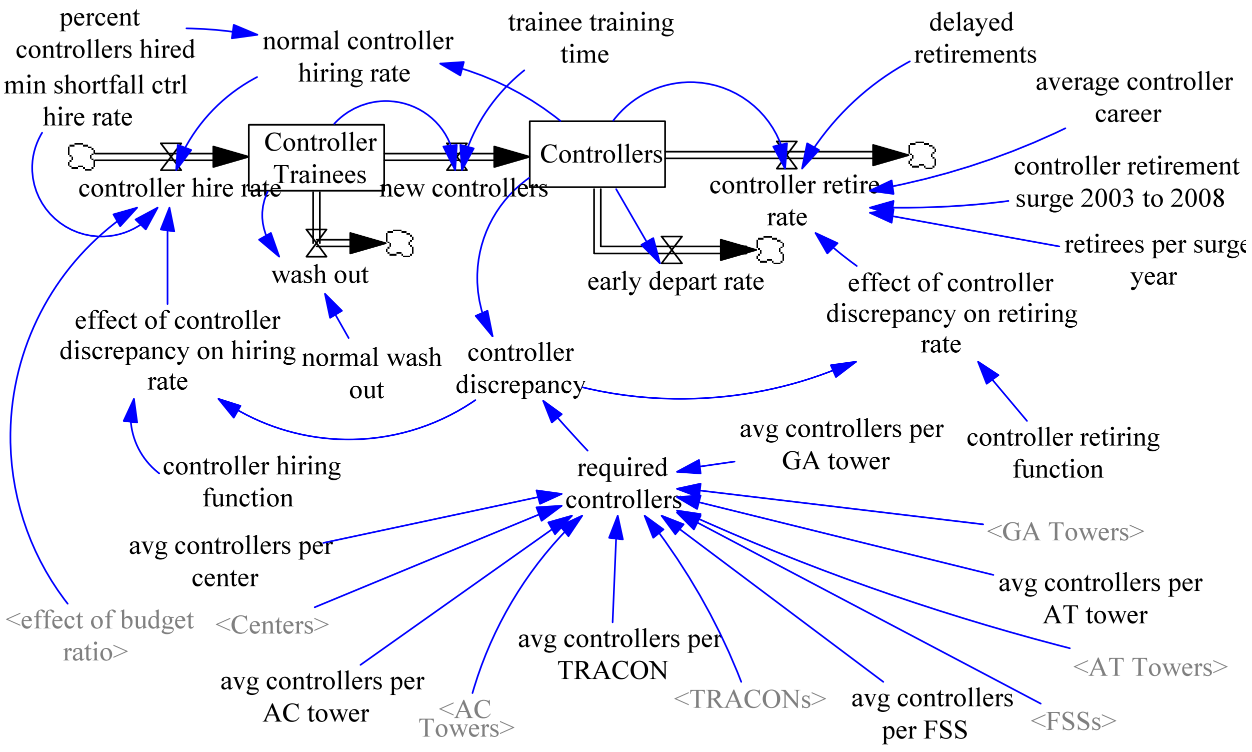

Figure 4-6: The controller stock and flow diagram.

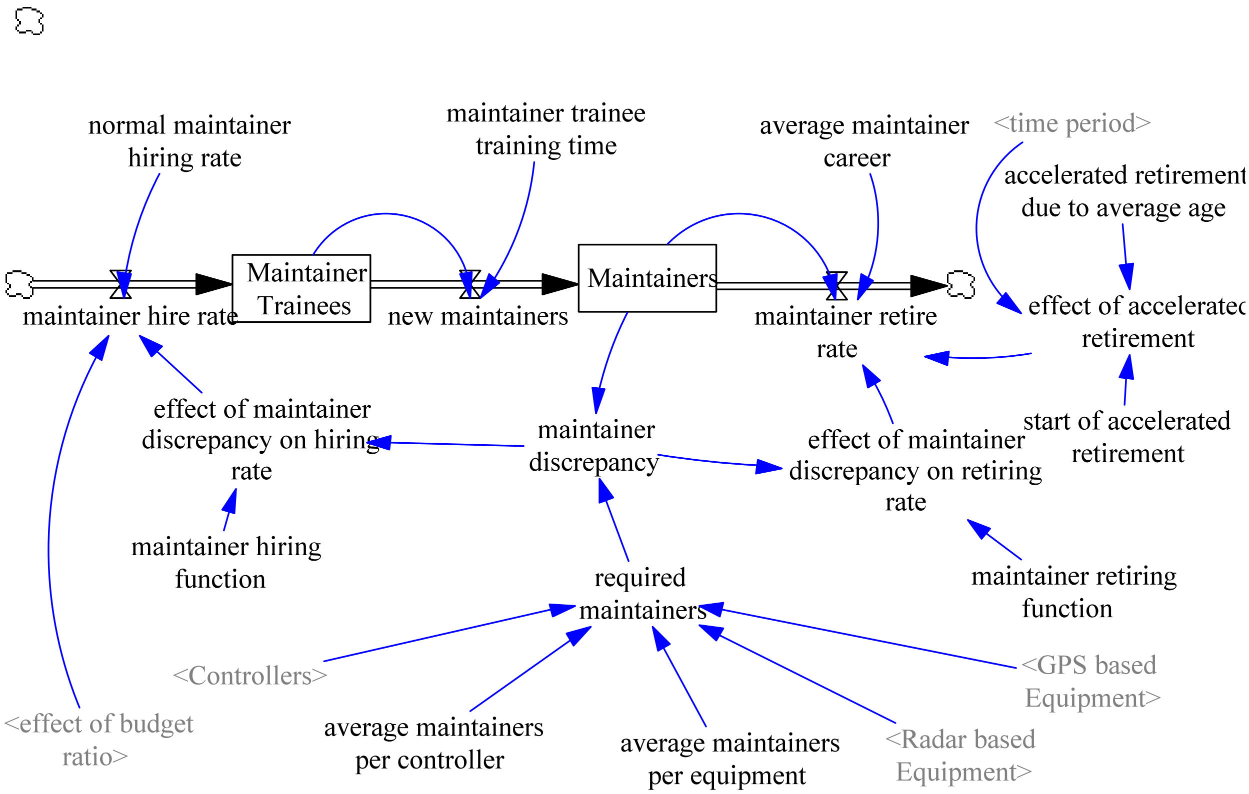

Figure 4-7: The maintainer stock and flow diagram.

4.7 The FAA Budget Subsystem

Resources that ATC managers use to purchase new infrastructure and pay employees reside in the FAA Budget subsystem. The Budget subsystem consists of both income and expenditures. The FAA generates revenue from excise taxes collected for the Airports and Airways Trust Fund. The FAA budget consists of four major components: Operations, Facilities and Equipment, Grants-in-Aid for Airports, and Research and Development. The FAA Budget submodel includes the Research and Development account as an amount equal to 2% of the FAA budget.

Within the FAA budget subsystem, management resource allocation decisions direct the funding for airports, facilities, and navigation equipment. The infrastructure created, maintained, and modernized through the resource allocation process influences the number of people needed to provide and maintain ATC services. Subsequently, the cost of employees and the operating costs of the existing infrastructure often require Congressional appropriation to fund expenses not covered by the AATF.

Aircraft demand ATC services from the system with each instrument flight operation. The ATC system supplies the services at a level that influences the growth or decline in the number of aircraft conducting operations. The number of aircraft conducting operations influences the growth or decline of the AATF, which completes the positive feedback loop by contributing to the FAA budget. Additionally, the number of aircraft and the amount of infrastructure available to support them creates other feedback that adjusts the stocks of aircraft or infrastructure. Overarching the dynamic behavior is a resource management strategy that constrains the adjustments in system behavior to emphasize a desired level of support for the radar or GPS-based strategy. Thus, both the endogenous structure of the system and the exogenous influences on the system create dynamic behavior over time.

4.7.1 Expenditures: The FAA Budget

The FAA annual fiscal budget contains three accounts that contain 98% of the resources used by the administration. Table 4-10 shows a consistent pattern of budget growth over the past decade.

Table 4-10: The FAA budget continues to grow.

$M

Type	1991	1992	1993	1994	1995	1996	1998	1999	2000	2001	2002
Grants	$1,600	1,900	2,050	1,690	2,161	2,214	1,700	1,950	1,896	3,193	3,300
Ops	4,037	4,360	4,538	4,581	4,583	4,643	5,253	5,586	5,958	6,603	7,091
F&E	2,095	2,394	2,350	2,120	2,033	1,875	1,900	2,121	2,034	2,651	2,914
Total	7,732	8,654	8,938	8,391	8,777	8,732	9,052	9,657	9,888	12,447	13,305

(Sources: 1998-2002 FAA, 2002a; 1991-1996: FAA; 1997 not available.)

The three accounts serve the following purposes:

1) **Grants-in-Aid for Airports**: Annually, the FAA grants money for airport improvement projects such as improving safety or increasing capacity. The Grants-in-Aid account may serve as the source of resources to transform many existing airports into airports that have the potential to become SATS airports (FAA, 2001).
2) **Operations Account**: The FAA operations account contains resources for all employee salaries and funding for the FAA administrative infrastructure such as

rent, contracted services, and office equipment. Approximately 75% of the operations account consists of the employee payroll (FAA, 2001). If the system becomes more SATS oriented, the need for people will adjust to the SATS requirements for controllers and maintainers of equipment and facilities.

3) **Facilities and Equipment Account**: The Facilities and Equipment portion of the FAA budget contains resources to operate, maintain, replace or modernize facilities and equipment. The GPS-based systems needed to support SATS will receive funding through the Facilities and Equipment account (FAA, 2001).

The data in Table 4-11 shows that the facilities and equipment and Grants-in-Aid accounts each traditionally account for 22% to 23% of the FAA budget.

Table 4-11: Percent distribution of the three main accounts of the FAA budget.

Type	1991	1992	1993	1994	1995	1996	1998	1999	2000	2001	2002	AVG
Grants	21%	22%	23%	20%	25%	25%	19%	20%	19%	26%	25%	**22%**
Ops	52%	50%	51%	55%	52%	53%	58%	58%	60%	53%	53%	**54%**
F&E	27%	28%	26%	25%	23%	21%	21%	22%	21%	21%	22%	**23%**

4.7.2 Improving Airports: The Grants-in-Aid Account

The Grants-in-Aid account is a resource the FAA uses to improve airport capacity, safety, security, runway conditions, airport financial standing, and noise abatement. The FAA designated approximately 3,300 airports as eligible to receive Grants-in-Aid. The smaller airports in the US, the prime candidates to support SATS operations, receive about half of the funding for their annual operations from the Grants-in-Aid account. (Dempsey, 2000). Table 4-12 shows the distribution of funding, GA aircraft, and passenger activity by type of airport.

Table 4-12: Airports receiving Grants-in-Aid funding from the FAA.

Grantee Airport	% funding	# airports	% GA Aircraft	% of all enplanements
Large Hub Primary	51	29	1.3	67.3
Medium Hub Primary	14	42	3.8	22.2
Small Hub Primary	8	70	4.7	7.1
Non Hub Primary	8	272	11.4	3.3
Other Commercial	1	125	2.1	0.1
Reliever	7	334	31.5	0.0
General Aviation	11	2,472	37.3	0.0
Total	100	3,344	92.1	100.0

(Source: FAA, 1999)

The 413 public use primary airports, serving as large, medium, small, and non-hub airports, receive a minimum of $500,000 annually in FAA Grants-in-Aid. The FAA determines the maximum amount based on number of enplanements. Large hub airports each support at least 1% of all US enplanements. Medium hubs enplane between 0.25% and 1% of all enplanements. Small hubs enplane between 0.05% and 0.25%. Non Hub primary airports enplane less than 0.05% of all enplanements, but exceed 10,000 enplanements annually. All other commercial service airports have at least 2,500 to 10,000 enplanements annually, but altogether only account for 0.1% of all US enplanements. Reliever airports provide GA aircraft with easy and inexpensive access to congested metropolitan areas. Usually, at least one General Aviation airport exists in each county in rural areas throughout the US.

The FAA uses the National Plan of Integrated Airport Systems (NPIAS) as the document that captures local, state, and regional airport capital improvement planning. The FAA distributes money through the Airport Improvement Program to fund one quarter to one third of all capital improvement projects at US public use airports initially identified in the NPIAS (FAA, 2001b). The NPIAS is a five-year forecast that includes a list of 3,334 US public use airports that require more than $35B of capital improvement. The capital projects consist primarily to improve safety, capacity, noise abatement, runway pavement, financial performance, and ground accessibility to airports. Future security improvement requirements will most likely increase as a result of the terrorist attacks of 2001. Air traffic control navigation facilities and equipment do not fall under the Airport Improvement Program, but rather receive funding through the facilities and equipment account of the FAA budget (DOT, 1999).

Although most SATS airport development efforts will involve navigation and approach systems, SATS airports may need to compete for AIP funding to make them fully operational. For example, almost 2,000 of the potential SATS airports have unpaved landing areas. The source of AIP funding will be the FAA Grants-in Aid account, which the data from Table 4-10 shows to be growing at a rate of $120M annually from 1991 to 2002 or $444M annually from 1998 to 2002. The model uses an annual growth rate of $170M for the Grants-in-Aid account.

Most NPIAS projects take place at airports supporting commercial air carriers. Data in the “% funding” column of Table 4-12 shows that only 18% of the $35B project plans address needs at General Aviation and Reliever airports that are the most likely candidates to become SATS airports. Only 1% of the $35B would go to construction of new airports. The primary purposes of the projects are to add capacity and bring existing airports up to acceptable standards. There are approximately 2,000 public use airports absent from the NPIAS list because they have low activity, are within 20 miles of an NPIAS airport, or are unsuitable for further expansion. Although NASA claims these may be suitable SATS airports, the model only recognizes the 3,344 NPIAS airports as potential SATS airports.

4.7.3 Supporting People: The Operations Account

The operations account is the largest of the three major accounts in the FAA budget. The operations account includes more than half of the FAA fiscal resources. Table 4-13 contains a breakdown of all the categories of expenditures in the operations account. Table 4-13 shows that the FAA abolished the "Airports" and "Administration" accounts in 2000, transferred some of the funding to Research and Acquisition and also replaced them with the new accounts "Regions/Centers Operations, Human Resources," and "Financial Services" (FAA, 2001). However, as seen in Table 4-14, the abolished and new accounts only comprise about 6% of the FAA budget.

Table 4-13: Distribution of funding in the Operations Account.

Operations	1998 $M	1999	2000	2001	2002	2003 (est)
Air Traffic Services	$4,080	4,351	4,670	5,446	5,792	6,096
Regulation and Certification	600	619	645	735	810	839
Civil Aviation Security	115	120	136	150	179	9
Research and Acquisitions	93	78	174	193	199	206
Commercial Space Transportation	6	6	6	12	12	12
Regions/Centers Operations	NR	NR	85	103	92	95
Human Resources	NR	NR	66	57	72	74
Financial Services	NR	NR	40	49	51	53
Staff Offices	76	84	76	109	114	113
Emergency Response Fund	NR	NR	0	1	473	0
Information Services	NR	NR	0	0	0	5
Airports	48	48	NR	NR	NR	NR
Administration	260	264	NR	NR	NR	NR
Total	5,277	5,570	5,898	6,855	7,794	7,502

NR = Not Reported; Source: FAA, 2002a

Table 4-14: Percent distribution of the Operations Account.

Operations	1998	1999	2000	2001	2002	2003 (est)	Avg
Air Traffic Services	77%	78%	79%	79%	74%	81%	78%
Regulation and Certification	11%	11%	11%	11%	10%	11%	11%
Civil Aviation Security	2%	2%	2%	2%	2%	0%	2%
Research and Acquisitions	2%	1%	3%	3%	3%	3%	2%
Commercial Space Transportation	0%	0%	0%	0%	0%	0%	0%
Regions/Centers Operations	NR	NR	1%	2%	1%	1%	1%
Human Resources	NR	NR	1%	1%	1%	1%	1%
Financial Services	NR	NR	1%	1%	1%	1%	1%
Staff Offices	1%	2%	1%	2%	1%	2%	1%
Emergency Response Fund	NR	NR	0%	0%	6%	0%	2%
Information Services	NR	NR	0%	0%	0%	0%	0%
Airports	1%	1%	NR	NR	NR	NR	1%
Administration	5%	5%	NR	NR	NR	NR	5%

NR = Not Reported; Source: FAA, 2000a

Table 4-14 shows that the bulk of the resources are in the Air Traffic Services (ATS) portion of the budget. Air Traffic Services is responsible for all ATC operations, facilities, and their upkeep – the heart of the FAA. Employees of ATS accomplish the FAA's mission. The remainder of the budget is for those parts of the ATC system that play a supporting role.

In 2001, the Air Traffic Services account, budget requested in the President's Budget Request contained the subcategories in Table 4-15. The table shows that 90% of the air traffic services subaccount provides resources to two primary functions: air traffic and system maintenance. These two functional subdivisions contain 60% percent of the FAA employees and provide the direct support to the ATC system. Essentially, all other components of the FAA support these two functions.

Table 4-15: The Air Traffic Services portion of the Operations Account of the FAA budget.

ATS Function	$M	%
Air Traffic	3,277	63%
Air Traffic System Requirements	24	0%
NAS Logistics	71	1%
System Maintenance	1,390	27%
Leased Telecommunications	356	7%
Flight Inspection	93	2%
TOTAL	5,211	100%

(Source: FAA, 2001)

The data in Table 4-16 shows that Payroll accounted for approximately 74% of the Operations account, which implies that payroll was 40% of the FAA's entire budget in 2001. Subsequently, an assumption built into the model is that 26% of the operations account is for contracts, services, rent, and travel related to the employees. Within the model, the initial distribution of funds from the operations account pays for employee salaries and the additional services. After paying for salaries and services, the model uses the remainder of the FAA budget to build facilities or purchase equipment as directed by the resource management strategy and the feedback from the system.

Table 4-16: The Operations Account pays for salaries and services.

Operations	$M	%
Payroll	4,861	74%
Contracts & Other Services	838	13%
Rent & Utilities	506	8%
Equipment & Supplies	256	4%
Travel & Transportation	131	2%
TOTAL	6,592	101%

Source: FAA, 2001

The 2001 President's Budget request also subdivided the Air Traffic Services (ATS) budget according to the six functional suborganizations in Table 4-17. The data in the table indicates that the preponderance of resources supports air traffic control and maintenance of the ATC system.

Table 4-17: Functional subdivisions of the Air Traffic Services account.

ATS Suborganizations	$	%
Air Traffic	3,277	63%
Air Traffic System Requirements Service	24	0%
NAS Logistics	71	1%
Systems Maintenance	1,390	27%
Leased Telecommunications	356	7%
Flight Inspection and Procedures	93	2%
TOTAL	5,211	

Source: FAA, 2001

1) **Air Traffic**: The Air Traffic subactivity of the ATS component of the FAA is responsible for the safe and efficient control of aircraft all day, every day. Air Traffic operates 21 en route centers, 437 control towers, 190 TRACONs, and 137 Flight Service Stations.
2) **Air Traffic System Requirements Service**: The requirements subactivity manages the processes for determining and fulfilling the immediate and future operational needs of Air Traffic Services.
3) **NAS Logistics**: The logistics subactivity procures equipment, land, and office space; provides spare parts; conducts limited maintenance; and manages the Mike Munroney Aeronautical Center.
4) **Systems Maintenance**: The maintenance subactivity maintains and repairs all FAA facilities and equipment such as navigation and landing aids, flight service facilities, and ATC equipment.
5) **Leased Telecommunications**: The telecommunications subactivity designs and creates the communications linkages throughout the FAA.
6) **Flight Inspection and Procedures**: The flight inspection and procedures subactivity conducts flight checks of navigation aids, facilities, and instrument flight procedures. The subactivity also provides transportation for the FAA and other federal agencies.

Within the model, the number of employees in each stock serves as feedback that the budget system uses to determine how much money to utilize in the FAA operations account to pay the employees' salaries, benefits, and expenses. Table 4-18 below contains data to determine the average annual salary per employee when aggregated at the system-wide level of analysis. The slope from $59,626 in 1996 to $87,721 in 2002 implies that there is a $4,638 annual average increase in employee compensation. However, the years 1998 to 2002 represent an unusual increase in the size of FAA operations accounts. In 1991 the average compensation per FAA employee was $44,852. The slope from $44,852 in 1991 to $87,721 in 2002 is $3,897. The model therefore uses an annual salary growth rate of $4,000.

According to the Bureau of Labor Statistics (2002), the average salary for FAA Air Traffic Controllers was $53,313 in 2001, indicating that approximately two thirds of the compensation per employee consisted of salary and the remainder paid for employee services, benefits, and other overhead expenses. Starting salaries for FAA maintenance employees is approximately $30,000 annually (FAA, 2002d). Thus, the average annual cost per employee used in the model is a marginal cost figure that adjusts the resources available to the system as the number of employees varies dynamically.

Table 4-18: Aggregated cost per FAA employee.

Type	1991	1996	1997	1998	1999	2000	2001	2002
FAA Budget ($M)	7,732	8,732		9,052	9,657	9,888	12,447	13,305
Operations Account ($M)	4,037	4,643	4,931	5,253	5,586	5,958	6,603	7,091
Personnel Compensation	2,422	2,820	2,957	3,152	3,353	3,581	3,962	4,255
% of Operations Account for Personnel Compensation	60%	61%	60%	60%	60%	60%	60%	60%
FAA Employees	54,000	47,295	48,266	48,799	49,068	48,463	49,901	48,506
Avg Payroll = Personnel Compensation / FAA Employees($)	$44,852	$59,626	$61,265	$64,591	$68,334	$73,891	$79,397	$87,721

Numbers in blue are estimates.

Figure 4-8 depicts the flow diagram from the model that determines the amount of money required by the operations account. The "other ops account requirements" parameter is a multiplier to include the 40% of the Operations Account that is other than Personnel Compensation. The "ops account requirement" value feeds into the FAA annual required budget along with the Grants-in-Aid and Facilities and Equipment accounts. The stocks of Controllers and Maintainers connect to Figure 4-8 from other sections of the model depicted in Figure 4-6 and Figure 4-7.

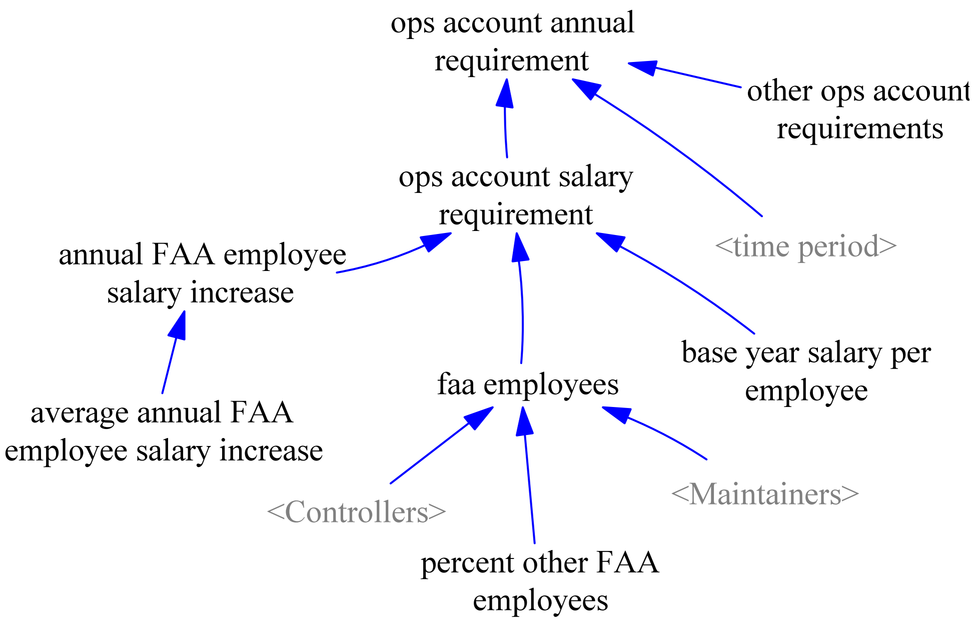

Figure 4-8: The model flow diagram leading to the operations account resource requirement.

4.7.4 Providing Infrastructure: The Facilities and Equipment Account

The Facilities and Equipment Account contains the resources FAA managers use to improve facilities, develop and procure new equipment, and complete the associated technical installation requirements. Most of the facilities and equipment resources support radar-based facilities and equipment. The facilities and equipment account consists of five subactivities, described below with their associated level of funding in 2001 (FAA, 2001):

1) **Engineering, Development, Test, and Evaluation**: This activity enhances the current ATC system and provides resources for system engineering and software development associated with new systems, such as the GPS-based Wide Area Augmentation System.
2) **Procurement and Modernization of Air Traffic Control Facilities and Equipment**: This activity primarily supports the continuance of the current radar based system by procuring new technology to enhance the capacity of the present system. Managers use a small amount of the subactivity resources to fund GPS related procurement efforts.
3) **Procurement and Modernization of Non-Air Traffic Control Facilities and Equipment**: This activity addresses environmental and security issues associated with FAA facilities.

4) **Facilities and Equipment Mission Support**: This activity consists of systems engineering, integration, and management of FAA capital improvement programs, such as automation, communications, and surveillance.
5) **Personnel and Related Expenses**: This account pays for travel and other expenses associated with FAA personnel who install equipment and implement procedures initiated by managers of the facilities and equipment Account.

The model divides the resources in the facilities and equipment account into three subcategories. The first category includes facilities occupied by people and the equipment used in those facilities. The second category includes all the remaining equipment in the system that supports radar-based ATC. The third category includes all equipment that supports GPS-based ATC. It is not an FAA accounting practice to distribute the facilities and equipment budget among the three categories. Therefore, Table 4-19 provides a breakdown of the distribution of resources from the FAA that fit into the three categories. The three categories reside in the model as an assumption of how the FAA distributes between radar-based or GPS-based ATC.

Table 4-19: The distribution of Facilities and Equipment resources among six categories.

Facilities & Equipment Programs	Category	2000 $M	2001 $M	2002 $M	Avg $M	Avg %
En Route Equipment	Equipment	268	320	446	345	
Terminal Equipment	Equipment	112	117	105	111	
Landing & Nav Aids	GPS	114	112	66	97	
Research, Test & Eval	Facility	13	14	16	14	
Advanced Technology	GPS	43	91	63	66	
En Route Facilities	E Facility	301	385	478	388	
Terminal Facilities	T Facility	427	530	587	515	
Flight Services Facilities	F Facility	24	48	65	46	
Landing & Nav Aids Eqpt	Equipment	31	177	124	111	
Other Facilities	Facility	42	70	104	72	
Support Eqpt	Equipment	90	96	101	96	
Support Eqpt for Facilities	Facility	91	95	101	96	
Training Facilities	Facility	0	11	15	9	
System Support for Eqpt	Equipment	111	131	133	125	
System Support for Facilities	Facility	112	131	134	126	
Personnel for Eqpt	Equipment	148	161	183	164	
Personnel for Facilities	Facility	147	162	184	164	
F & E TOTAL:		2,034	2,651	2,914	2,533	
En Route FACILITY TOTAL:		301	385	478	388	15%
Terminal FACILITY TOTAL:		427	530	587	515	20%
FSS FACILITY TOTAL:		24	45	65	45	2%
Other FACILITY TOTAL:		405	481	554	480	19%
Radar EQUIPMENT TOTAL:		761	1,002	1,092	952	37%
GPS TOTAL:		157	203	129	163	6%

(Source: FAA Budget in Brief, 2001 & 2002)

The model uses the Table 4-19 baseline distribution of resources within the facilities and equipment account of 15% for en route facilities, 20% for terminal facilities, 2% for Flight Service Stations, 19% for other facilities, 37% for radar-based equipment, and 6% for GPS-based equipment. Annually, the Facilities and Equipment budget usually consumes approximately 23% of the entire FAA budget as indicated in Table 4-11. The six categories in Table 4-19 further refine the distribution of the facilities and equipment account. Within the model, each facility and piece of equipment requires a portion of the facilities and equipment budget in order to modernize and replace components of the ATC system. The $515M for Terminal facilities represents 20% of the F&E account and further subdivides into $148M for TRACONs (6% of F&E) and three types of control towers: $222M for AC towers (9%), $85M for AT towers (3%), and $63M for GA towers (2%). Accordingly, Table 4-20 provides the assignment of the portion of the facilities and equipment budget to each item listed in the first column.

Table 4-20: Facilities and equipment account requirements generated by the ATC infrastructure.

Facility or Equipment	Number in ATC System in 1998	Total Required F&E Budget in 1998	Annual $M per in 1998
ARTCC	21	1900*0.15 = $285M	285/21 = 13.57
TRACON	170	1900* 0.06 = $114M	114/170 = 0.67
AC Towers	170	1900 * 0.09 = $171M	171/170 = 1.01
AT Towers	135	1900 * 0.03 = $57M	57/135 = 0.42
GA Towers	160	1900 * 0.02 = $38M	38/160 = 0.35
FSSs	137	1900 * 0.02 = $38M	38/137 = 0.28
Radar Equipment	7,468	1900 * 0.37 = $703M	703/7468 = 0.09
GPS Equipment	250	1900* 0.06 = $114M	114/250 = 0.46
Other Facilities	1	1900* 0.19 = $361M	361
		Total: $1,900M	

The first column of Table 4-20 lists the facilities or equipment that require funding from the facilities and equipment account for modernization or replacement. The second column lists the number of each type facility or equipment in the ATC system during the model base year 1998. The number of AC Towers, AT Towers, and GA Towers reflects the data in section 4.8.2. The number of pieces of radar equipment comes from Table 4-26. The number of pieces of GPS equipment comes from an estimate of installations discussed in section 4.9.2. The third column adjusts the facilities and equipment budget numbers from Table 4-19 to revise them down to the 1998 levels by multiplying each entry by the ratio of the total facilities and equipment account in

1998 divided by the average total facilities and equipment account value in Table 4-19. The final column provides the amount used in the model to determine the required facilities and equipment account based on the numbers of facilities and equipment in the ATC system as it dynamically changes over time.

Within the model, a combination of the budget distribution ratios above and the feedback mechanisms caused by interactions of the subsystems influences the distribution of the resources in the facilities and equipment account among the different areas: facilities, radar-based equipment, and GPS-based equipment. The FAA policy regarding the distribution of resources to support the radar-based approach to ATC or the GPS-based approach to ATC will further refine the funding levels of facilities and equipment throughout the system.

Figure 4-9 shows the decision-making associated with the flow of resources through the facilities and equipment account. The number of entities within the stocks in the system and the costs per entity create an overall budget requirement for the Facilities and Equipment Account. The model also includes a parameter accounting for 19% of the Facilities and Equipment requirement as a system-wide overhead requirement. Finally, the model includes a parameter to account for the historic growth rate within the Facilities and Equipment Account. The "operating cost growth factor" stems from the linear increase of 3% annual growth from the Facilities and Equipment account of $2,095M in 1991 to $2,914M in 2002.

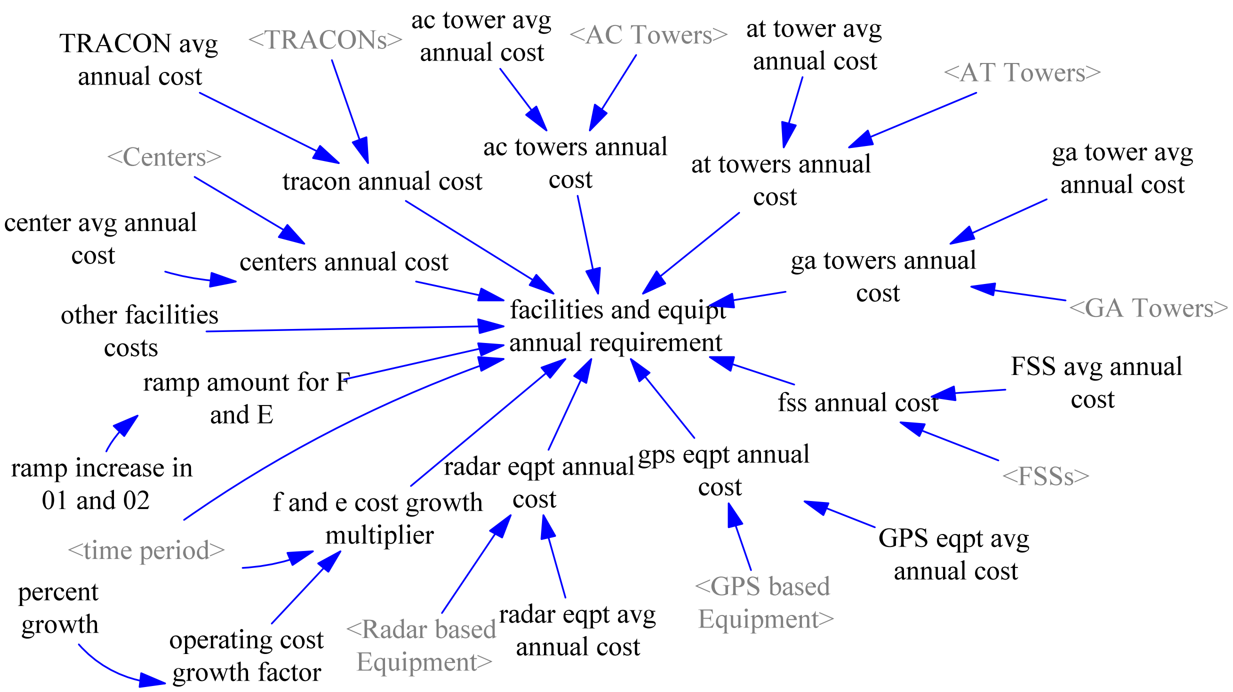

Figure 4-9: The requirement for resources to support the facilities and equipment account.

4.7.5 ATC Revenue: The Airport and Airway Trust Fund

Federal law allows tax receipts from sources such as passenger tickets, landing fees, and aviation fuel sales to accumulate in an account that is the sole source of resources for the FAA's capital and operations accounts. Table 4-21 shows the distribution of these fund sources during the past few years as well as estimates for the next two years. In 2001, the fund collected $10 billion in taxes, gained $0.88 billion in interest, and had an uncommitted balance of $7.5 billion (FAA, 2001).

Table 4-21: Sources of revenue for the Airport and Airways Trust Fund.

Trust Fund Receipts from Excise Taxes	1998	1999	2000	2001	2002 (est)	2003 (est)
Passenger Ticket Tax	$5,445	5,941	5,103	4,805	4,248	4,763
Passenger Flight Segment Tax	547	1,339	1,655	1,556	1,634	1,771
Waybill	313	412	500	493	585	606
Fuel Tax	659	1,009	887	769	849	882
Intl Departure/Arrival Tax	948	1,484	1,349	1,336	1,371	1,401
Rural Airports Tax	48	57	86	82	93	96
Frequent Flyer Tax	141	149	159	150	158	162
Interest on Investments	543	698	805	882	869	623
Offsetting Collections	NR	32	144	76	224	136
Total	8,654	11,121	10,688	10,149	10,031	10,440

Source: FAA, 2002a

Passenger enplanement data from the FAA provides an indication of the sources of revenue for the AATF. The data in Table 4-21 indicates that the preponderance of AATF revenue relates to the volume of passengers in the system. Data available for the year 1996 shows that of the 558.1 million passengers enplaned on domestic US flights, over 97% traveled via AC aircraft (FAA, 1997). Therefore, a modeling assumption is that 95% of all AATF revenue emanates from AC flights and the remaining 5% comes from AT and GA aircraft. Accordingly, Table 4-22 contains the data and calculations that justify the AATF revenue generated by each aircraft in the NAS.

Table 4-22: Tax revenue from aircraft.

Trust Fund Receipts from Excise Taxes	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**AVG**	**Slope**
$M Total	8,654	11,121	10,688	10,149	10,032	10,439		
$M 95% of Receipts	8,221	10,565	10,154	9642	9530	9917		
AC Aircraft	8,111	8,228	8,405	8,625	8,845	9,065		
Average tax revenue $M per AC Aircraft	1.014	1.284	1.208	1.118	1.077	1.094	**1.133**	**-0.009**
$M 5% of Receipts	433	556	534	507.45	501.6	521.95		
AT & GA IFR Aircraft	66,453	74,596	76,125	78,687	81,249	83,811		
Average tax revenue $ per AT & GA Aircraft	6,511	7,454	7,020	6449	6174	6228	**6,639**	**-167**

However, since future projections for air travel forecast increases in the long term (FAA, 2001c), the model uses a more optimistic slope to provide growth in the future revenue collected from each aircraft. Therefore, the model includes the average tax revenue collection amounts of $1,133,000 for AC aircraft and $6,639 for AT, GA, and SATS aircraft. The model also contains annual linear growth rates that are 2.5% of each of the average collection amounts: $28,325 annually for AC aircraft and $166 annually for AT, GA and SATS aircraft. Figure 4-10 depicts the stock and flow diagram for the AATF revenue in the model.

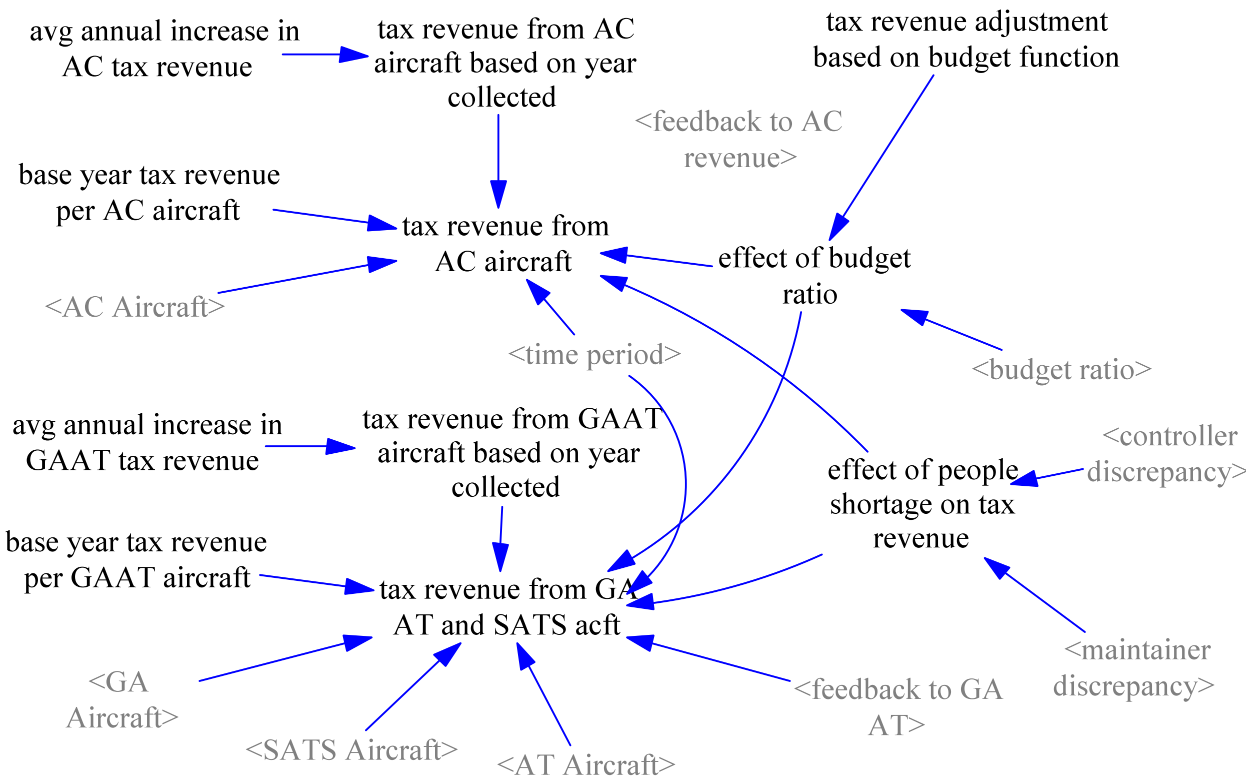

Figure 4-10: The stock and flow diagram of the revenue collected by the AATF.

Table 4-23 below includes another important piece of the Budget Subsystem. The AATF annually collects interest on invested assets. The average interest rate over the years 1998 to 2003 was 7.2%. The model includes a conservative interest rate of 6.5% of the AATF.

Table 4-23: The AATF gains approximately 7% interest annually.

Trust Fund	1998	1999	2000	2001	2002 (est)	2003 (est)
Total AATF	8,654	11,121	10,688	10,149	10,031	10,440
Interest on Investments	543	698	805	882	869	623
Percent of AATF	6.3%	6.3%	7.5%	8.7%	8.7%	6.0%

4.7.6 Budget Subsystem Stock & Flow Diagram

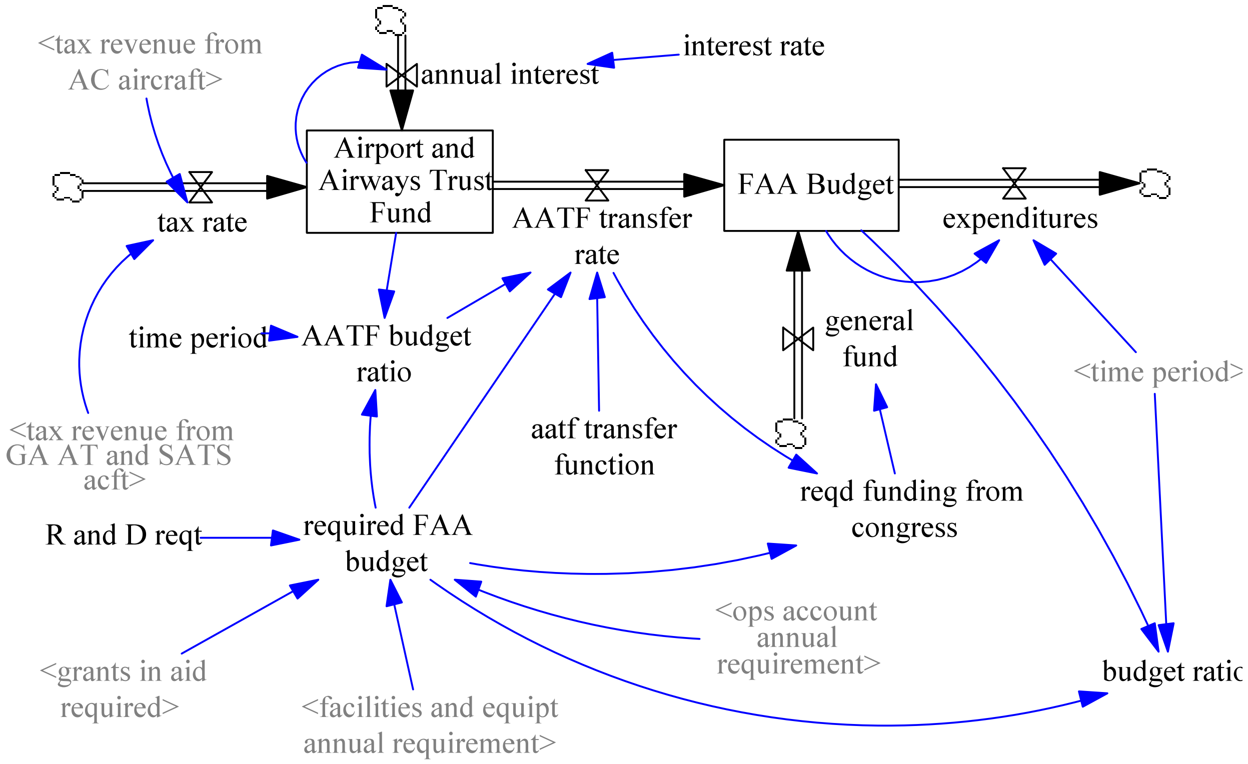

Figure 4-11: The FAA Budget stock and flow diagram.

4.8 The Facilities and Equipment Subsystem

The principle air traffic control facilities consist of Air Route Traffic Control Centers (ARTCC), Air Traffic Control Towers (ATCT), Terminal Area Approach Controls (TRACON), Flight Service Stations (FSS), and Automated Flight Service Stations (AFSS). Major pieces of air traffic control equipment include radars, navigational aid transmitters, instrument landing systems, and Wide Area Augmentation Systems. The FAA also classifies thousands of small, unmanned, communication devices, weather monitoring stations, and warehouses as facilities and equipment. The quantity of facilities and equipment influences several aspects of the ATC system: the quantity of people in the system, the system's operational service metrics, the annual operating cost of the system, and the requirement to modernize the system.

Although ATC facilities are the heart of the current ATC system, theoretically, they will not be an essential part of SATS. The equipment that supports GPS navigation and aircraft "self-separation" will provide the greatest support to SATS. Navigation equipment generally supports either the current radar-based ATC system or the evolving GPS-based ATC system required by SATS aircraft. The principle facilities in the modern ATC system consist of 21 centers, 470 control towers, 170 TRACONs, and 137 flight service stations.

4.8.1 Centers, Approach Controls, and Flight Service Stations

The FAA has the authority to separate civilian and military air traffic in controlled airspace in the US. Currently, the FAA subdivides its authority among 21 air route traffic control centers (ARTCC), down from 24 centers in the 1980s. Normally, the ARTCC separates en route traffic and delegates the separation of traffic near airports to the FAA or military ATC facility at the airport (Nolan, 1999). A modeling assumption is that there will be no further growth in the number of centers. Rather, efficiencies from automation will cause the number of centers to decline by two centers consolidating every 7 years. The expansion of free flight may change the nature of the center controllers' duties from air traffic control to air traffic management and monitoring.

Approach controllers monitor radar displays to separate aircraft within a distance of approximately 20 miles from an airport to facilitate the transition of arriving or departing aircraft. Approach controllers ease the workload on both tower controllers and controllers in the air traffic control centers (Nolan, 1999). There are currently 170 Terminal Area Approach Control (TRACON) facilities in the US ATC system. The model includes consolidation events due to technological efficiencies among TRACONs at the rate of one consolidation every 10 years.

Controllers at Flight Service Stations (FSS) and Automated Flight Service Stations (AFSS) provide air traffic control services consisting of weather briefings, flight advisories, radio communications, flight planning, and search and rescue coordination (Lammes, 2002). In the model, FSSs and AFSSs perform the same functions and reside in the stock labeled FSS. The model uses a 1998 base year value of 137 FSSs with a growth rate of one new FSS annually.

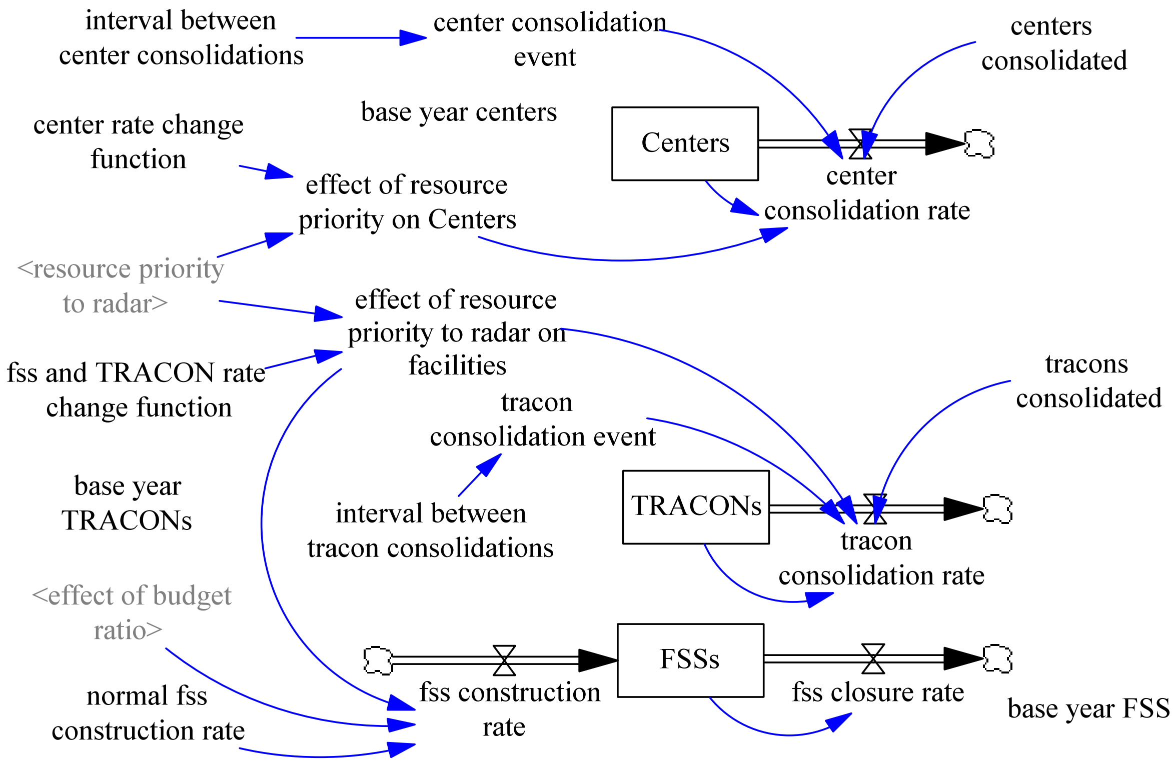

Figure 4-12: Centers, Approach Controls, and Flight Service Stations Stock and Flow Diagram

4.8.2 Control Towers

There are three types of control towers: VFR Towers, Nonradar-approach control towers, and Radar-approach control towers. The Nonradar and Radar-approach control towers have IFR separation responsibilities (Nolan, 1999). The Air Traffic Activity Data System (ATADS) (check acronym) database used by the FAA to record control tower operations contains five categories of towers. Table 4-24 shows the categories and numbers of control towers in the US from 1990 to 2002 and Figure 4-13 graphically depicts the same data. The table and graph indicate that there are two types of radar and two types of VFR control towers and that the total number of towers climbed moderately during the time period depicted. It is also evident that Contract VFR towers replaced many VFR towers and Limited Radar towers replaced almost all Non-radar towers. The number of Radar towers remained virtually the same.

Table 4-24: Air Traffic Control Towers in the US.

Year	Radar	Limited Radar	Non-radar	VFR	Contract VFR	Total
1990	151	36	16	197	24	424
1991	149	39	14	197	26	425
1992	148	40	15	198	27	428
1993	147	43	15	196	27	428
1994	150	42	12	198	32	434
1995	149	43	7	152	95	446
1996	150	42	4	119	127	442
1997	148	42	4	94	160	448
1998	150	42	3	93	161	449
1999	150	42	3	93	165	453
2000	150	42	3	71	191	457
2001	149	42	3	70	203	467
2002	150	42	3	71	209	475
Average	149	41	8	135	111	444
Slope	0	0	-1	-14	19	4

Source: ATADS

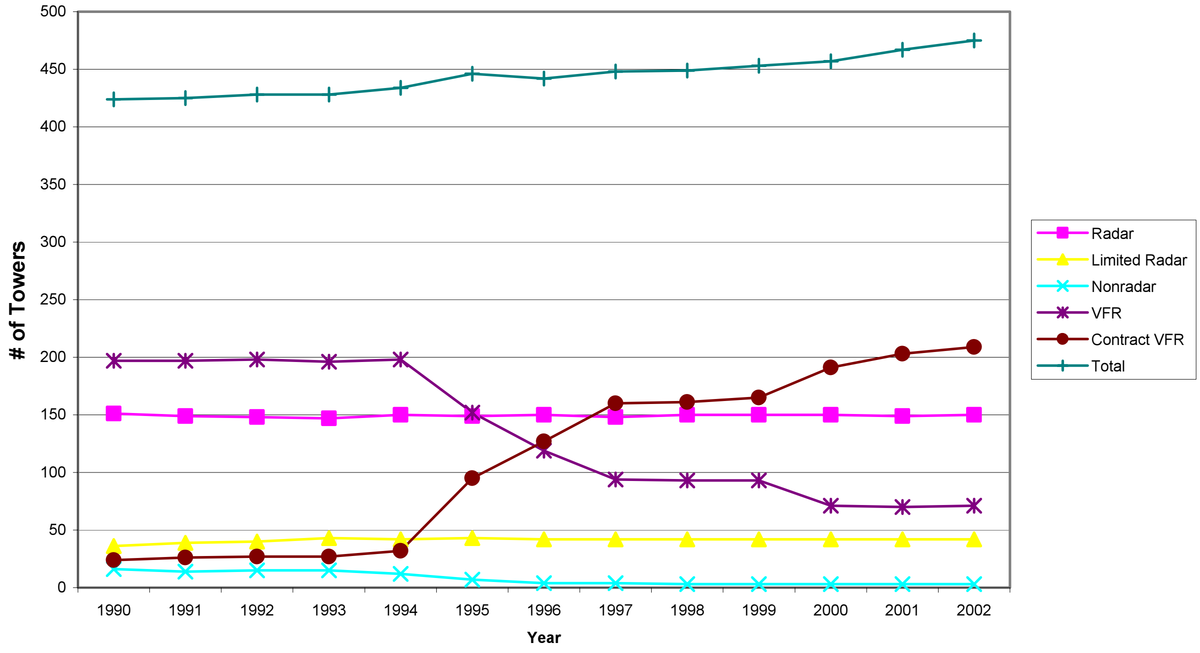

Figure 4-13: Control towers in the US by type.

A more thorough analysis of the numbers and activities of control towers will help to determine what level of aggregation of control tower data is appropriate to use in modeling the facilities in the ATC system. Figure 4-14 depicts the average annual number of total instrument operations for all control towers in the US. Four towers, Chicago, Dallas-Fort Worth, Atlanta, and Los Angeles, each had over 700,000 annual operations. The other 470 control towers had annual operations counts ranging from over 500,000 to almost zero.

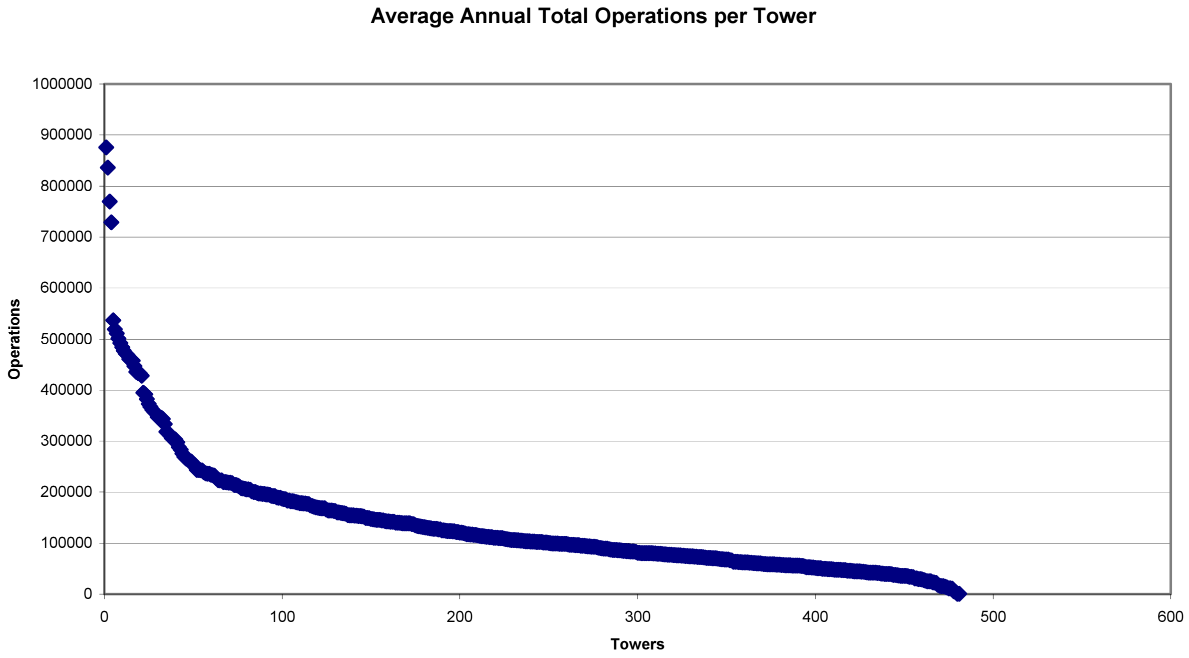

Figure 4-14: Average annual total Operations for all control towers

Table 4-25 contains the average number of operations for each of the five categories of control towers. Figure 4-15 depicts the same data. The data indicate that Limited Radar towers conduct about 45% of all operations. Radar towers continue to operate at a relatively steady rate. The VFR towers are experiencing the greatest growth in operations. Contract VFR towers are increasing operations at a modest rate and Nonradar towers are decreasing operations. It appears that the VFR towers manned by FAA air traffic controllers are the VFR towers with the highest rate of operations and the VFR towers that become Contract VFR towers are those with the lower operational rates among all VFR towers. Further analysis of the control tower data at the group and individual tower level of analysis will determine the homogeneity of the towers.

Table 4-25: Average annual operations per type of control tower.

Year	Radar	Limited Radar	Nonradar	VFR	Contract VFR
1990	133,387	318,095	60,478	124,809	54,440
1991	140,395	322,954	69,011	137,006	60,017
1992	140,229	326,081	70,599	134,341	61,738
1993	139,900	313,958	70,276	127,314	61,037
1994	138,508	339,466	78,905	122,728	58,887
1995	138,221	334,970	94,462	146,701	46,806
1996	135,363	344,583	58,606	162,946	59,048
1997	140,050	347,396	55,724	188,327	65,083
1998	141,581	349,204	67,147	181,311	76,216
1999	148,828	360,232	43,909	187,584	79,235
2000	149,937	362,616	41,455	215,888	81,220
2001	144,459	353,125	37,900	200,266	76,137
Average	140,905	339,390	62,373	160,768	64,989
Slope	972	4,164	-2,812	8,377	2,303

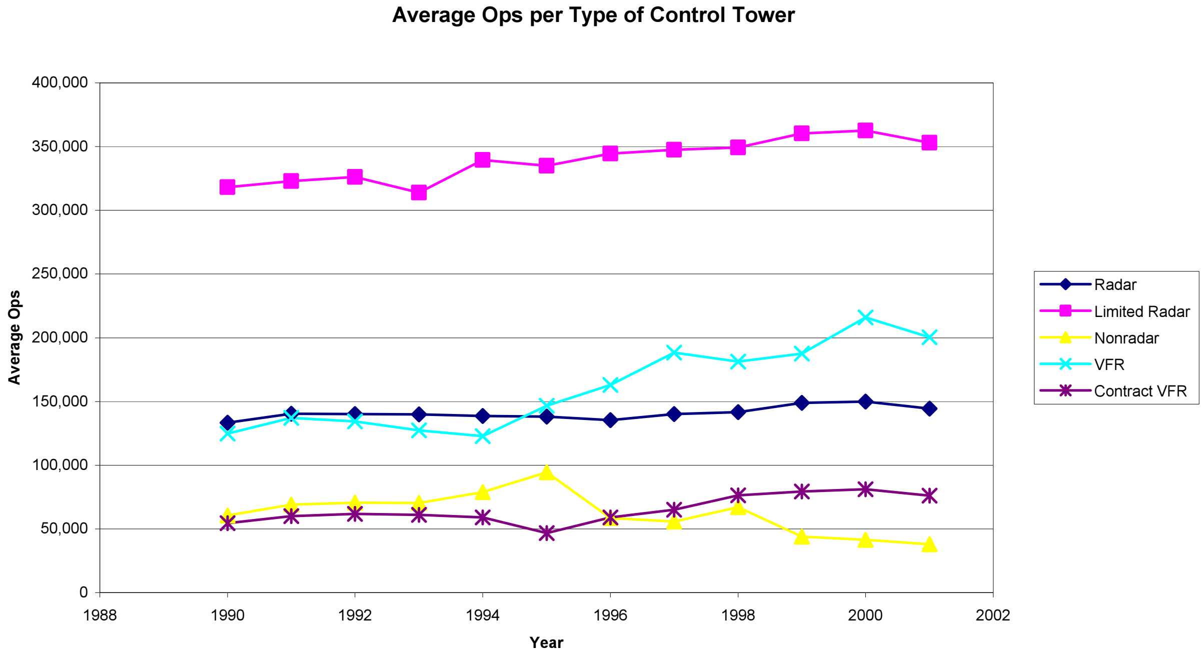

Figure 4-15: Average annual operations per type of control tower.

The ATADS data displayed in the tables and graphs above reflect the operations of all domestic air carrier, general aviation, air taxi, and military aircraft. The tables and graphs below provide group and individual level insight to determine the best method to incorporate control towers into the model. The information presented below leads to the homogeneous grouping of control towers into thee core groups as the appropriate level of analysis for the modeling effort.

Figure 4-16 contains data for the average AC operations per tower from 1990 to 2001. The data shows that 99% of the AC activity occurred at the top 170 towers. Therefore, the model includes all the top 170 towers in the core part of the ATC system that supports AC operations, regardless of the presence of SATS aircraft. The data indicates that AC operations occurred at 111 out of 150 Radar towers and 39 of 42 Limited Radar air traffic control towers. Some limited Radar and Radar towers had minimal AC operations as they primarily serve GA and Air Taxi operations in the vicinity of major AC airports.

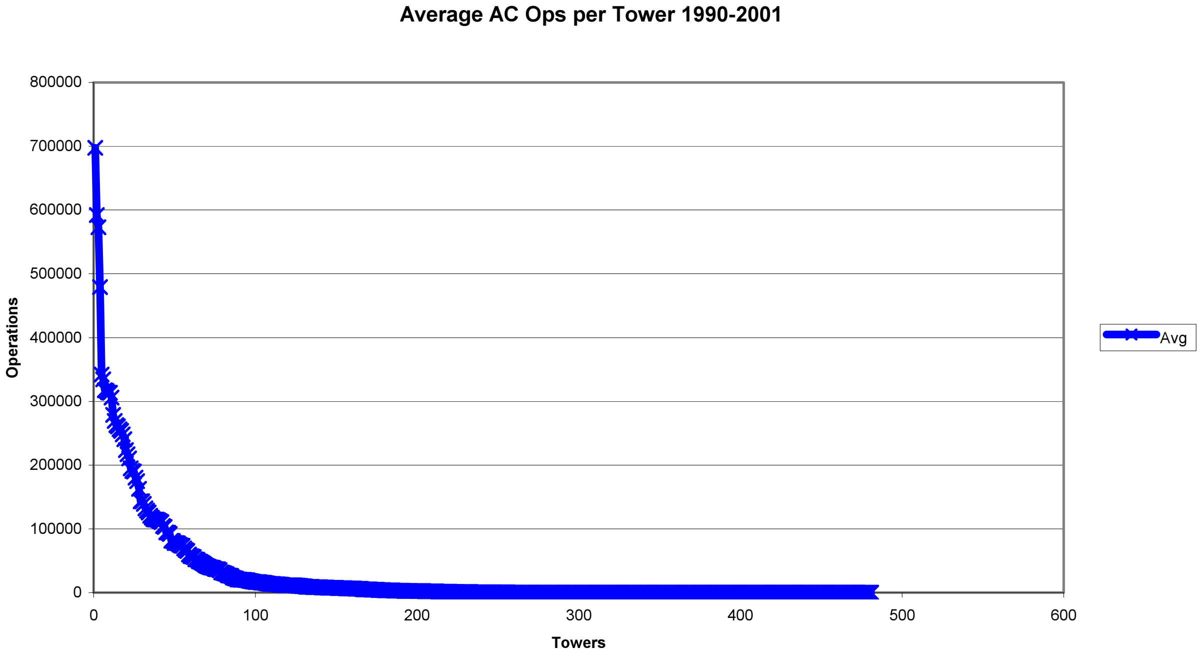

Figure 4-16: Average annual air carrier operations per tower.

Figure 4-17 shows the distribution of average Air Taxi (AT) operations per tower from 1990 to 2001. The data shows that the bulk of Air Taxi aircraft operations occurred at the top 300 towers. All of the 170 towers supporting the top AC operations are also in the top 300 towers that support AT operations. All 42 limited-radar towers are within the top 300 towers. Of the 150 radar towers, 145 are within the top 300 towers. Many of the control towers that served Air Taxi aircraft changed from VFR towers to Contract VFR towers.

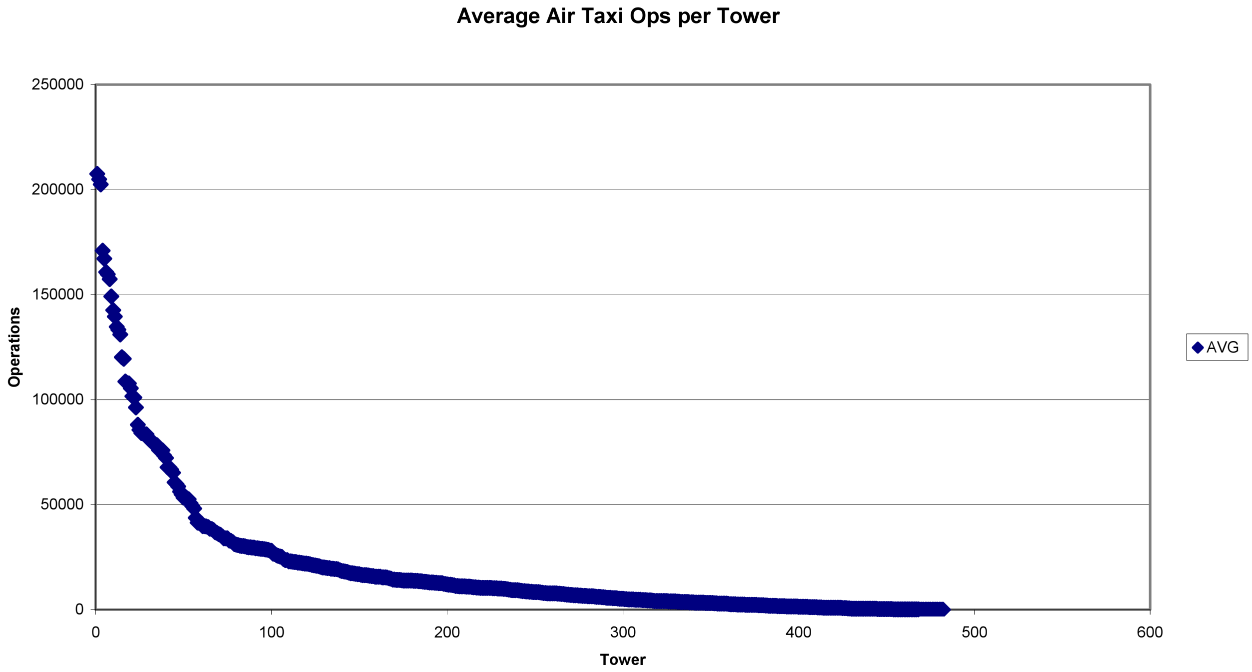

Figure 4-17: Average annual air taxi operations per tower.

Figure 4-18 indicates that GA operations occur throughout most airports with control towers in the NAS. In fact, 460 control towers provide at least 8,000 annual control tower operations for GA aircraft. Of the 460, approximately 150 provide almost all their services to GA aircraft, with little to none of the services going to AC or AT aircraft. These 150 towers serve the core GA-only ATC requirements. There are only about ten towers that provide less than 8,000 total operations for all types of aircraft combined. These ten represent only 2% of all control towers, indicating that the system does not contain many underutilized assets.

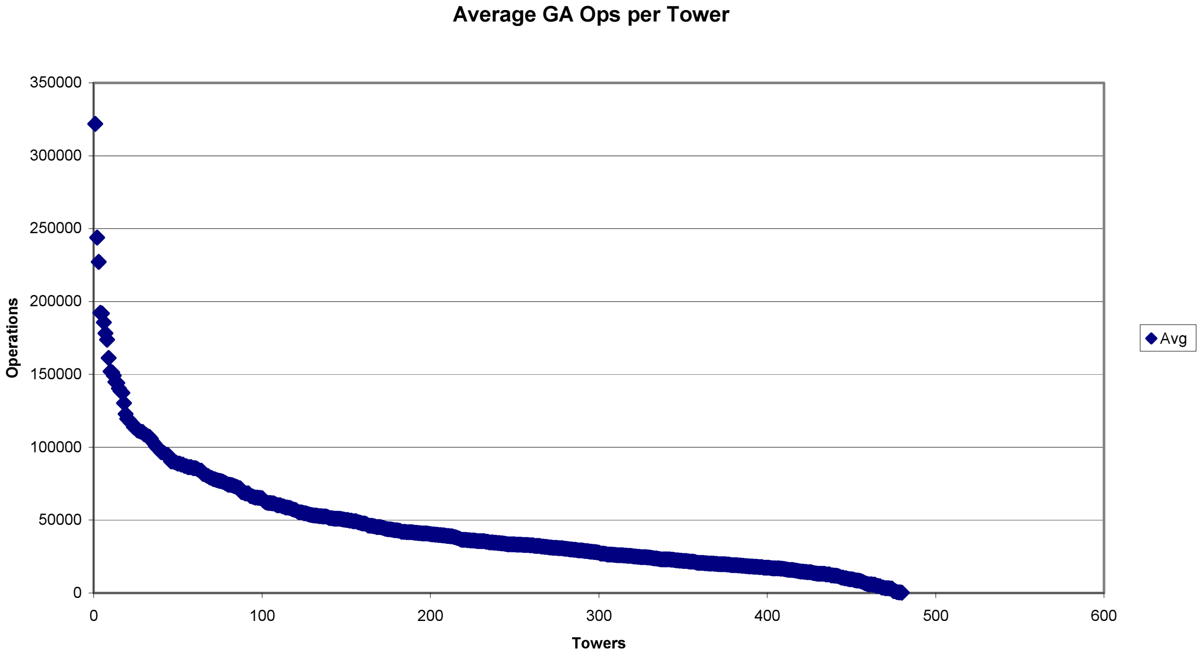

Figure 4-18: Average annual GA operations per tower.

Figure 4-19 indicates that the preponderance of military operations at public use airports receive support from about 200 air traffic control towers. Three of the 200 control towers are among the ten in the system that provide less than 8,000 operations annually to all types of aircraft. An assumption used to build the model is that military aircraft will make adjustments to utilize other available public use airports if SATS airports preclude military operations.

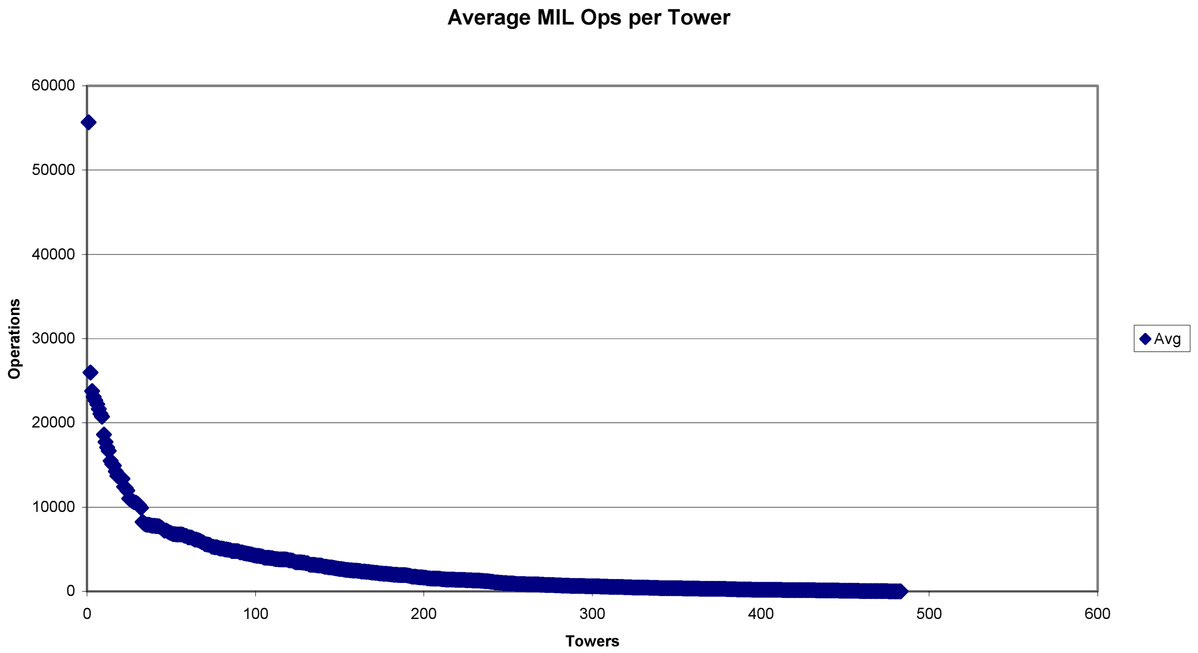

Figure 4-19: Average annual military operations per tower.

The evidence above points toward the need to divide the 470 control towers in the ATC system into three groups considered homogeneous for modeling purposes. The three groups correspond with the types of aircraft primarily served by the towers. The first group consists of 170 towers that primarily serve AC aircraft, the second group consists of 135 towers that primarily serve AT aircraft, and the third group consists of 150 towers that primarily serve GA aircraft. The model will not include a fourth grouping of the ten peripheral towers that do not provide significant levels of service to non-military aircraft. Appendix 2 contains a listing and ranking of all of the control towers in the ATC system.

4.8.3 Control Towers Stock and Flow diagrams

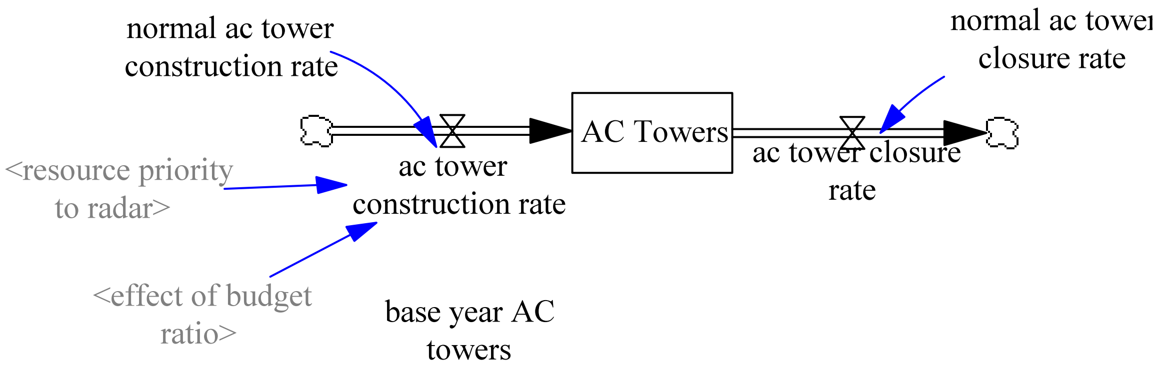

Figure 4-20: Stock and Flow diagram for AC Control Towers.

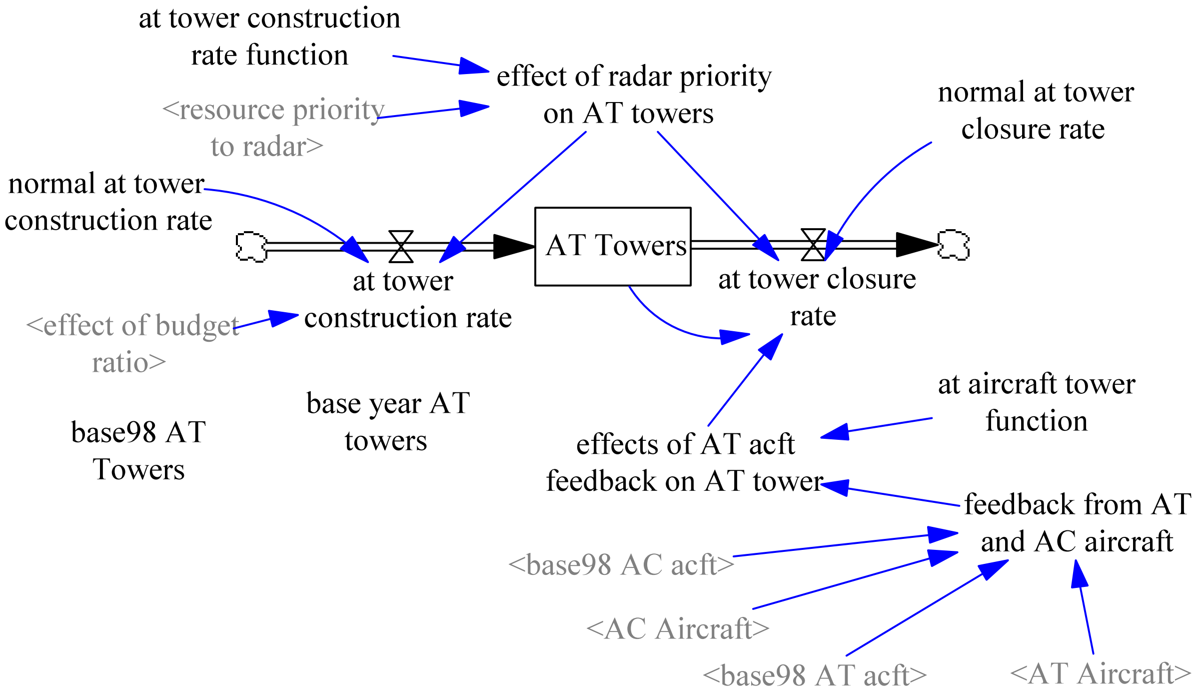

Figure 4-21: Stock and Flow diagram for AT Control Towers.

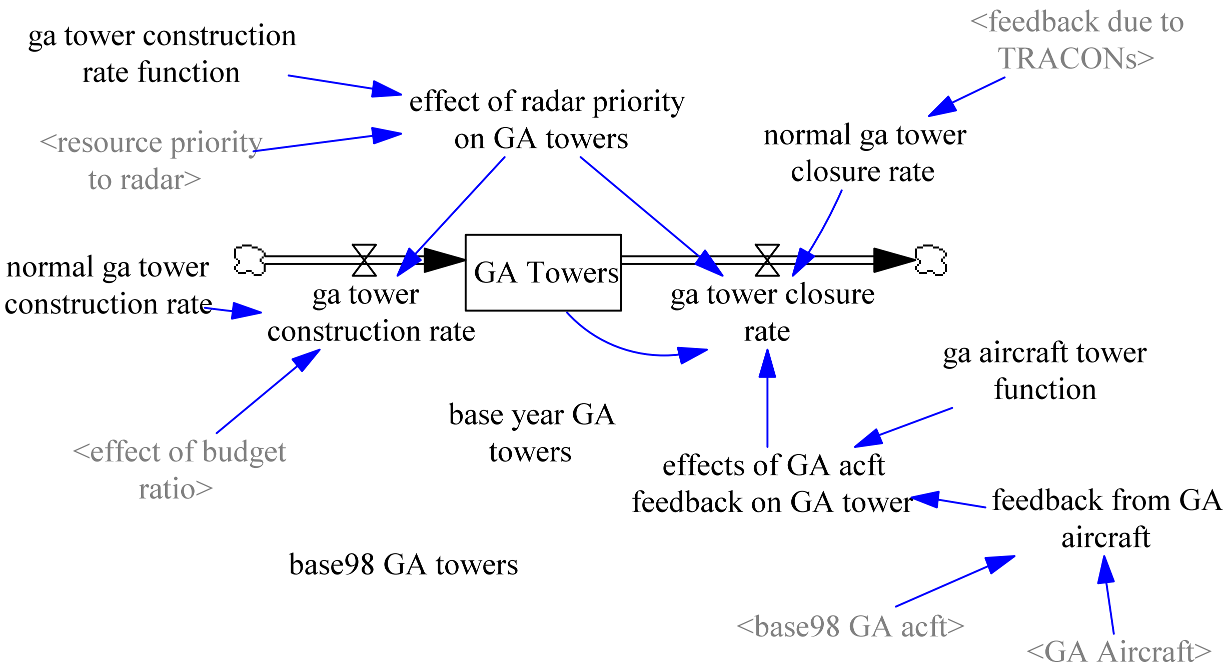

Figure 4-22: Stock and Flow diagram for GA Control Towers.

4.9 The Equipment Subsystem

4.9.1 ATC Radar Equipment

The Navigation Equipment subsystem contains the major physical components listed in Table 4-26 that support the radar-based ATC system. The distribution among facilities column indicates whether the equipment supports air traffic control towers or is part of the base infrastructure that supports the entire ATC system. Within the model, the number of control towers will influence the number of pieces of equipment associated with air traffic control towers. The number of pieces of base infrastructure equipment will vary according to the level of AC aircraft in the system and the resource management strategies used by FAA managers. The trends from 1996 to 1999 indicate relative stability among the radar-based equipment, with the exception of Direction Finder Equipment (DFE) showing significant decline as a technology phasing out of the ATC system.

Other equipment linked to the radar-based ATC system includes: the VHF Omnidirectional Range (VOR) and Non-directional Beacon (NDB) for aircraft navigation, the

Instrument Landing System (ILS), the Airport Surveillance Radar-Terminal (ASR-T), the Automated Radar Terminal System (ARTS), the Air Route Surveillance Radar-Enroute (ARSR-E), the Remote Center Air-Ground Facility (RC A-G), the Remote Communications Outlet (RCO) and the Visual Approach Slope Indicator (VASI). Table 4-27 shows distribution of equipment among the facilities in the model.

Table 4-26: Types and Distribution of Radar-based ATC equipment.

Type	Distribution among Facilities	1996	1997	1998	1999	Avg
VOR	Base Infrastructure	1,027	976	977	1,026	1,002
NDB	Base Infrastructure	1,000	1,000	1,000	1,000	1,000
ILS	All Towers	1,197	1,044	1,067	1,248	1,139
ASR-T	AC and AT Towers	228	232	233	235	232
ARTS	AC and AT Towers	195	197	194	195	195
ARSR-E	Base Infrastructure	118	123	125	120	122
RC A-G	Base Infrastructure	701	742	714	712	717
RCO	Base Infrastructure	1,726	1,702	1,716	1,733	1,719
DFE	GA Towers	202	143	139	132	154
VASI	All Towers	1,308	1,273	1,257	1,227	1,266
TOTAL		7,702	7,432	7,422	7,628	7,546

Table 4-27: Distribution of radar equipment among the facilities.

Facility	Type of Equipment	Distribution	Equipment per Facility
Base Infrastructure	VOR	1,002	1,002
Base Infrastructure	NDB	1,000	1,000
170 AC Towers	ILS	1,139 * ((2 * 170)/455) = 601	601/170 = 3.5
135 AT Towers	ILS	1,139 * ((1.2 * 135)/455) = 406	406/135 = 3.0
150 GA Towers	ILS	1,139 * ((0.35 * 150)/455) = 131	131/150 = 0.87
170 AC Towers	ASR-T	170	1
135 AT Towers	ASR-T	62	0.46
170 AC Towers	ARTS	170	1
135 AT Towers	ARTS	25	0.19
Base Infrastructure	ARSR-E	122	122
Base Infrastructure	RC A-G	717	717
Base Infrastructure	RCO	1,719	1,719
150 GA Towers	DFE	150	1
170 AC Towers	VASI	1,266 * ((2 * 170)/455) = 668	668/170 = 3.93
135 AT Towers	VASI	1,266 * ((1 * 135)/455) = 376	376/135 = 2.79
150 GA Towers	VASI	1,266 * ((0.53 * 150)/455) = 221	221/150 = 1.47

The FAA (2001b) calculates the useful life of most radars and navigation aids as 20 years. Weather related equipment lasts 15-20 years, and the useful life of communication equipment is 10 to 20 years. Accordingly, a modeling assumption is that all equipment has a 20-year lifespan. Therefore, the last column in Table 4-28 contains the annual replacement rate of equipment, obtained by dividing the equipment per facility by 20 years.

Table 4-28: Total Pieces of Radar-based equipment per tower and base infrastructure and replacement rates.

Facility	Type of Equipment	Equipment per Facility	Annual Replacement Rate
170 AC Towers	ILS, ASR-T, ARTS, VASI	9.43	0.52
135 AT Towers	ILS, ASR-T, ARTS, VASI	6.44	0.37
150 GA Towers	ILS, DFE, VASI	3.34	0.22
Base Infrastructure	VOR, NDB, ARSR-E, RC A-G, RCO	4,560	228.00

A modeling assumption is that there is no growth in the overall quantity of radar-based ATC equipment. Any growth in the size of the NAS is offset by improved efficiencies in equipment capabilities. Any management strategy that changes the amount of resources devoted to replacing equipment has a directly proportional impact on the amount of resources replaced.

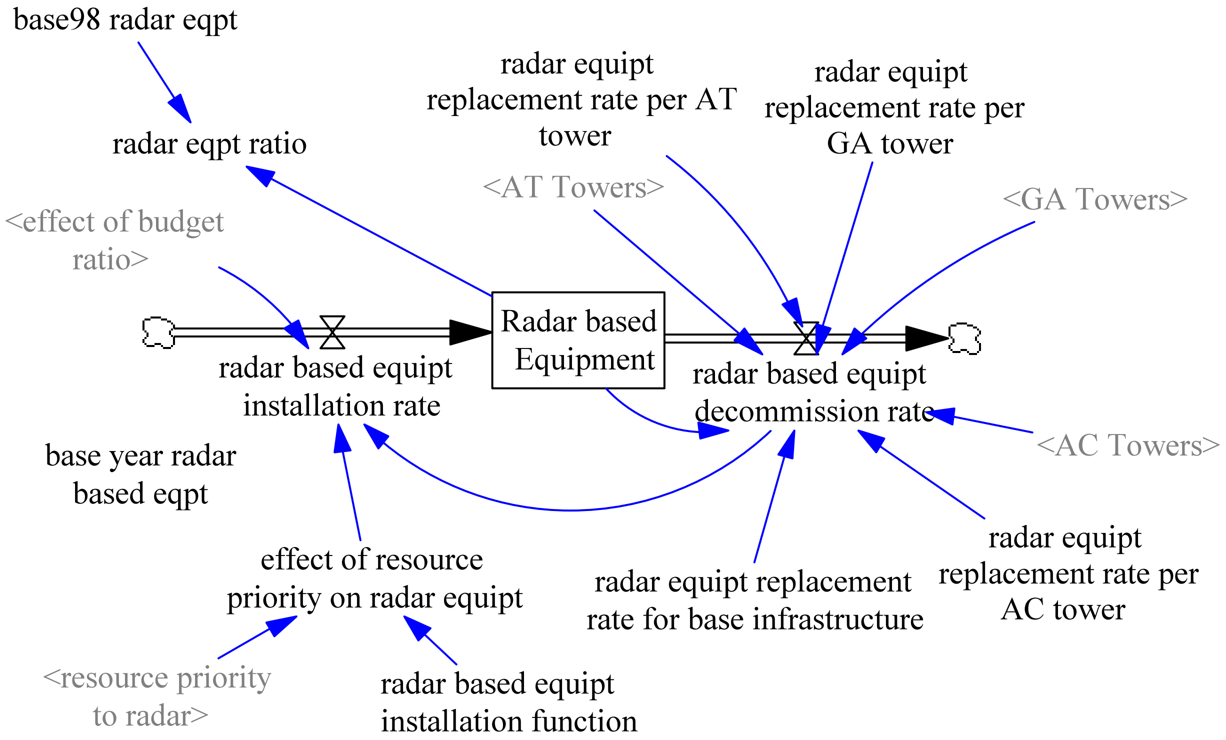

Figure 4-23: Radar-based equipment stock and flow diagram.

4.9.2 ATC GPS Equipment

The FAA is currently implementing two GPS augmentation systems. The wide area augmentation system (WAAS) will allow GPS users to navigate en route and perform nonprecision instrument approaches. The local area augmentation system (LAAS) will allow GPS users to conduct precision instrument approaches. The US will transition from the current VOR-based navigation system to a GPS-based system in the early twenty-first century (Nolan, 1999). The FAA plans to install LAAS at approximately 160 airports between 2002 and 2006, which equates to a rate of 32 LAAS per year (FAA, 2001c).

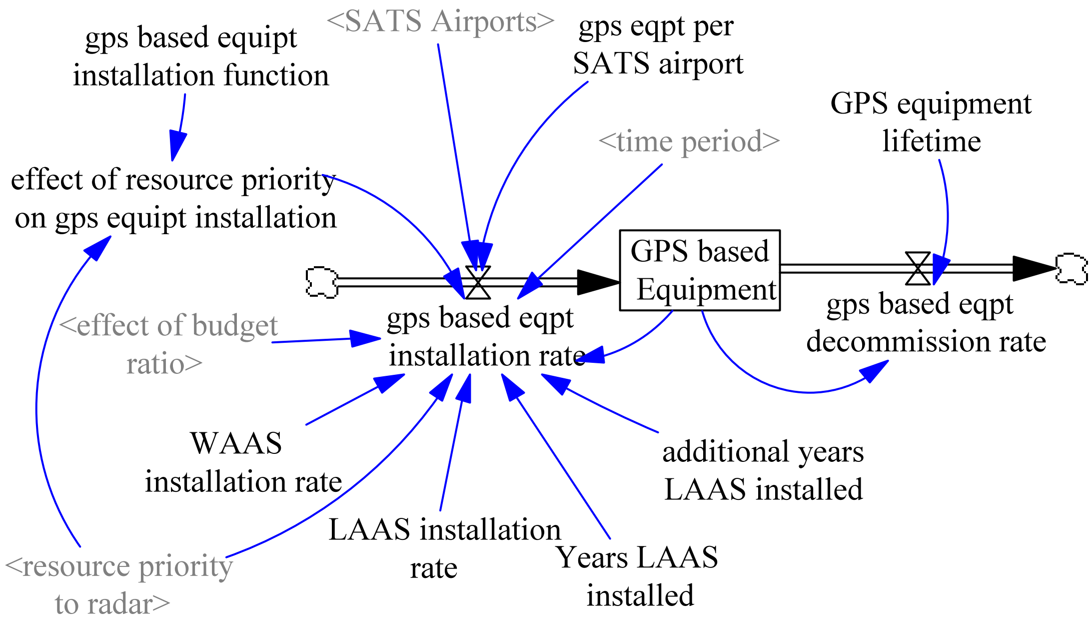

Figure 4-24: Stock and Flow diagram for GPS equipment.

4.10 The Airports Subsystem

Public use airports in the continental US with runways at least 3,000 feet long that are not already in the hub and spoke system are candidates to become SATS airports (NASA, 2000a). The public use airports fall into four categories: non-towered, VFR towered, nonradar-approach control towered, and radar-approach control towered. The nonradar-approch control towered and radar-approach control towered airports comprise about one half of the approximately 400 airports in the hub and spoke system. A modeling assumption is that the towered airports in the hub and spoke system will continue to remain and operate according to historical growth rates. The existing non-towered airports, possibly some of the VFR towered airports, and VFR towered reliever airports are candidates to become SATS airports. These airports reside within two stocks in the model: the nonSATS airports stock and the SATS airports stock depicted in Figure 4-25 below.

Advocates for SATS claim that all of the approximately 5,400 public use airports in the US are potential SATS airports. However, the model uses a pool of potential airports that is significantly smaller than the pool advocated by NASA. Of the 5,400 public use airports, only 3,344 are eligible to receive Grants-in-Aid funding for airport improvement (Department of Transportation, 1999). Of the 3,344 eligible for funding, 419 are primary airports that support the commercial airline system and 125 are non-primary commercial that support cargo operations. Both types of commercial airports would not be available as SATS only airports. Therefore, the model uses 334 reliever airports and 2,472 GA airports for a total of 2,806 potential SATS airports. In the model, an airport from the pool of 2,806 becomes a SATS airport when there is sufficient funding available for conversion and the conversion is in keeping with the resource management priority to expand the GPS-based ATC system.

Many public use airports require significant improvements, such as runway improvements and lighting, as indicated below in Table 4-29. However, as indicated in the earlier description of the Budget Subsystem and as depicted in Table 4-12 above, the pool of 2,806 potential SATS airports usually receive at best 18% of the entire Grants-in-Aid funding. Most of the Grants-in-Aid funding supports the hub and spoke system.

Table 4-29: Many Public Use Airports require improvements.

Type	1980	1985	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Public Use	4,814	5,858	5,589	5,551	5,545	5,538	5,474	5,415	5,389	5,357	5,352	5,354
# Unlighted	1,627	1,869	1,598	1,560	1,536	1,506	1,451	1,392	1,374	1,361	1,349	1,274
# Unpaved	1,333	1,951	1,638	1,582	1,575	1,540	1,483	1,446	1,417	1,393	1,381	1,381

According to the Aircraft Owners and Pilots Assn (AOPA), public use airports close at the rate of one every two weeks (Aviation Week, 15 April 2002). The model uses only half that rate by assuming that only half of the closures occur at the airports in the non-SATS airports stock. Additional modeling assumptions are that there will be one new non-SATS airport built annually until 2010 and one new SATS airport built annually thereafter, and, that the remainder of SATS airports will evolve from existing unimproved airports that receive upgrades.

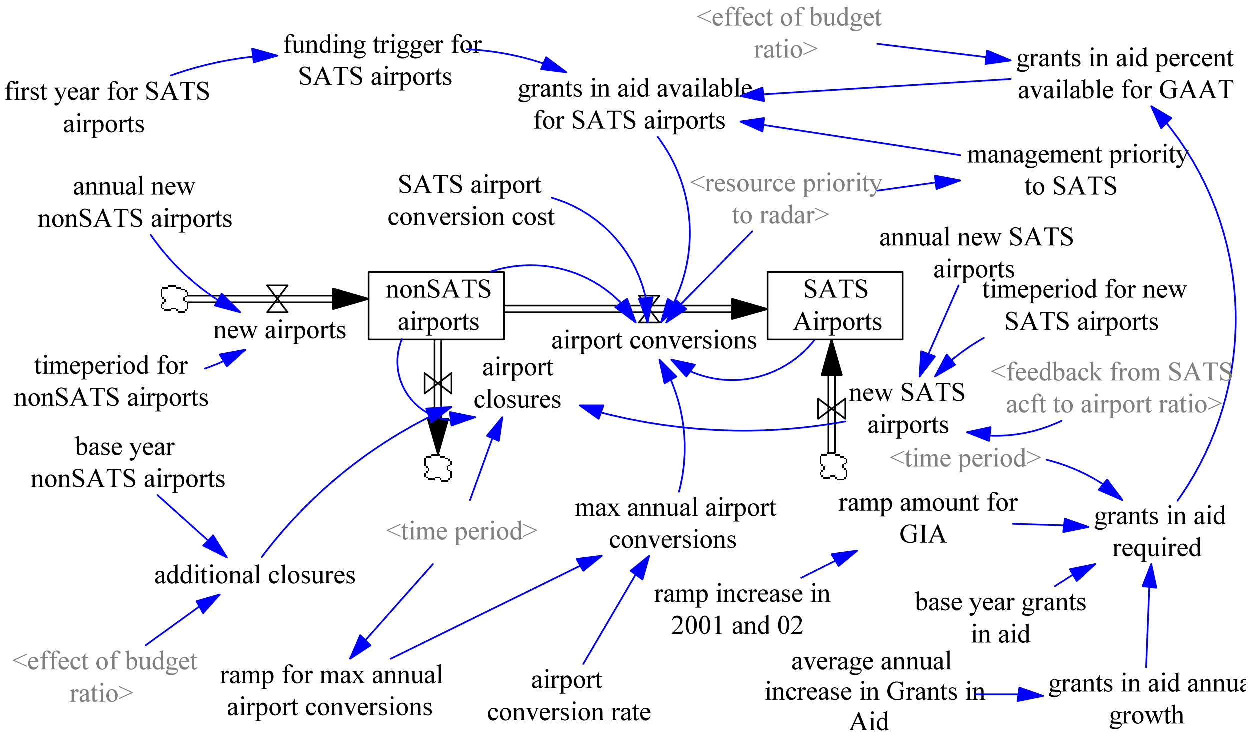

Figure 4-25: Airports Subsystem Stock and Flow Diagram,

4.11 The Aircraft Subsystem

The Aircraft subsystem includes all AC, AT, and GA aircraft in the US that demand ATC services for IFR flight and contribute to the Airport and Airways Trust Fund through various aviation taxes. The model also includes SATS aircraft that entered the system as new aircraft or as replacements for AT and GA aircraft that depart the system. The model definition for SATS aircraft mirrors that of NASA (2000a), where SATS aircraft are small four to eight passenger aircraft enabled by advanced technology to conduct self-separation and precision landings at the small, public use airports in the US. Military aircraft do not reside in a stock in the model;

however, variables representing relative ratios of military aircraft operations influence the behavior of the modeled system.

Table 4-30 shows the number of AC, AT, and GA aircraft registered in the US from 1960 through the late 1990s. The figure shows that GA aircraft peaked in 1980, declined about 17% through the mid 1990s and returned to the 1980 level by the end of the 1990s. The historic GA aircraft growth rate is 2,489 yearly from 1990-2000. Therefore, the model includes a growth rate of 2489/204710 = 0.01. Although the AT data is limited, the model uses a growth rate of 7%. In the model, both the GA and AT growth rates adjust downward as SATS aircraft become more popular. The historic AC aircraft growth rate is 177 yearly from 1960-1998. Therefore, the model includes the assumption that there are 200 new aircraft registered and 23 aircraft decommissioned or destroyed annually. The last two columns of the table provide additional evidence of historic aircraft sales that correspond with growth rates.

Table 4-30: Aircraft registered in the US and new aircraft sales.

Year	AC	AT	IFR GA	All GA		New AC	New GA
1960	2,135			76,549		7,588	245
1965	2,125			95,442		11,852	233
1970	2,679		46,432	131,743		7,283	311
1975	2,495			168,475		14,072	315
1980	3,808		81,102	211,045		11,881	387
1985	4,678		69,590	210,654		2,029	278
1990	6,083	5,800		196,800		1,144	521
1991	6,054			199,600		1,021	589
1992	7,320			187,000		899	567
1993	7,297			180,700		964	408
1994	7,370	3,800	56,694	176,600		928	309
1995	7,411	4,100	56,895	188,100		1,077	256
1996	7,478	3,900	61,896	191,100		1,130	269
1997	7,616	4,948		192,400		1,569	374
1998	8,111	5,190	66,453	204,710		2,213	559
Slope	220	363	2,562	427			
Growth	0.03	0.07	0.038	0.002			

Source: 1960-1998 BTS

Table 4-31 shows the functional distribution among several categories of use of GA aircraft over a 30-year time period. The trends in the distribution are consistent throughout all of the functional subcategories of GA aircraft, with the exception that there has been a decline in the percent of GA business aircraft. The data in Table 4-32 indicates that over 60% of GA aircraft serve as personal means of transportation. Although some of the personal aircraft may be SATS aircraft, a modeling assumption is that most SATS aircraft will serve as corporate, business, or air taxi aircraft. Thus, the data in the two tables indicates that approximately 40% of all GA aircraft would have a high propensity to become SATS aircraft. However, the model uses a conservative estimate of conversions to SATS aircraft beginning at 0.5% in 2008 and rising to 5% by 2028.

Table 4-31: GA Aircraft by function.

GA Aircraft	1970	1980	1990	1994	1995	1996	1998	2000
Corporate	6,835	14,869	10,100	9,400	9,800	9,300	11,250	11,000
Business	26,900	49,391	33,100	26,500	26,200	28,200	32,611	25,200
Instructional	10,727	14,862	18,600	15,000	14,800	14,300	11,375	14,900
Personal	65,398	96,222	112,600	102,500	109,300	109,600	124,347	148,200
Air Taxi	N[2]	N	5,800	3,800	4,100	3,900	5,190	4,000
Government	N	N	N	N	N	4,200	4,029	4,100
Other[1]	19,913	33,721	14,610	13,206	21,905	19,604	13,910	8,100
TOTAL	131,743	211,045	196,800	172,400	188,100	191,100	204,710	217,500
% IFR[3]	35%	38%	35%	33%	30%	32%	32%	28%

Source: NTS website and FAA Fact Book, February 2002.

[1] Other includes aerial application, aerial observation, sight seeing, and external load

[2] N = Data does not exist

[3] %IFR includes all categories except Personal and Other.

Table 4-32: Percent distribution of GA Aircraft by function.

GA Aircraft	1970	1980	1990	1994	1995	1996	1998	2000
Corporate	5%	7%	5%	5%	5%	5%	5%	5%
Business	20%	23%	17%	15%	14%	15%	16%	12%
Instructional	8%	7%	9%	9%	8%	7%	6%	7%
Personal	50%	46%	57%	59%	58%	57%	61%	68%
Air Taxi	0%	0%	3%	2%	2%	2%	3%	2%
Government	0%	0%	0%	0%	0%	2%	2%	2%
Other	15%	16%	7%	8%	12%	10%	7%	4%

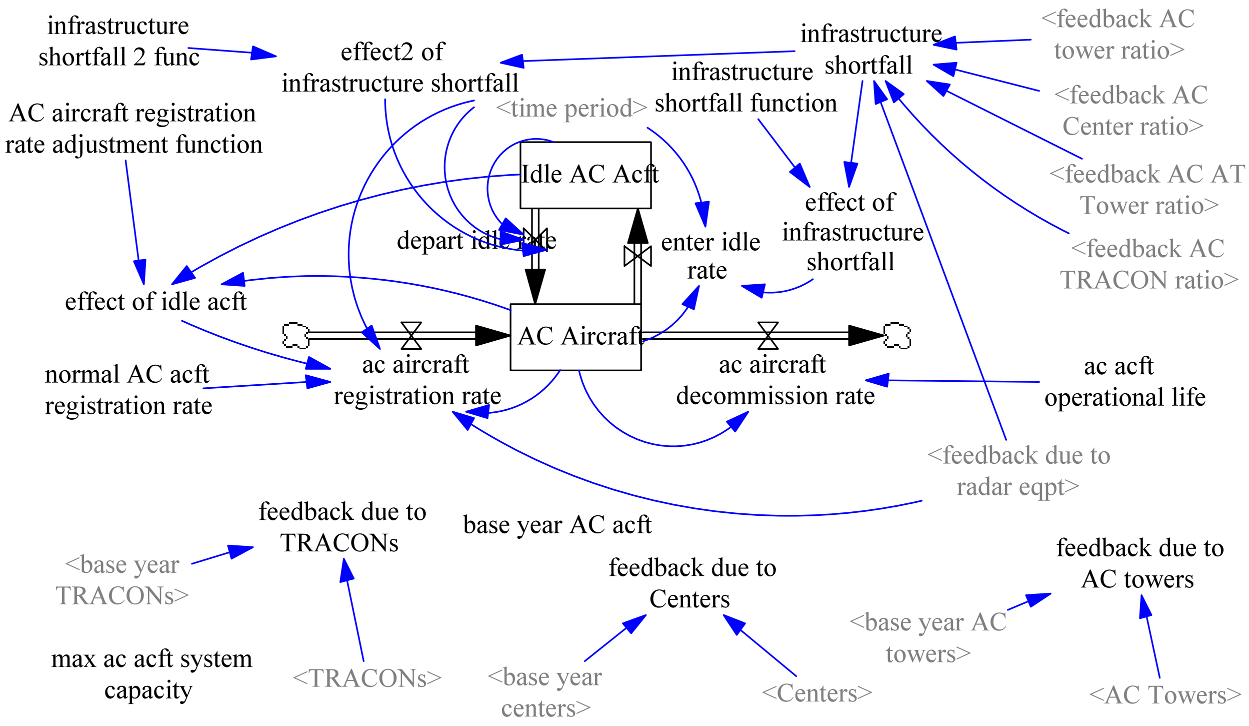

Figure 4-26: AC Aircraft stock and flow diagram.

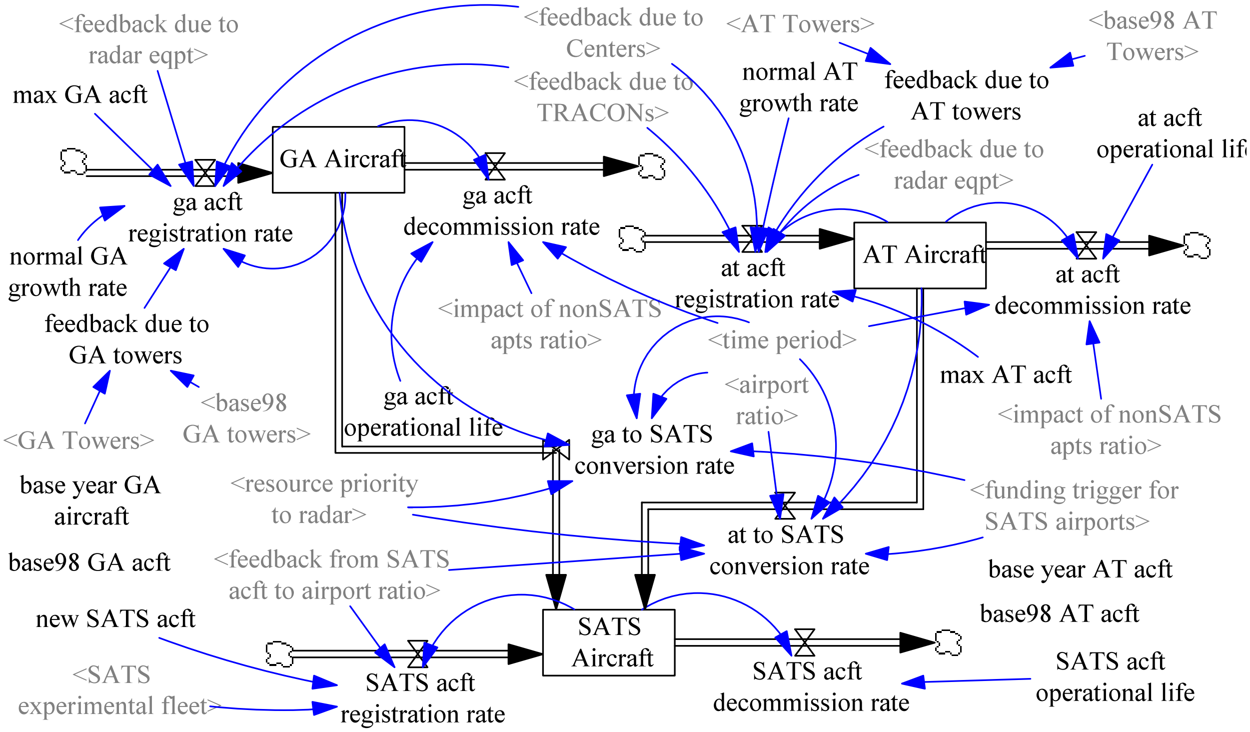

Figure 4-27: AT, GA, and SATS aircraft stock and flow diagram.

Several factors influence the conversion rates to SATS aircraft in Figure 4-27. First, the stocks of AT or GA aircraft provide the pools of potential SATS aircraft. Second, the SATS to non-SATS airport ratio adjusts the flow of conversions. Third, the resource management strategy, represented by the "resource priority to radar" auxiliary variable, changes the amount of conversions. Finally, the level of funding available for SATS airports further adjusts the conversion rate. These factors continually interact over time to create the dynamic behavior in the model.

4.12 Summary

The model developed and presented above depicts the structure and relationships among the key components of the ATC system that have bearing on the research questions. The modeling process began with a system framework in the form of an influence diagram. The process then involved identification of the exogenous and endogenous parts of the system. Finally, the process led to the development of detailed submodels in the areas of people, budget, facilities and equipment, airports, and aircraft. The next chapter will continue the System Dynamics modeling process with the application of several procedures to verify and validate the model developed above.

Chapter 5: Model Verification and Validation

The utility of the model developed in Chapter 4 depends on its ability to provide accurate and realistic results. The System Dynamics Modeling process requires verification and validation of models to ensure they will be useful. The Vensim software includes several functions that help modelers to verify and validate the results produced by models. The software includes tools to ensure unit integrity, tools to trace numerical output, tools to observe graphical output, tools to evaluate time steps, and tools to conduct sensitivity analysis. This chapter uses many of the built in software tools in concert with several other tests and checks to create a useful model. The other methods of validation include model simplicity tests, model parameter checks, behavior reproduction tests, and behavior anomaly tests.

5.1 Verification

Model verification consists of several procedures to ensure that a model operates correctly and as intended by the model developer. The System Dynamics model of ATC resource management strategies operates in the Vensim language. Vensim has embedded tools to aid in model verification. Modelers can also verify the accuracy of their works by running them on other computers to verify that the software creates the same output. Finally, another useful verification technique is to trace numerical values through the system.

5.1.1 Use Vensim Verification Tools

The Vensim software includes the capability to automatically verify the mathematical structure of equations input through the Vensim equation editor. The software checks the syntax of the equation and identifies errors such as an imbalance of parentheses. The software also identifies missing or improper variables in the equation. The equation editor is intuitively sound as a graphic user interface to align the mathematical equations in the model with the graphic structure of the model's stock and flow diagrams.

In addition to the syntax checks made in the equation editor, the Vensim software also conducts user prompted checks of the structure and connectivity of the entire model. The software alerts the user that the model attempts to use undefined variables or neglects to use a defined variable. Similarly, the software includes a tool that checks the integrity of units used throughout the model. The unit-checking tool identifies inconsistencies in the use of units throughout the equations in the model. After all structural or mathematical changes to the model, it is easy practice to quickly verify the structural integrity of the model by using the model-checking and units-checking tools in Vensim.

5.1.2 Run the model on a second computer

The model runs quickly on a relatively modest PC platform with at least a 266 megahertz processor and 64 megabytes of random access memory. The model runs successfully on an IBM Thinkpad with a Celeron processor and a Dell Dimension Desktop with a Pentium II processor.

5.1.3 Trace numerical values through the system

There are many interdependencies in the model represented by numerical relationships. The numerically interdependent parts of the model provide the data to verify that the model works as the designer intended. The numerical values of parameters in the model directly impact upon other parameters. As an example, Table 5-1 contains the numerical values of several parameters that influence the FAA Budget. The data in the table shows that the input into the Required FAA budget parameter aligns with the value of the required FAA budget. Figure 4-11 depicts the relationships among the parameters in the table.

Table 5-1: Numerical tracing of parameter values verifies their accuracy.

Parameter	2000	2005	2010	2015	2020	2025
Grants in aid required	1.87	3.32	4.17	5.02	5.87	6.72
Facilities and equipment annual requirement	2.12	3.25	3.72	4.31	4.91	5.55
Ops account annual requirement	5.77	7.86	9.69	11.79	14.25	16.98
R and D requirement	0.20	0.29	0.35	0.42	0.50	0.59
Sum of above	9.96	14.72	17.93	21.54	25.53	29.84
Required FAA Budget	9.96	14.7	17.93	21.53	25.53	29.83
Delta	0.00	0.02	0.00	0.01	0.00	0.01

The values of Stocks and Flows vary at each time step according to the feedback inherent in the system. Therefore, it is best to trace numerical changes graphically. The Vensim software includes a feature called “causes strip” that links behavior in a system to its causes. The

Controller Subsystem described in Section 4.6 and depicted in Figure 4-6 above included the Controller Trainees stock. Graphical numerical tracing of the Controller Trainee stock and its causes serves as an example of model verification. Figure 5-1 below shows the changes and causes linked to the numerical values of the Controller Trainees stock. The top graph represents the number of controller trainees in the system over time. The second graph depicts the hiring rate that causes a flow of people into the stock. The third and fourth graphs depict the flow of people out of the Controller Trainee stock as either graduates or wash outs. As the system stabilizes over time, the graphs indicate that the steady state system contains approximately 1,800 controller trainees, 600 new controllers graduating yearly, 175 annual wash outs, and 775 annual new hires. The verification of all other stocks in the model occurred in a similar manner using the causal strip tool.

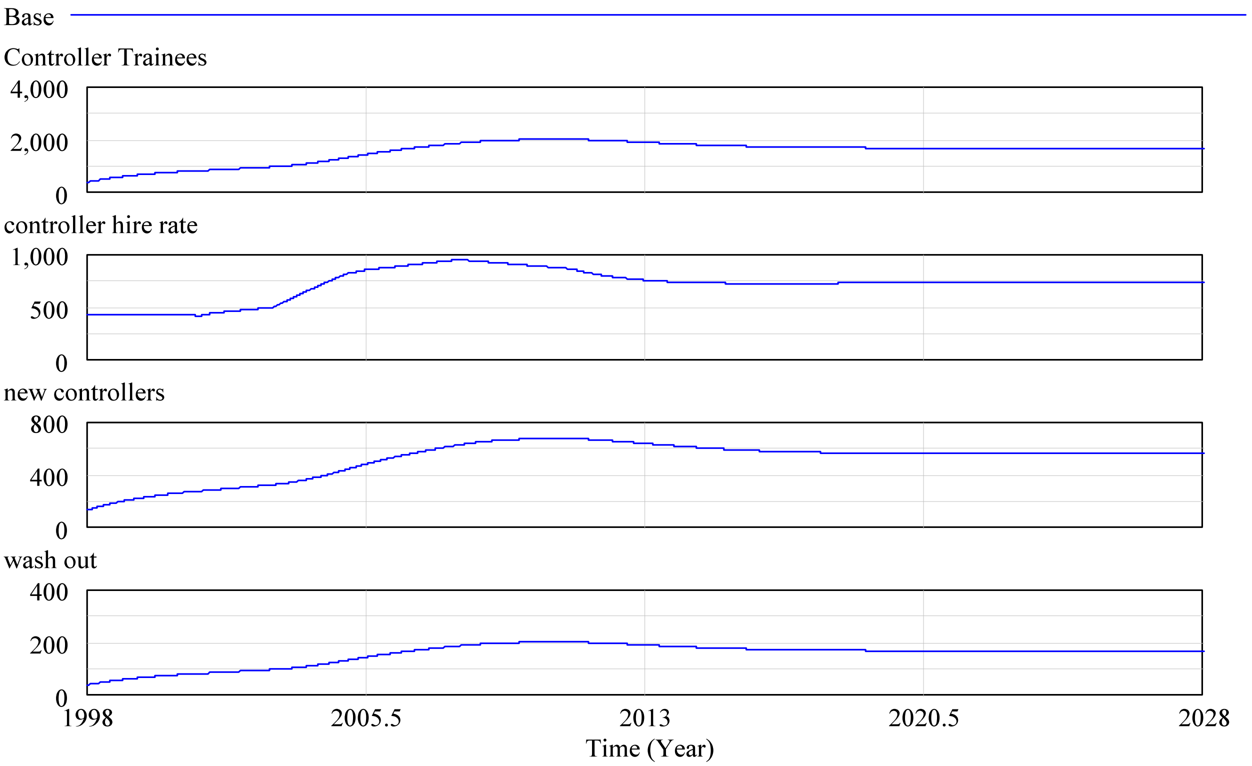

Figure 5-1: The "Causes Strip" aids graphical numerical verification.

5.2 Validation

Model validation consists of a variety of tests to determine if the model replicates the real system. Although some may claim, "all models are wrong," the validation process provides a measure of the usefulness of a model. The validation process must convince those who find utility in the model that the model fulfills their needs. The validation process involves a series of checks that result in a model being accepted or rejected for its intended purpose. Ideally, real world data would be available to compare to the model output. Historic data comparisons are useful. However, there is no real world system in place to compare the model output that depicts the future behavior of the ATC system. The checks used to validate the ATC resource management model included: model simplicity, adherence to physical laws, adherence to decision-making procedures, absence of fudge factors, model parameter checks, face validity, extreme values checks, time step testing, behavior anomaly testing, and sensitivity testing.

5.2.1 Model simplicity

System Dynamics models attempt to convey the behavior of systems by capturing the key relationships in systems while minimizing the detail complexity of systems. Thus, assessments of the structure of the model aid in creating a simple, valid model. Structural assessments help to determine the necessity of components and the level of detail required in the components of a model. The objective of this aspect of model validation is to use the simplest model that accurately represents the system. Simpler models that accurately reproduce the behavior of the real world system offer the advantages of increased clarity of the model structure, and a reduction in the requirements for processing and assessing the model.

Figure 5-2 depicts an early causal loop diagram used to guide modeling. However, as the modeling effort progressed, the final causal loop diagram depicted in Figure 5-3 did not require some of the structural detail from the original concept. The second figure described a model that generated sufficient data to evaluate the research questions. Thus, the second model depicted the complexity of the ATC system behavior, without including all of the complexity of the details of the ATC system.

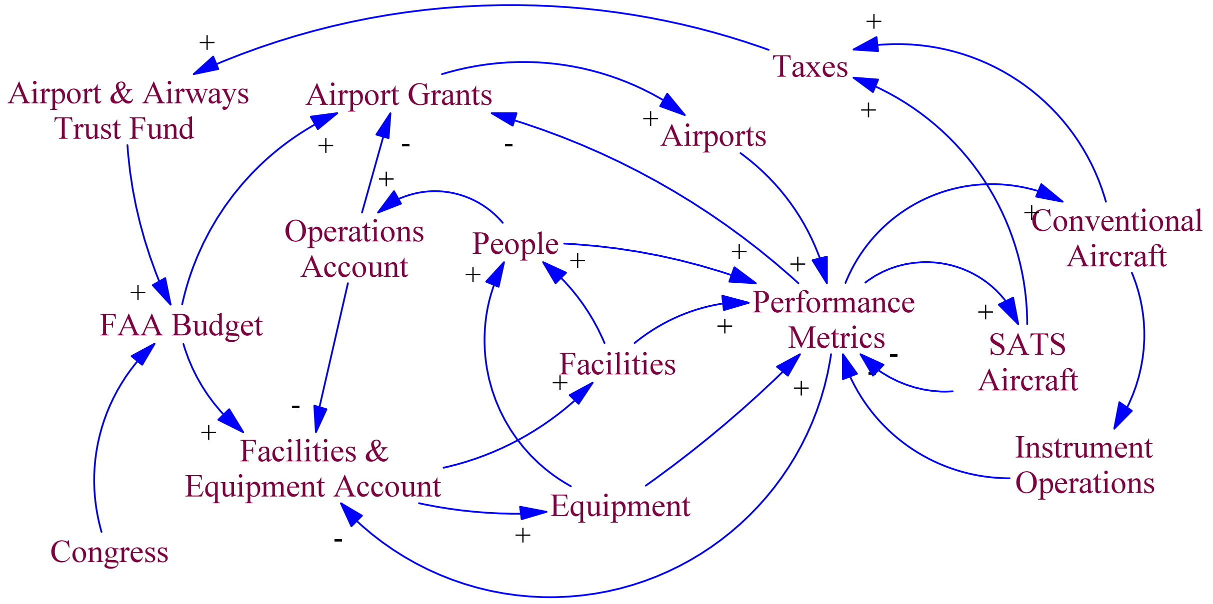

Figure 5-2: An early causal loop diagram includes detail complexity of the ATC system.

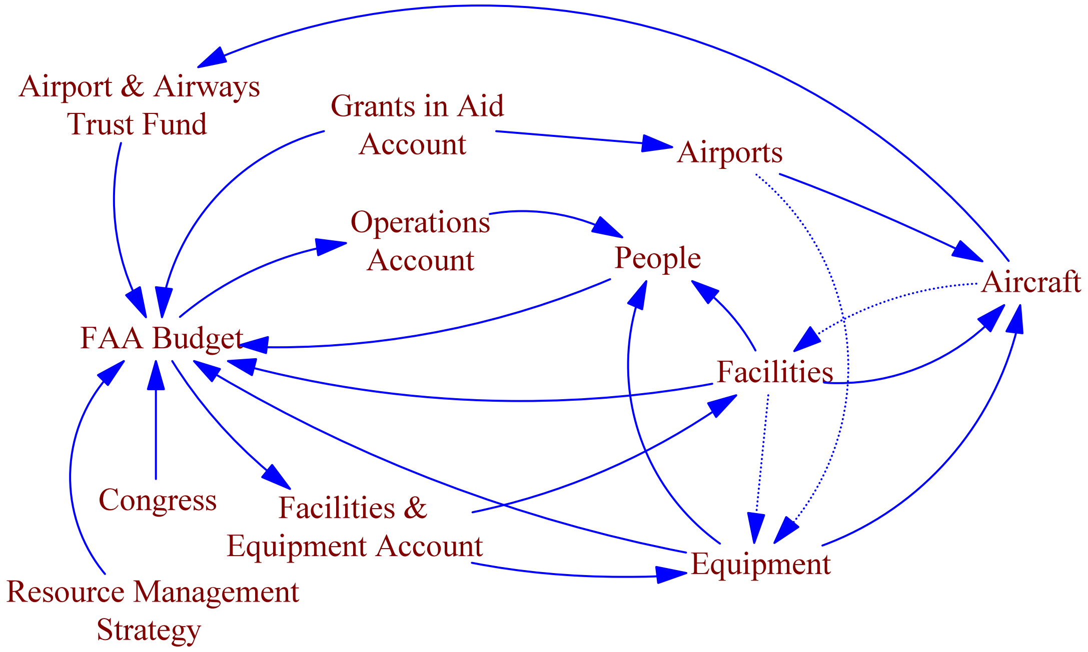

Figure 5-3: The final causal loop diagram captures system behavior with less detail complexity.

Assessment of the model components provides further opportunities for simplification. For example, the employee salary component of the model largely determines the annual requirements for the Operations Account of the FAA budget. Disaggregating employee pay from one average amount for all employees into three separate accounts for controllers, maintainers, and all others increased the model's detail complexity. Figure 5-4 depicts the more complex employee pay component of the model where groups of employees receive different salaries. In the figure, the two shadow variables "Maintainers" and "Controllers" represent the influence of the two stocks in another part of the model.

Similarly, Figure 5-5 shows the Operations Account component of the model where all employees receive an average salary. A comparison of the model output in Figure 5-6 shows that the two components produce virtually the same results. Both the simple results in red and the detailed results in blue show the same system behavior. In fact, the blue line covers the red making it appear as if there is only one line on the graph. Therefore, the final model includes the simpler design with the aggregated average salary.

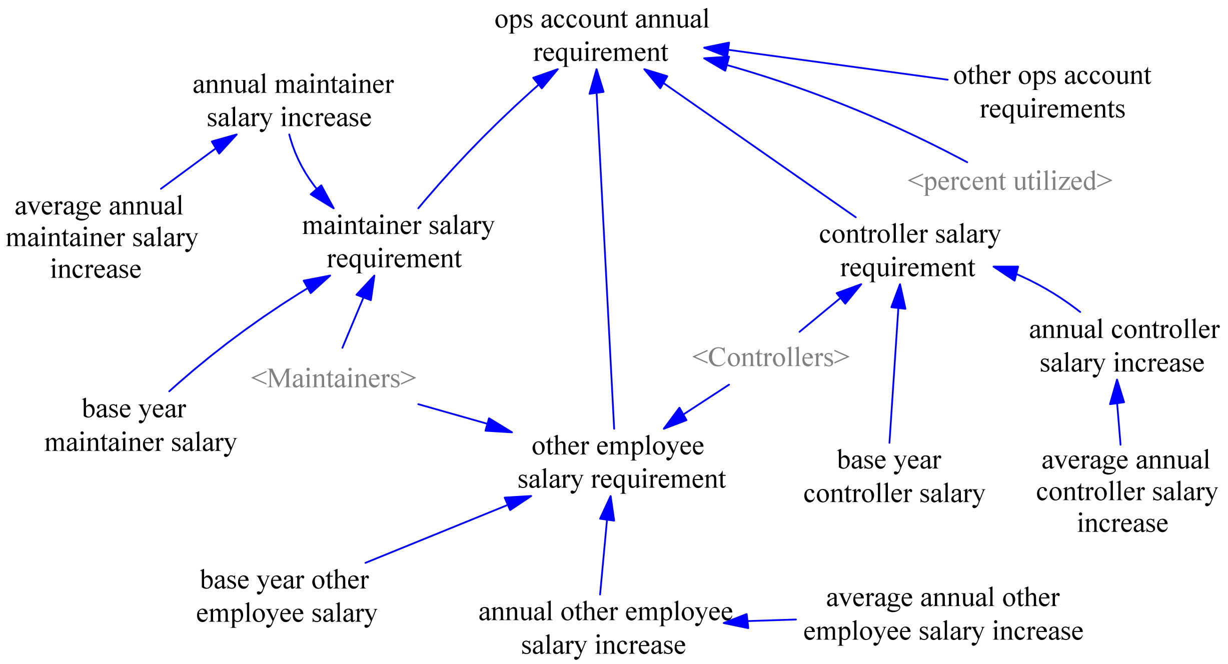

Figure 5-4: The detailed Operations Account model component includes three separate employee pay rates.

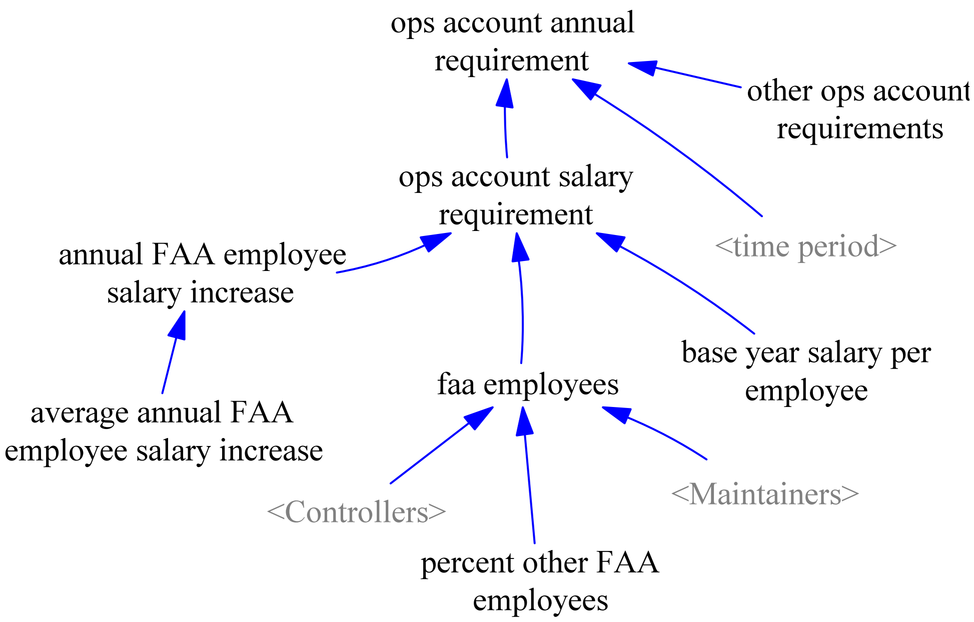

Figure 5-5: The simplified Operations Account model component includes an aggregated employee pay rate.

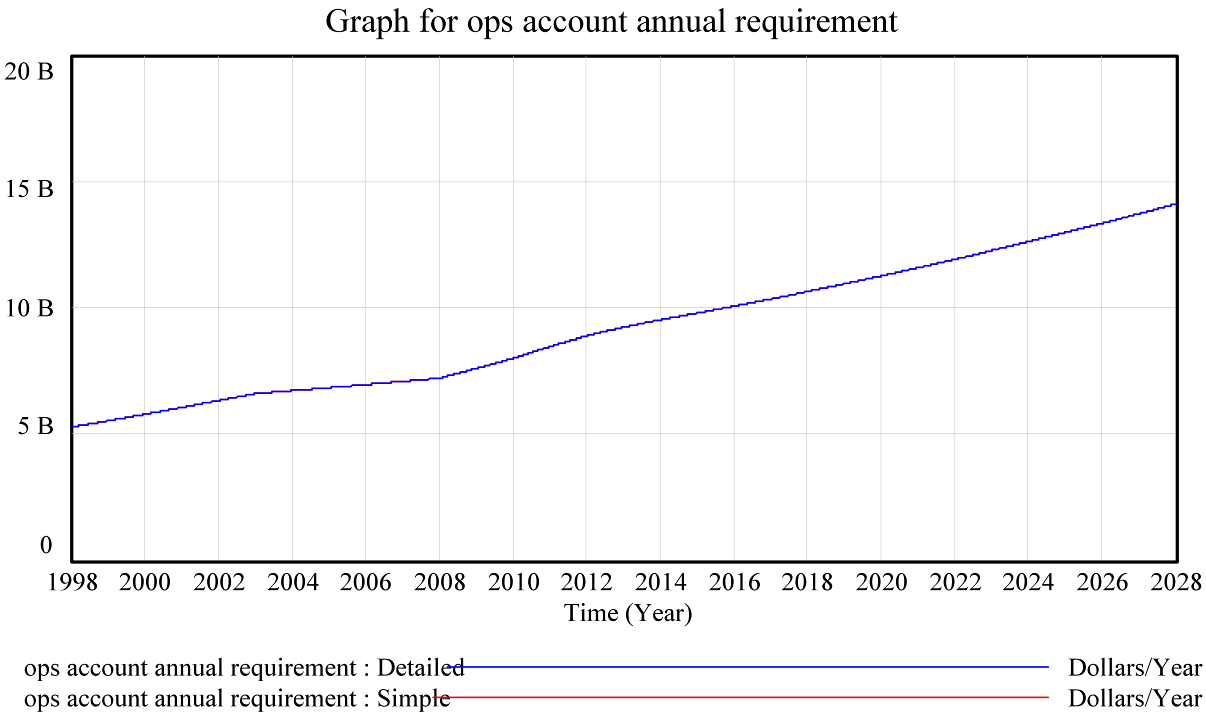

Figure 5-6: A comparison of the two Operations Account model components shows similar results.

More often than not, the modeling effort involved expanding to more detail than aggregating to less. For example, an early version of the model combined all GA and AT aircraft into one pool. However, two modeling necessities created the need to explicitly model both GA aircraft and AT aircraft as separate entities. First, the analysis of air traffic control tower operations showed that the towers were non-homogenous. Subsequently, the model required distinct GA and AT aircraft stocks to measure changes in aircraft populations that influenced the numbers of control towers required in the system. Second, the conversion rates of GA and AT aircraft into SATS aircraft differ. Therefore, the model uses two stocks to distinguish between the flow of converted GA aircraft into SATS aircraft and the flow of converted AT aircraft into SATS aircraft.

5.2.2 Adherence to Physical Laws

The model adheres to physical laws. All stocks of entities; such as control towers, aircraft, and people; maintained positive or zero values throughout normal model runs and during all validation procedures.

5.2.3 Adherence to Decision-making procedures

The model contains a user interface to allow for adjustments in the resource management guidance input into the ATC system. The guidance imbeds decision-making into the model that adjusts the flow of resources according to the desired resource management strategy. Within the model, a variety of feedback occurs that corresponds to decision-making within the system. For example, the FAA hired 430 people on average annually from FY1997 to FY2001 (Government Accounting Office, 2002). The system adjusts the controller hiring rate based on the requirements for controllers demanded by the ATC facilities in the system. As facilities open or close, the requirement for controllers changes. Additionally, the number of controllers in the system also changes based on retirements, early departures, and the flow of trainees. The extreme values testing in section 5.2.7 included checks for adherence to proper decision-making by all the feedback loops in Figure 5-3.

5.2.4 Absence of “fudge factors”

All parameters in the model correspond to real world values. The units used in the model correspond with the stocks. All but two of the units in the model consist of the actual entities: People, Towers, Centers, TRACONS, FSSs, Aircraft, Airports, Equipment, and Dollars. The other two units include time, expressed as Years, and a non-unit descriptor, expressed as Dimensionless. Some of the parameters express estimates of the feedback from one component of the model to another. For instance, the parameter "effect of people shortage on tax revenue" causes a reduction of tax revenue when either the controllers or maintainer populations are at less than 70% of the required manning level. The effect is an example of an estimate that corresponds to a real world value, but the exact value is not known. The intent of using such estimates is to capture the general relationships that cause feedback in the ATC system. To disregard the relationship by not including it in the model would, by default, assign the value of zero.

5.2.5 Model Parameter Checks

Although model parameters have meaning in the real world, the required accuracy of parameter estimates depends on how sensitive the final policy recommendations are to the particular estimate. Parameters embellish the flows into and out of the stocks. The importance of individual parameters in the model varies according to their effect on the system behavior relevant to decision-making.

Two techniques are useful for checking model parameters. The first technique is to ask experts knowledgeable of the system to confirm the accuracy of the parameters. Experts from the FAA provided several parameters for the People Submodel. The second technique is to use partial model tests to isolate and evaluate parameters. Table 5-2 provides a list of all model parameters, their values, units, origins, and the results of partial model tests. The entries in bold font describe the results of the partial model tests on the submodel groupings in the lines below. Blue font delineates the submodel groupings. Although experts provided some of the values, most entries in the table are a result of calculations.

The results in Table 5-2 lead to several conclusions. First, when isolated, the parameters that are constants cause no dynamic behavior in the system. All stocks remain at their initial values during partial model tests involving only constants. However, when evaluated as submodels, the groups of parameters in a submodel cause dynamic behavior in the model. In particular, the Operations Account submodel has the most influence on the FAA budget due to the exponential growth it causes. Conversely, the Controller and Maintainer submodels contain balancing loops that seek stability. The Aircraft submodel grows or declines because of the availability of resources in the system. Overall, all submodels exhibited valid behavior throughout the partial model tests, described in black, bold font for each stock in each submodel.

Table 5-2: Partial model tests are useful validation tools.

Value	Units	Origin
BUDGET SUBSYSTEM – exponential growth when all other variables held constant.		
annual interest (interest on the unused portion of the Airport and Airways Trust Fund)		
4%	1/Year	Estimate
R and D requirement (2% of the FAA budget funds the Research and Development program.)		
2%	Dimensionless	Calculation
time period (Adjusts units to account for a time period over which change occurs.)		
1	1/Year	Calculation
Operations Account – exponential growth when all other variables held constant.		
base year salary (Base year salary from 1998 = $74,202 average for all FAA employees.)		
74,202	Dollars/People	Calculation
Average annual FAA employee salary increase ($8,879 annually (slope from 1998-2002 data))		
8,879	(Dollars/People)/Year	Calculation
percent other FAA employees (40% of FAA employees are inspectors and administrators. Therefore, 100/60 = 1.67, the multiplication factor to obtain the total number of employees.)		
1.67	Dimensionless	Calculation
other ops account requirements (Factor to multiply ops account salary figure by to obtain entire ops account requirement. 74% of ops account pays for salaries, the remaining 26% pays for rent, contracts, travel, and other services for employees.)		
1.35	Dimensionless	Calculation
Facilities and Equipment Account – linear growth or decline when all other variables held constant.		
radar eqpt avg annual cost ($90,000 per piece of radar-based ATC equipment is required from the F&E account annually)		
90,000	Dollars/Equipment	Calculation
GPS eqpt avg annual cost ($460,000 per piece of GPS-based ATC equipment is required from the F&E account annually)		
460,000	Dollars/Equipment	Calculation
FSS avg annual cost ($280,000 per FSS is required from the F&E account annually)		
280,000	Dollars/FSSs	Calculation
ga tower avg annual cost ($350,000 per GA tower is required from the F&E account annually)		
350,000	Dollars/Towers	Calculation
at tower avg annual cost ($420,000 per AT tower is required from the F&E account annually)		
420,000	Dollars/Towers	Calculation
ac tower avg annual cost ($1,010,000 per AC tower is required from the F&E account annually)		
1,010,000	Dollars/Towers	Calculation
TRACON avg annual cost ($670,000 per TRACON is required from the F&E account annually)		
670,000	Dollars/TRACONs	Calculation
center avg annual cost ($13,570,000 per Center is required from the F&E account annually)		
13,570,000	Dollars/Centers	Calculation
other facilities costs (All other facilities cost $361M in base year 1998 and include 19% of the F&E account)		
361,000,000	Dollars	Calculation
ramp increase in 01 and 02 ($450M increase to F&E account in 2001 and 2002)		

<table>
<tr><td>450,000,000</td><td>Dollars/Year</td><td>Calculation</td></tr>
<tr><td colspan="3">Operating cost growth factor (2% operating cost growth rate)</td></tr>
<tr><td>2</td><td>Year</td><td>Estimate</td></tr>
<tr><td colspan="3">Grants-in-Aid Account – linear growth when all other variables held constant.</td></tr>
<tr><td colspan="3">average annual increase in Grants in Aid (estimate of the average annual increase in the Grants-in-Aid account is $170M annually)</td></tr>
<tr><td>170,000,000</td><td>Dollars/Year</td><td>Calculation</td></tr>
<tr><td colspan="3">base year grants in aid (The 1998 Grants in Aid account was $1.7B.)</td></tr>
<tr><td>170,000,000,000</td><td>Dollars</td><td>Calculation</td></tr>
<tr><td colspan="3">ramp increase in 2001 and 02 ($600M increase to Grants in Aid account in 2001 and 2002)</td></tr>
<tr><td>600,000,000</td><td>Dollars/Year</td><td>Calculation</td></tr>
<tr><td colspan="3">Airport and Airway Trust Fund – linear growth in aircraft when all other variables held constant.</td></tr>
<tr><td colspan="3">base year tax revenue per AC aircraft (Assume base year is avg of revenue from 1998-2003 calculated in part 4.7.5 in dissertation is $1,133,000.)</td></tr>
<tr><td>1,133,000</td><td>Dollars/Aircraft</td><td>Calculation</td></tr>
<tr><td colspan="3">avg annual increase in AC tax revenue (Assume average increase in taxes is $50,000 annually)</td></tr>
<tr><td>50,000</td><td>(Dollars/Aircraft)/Year</td><td>Estimate</td></tr>
<tr><td colspan="3">base year tax revenue per AT GA or SATS aircraft (Assume base year is $6,639 = avg of revenue from 1998-2003,)</td></tr>
<tr><td>6,639</td><td>Dollars/Aircraft</td><td>Calculation</td></tr>
<tr><td colspan="3">avg annual increase in AT GA or SATS tax revenue (Assume average increase in taxes is $300 annually)</td></tr>
<tr><td>300</td><td>(Dollars/Aircraft)/Year</td><td>Estimate</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">AIRPORTS – linear growth or decline when all other variables held constant.</td></tr>
<tr><td colspan="3">ramp for max annual airport conversions (The maximum number of nonSATS airports that can be converted to SATS airports annually. A RAMP function starting with 5 airports per year in 2010 and increasing by 5 airports annually until 2015.)</td></tr>
<tr><td>5 annually for 5 years</td><td>Dimensionless</td><td>Estimate</td></tr>
<tr><td colspan="3">base year nonSATS airports (There were 2806 public use nonSATS airports in the US in the baseyear 1998 that were also potential candidates to become SATS airports due to their inclusion on the National Plan of Integrated Airport Systems (NPIAS) list.)</td></tr>
<tr><td>2,806</td><td>Airports</td><td>Calculation</td></tr>
<tr><td colspan="3">timeperiod for nonSATS airports (Assume 1 new airport is built annually from 1998 until 2010.)</td></tr>
<tr><td>1</td><td>Dimensionless</td><td>Estimate</td></tr>
<tr><td colspan="3">annual new nonSATS airports (Assume 1 new airport is built annually from 1998 until 2010.)</td></tr>
<tr><td>1</td><td>Airports/Year</td><td>Estimate</td></tr>
<tr><td colspan="3">first year for SATS airports (The first year a SATS airport becomes operational.)</td></tr>
<tr><td>2010</td><td>Year</td><td>Estimate</td></tr>
<tr><td colspan="3">SATS airport conversion cost (Assume it cost $2M to convert an airport to a SATS airport.)</td></tr>
<tr><td>2,000,000</td><td>Dollars/Airports</td><td>Estimate</td></tr>
<tr><td colspan="3">PEOPLE</td></tr>
<tr><td colspan="3">Controllers – balancing behavior, seeks approx 19,300 when all other variables held constant.</td></tr>
</table>

avg controllers per center (Assume average Center has 375 people.)			
375	People/Centers	Calculation	
avg controllers per TRACON (Assume average TRACON has 25 people.)			
25	People/TRACONs	Calculation	
avg controllers per FSS (Assume average Flight Service Station has 22 people.)			
22	People/FSSs	Calculation	
avg controllers per AC Tower (Assume average AC tower has 18 people.)			
18	People/Towers	Calculation	
avg controllers per AT Tower (Assume average AT tower has 8 people.)			
8	People/Towers	Calculation	
avg controllers per GA Tower (Assume average GA tower has 5 people.)			
5	People/Towers	Calculation	
percent controllers hired (From data in GAO report 02-591, the FAA hired 430 people on average annually from FY1997 to FY2001. This implies an average hiring rate of 0.025 of the available controller pool.)			
0.025	1/Year	Report	
min shortfall ctrl hire rate (The minimum number of cotrollers hired when there is a shortfall of contollers.)			
430	People/Year	Estimate	
trainee training time (According to a GAO report (02-591 Air Traffic Control) controllers take from 2 to 4 years to become proficient as air traffic controllers.)			
3	Year	Report	
normal wash out (Assume 10% of trainees wash out of the system. Note: The GAO report indicated the wash out rate was as high as 50% recently. Also, higher numbers of off the street hires could also increase the wash out rate.)			
0.1	1/Year	estimate	medium
average controller career (Assume the average controller has a 30 year career with the FAA.)			
30	Year	Estimate	
retirees per surge year (Approximately 1000 controllers will retire annually from 2003 to 2008 due to the hiring surge after the 1981 controllers strike.)			
1,000	People/Year	Report	
early depart rate (The GAO report indicates that the FAA expects approximately 100 controllers to leave the system prematurely each year.)			
100	People/Year	Report	
Maintainers – balancing behavior when all other variables held constant.			
average maintainers per controller (Estimated from 1998 through 2002 data that there are 0.4 maintainers for every controller)			
0.4	Dimensionless	Calculation	
average maintainers per equipment (Estimated from 1998 and 1999 ratios that there is one maintainer per 1.09 pieces of ATC equipment)			
1.09	People/Equipment	Calculation	
normal maintainer hiring rate (Normal maintainer hiring rate is approximately 200 maintainers per year, according to Dr Judy Holcomb of the FAA Academy in Oklahoma City.)			
200	People/Year	Expert	

maintainer trainee training time (According to Dr Holcomb at the FAA Academy, it takes about 2 years for a system maintainer to become fully proficient.)		
2	Year	Expert
average maintainer career (Average maintainer career is 35+ years according to Dr Holcomb, FAA Academy.)		
35	Year	Expert
accelerated retirement due to average age (Since average maintainer career is 35+ years and the average age of maintainers is 47 in 2002, there will be an accelerated retirement rate until the average age of the workforce delcines. This variable causes a linear decline in the retirement rate for 20 years.)		
-0.1	Year	Expert
FACILITIES AND EQUIPMENT		
Centers, TRACONS, FSSs – linear growth or decline when all other variables held constant.		
interval between center consolidations (Assume two centers consolidate every 7 years.)		
7	Year	Estimate
interval between tracon consolidations (Assume two TRACONs consolidate every 10 years.)		
10	Year	Estimate
normal fss construction rate (Assume two new FSSs built per year.)		
2	FSSs/Year	Estimate
AC Control Towers – linear growth when all other variables held constant.		
normal ac tower construction rate (Assume 1 new towers opens every four years.)		
0.25	Towers/Year	Calculation
normal ac tower closure rate (Assume 1 tower closes every 8 years.)		
0.125	Towers/Year	Calculation
AT Control Towers – linear growth when all other variables held constant.		
normal at tower construction rate (Assume 1 new towers opens every two years.)		
0.5	Towers/Year	Calculation
normal at tower closure rate (Assume 1 tower closes every 4 years.)		
0.25	Towers/Year	Calculation
GA Control Towers – linear growth when all other variables held constant.		
normal ga tower construction rate (Assume 1.5 new towers open every two years.)		
1.5	Towers/Year	Calculation
normal ga tower closure rate (Assume 0.5 tower closes every year.)		
0.5	Towers/Year	Calculation
normal ga tower closure rate (Assume 0.5 tower closes every year.)		
0.5	Towers/Year	Calculation
Radar-based Equipment – linear growth when all other variables held constant.		
radar equipt replacement rate per AC tower (AC Towers annually require 0.52 replacement pieces of radar-based equipment to replace ILS, ASR-T, ARTS, and VASI.)		
0.52	Equipt/Towers/Year	Calculation
radar equipt replacement rate per AT tower (AT Towers annually require 0.37 replacement pieces of radar-based equipment to replace ILS, ASR-T, ARTS, and VASI.)		
0.37	Equipt/Towers/Year	Calculation

radar equipt replacement rate per GA tower (GA Towers annually require 0.22 replacement pieces of radar-based equipment to replace ILS, ASR-T, ARTS, and VASI.)		
0.22	Equipt/Towers/Year	Calculation
radar equipt replacement rate for base infrastructure (Radar-based infrastructure required 228 replacement pieces of radar-based equipment to replace VOR, NDB, ARSR-E, RC A-G, RCO in the base year with 7422 pieces of equipment. Therefore, rate is 228/7422 = 0.03.)		
0.03	1/Year	Calculation
GPS-based Equipment – linear growth or decline when all other variables held constant.		
WAAS installation rate (WAAS = Wide Area Augmentation System)		
5	Eqpt/Year	Estimate
LAAS installation rate (LAAS - Local Area Augmentation System: 32 systems installed annually from 2002 until 2006 and thereafter when directed as a resource priority)		
32	Eqpt/Year	Report
GPS equipment lifetime (Assume GPS equipment lifetime is 20 years.)		
20	Year	Report
gps eqpt per SATS airport (Assume each SATS airport contributes a GPS-based ATC piece of equipment.)		
1	Equipment/Airports	Estimate
AIRCRAFT		
AC Aircraft – balancing feedback caused by capacity of Centers to handle growth of AC aircraft.		
normal AC acft registration rate (Historic registration rate for AC acft is 7% of AC acft population.)		
0.07	Dimensionless	Calculation
ac acft operational life (Assume AC acft have a 20 year operational life.)		
20	Year	Estimate
AT Aircraft – continuous growth when all other variables held constant.		
normal AT growth rate (Base value for 1998 is 5,190 AT aircraft. Historic AT aircraft growth rate is approximately 363 yearly from 1994-1998. Therefore, assume growth rate is 363/5190 = 0.07.)		
0.07	1/Year	Calculation
at acft operational life (Assume AT acft have a 20 year operational life.)		
20	Year	Estimate
GA Aircraft – continuous growth when all other variables held constant.		
normal GA growth rate (Base value for 1998 is 204,710 GA aircraft. Historic IFR GA aircraft growth rate is approximately 2,562 yearly from 1994-1998. Therefore, assume growth rate is 2562/66453 = 0.038.)		
0.038	1/Year	Calculation
ga acft operational life (Assume AT acft have a 30 year operational life.)		
30	Year	Estimate
SATS Aircraft – balancing feedback caused by lack of resources causes continuous decline.		
New SATS acft (Assume SATS annual growth rate is 2% of the existing fleet of SATS acft.)		
0.02	1/Year	Estimate
SATS acft operational life (Assume AT acft have a 20 year operational life.)		
20	Year	Estimate

5.2.6 Face Validity

Bruce Henry, an FAA subject matter expert who evaluated the model structure and feedback loops on February 8, 2002 indicated that they were valid representations of the real system. Other FAA subject matter experts, such as Dr Judy Holcomb of the FAA Academy in Oklahoma City, provided some of the parameter values used in the model. Considerations of face validity guided the model development process as the modeler used personal judgment of face validity to evaluate the behavior of the model throughout the development process.

5.2.7 Extreme Values Testing

Extreme values testing uncovers features of the model that cause it to produce desirable output under normal conditions, but cause erratic behavior under unusual conditions. Table 5-3 captures the behavior of the model under extreme values for the initial conditions of the stocks. For the testing, "normal" behavior occurred for a base case run of the model using all the normal initial values for the stocks. Numerous additional model runs occurred to test each high and low initial stock value. The high and low values used for testing were generally an order of magnitude larger or smaller than the base case initial values. The resource management strategy used to conduct the extreme values testing devoted a maximum of 30% of the FAA budget to GPS-based ATC by linearly increasing GPS support from 2010 to 2020.

Table 5-3: The results of the Extreme Values Testing highlight the function of the feedback loops in the system.

Stock	Normal Value	Low Value	High Value	System Behavior
FAA Budget	$9.052B	$100	$25B	Balancing loop – system returns to normal by seeking equilibrium.
AATF	$11B	$100	$25B	Balancing loop – system returns to normal by seeking equilibrium.
NonSATS airports	2806	10	10000	Balancing loop – system returns to normal by seeking equilibrium.
SATS airports	1	0	1000	Reinforcing loop: Normal growth or decline
Controller Trainees	400	10	2000	Balancing loop – system returns to normal by seeking equilibrium.
Controllers	20,850	2,000	100,000	Balancing loop – system returns to normal by seeking equilibrium.
Maintainer Trainees	200	20	4,000	Balancing loop – system returns to normal by seeking equilibrium.
Maintainers	8,300	80	80,000	Balancing loop – system returns to normal by seeking equilibrium.

Centers	21	2	200	Balancing loop – system slowly returns to normal by seeking equilibrium.
TRACONs	170	10	2,000	Balancing loop – system slowly returns to normal by seeking equilibrium.
Flight Service Stations	137	10	1,500	Balancing loop – system slowly returns to normal by seeking equilibrium.
AC Towers	170	10	2,000	Balancing loop – demand for radar-based equipment exhausts supply, preventing return to equilibrium.
AT Towers	135	10	1,500	Balancing loop – demand for radar-based equipment exhausts supply, preventing return to equilibrium.
GA Towers	160	10	2,000	Balancing loop – demand for radar-based equipment exhausts supply, preventing return to equilibrium.
Radar Based Equipment	7,422	70	70,000	Balancing loop – system slowly returns to normal by seeking equilibrium.
GPS Based Equipment	250	25	2,500	Balancing loop – system slowly returns to normal by seeking equilibrium.
AC Aircraft	8,111	800	80,000	Balancing loop – system slowly returns to normal by seeking equilibrium.
AT Aircraft	5,190	500	50,000	Balancing loop – system returns to normal by seeking equilibrium.
GA Aircraft	66,453	6,000	600,000	Balancing loop – system returns to normal by seeking equilibrium.
SATS Aircraft	20	2	200	Reinforcing loop for SATS growth, little impact on system.

5.2.8 Time Step Testing

The model exhibited consistent behavior when run under several time step values. A time step value of one corresponds to one year; a time step value of 0.25 corresponds to one quarter of a year. The Vensim software includes two useful tools for evaluating the impact of time step changes. The first tool allows the model user to change the value of the time step. Figure 5-7 is a graph of the stock of AC aircraft under several time step values: grey (0.125), green (0.0625), red (0.03125), and blue (0.015625). Since the results remained the same for each time step, the graph appears as only one solid blue line. All four time step results produced the same output under the visible blue line. The AC aircraft stock exhibited goal-seeking behavior caused by balancing loop feedback restraining the growth of the number of AC aircraft. The test showed that any of the evaluated time steps is sufficiently small to show consistent behavior throughout the model.

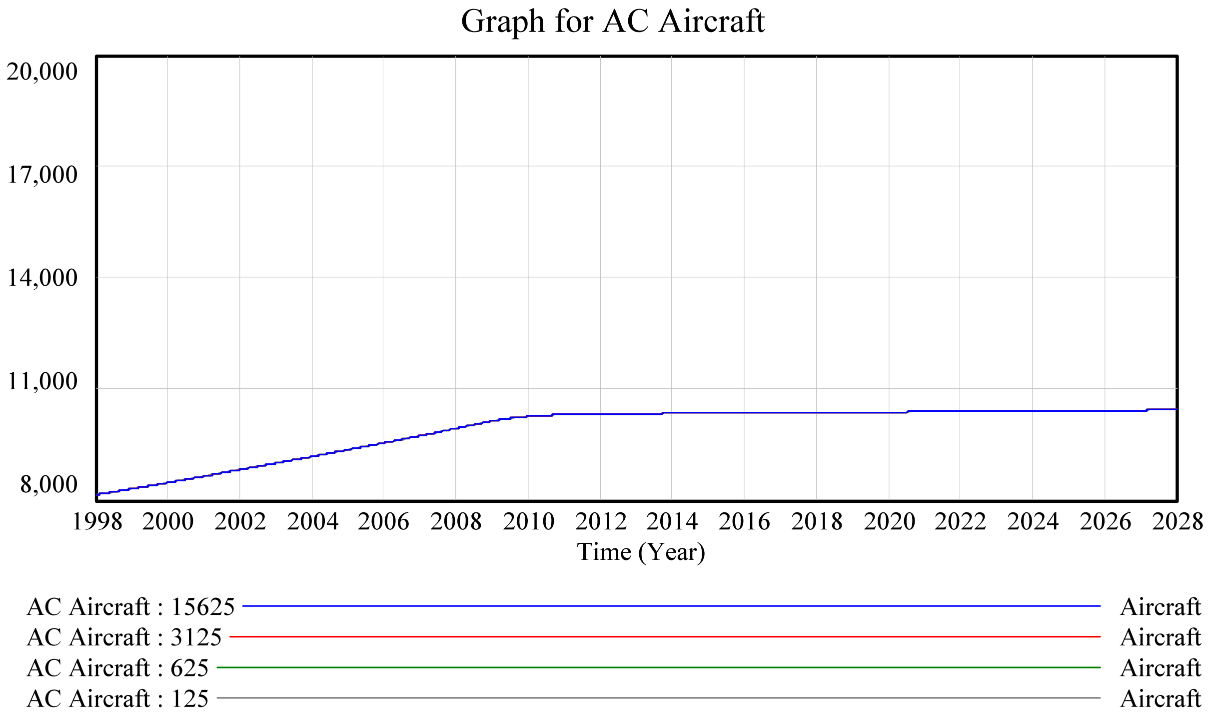

Figure 5-7: Four different time steps show the impact of reducing the size of the time step in the model.

The second tool to evaluate the time step involves changing the method of integration used by the model to advance the model in time to create system behavior. Figure 5-8 is a graph of the same stock of AC aircraft using a time step of 0.015625 of a year under four of the six types of integration available in Vensim: Euler, Diff, and two types of Runge-Kutta. Euler is the fastest and least accurate method, Diff is a more accurate version of Euler, and Runge-Kutta automatic is more accurate than fixed. The output shows that all four approaches produce the same results. As in the time step testing, the output for the integration method also produced the same results under the visible blue line. Thus, the Euler technique is sufficient as a quick and accurate method of time advancement.

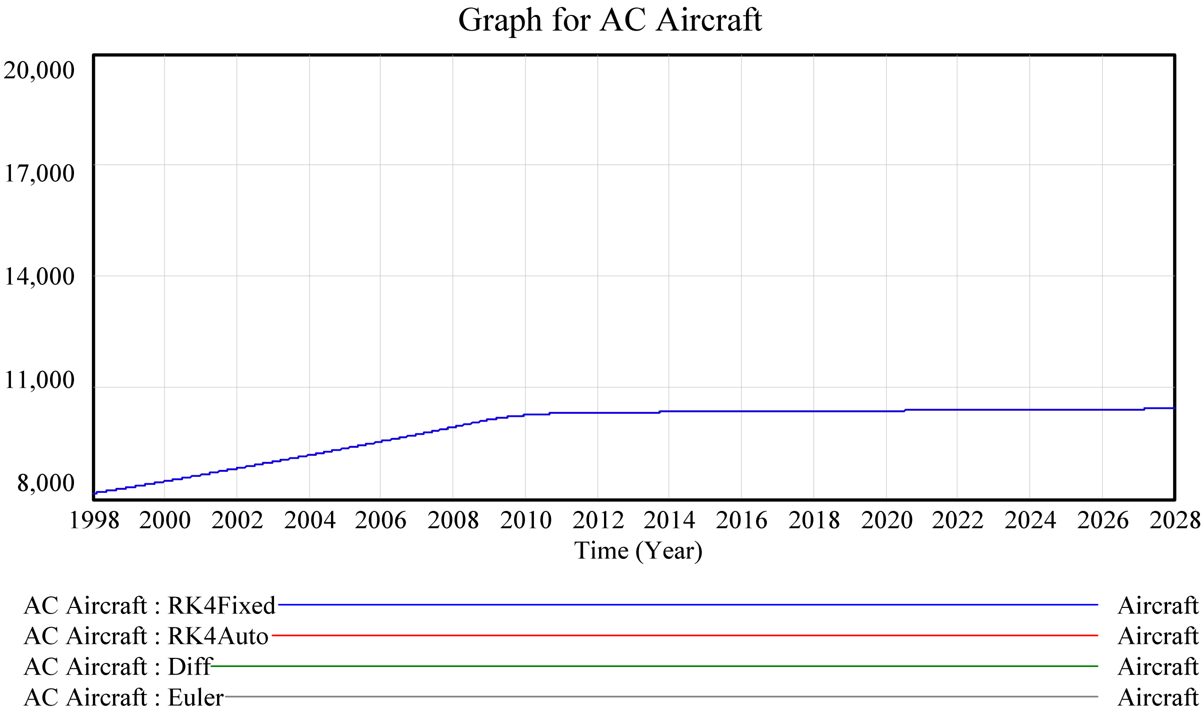

Figure 5-8: Four different time advancing integration techniques all produce the same results.

5.2.9 Behavior Reproduction Testing

Behavior reproduction testing is an attempt to model past system behavior to reproduce historical data generated by real-world performance of the system. Table 5-4 below contains actual and estimated initial values of the stocks in the ATC system in 1991. Table 5-5 below contains additional initial values for parameters in the model. The 1991 Facilities and Equipment values in Table 5-5 result from the formula: 1991 values = (1991 FAA Budget/1998 FAA Budget)*(1998 Value). The values in both tables define the initial conditions set in the model to conduct the behavior reproduction test.

Table 5-4: Initial stock values for 1991 provide a basis for behavior reproduction testing.

Stock Initial Values	1991 Value	1998 Value
FAA Budget	$7.732B	$9.052B
AATF – estimate	$9.0B	$11B
NonSATS airports – estimate	2,550	2,806
SATS airports	0	1
Controller Trainees – estimate	500	400
Controllers	24,000	20,850

Maintainer Trainees – estimate	160	200
Maintainers	6,600	8,300
Centers	24	21
TRACONs - estimate	180	170
Flight Service Stations – estimate	110	137
AC Towers – estimate	160	170
AT Towers – estimate	140	135
GA Towers – estimate	125	160
Radar Based Equipment – estimate	7,500	7,422
GPS Based Equipment – estimate	5	250
AC Aircraft	6,054	8,111
AT Aircraft	5,800	5,190
GA Aircraft – estimate	65,000	66,453
SATS Aircraft	0	20

Table 5-5: Initial parameter values for 1991 provide a basis for behavior reproduction testing.

Parameter Initial Values	1991 Value	1998 Value
base year salary - estimate	$44,852	$64,591
Radar eqpt avg annual cost - estimate	$76,500	$90,000
GPS eqpt avg annual cost – estimate	$391,000	$460,000
FSS avg annual cost – estimate	$238,000	$280,000
ga tower avg annual cost – estimate	$297,500	$350,000
at tower avg annual cost – estimate	$357,000	$420,000
ac tower avg annual cost – estimate	$858,500	$1,010,000
TRACON avg annual cost – estimate	$569,500	$670,000
center avg annual cost – estimate	$11,534,500	$13,570,000
Other facilities costs – estimate	$307M	$361M
Base year grants in aid	$1.6B	$1.7B

Table 5-6 below contains the results of the behavior reproduction testing. The left justified Grants, Ops, F&E, and Total rows show the historical expenditures of the FAA from 1991 to 2002. The right justified "Model" rows show the output of the model for the same time period. The four figures below the table graphically depict the comparison of the model behavior to the historic behavior of the system. The graphs indicate that the model provides a valid representation of the real world system. Table 5-7 shows the results of statistical t-tests to determine if the model and historical distributions were from the same distribution. In each case, the hypothesis that the distributions differed was rejected, thus reinforcing the accuracy of the model's ability to reproduce past behavior.

Table 5-6: The rows under the actual data contain the model data for the same time period.

Type	1991	1992	1993	1994	1995	1996	1998	1999	2000	2001	2002
Grants	$1,600	1,900	2,050	1,690	2,161	2,214	1,700	1,950	1,896	3,193	3,300
Model	1,600	1,722	1,840	1,960	2,080	2,200	2,440	2,560	2,680	3,400	3,520
Ops	4,037	4,360	4,538	4,581	4,583	4,643	5,253	5,586	5,958	6,603	7,091
Model	3,827	4,066	4,331	4,611	4,897	5,180	5,719	5,976	6,231	6,491	6,763
F&E	2,095	2,394	2,350	2,120	2,033	1,875	1,900	2,121	2,034	2,651	2,914
Model	1,512	1,559	1,605	1,651	1,698	1,744	1,837	1,884	1,930	2,427	2,474
Total	7,732	8,654	8,938	8,391	8,777	8,732	9,052	9,657	9,888	12,447	13,305
Model	7,079	7,491	7,932	8,388	8,849	9,307	10,190	10,620	11,050	12,560	13,010

(Sources: 1998-2002 FAA, 2002a; 1991-1996: FAA; 1997 not available.)

Table 5-7: Statistical t-tests showed that the model reproduces the historical data when T>t.

$t_{(9,\ 0.025)} = 2.26$	Grants in Aid	Operations	Facilities & Eqpt	Total
Calculated T statistic	4.50	8.92	2.76	6.67
Same Distribution	Yes	Yes	Yes	Yes

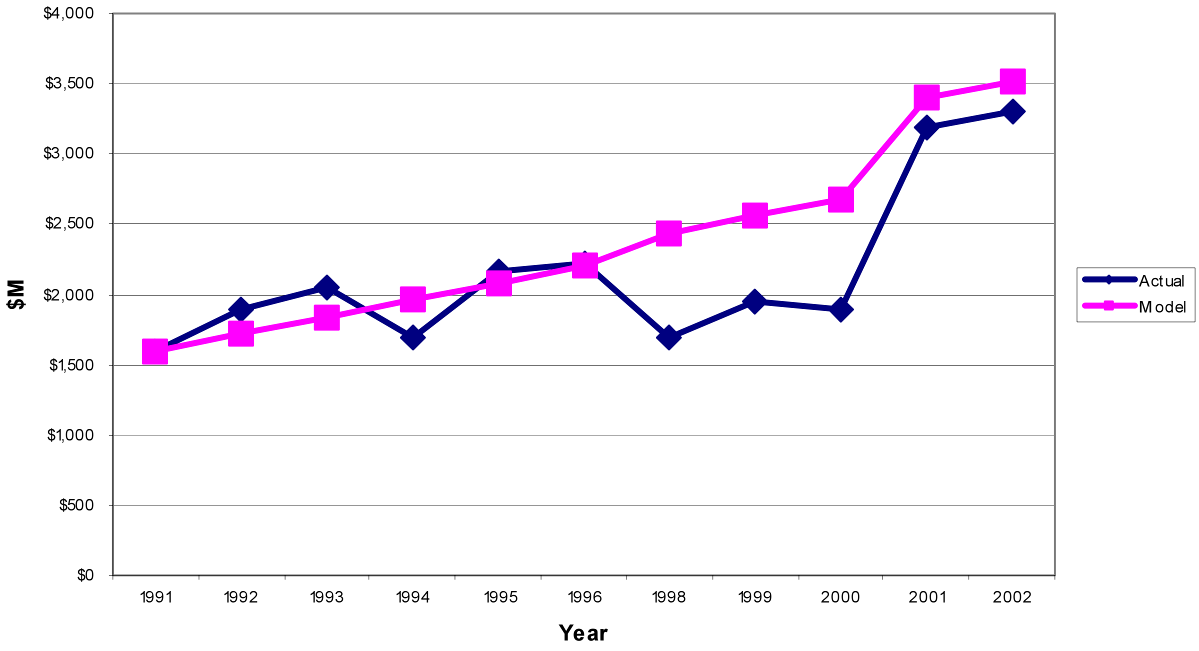

Figure 5-9: The historic Grants-in-Aid account shows more variability than the model.

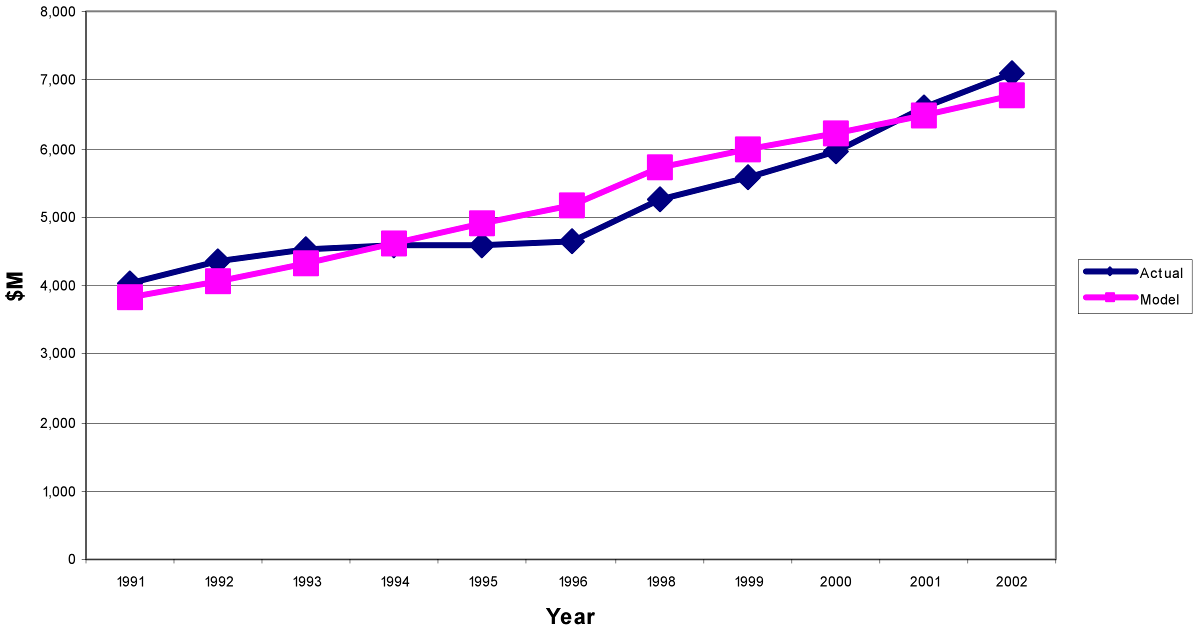

Figure 5-10: The actual and modeled Operations Account show similar trends.

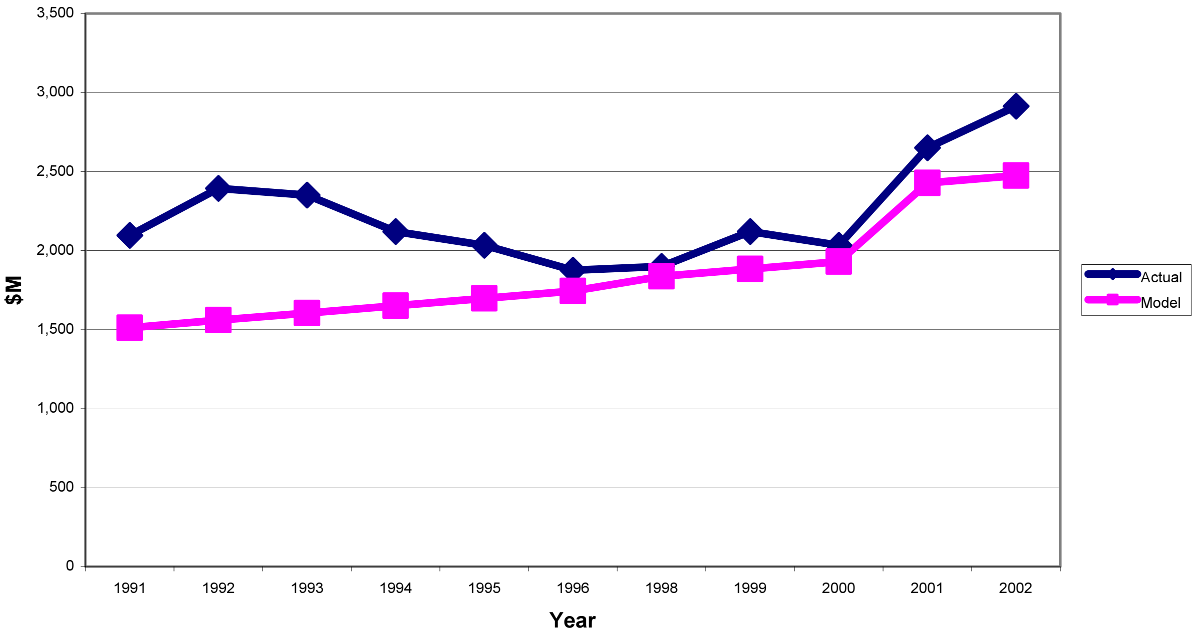

Figure 5-11: The historic Facilities and Equipment Account shows more variability than the model.

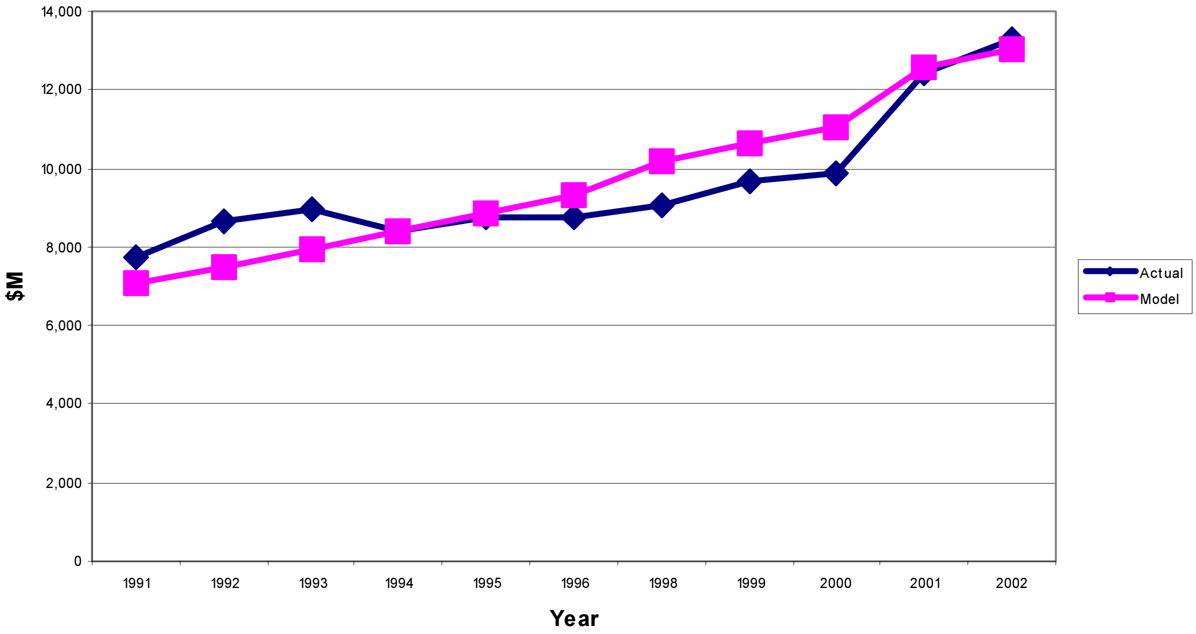

Figure 5-12: The actual and modeled FAA Budgets show the same trends.

5.2.10 Behavior Anomaly Testing

Removing pieces of the model structure changed the behavior of the modeled system. The degree of impact upon the system caused by removing sections of the model was useful to determine how important the eliminated structure was to the behavior of the entire model. The test involved removing sections of the model related to money, infrastructure, and aircraft. The changes in the model's behavior due to the absence of several feedback loops caused by removal of pieces of the structure validated that the all the stocks and flows in the model are important and must remain in the model.

The Operations, Grants-in-Aid, and Facilities and Equipment Account relate to the flow of money in the system. Removing any of the funding requirements for the accounts caused the AATF to grow exponentially and reduced the size of the FAA budget. Removing revenue from the system caused the General Fund of the US government to pay for the entire FAA budget. Removing revenue and the General Fund caused the FAA budget to go to zero and resulted in declines in the stocks associated with infrastructure and personnel. The changes caused by removing sections of the system associated with the flow of money indicate that the sections all play important roles in the model.

Removing the parts of the system associated with infrastructure also caused changes to the system behavior. The removal of airports from the system prevented the expansion of the pool of SATS aircraft and prevented the construction of SATS airports. Otherwise, the system behaved normally because the model only includes nontowered public use airports. However, the airports stocks are important for the growth of the SATS. Removing Centers, TRACONs, Flight Service Stations, and Control Towers caused continuous reductions in the stocks of revenue, airports, personnel and all aircraft except SATS aircraft. Removing radar-based or GPS-based equipment caused an immediate decline in the population of all aircraft stocks. Subsequently, the revenue and infrastructure stocks declined as well.

5.2.11 Sensitivity Analysis

The sensitivity of the behavior of the modeled ATC system varies with each of the parameters in the model. If a parameter has a large influence on the range of behavior of the system, then it is important to establish the accuracy of the parameter to increase the validity of the model. The Vensim software contains procedures to conduct sensitivity testing using the Monte Carlo approach. The approach involves inputting randomly generated parameter values according to a selected probability distribution and a range of values for one or more parameters in the model. The approach also involves running 200 simulations using the randomly generated values, and then plotting the output within confidence bounds. The procedure is useful to determine how changes in estimates or assumptions cause changes in the numerical and graphical output of the model.

Table 5-8 below summarizes the results of the numerical sensitivity analysis. The results show that several key parameters can influence the size of the AATF. For all sensitivity runs, the modeled variables changed according to a random uniform distribution. For the runs below, the ATC system resource managers maintained the current radar-based system with a small annual investment in GPS equipment. Therefore, the runs below reflect the impact of the variable changes on the continuance of the current ATC system into the future with no significant increase in investment in the GPS-based approach to ATC. The determination of

Table 5-8: The AC aircraft and people parameters are the most sensitive influences on the AATF.

Parameter(s)	Normal Value	Low Value	High Value	Impact on AATF
Base year AC aircraft tax revenue (average annual increase = $28,835)	$1,133,000	$900,000	$1,250,000	Med
Base year AT, GA, and SATS aircraft tax revenue (average annual increase = $166)	$6,639	$5,000	$7,500	Low
Average annual increase AC aircraft tax revenue	$28,325	-$9,000	$50,000	High
Base year AT, GA, and SATS aircraft tax revenue; average annual increase	$166	-$167	300	Low
Interest rate for AATF	6.5%	6%	9%	Low
Base year salary per employee & Average annual FAA employee salary increase	$64,591 & $4,000	$50,000 & $2,000	$80,000 & $6,000	High
Radar & GPS equipment average annual cost	$90,000 & $460,000	$60,000 & $350,000	$120,000 $500,000	Low
AC/AT/GA Towers annual cost	$1,010,000 $420,000 $350,000	$900,000 $300,000 $250,000	$1,200,000 $550,000 $450,000	Low
Center/TRACON/FSS annual cost	$13,570,000 $670,000 $280,000	$8,000,000 $500,000 $200,000	$20,000,000 $800,000 $400,000	Low
Operating cost growth factor	3%	1%	6%	Low
Average annual increase in Grants-in-Aid	$170M	$120M	$444M	Low
Average controllers per AC/AT/GA tower, TRACON, Center, and FSS	18, 8, 5, 25, 375, 22	10, 4, 3, 15, 300, 15	30, 12, 7, 35, 450, 30	Medium
Average maintainers per controller, average maintainers per equipment	0.4, 1.09	0.2, 0.5	0.8, 2	Medium
AC/AT/GA Tower construction rate; AC/AT Tower closure rate	0.25, 0.5, 1.5; 0.125, 0.25	0.125, 0.25, 0.75; 0.06, 0.12	0.5, 1, 3; 0.25, 0.5	Low
Radar equipment replacement rate in AC/AT/GA towers	0.52, 0.37, 0.22	0.25, 0.18, 0.11	1.04, 0.74, 0.44	Low
Normal AC aircraft registration rate, AC aircraft operational life	0.07, 20	0.03, 10	1.5, 30	High
Normal GA growth rate, normal AT growth rate; GA aircraft operational life, AT aircraft operational life	0.038, 0.07; 30, 20	0.02, 0.3; 20, 10	0.08, 0.14; 40, 30	Medium

high, medium, or low impact resulted from a subjective evaluation of the relative effect of each parameter.

The sensitivity graphs below are representative of the types of results recorded in Table 5-8 above. The first two figures Figure 5-13 and Figure 5-14 show that the AATF is most sensitive to the tax revenue generated by AC aircraft and the salaries of FAA employees. Figure 5-13 indicates that there is the potential for a great deal of uncertainty in the AATF caused by variations in the amount of revenue generated by AC aircraft. The output indicates how much the AATF may change when the base year tax revenue for AC aircraft randomly varies from $900,000 to $1,250,000 and the average annual increase in AC tax revenue remains fixed at $28,325. The unusual shape of the output indicates a relationship with the accelerated retirements of controllers and maintainers during the first 20 years of the evaluated time period. Figure 5-14 indicates that FAA salaries may cause the AATF to increase exponentially under some conditions. The output indicates how much the AATF may change when FAA employee annual salaries vary from $50,000 to $80,000 and salary increases vary from $2,000 to $6,000. Employee salaries account for about 40% of the entire FAA budget; accordingly, the AATF is very sensitive to adjustments in salaries.

The third and fourth figures below indicate that the AATF is moderately sensitive to potential variations in the number of Maintainers in the ATC system and to variations in the AATF interest rate. The output in Figure 5-15 indicates how much the AATF may change when average Maintainers per controller and Maintainers per piece of equipment varies from 0.2 to 0.8 and 0.5 to 2.0. The system is very sensitive initially until narrowing to a tighter band of values at approximately 2010. Figure 5-16 shows how the AATF is not very sensitive to variations in the interest rate from 6% to 9%, indicated by the narrow band of potential values.

The fifth and final sensitivity graph shows that the AATF is barely sensitive to potential variations in the tax revenue collected for AT, GA, and SATS aircraft. The output in Figure 5-17 indicates how much the AATF may change when the base year tax revenue for AT, GA, and SATS aircraft randomly varies from $5,000 to $7,500 and the average annual increase in AT, GA, and SATS tax revenue remains fixed at $166. Revenue for the AATF from AT and GA aircraft only accounts for approximately 5% of the fund, thus, the AATF shows little sensitivity to variations in the AT, GA, and SATS revenue.

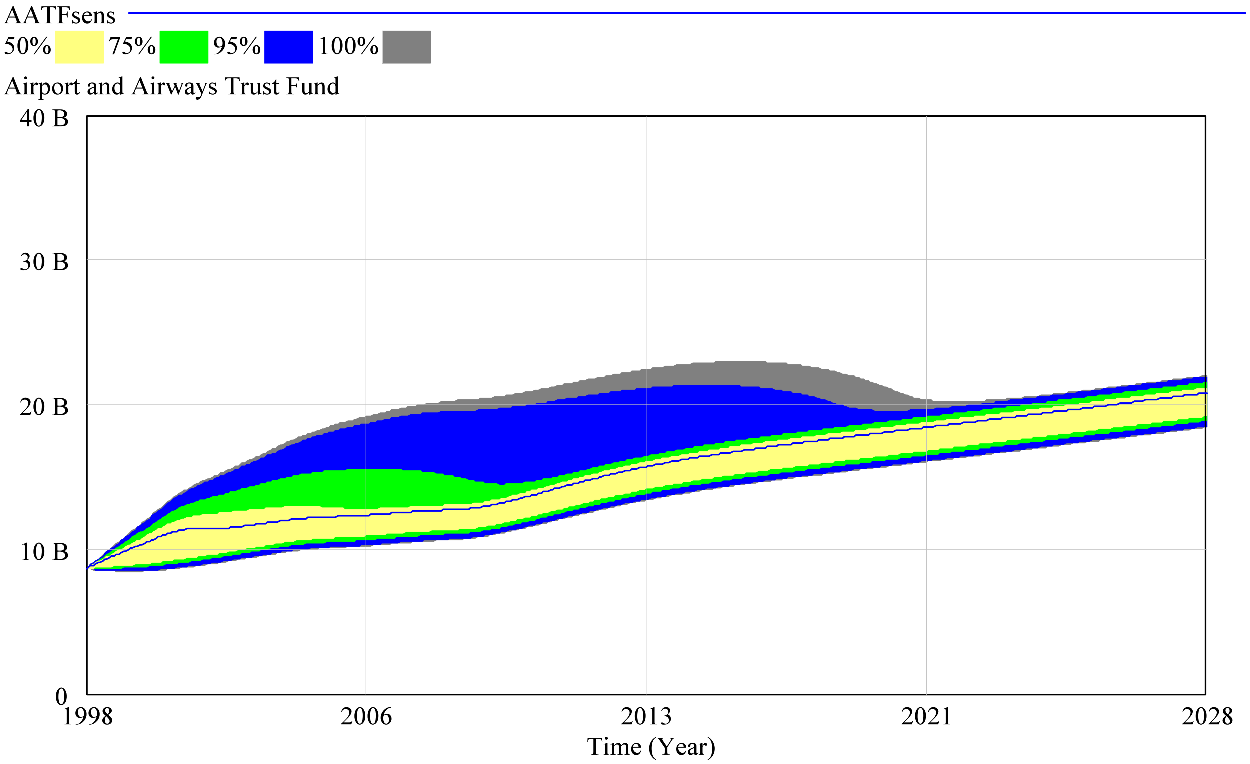

Figure 5-13: The base year tax revenue per AC aircraft significantly influences the AATF.

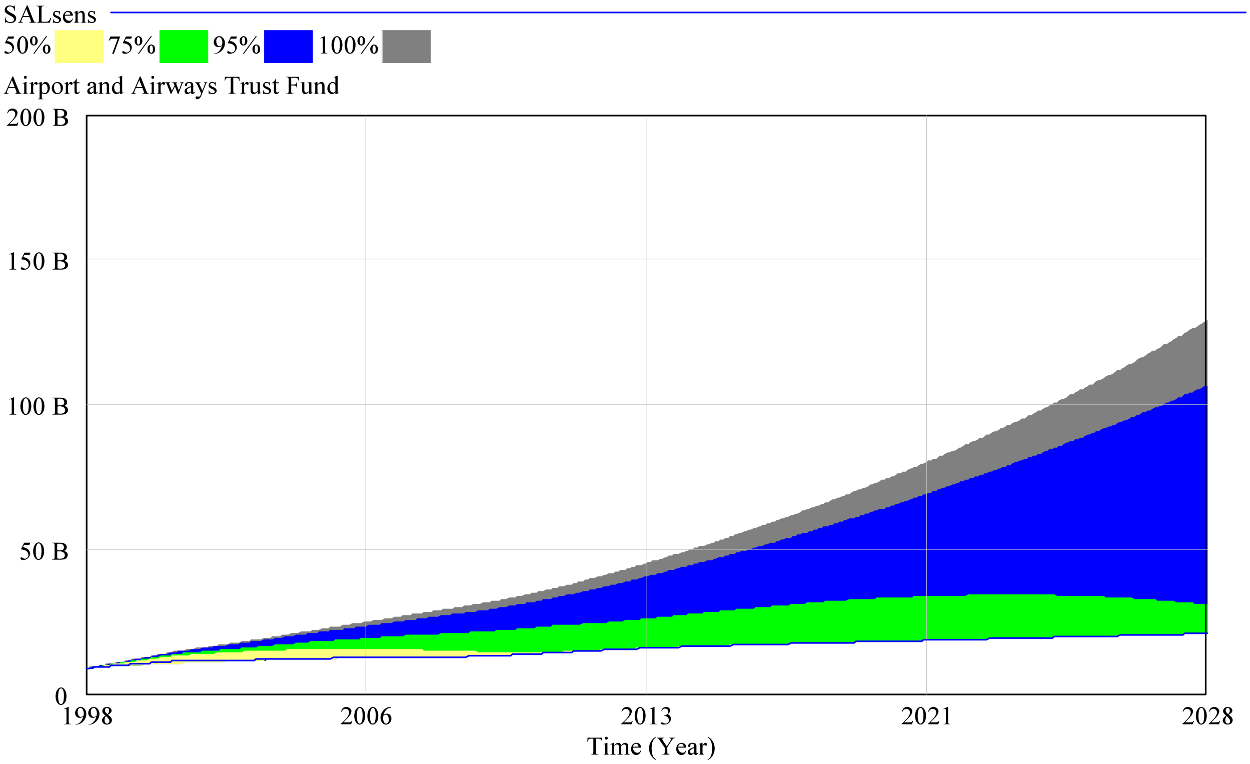

Figure 5-14: The AATF is very sensitive to the salary of FAA employees.

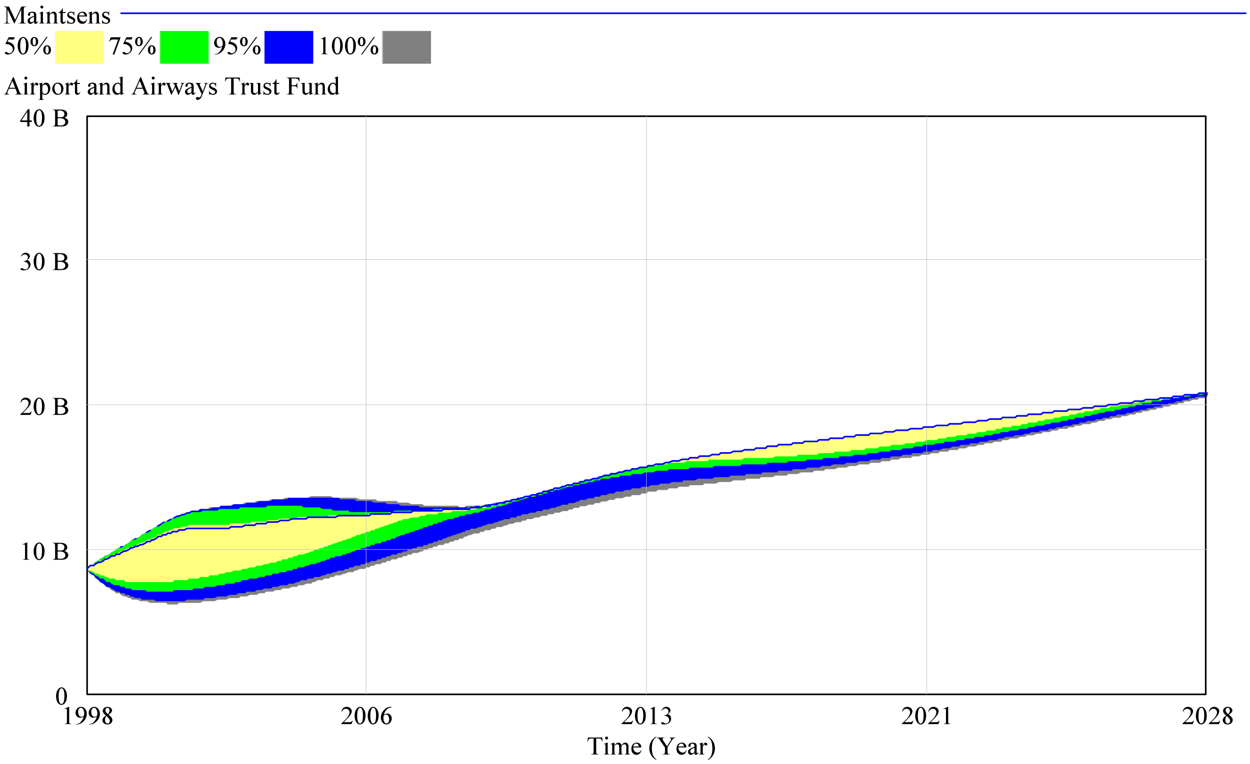

Figure 5-15: The AATF is moderately sensitive to the number of maintainers in the ATC system.

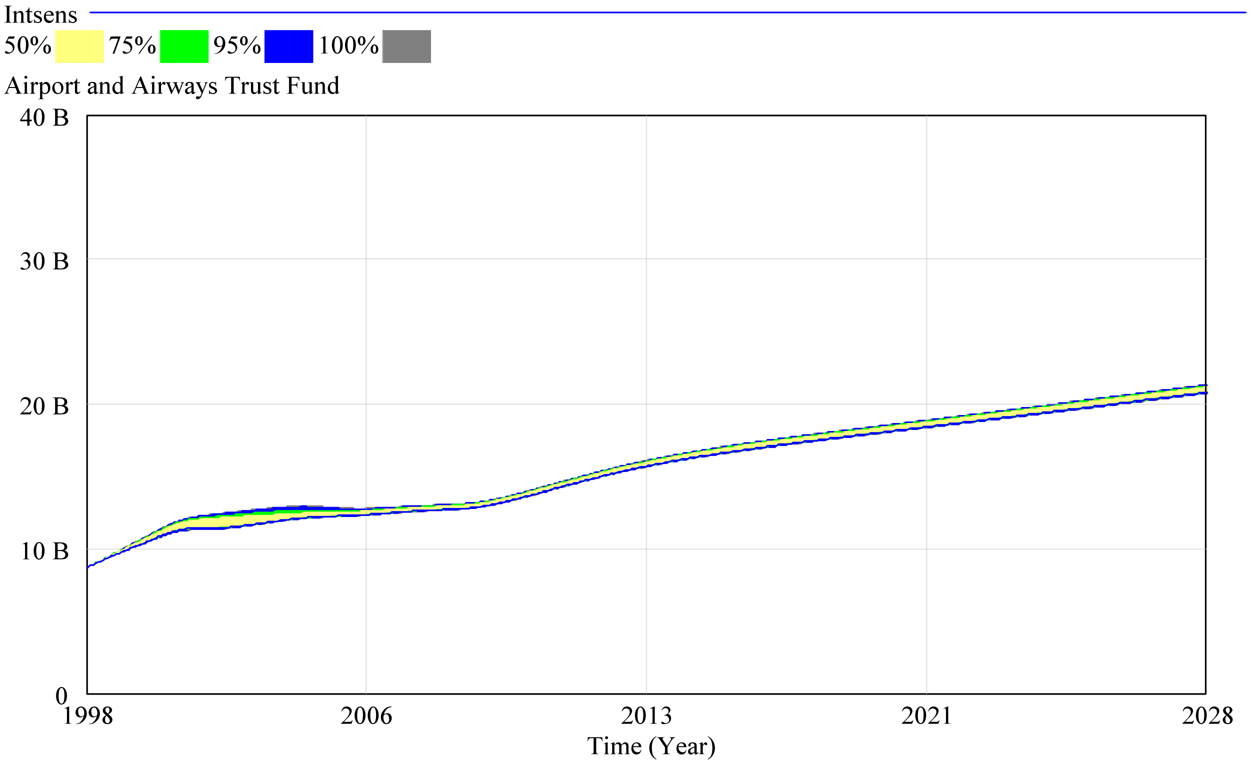

Figure 5-16: The AATF is barely sensitive to changes in the interest rate gained on uncommitted revenue.

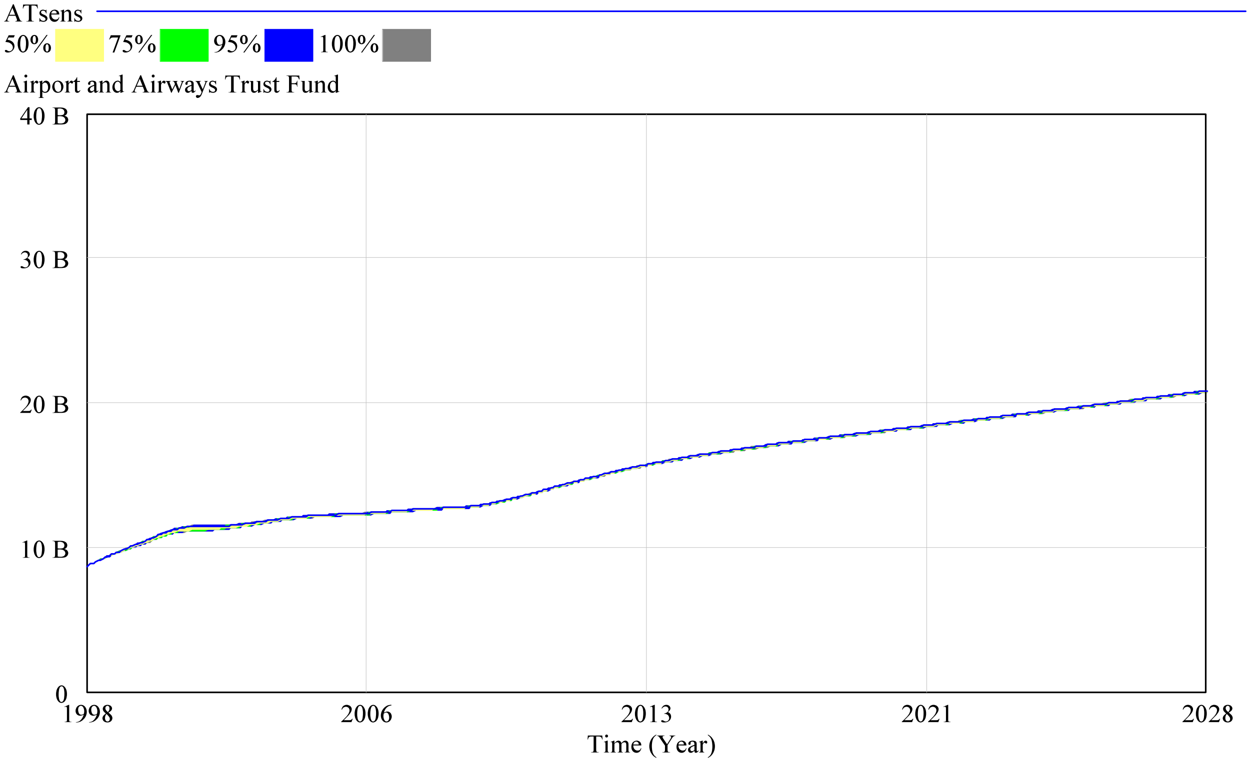

Figure 5-17: The base year tax revenue per AT, GA, and SATS aircraft has little influence on the AATF.

5.3 Summary

The verification and validation procedures discussed above provide evidence that the ATC Resource Management Model provides accurate and realistic results. The units in the model are consistent and the numerical relationships are sound. The model has adequate detail complexity and adheres to physical laws. The parameters in the model are reasonable and they create intuitively correct behavior when replaced with extreme values. The model structure has face validity; it exhibits normal behavior under various time steps and integration techniques. The model generated reasonable results when reproducing ATC system behavior in the 1990s. Finally, sensitivity analysis identified those parts of the model that have the greatest potential to influence the results. The next chapter will describe the application of the model and the results derived from it.

Chapter 6: Simulation, Analysis, and Results

Chapter six presents a discussion of the results of the simulation and the analysis of the three scenarios used to address the research questions. The first section presents an overview of the three scenarios. The second section presents the base case conditions in the first scenario when the resource management strategies support an ATC system continuing to operate as a primarily radar-based system. The third section presents the resource management conditions that cause the system to undergo an intentional transition toward the GPS-based approach to ATC in the second scenario. The fourth section presents a resource management strategy designed to create a balanced combination of both radar- and GPS-based ATC in the third scenario.

The intent of this chapter is to illuminate the evidence and interpret it so as to arrive at the proper conclusion. Specifically, the simulation and analysis should lead to a determination of what air traffic control resource management strategy will support the future needs of the SATS and create adequate tax revenue to fund the FAA. The development of the model in chapter four and validation of the model in chapter five indicated that the resources generated by the AATF are necessary to support SATS and provide money to run the FAA.

Essentially, the adequacy of the revenue generated for the AATF determines if the system will be viable. The amount of money generated under each resource management scenario will serve as a measure of viability. The strategy is viable if the amount of FAA funding required from the General Fund does not exceed 20% of the FAA budget. The other two key variables used to evaluate the merit of each resource management strategy are the numbers of SATS aircraft and airports. Other metrics useful to understand and interpret the behavior of the system include: the ratio of aircraft to airports, the control tower growth rate, the distribution of funds across the major accounts of the FAA budget, the amount of money appropriated by Congress for the FAA, and the conversion of public use airports into SATS airports.

6.1 Three ATC Scenarios

The valid model is useful to investigate the behavior of the ATC system with respect to two primary influences. The first influence, an endogenous influence, alters system behavior due to feedback from the values of the stocks within the system. For example, the AATF provides funds to the FAA budget to pay for air traffic control towers. Changes to the population of air traffic control towers influences the population of aircraft in the system. Subsequently, changes in the aircraft population causes changes in the taxes collected for the AATF, which changes the budget for control towers. Through feedback loops, the system behaves in a manner that seeks growth and balance. The second influence, an exogenous influence, alters system behavior because of management intervention to adjust the flow of dollar resources that pay for facilities, equipment, and airports. For example, the desired level of support for GPS-based ATC causes changes in the stocks of radar-based ATC facilities and equipment, which ripples through the system by means of feedback loops.

In the model, managers distribute resources to support the radar-based or GPS-based approach to ATC. The purpose of modeling the two influences is to determine what air traffic control resource management strategy will support the future needs of the Small Aircraft Transportation System and create adequate tax revenue to fund the Federal Aviation Administration. The exogenous influences of the resource management strategy set the stage for three scenarios that the model supports. The endogenous influences of the feedback loops among the stocks in the system generate behavior that provides information to evaluate the best resource management strategy.

6.1.1 Scenario 1: Maintain the Radar-Based System

The first resource management strategy is to maintain the current ratio of spending for radar-based ATC and GPS-based ATC airports, equipment, and facilities.

Figure 6-1 depicts the continuation of the current resources management practices in the first scenario that consist of providing GPS related funding to purchase only GPS-based ATC equipment. Radar-based equipment receives 93% percent of all money provided for equipment. Airports and facilities receive funding only for radar-based ATC requirements.

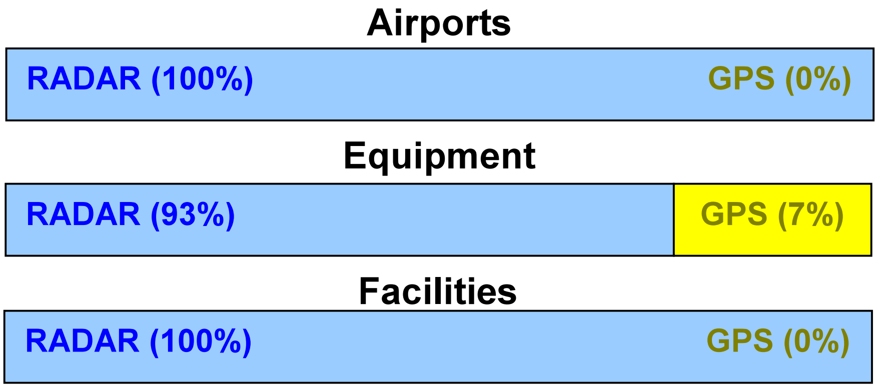

Figure 6-1: The first scenario maintains the resource management practices of the current ATC system.

6.1.2 Scenario 2: Maximize funding for the GPS-Based System

The second resource management strategy is to rapidly transition to a GPS-based ATC system by directing the preponderance of new spending toward GPS equipment and SATS airports. In scenario 2, funding for radar-based ATC pays to maintain the established radar-based system while accelerating the retirement of radar-based facilities and equipment. As depicted in Figure 6-2, scenario 2 ceases investment in new airports, facilities, or equipment. Scenario 2 initiates a transition to GPS-based ATC while continuing to operate radar-based ATC required to support the commercial airline industry. The resource management strategy accelerates the elimination of facilities and equipment associated with GA and Air Taxi operations. Accordingly, radar-based equipment receives a maximum of 30% percent of all money provided for equipment. Airports receive funding to transition to SATS airports. Otherwise, the radar-based ATC system receives money to continue operation of the existing infrastructure without replacement of retired facilities and equipment.

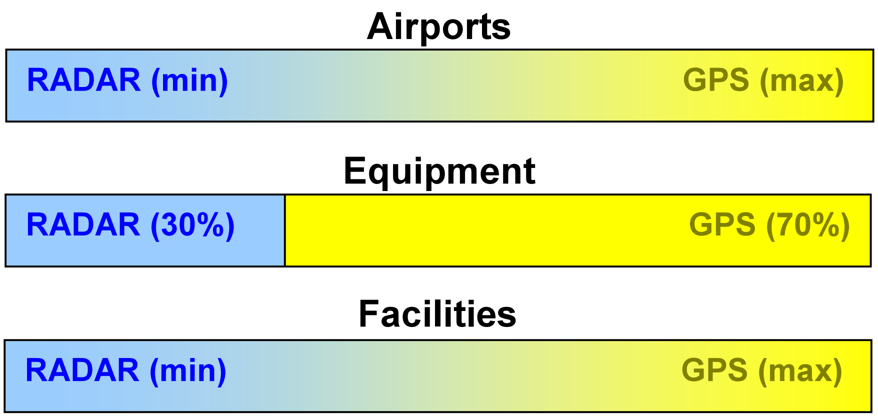

Figure 6-2: The resource management strategy for the second scenario attempts to rapidly transition to GPS-based ATC.

6.1.3 Scenario 3: Supplement the Radar-Based System

The third resource management strategy consists of a moderate transition to a combined GPS- and radar-based ATC system. Funding for radar-based ATC pays to maintain the established radar-based system and replace some of the retired radar-based facilities and equipment. Simultaneously, the GPS-based ATC system expands through increased funding for GPS-based equipment and acceleration of the transition of airports into SATS airports. Figure 6-3 depicts scenario 3 as a blend of both ATC capabilities.

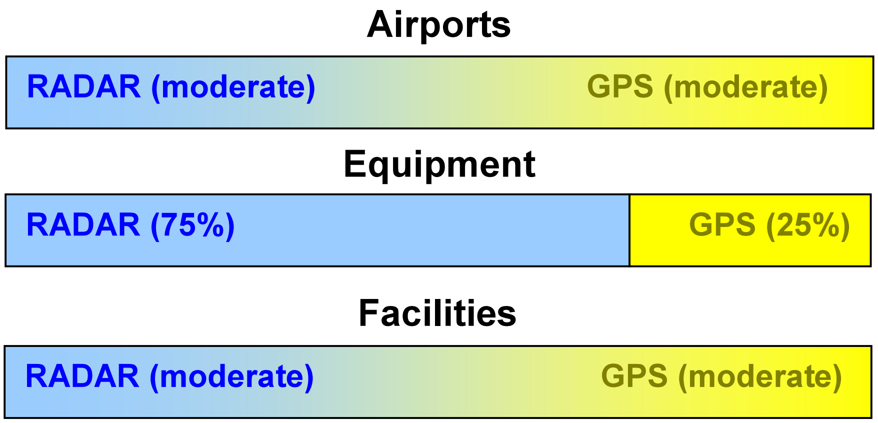

Figure 6-3: The third scenario attempts to strike a balance between growth of GPS-based ATC and contiuity of the radar-based system.

6.2 Scenario 1: Simulation and Analysis of the Radar-based System

The first scenario serves as a baseline for comparison to the other two scenarios. The first scenario represents continuation of the FAA's current means of controlling air traffic by using radar-based facilities, equipment, and procedures. Although the resource management strategy in Scenario 1 includes a small amount of funding for GPS-based ATC, resource managers develop the FAA budget to maintain or expand the radar-based approach to ATC in the first scenario. The simulation represents the 30-year time period from 1998 to 2028. The simulation occurs over that time period because NASA planners anticipate it will be feasible to develop SATS aircraft and establish a system of SATS airports and infrastructure by 2025 (NASA, 2000a).

6.2.1 Simulation of the Radar-based System

The simulation of the radar-based system demonstrated that the FAA will have sufficient resources to support its mission to provide air traffic control, however, the Small Aircraft Transportation System will not have sufficient resources to grow. Table 5-2 and Table 5-3 above contain the initial stock and parameter values used in the base case. All the stocks are endogenous to the system. The only exogenous variable, which is zero for scenario 1, is the policy for the maximum percent of available funding resource managers should invest in the GPS-based ATC system. Otherwise, all variables in the model are endogenous and reside in feedback loops. The only major component of the model that is not endogenous is the Grants-in-Aid account. The model contains a function to calculate the value of the Grants-in-Aid account from a base year value and an annual growth rate that aligns with historical trends. Since the first scenario represents continuity of the past FAA resource management strategy, managers do not influence any of the variables any differently than they normally would.

The figures below contain output that describes the system's behavior. The x-axis of each graph represents the time period 1998 through 2028. The y-axis provides values for the stocks in the model, parameters, or other metrics. The graphs depict the growth or decline of system variables over time if the FAA continues to utilize a resource management strategy that supports the radar-based approach to ATC. Figure 6-4 through Figure 6-6 describe the flow of money through the major accounts of the budget. Figure 6-7 and Figure 6-8 show the flow of air traffic controllers and system maintainers. Figure 6-9 through Figure 6-14 depict the changes in the Facilities and Equipment stocks. Figure 6-15 to Figure 6-18 illustrate the growth or decline of the four aircraft stocks. Figure 6-19 and Figure 6-20 portray the adjustments in the growth or decline of non-SATS or SATS airports.

Figure 6-4 depicts the general pattern of growth exhibited by the AATF under the first scenario. Figure 6-5 shows an FAA budget growth pattern that aligns with the AATF growth. Figure 6-6 shows the amount of funding the FAA requires from the General Fund to account for the shortfalls in the AATF. Overall, the future flow of revenue and resources represents feasible and acceptable conditions to enable the future operation of the ATC system.

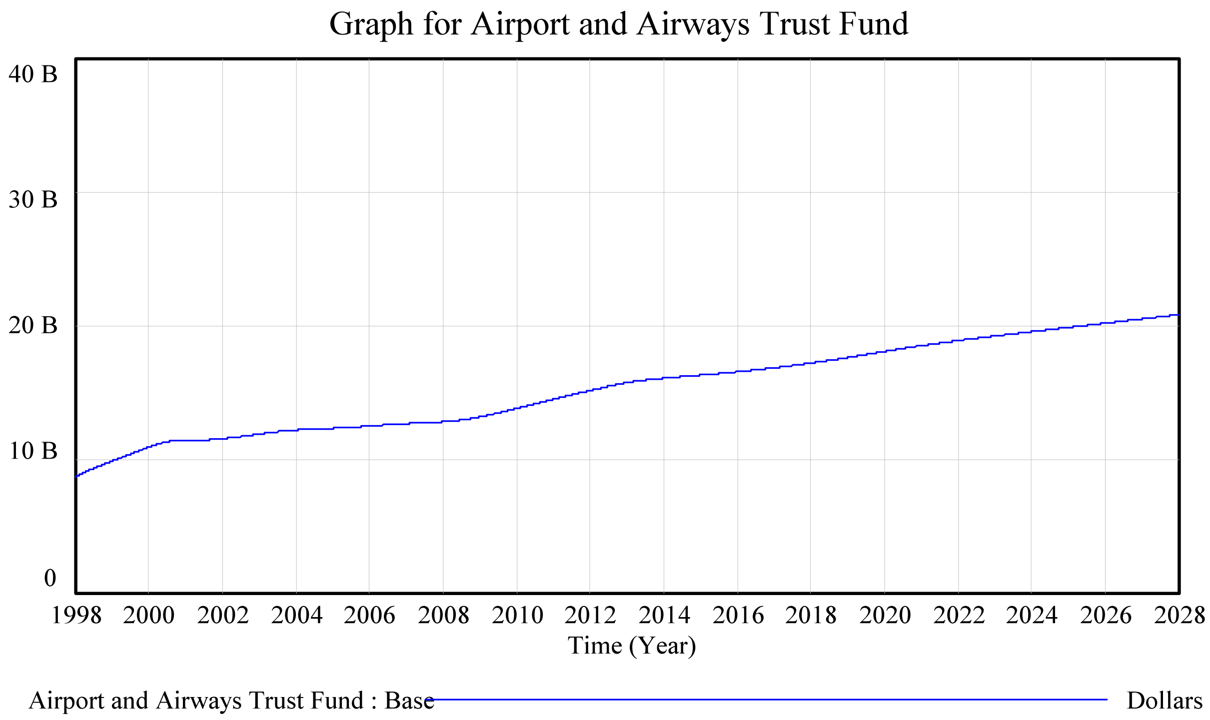

Figure 6-4: Revenue generated by the Airport & Airways Trust Fund shows a general growth trend.

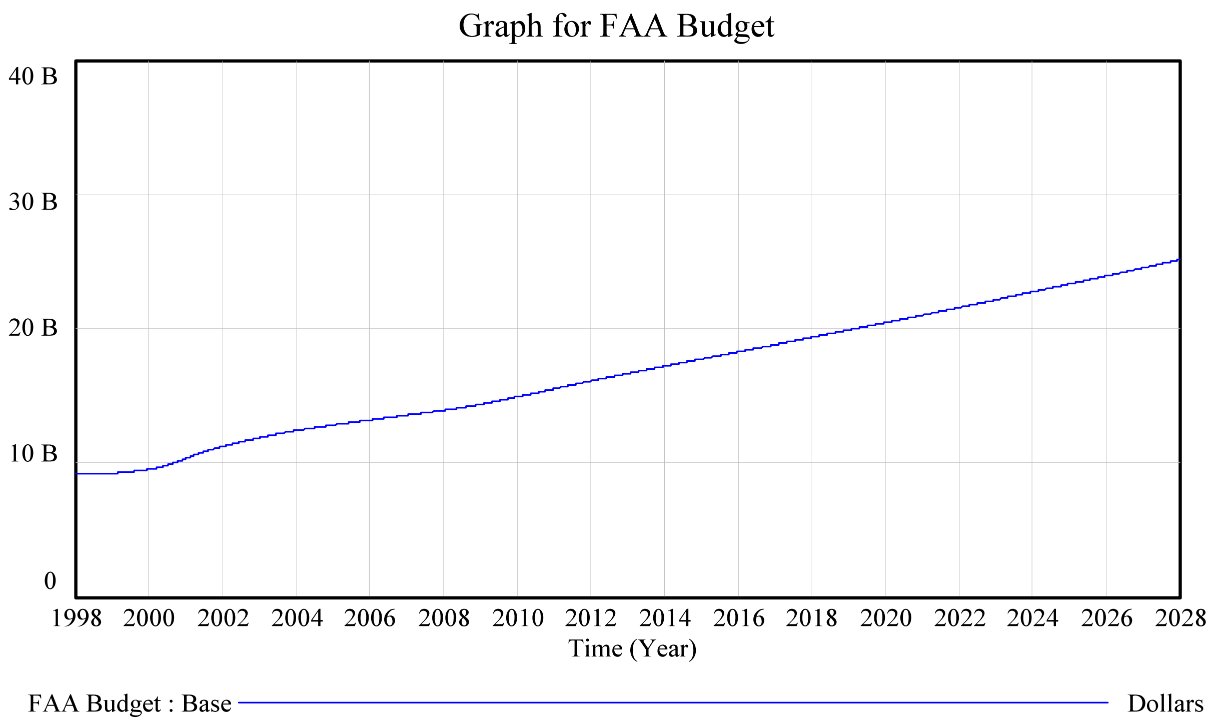

Figure 6-5: Future FAA budgets will continue to grow.

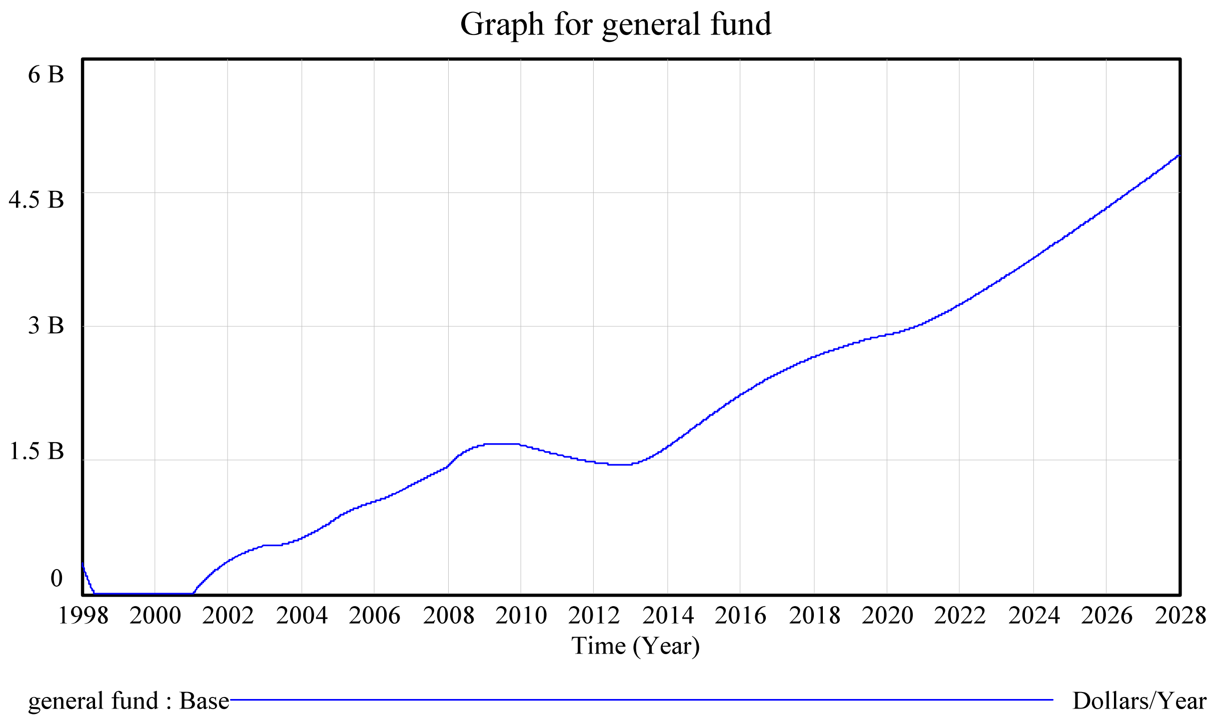

Figure 6-6: Congress supplements the FAA budget when there are AATF shortfalls.

The following charts describe the behavior of three other parts of the ATC system: the people, the facilities, and the equipment. Figure 6-7 depicts the changes in the numbers of Air Traffic Controllers. There is decline of about 4,000 controllers during the first ten years of the model, largely attributable to the retirement surge between 2003 and 2008. The system appears to seek equilibrium of approximately 19,000 controllers. Figure 6-8 illustrates the changes in the number of maintainers over time. Similar to the controllers, the maintainers undergo a long steady decline in number due to retirements. Eventually, the training of new hires compensates for the decline. The trend in facilities growth in Figure 6-9 through Figure 6-12 indicates continued expansion of both Flight Service Stations and control towers. The FSSs portrayed in Figure 6-9 primarily serve the non-commercial air traffic and the three types of control towers depicted in Figure 6-10 to Figure 6-12 all serve a core portion of the aviation system. Under the conditions of the first scenario, all three types of control towers show steady grow, with GA towers being the most expansive. The radar-based equipment portrayed in Figure 6-13 neither grows nor declines due to moderate system expansion offset by technological efficiencies. A lack of resources constrains the growth of the stock of GPS equipment in Figure 6-14.

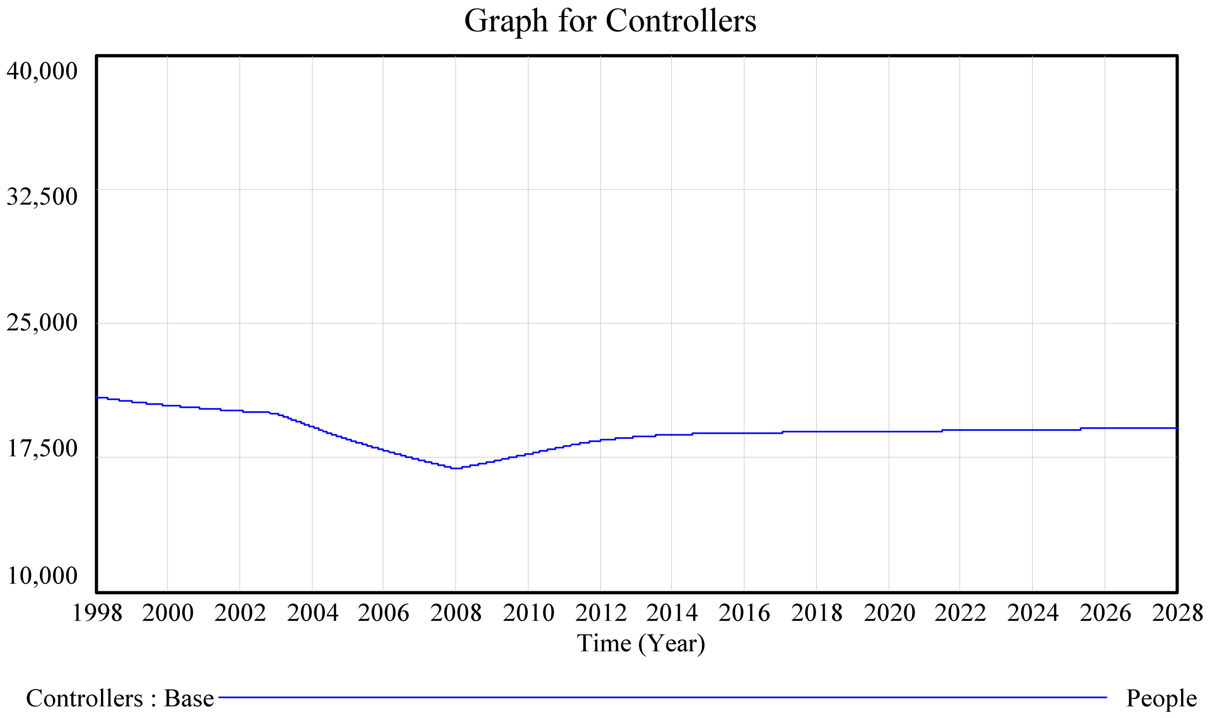

Figure 6-7: Retirements cause an initial decline in the controller population.

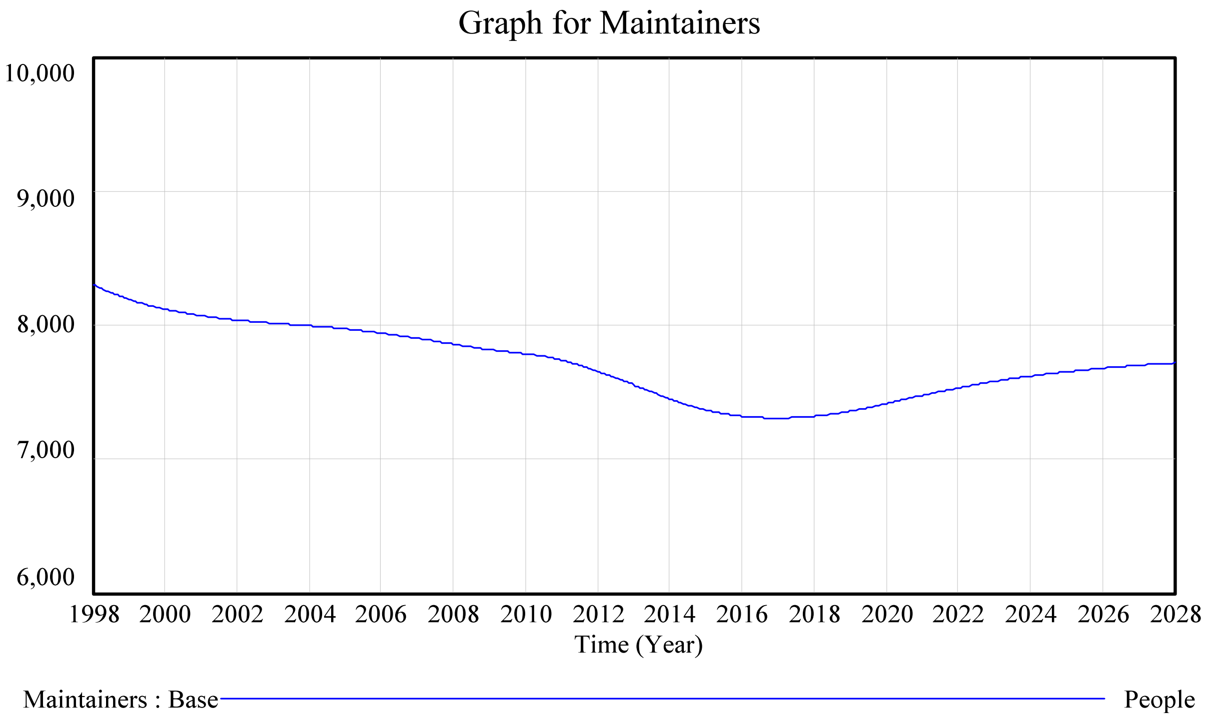

Figure 6-8: The maintainer-training program eventually compensates for retirements.

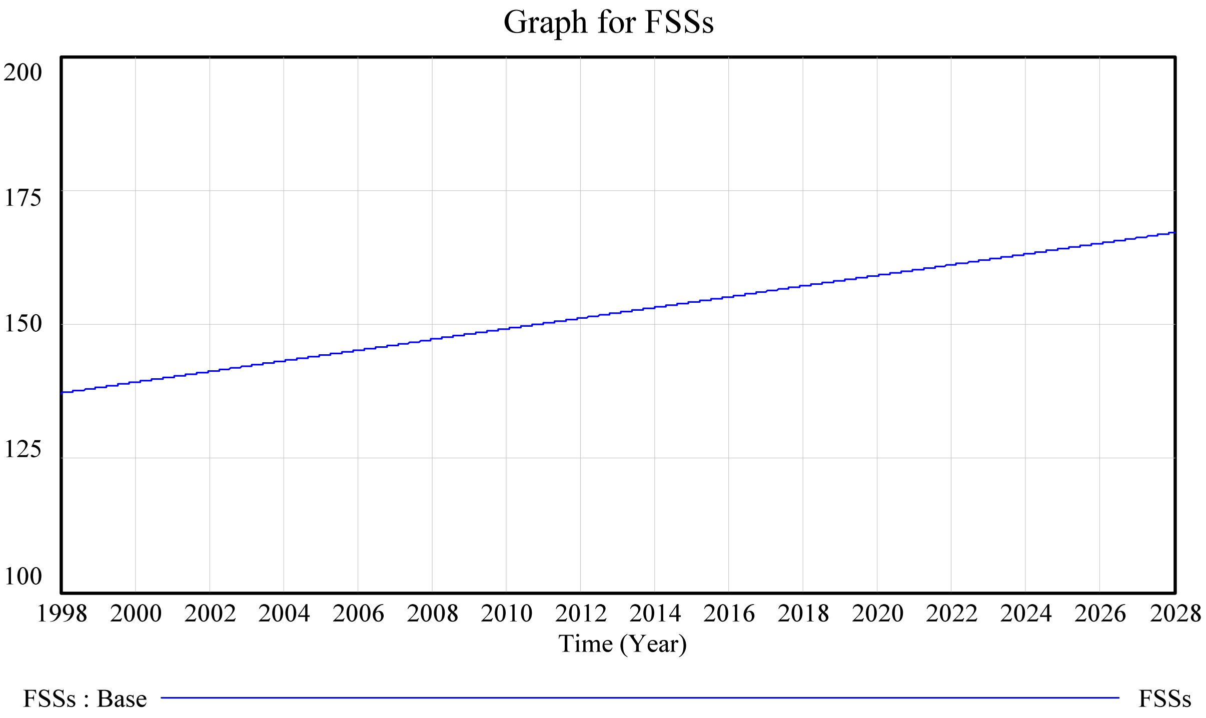

Figure 6-9: Flight Service Stations continue a steady climb in number.

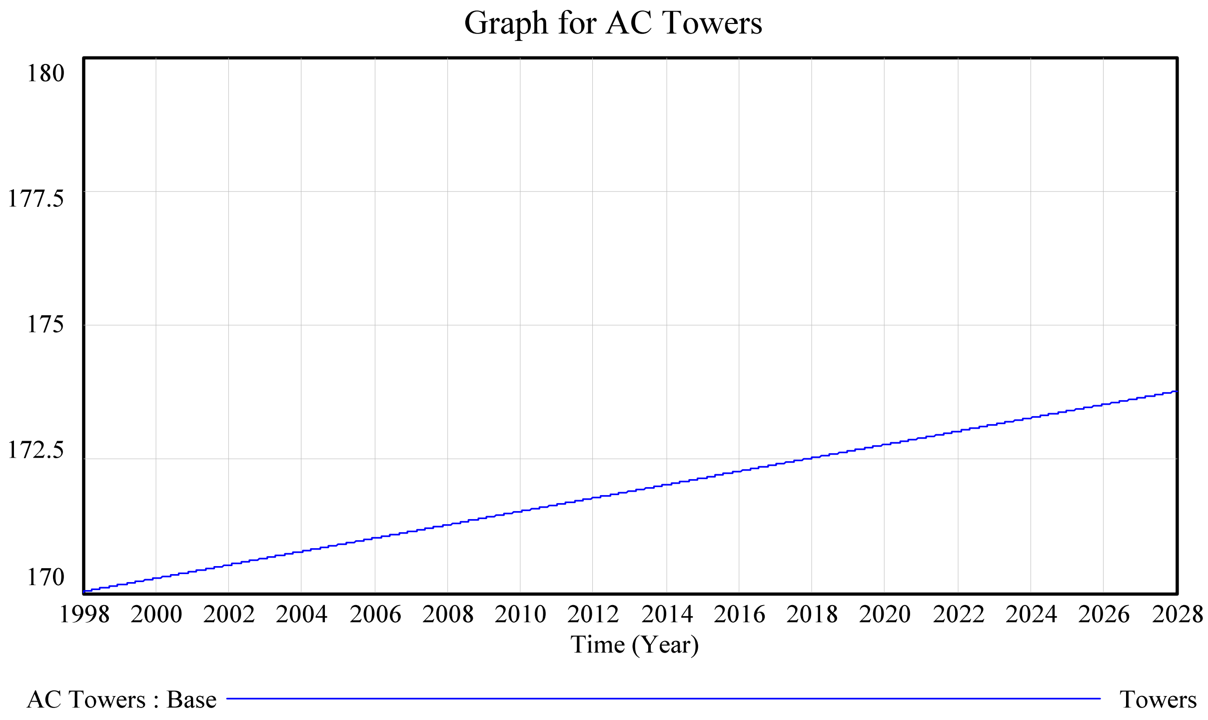

Figure 6-10: There are few locations to create more control towers for airliners.

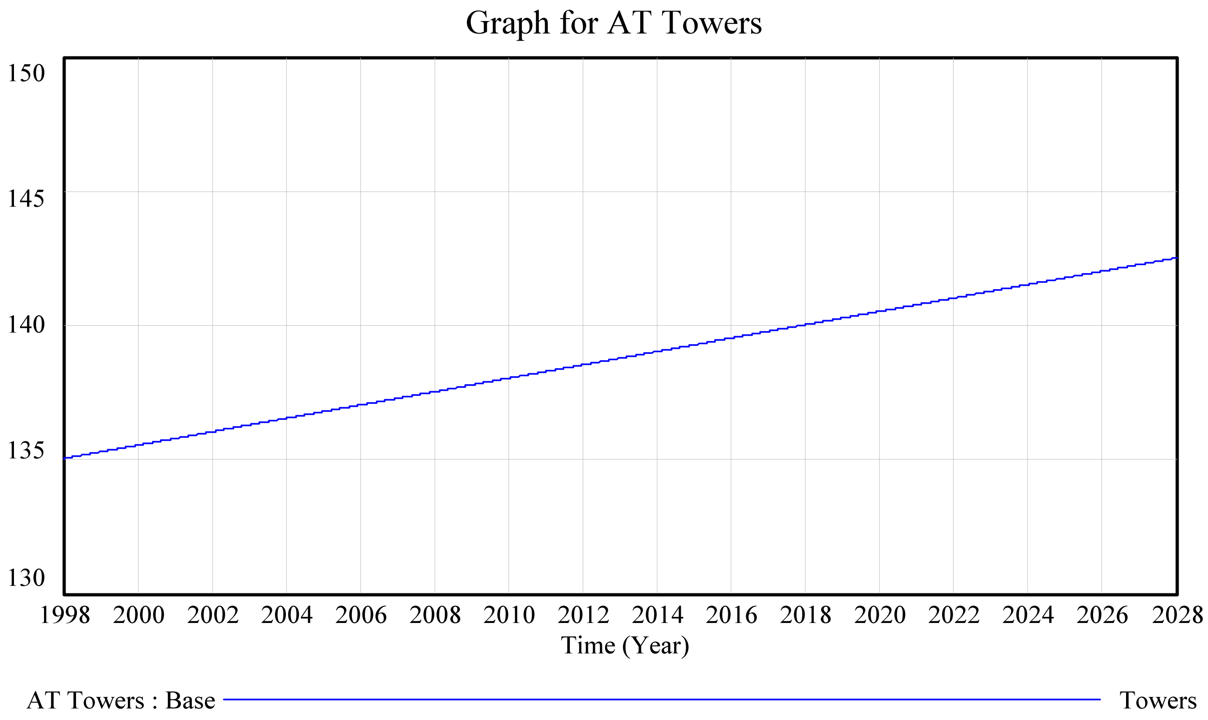

Figure 6-11: Radar-based ATC will require more control towers at Air Taxi airports.

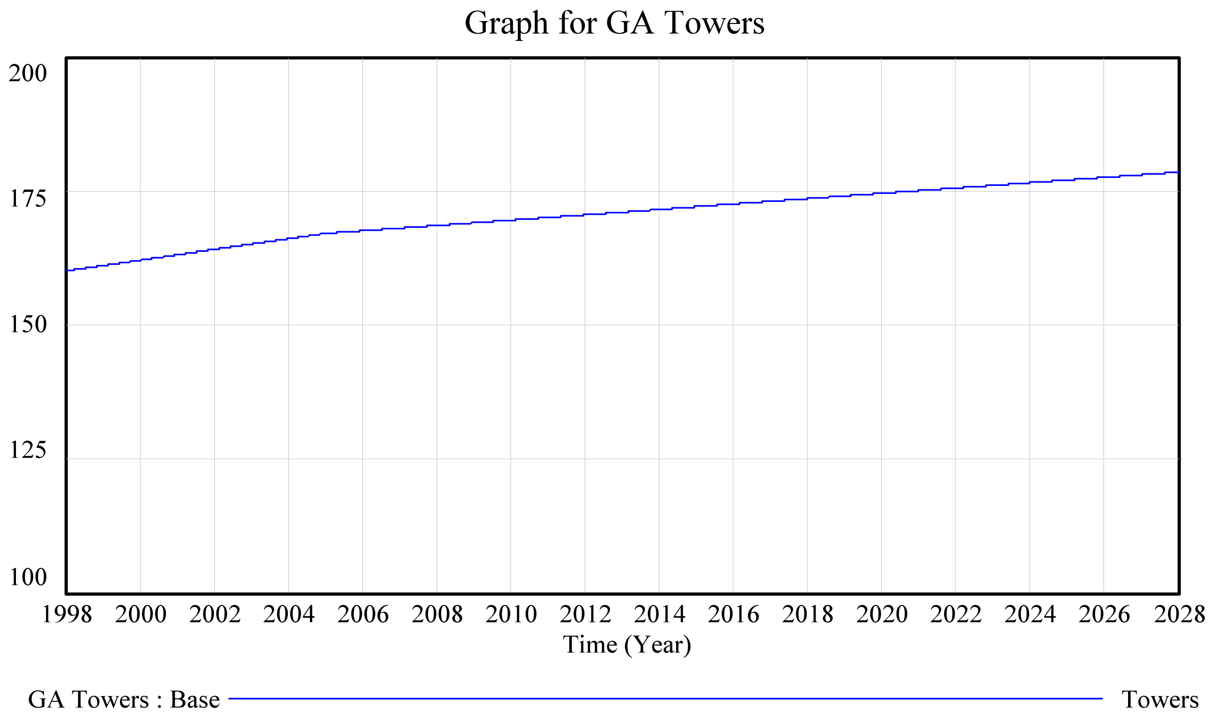

Figure 6-12: General Aviation control towers will continue to grow in numbers.

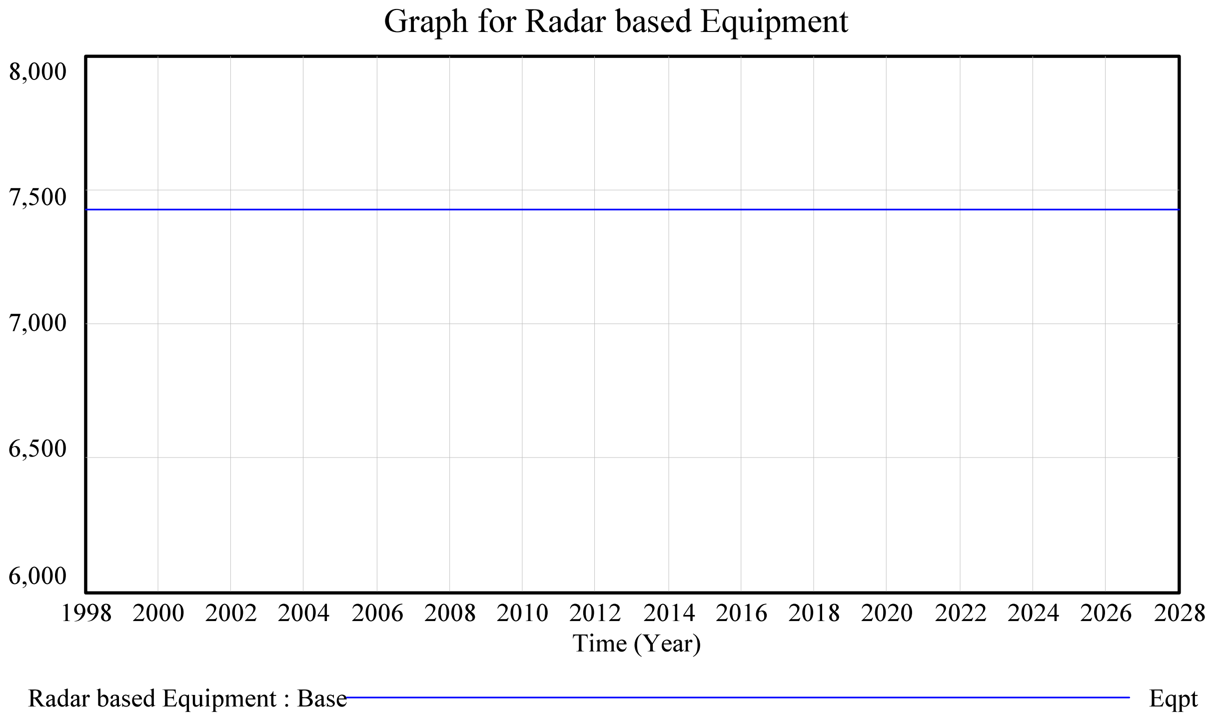

Figure 6-13: The pool of radar-based equipment remains constant in the first scenario.

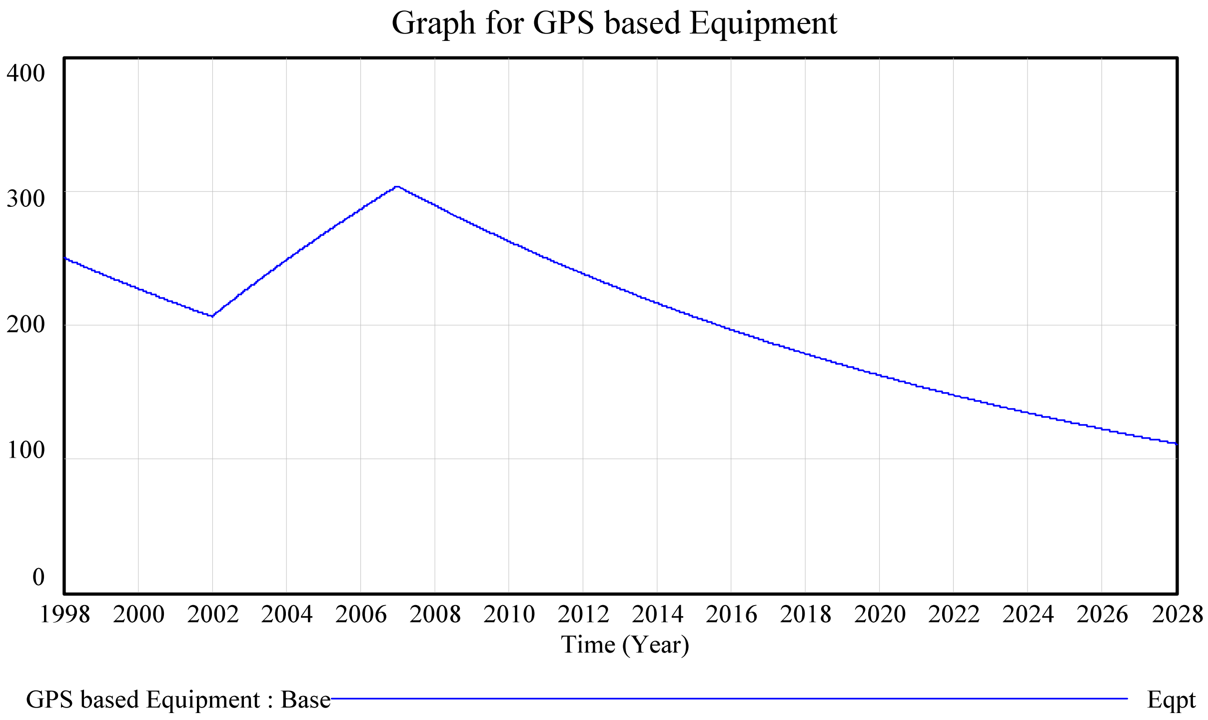

Figure 6-14: The GPS-based equipment decommission rate eventually overtakes the installation rate.

The model addresses two other key parts of the ATC system: aircraft and airports. Figure 6-15 to Figure 6-18 describe the populations of AC, AT, GA, and SATS aircraft. The AC aircraft in Figure 6-15 plateau in number around 2010 due to inherent limitations in the ATC system. The timeframe and behavior of the AC population also corresponds with the NASA study discussed previously in section 2.1 and depicted in Figure 2-3. The AT and GA aircraft show continued growth in Figure 6-16 and Figure 6-17, unconstrained by the more restrictive limitations of the ATC system placed on the AC aircraft. The number of SATS aircraft, depicted in Figure 6-18, does not grow beyond a minor experimental fleet in the first scenario, due to a lack of supporting GPS infrastructure.

Figure 6-19 and Figure 6-20 capture the changes in the population of SATS and non-SATS airports. The non-SATS airports in Figure 6-19 continue to decline in number due to the normal demise of public use airports at the rate of approximately one every two weeks. The growth in SATS airports in Figure 6-20 during the first scenario results from a modest conversion rate of one public use airport into a new airport every two years to support the experimental fleet of SATS aircraft.

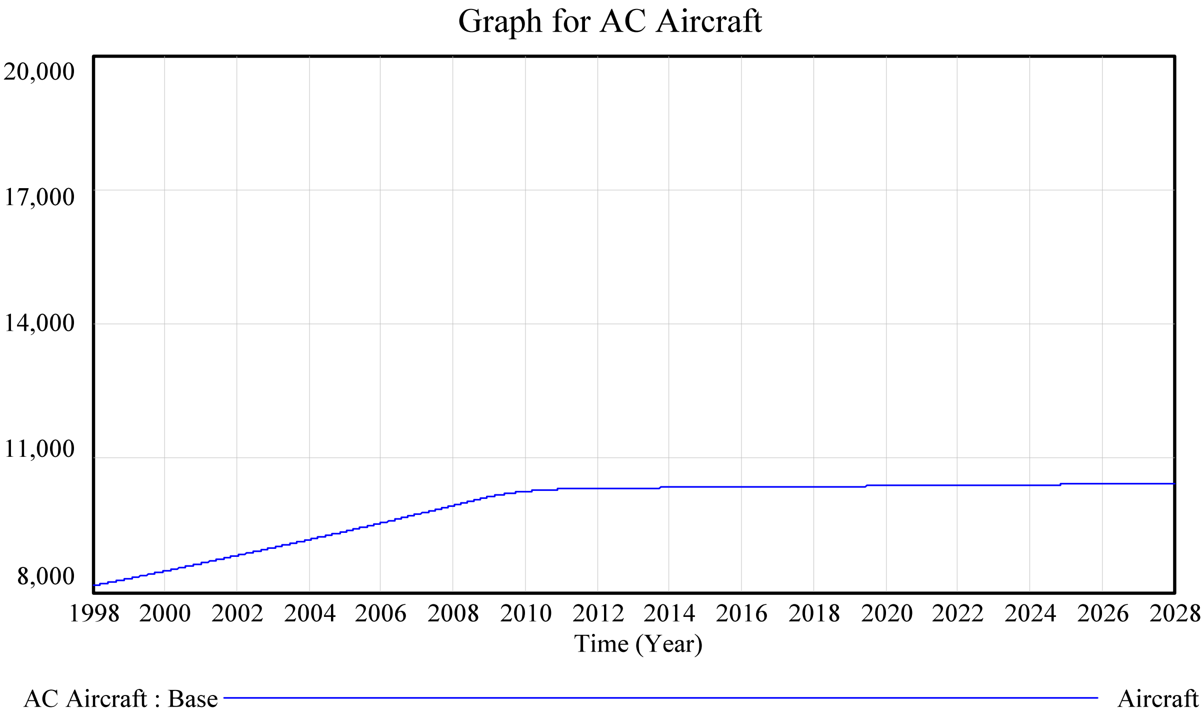

Figure 6-15: Inherent constraints in the ATC system restrict the growth in the number of AC aircraft.

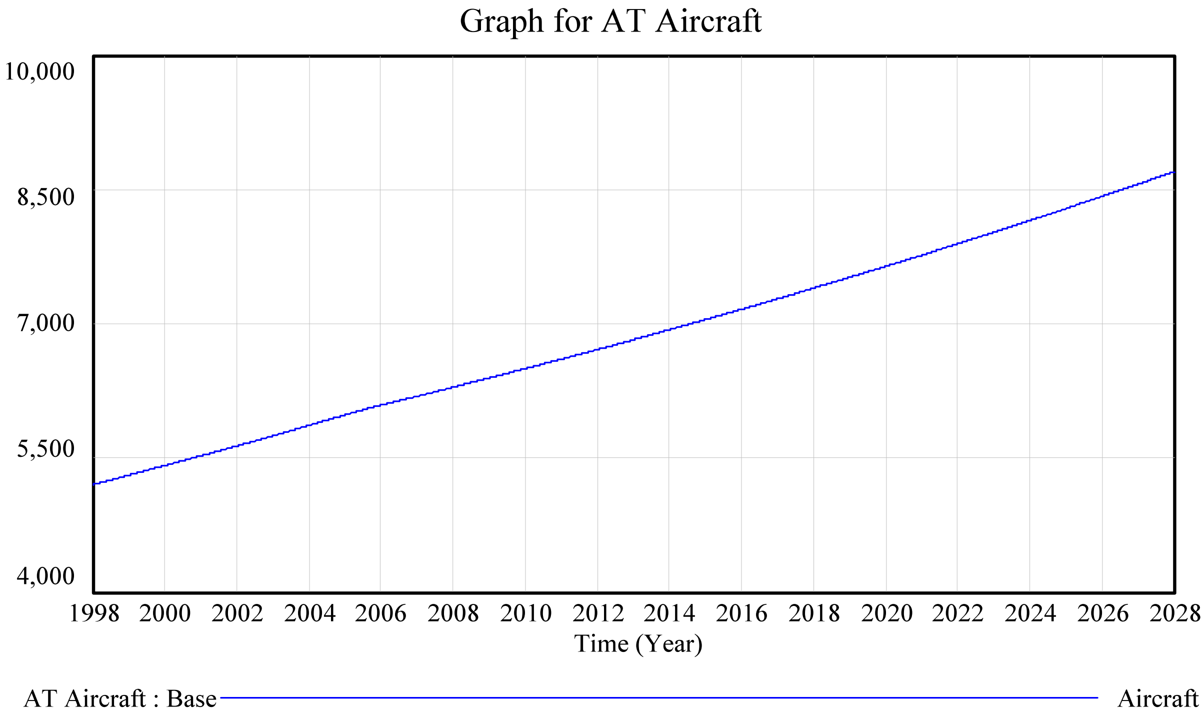

Figure 6-16: The population of AT aircraft growth significantly in the first scenario.

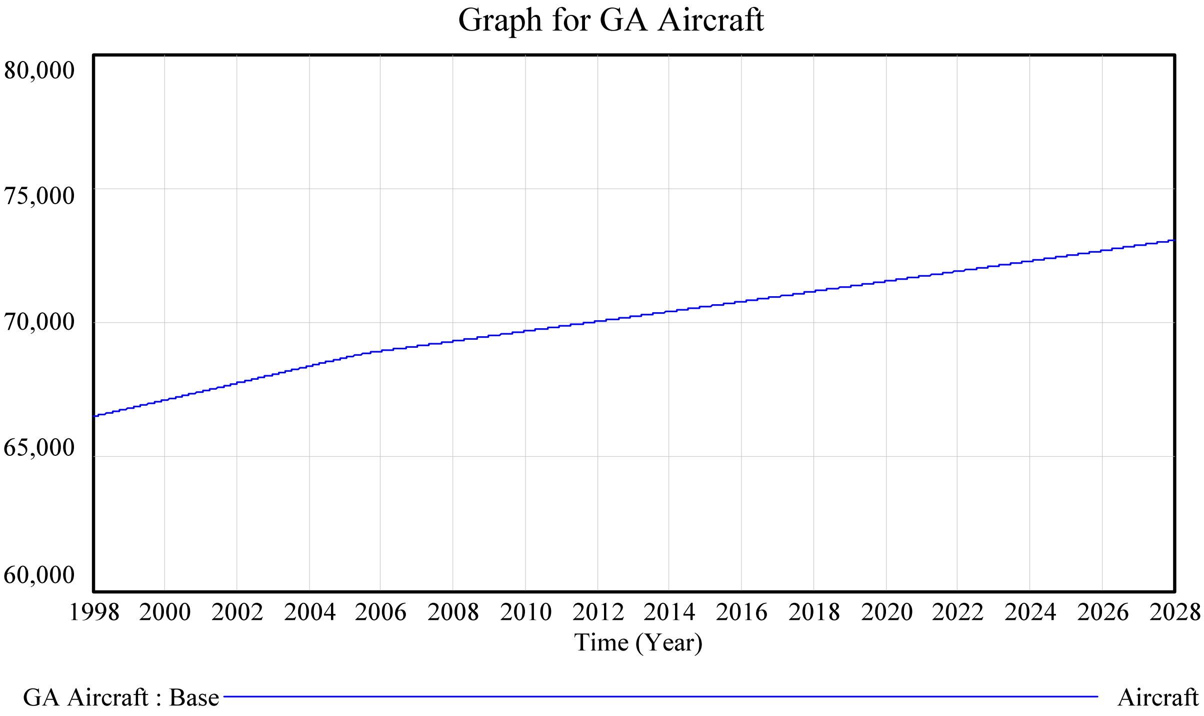

Figure 6-17: The number of GA aircraft grows continuously in a radar-based ATC system.

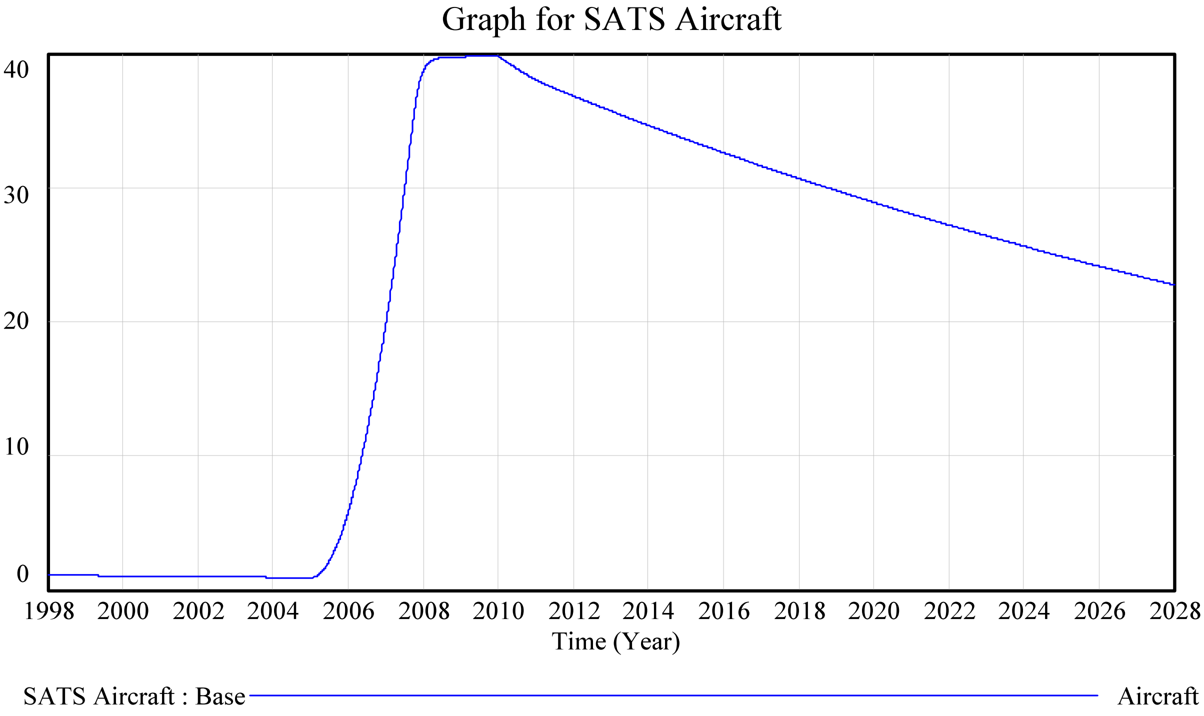

Figure 6-18: The lack of GPS support precludes the growth of the SATS program.

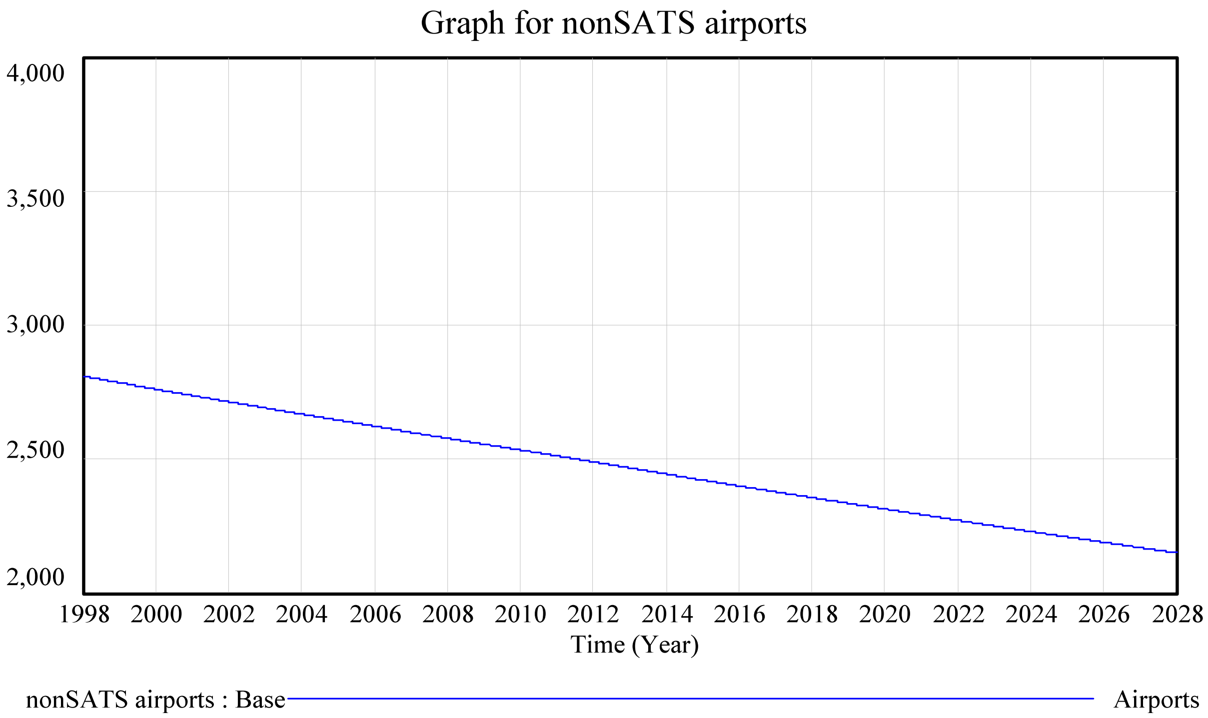

Figure 6-19: Non-SATS airports decline at a rate of approximately two per month.

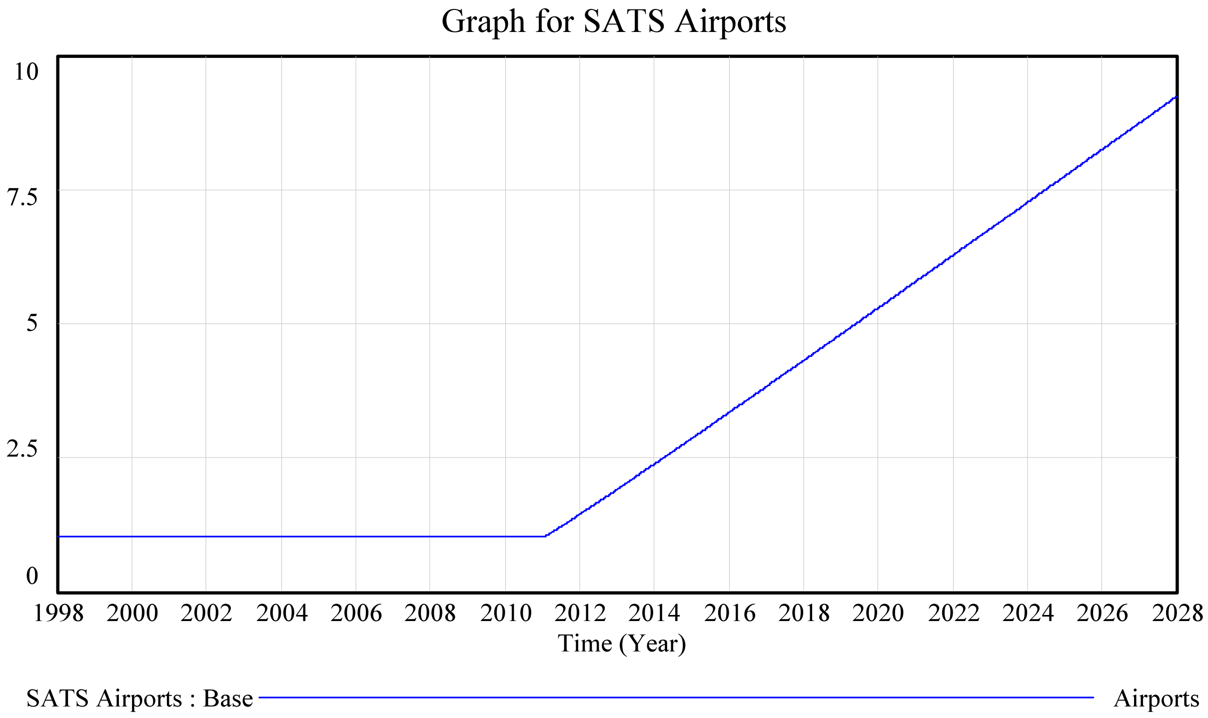

Figure 6-20: A modest growth rate creates a handful of SATS airports in the first scenario.

6.2.2 Analysis of Scenario 1

The results of the ATC Resource Management Model for the first scenario showed that the ATC system will continue to function almost as it has for the past decade. Nevertheless, there are several exceptions to the normal behavior patterns: GPS equipment enters the system and slowly fades away, AC aircraft growth plateaus, radar-based equipment plateaus, and a modest amount of SATS aircraft and SATS airports enter the ATC system. However, the SATS does not establish itself and survive as a transportation system. Despite the exceptions to normal behavior, the first scenario includes two components that allow it to serve as a good baseline. First, the scenario includes a viable radar-based ATC system, and second, the scenario will not support the growth of the SATS.

Several characteristics of the system indicate that it will continue to operate as viably as it had in the past. First, the flow of dollar resources provides adequate revenue to the AATF, which in turn supports the requirements emanating from the FAA budget. Table 6-1 shows that the requirements of the FAA budget continue to generally align with those of the past. Some of the funding appears to migrate from the Facilities and Equipment account to the Grants-in-Aid account. Second, Figure 6-21 shows how the growth in facilities, in this case control towers, also reflects past growth trends. However, the model growth is less aggressive than the actual growth exhibited in the 1990s. The decline in growth rate makes sense in light of the plateau of AC aircraft, which may indicate a reduction in overall system growth. Third, the ratio of the number of AT and GA aircraft per airport (IFR capable aircraft per the pool of 2,400 Public Use airports), which varied between 20 and 30 IFR aircraft per airport in the 1980s and 1990s, grew steadily into the upper 30s in the model as illustrated in Figure 6-22. However, the decline in the number of available airports depicted in Figure 6-19 above explains why the aircraft to airports ratio grew so much.

Table 6-1: The distribution of resources among the major accounts of the FAA budget changes slightly.

Account	2000	2004	2008	2012	2016	2020	2024	2028	1991 – 2002
Grants	19%	25%	28%	27%	28%	29%	29%	29%	**22%**
Ops	60%	54%	52%	54%	54%	55%	55%	56%	**54%**
F&E	20%	21%	21%	19%	18%	17%	16%	15%	**23%**

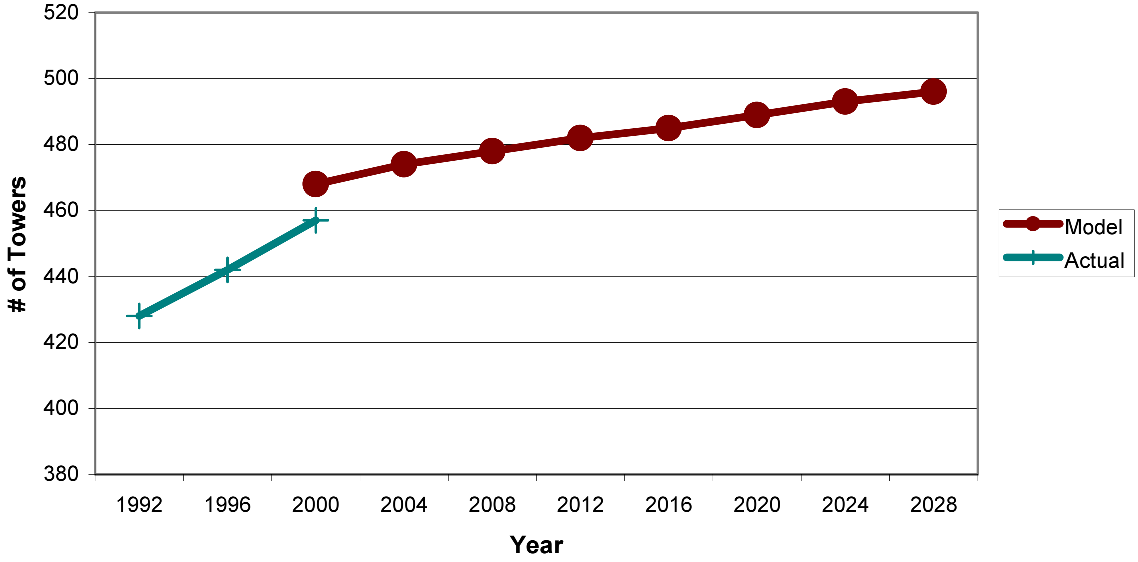

Figure 6-21: The Control Tower growth rate declines from that of the 1990s.

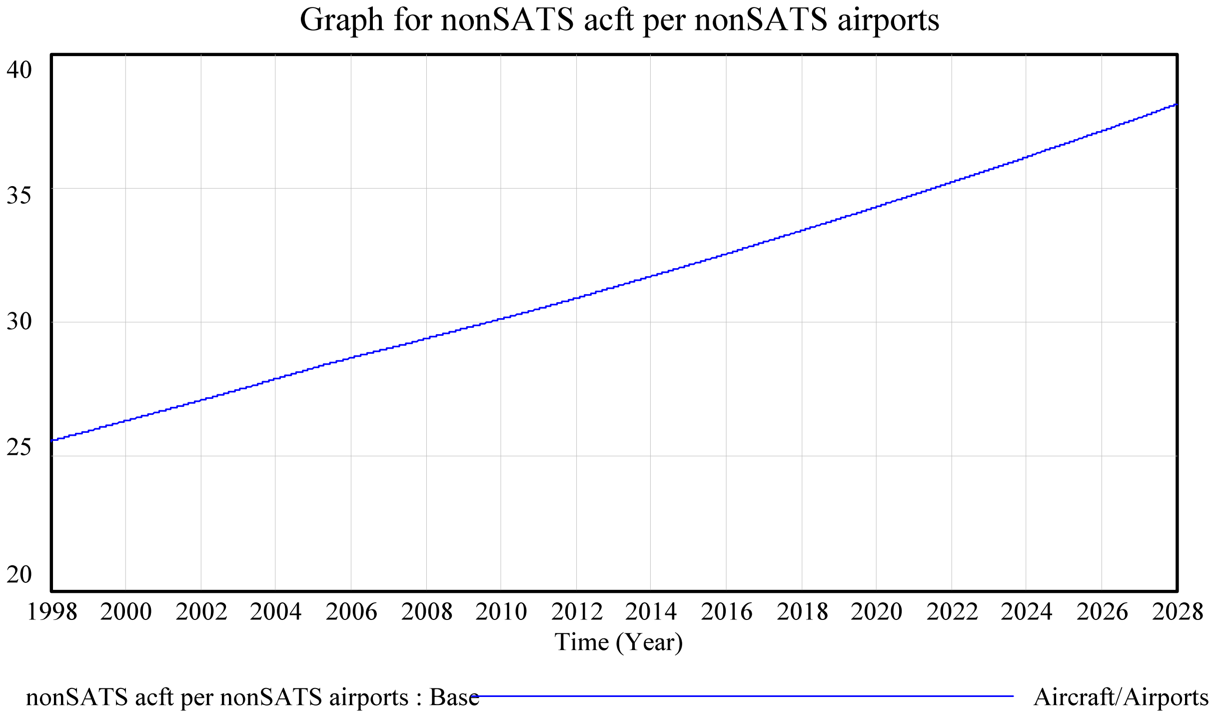

Figure 6-22: The decline in public use airports attributed to the growth in the aircraft/airports ratio.

The characteristics of the ATC system that differ in the future will not preclude the system from functioning. Despite the plateau in the number of AC aircraft beginning in 2010, the AATF and FAA budgets differ by an acceptable amount. The US Congress appropriates funds from the US General Fund, depicted in Figure 6-6 above, to account for the differences between the AATF and the FAA budget. The US Congress established the AATF in 1970s to create a source of funds for the Facilities and Equipment account and the Grants-in-Aid account, as well as at least 36% of the annual FAA operations account, which means the General Fund contribution must be 20 % or less. Thus the shortfall covered by the General Fund, recorded in Table 6-2, complies with the Congressional requirement.

Table 6-2: Over time, the percentage amount of funding provided by Congress for the FAA budget increases.

Account $M	2000	2004	2008	2012	2016	2020	2024	2028
Gen Fund	$0	0.623	1,436	1,688	1,966	2,796	3,826	4,982
FAA Budget	9,419	12,320	13,840	16,160	18,410	20,500	22,750	25,150
Gen Fund %	0.00%	0.01%	10%	11%	11%	14%	17%	20%

The plateau in radar-based equipment in Figure 6-13 reflects technological efficiencies that reduce the number of equipment needed in the system. Additionally, the technological capabilities of aircraft will allow them to conduct many radar-based navigation tasks by using GPS receivers that do not require GPS-based ATC equipment on the ground.

Conversely, SATS requires the precision and signal assurance of the ground-based GPS augmentation systems to enable safe landings, aircraft separation, moving map displays, and ground operations. Figure 6-14 above shows the decline of GPS-based equipment in the first scenario. The loss of GPS equipment combined with the small amount of SATS airports depicted in Figure 6-20, caused a lack of SATS infrastructure. The lack of SATS infrastructure in the first scenario prohibited the system from advancing beyond a small number of experimental aircraft and airports. The source of airports and aircraft came from intentional construction rather than system driven conversion of non-SATS aircraft and airports. From a performance metrics standpoint, the first scenario stacks up as follows: the AATF is sufficient to maintain a viable ATC system, but the number of SATS aircraft, SATS airports, and ground-based GPS equipment precludes the establishment of the Small Aircraft Transportation System.

6.3 Scenario 2: Simulation and Analysis of the GPS-based System

The second scenario represents a major change in the philosophy of ATC within the FAA. In this scenario, resources managers shift resources away from the radar-based approach to the GPS-based approach for the AT and GA communities. The second scenario maintains the radar-based system as the primary means of ATC for commercial AC airliners. However, those airports, facilities, and equipment outside of the hub and spoke system undergo a 5-year transition to GPS-based ATC from 2005 until 2010. During that time period, resource managers direct funding away from the radar-based facilities and equipment that support AT and GA aircraft. The resources support the installation and maintenance of GPS-based equipment and the conversion of airports into SATS airports. As in the first scenario, the simulation represents the 30-year time period from 1998 to 2028.

6.3.1 Simulation of the GPS-based System

The simulation of the GPS-based system demonstrated that the FAA will have sufficient resources to support its mission to provide air traffic control, the Small Aircraft Transportation System will have sufficient resources to grow, however, there is a disturbing decline in radar-based equipment that may induce safety or delay problems not captured by the model. Additionally, feedback from the changes in the system causes the population of AC aircraft to decline beginning in about 2010. As in the base case, Table 5-2 and Table 5-3 above contain the initial stock and parameter values used in the second scenario as well. All the stocks are endogenous to the system. The only exogenous variable, which is 100% for scenario 2, is the policy for the maximum percent of available funding resource managers should invest in the GPS-based ATC system. The resource managers linearly increase the transfer of funding from the radar-based approach to the GPS-based approach over the five-year period. Otherwise, all variables in the model are endogenous and reside in feedback loops. As explained in scenario 1 above, the only major component of the model that is not endogenous is the Grants-in-Aid account. The second scenario represents a radical change from past FAA resource management strategies; managers purposefully underfund the radar-based approach to ATC in order to advance the GPS-based approach, which is necessary for the success of the SATS.

The figures below contain the same series of output that describes the system's behavior under the conditions of both the first scenario in blue, and the second scenario in red. Again, the x-axis of each graph represents the time period 1998 through 2028 and the y-axis provides values for the stocks, parameters, or other metrics. The lines in blue depict the growth or decline of system variables over time from the first scenario. The lines in red depict the changes in system variables if the FAA changes to a resource management strategy that supports the GPS-based approach to ATC. Figure 6-23 through Figure 6-25 describe the flow of money through the major accounts of the budget. Figure 6-26 and Figure 6-27 show the flow of air traffic controllers and system maintainers. Figure 6-28 through Figure 6-33 depict the changes in the Facilities and Equipment stocks. Figure 6-34 to Figure 6-37 illustrate the growth or decline of the four aircraft stocks. Figure 6-38 and Figure 6-39 portray the adjustments in the growth or decline of non-SATS or SATS airports.

Figure 6-23 depicts the general pattern of growth exhibited by the AATF under the first and second scenarios. Figure 6-24 shows that the FAA budget growth pattern of the second scenario aligns closely with the budget from the first scenario. The budgets are similar because the reductions in some parts of the infrastructure, such as control towers, are offset by increases in other parts of the system, such as Flight Service Stations. Figure 6-25 shows that the amount of funding the FAA requires from the General Fund under the second scenario increase from the amount required in the first scenario to account for the shortfalls in the AATF. Congress may not support the increase in funding from the General Fund required under the second scenario. Thus, the future flow of revenue and resources may place the feasibility and acceptability of the second scenario in jeopardy.

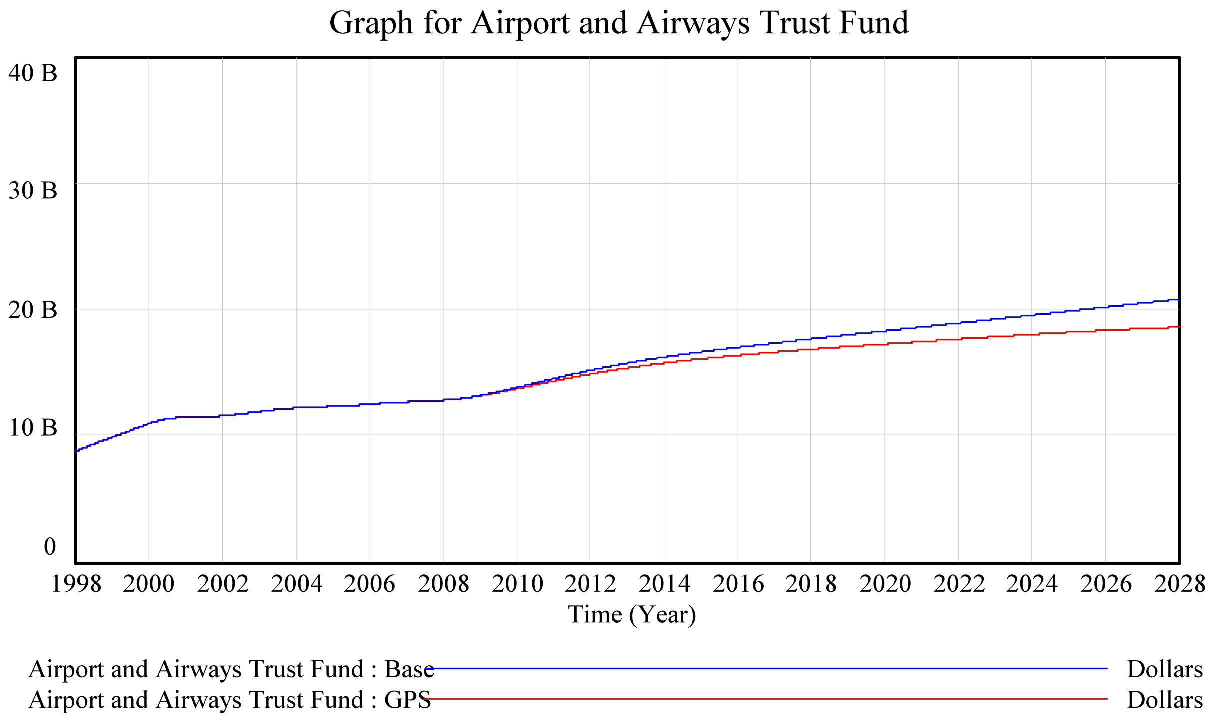

Figure 6-23: The GPS-based approach in the second scenario generated less for the AATF downstream.

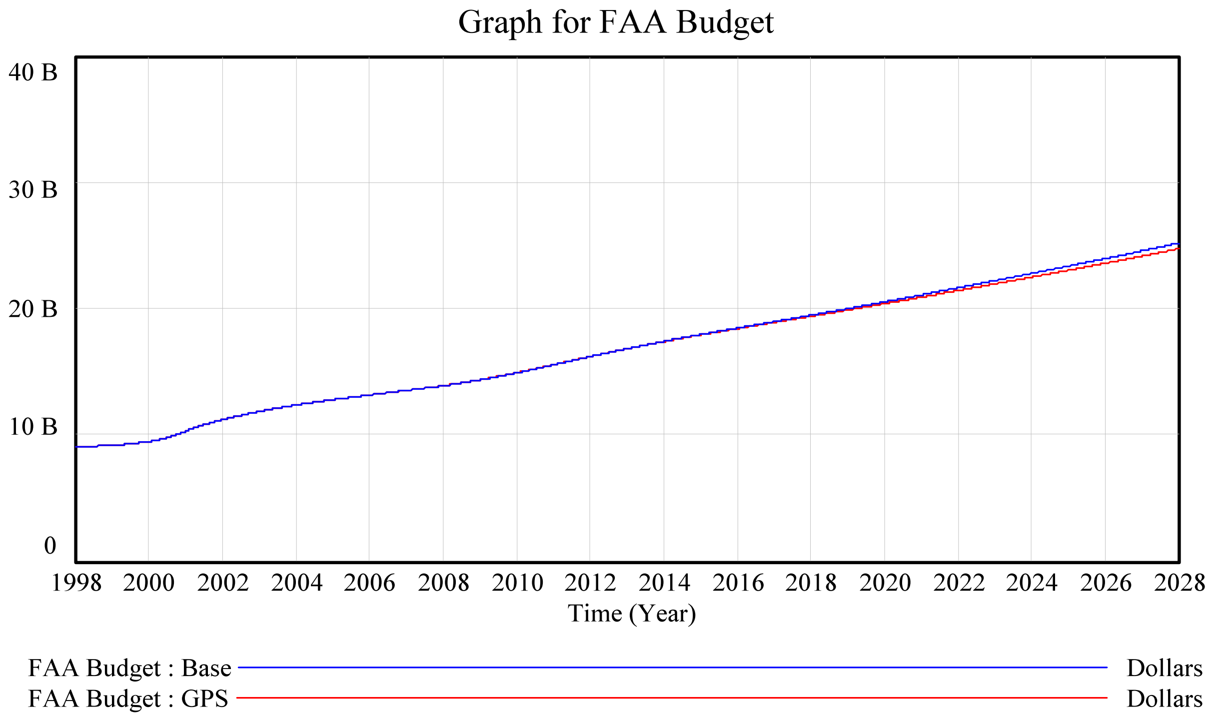

Figure 6-24: The Future FAA budgets of the first and second scenario are very similar.

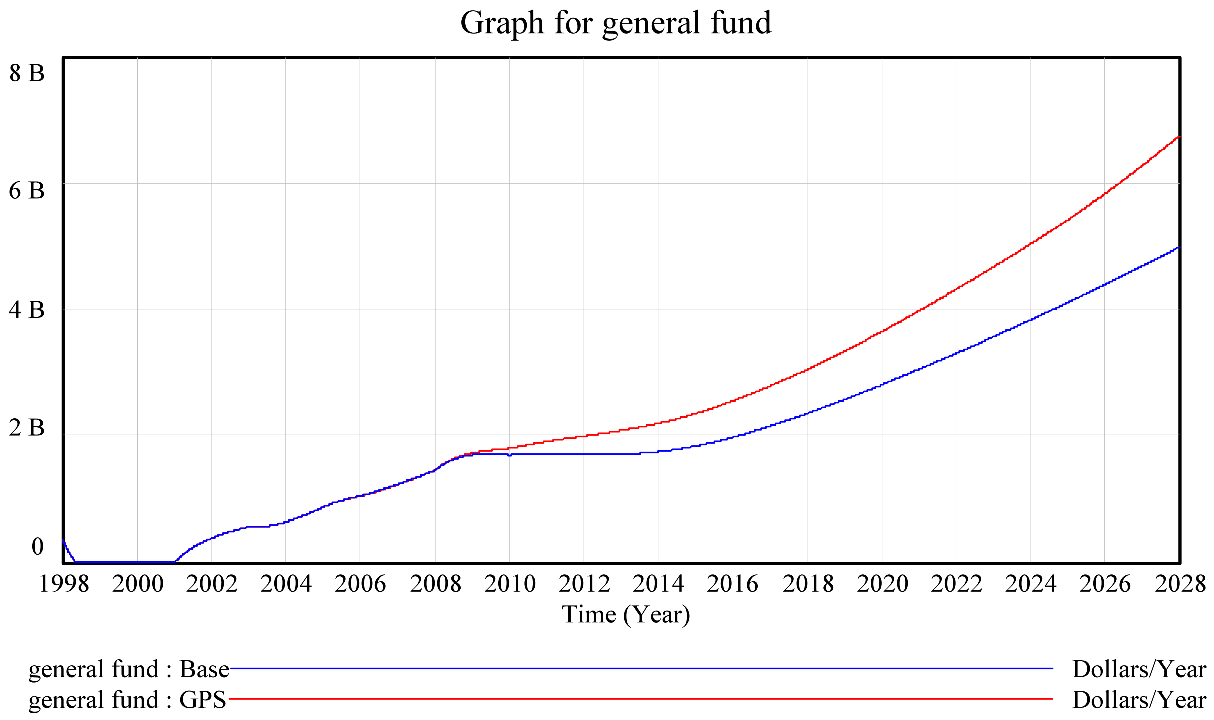

Figure 6-25: The additional funding required by the second scenario may jeopardize its implementation.

The following charts describe the behavior of three other parts of the ATC system: the people, the facilities, and the equipment. Figure 6-26 shows that the GPS-based ATC system will not reduce the need for air traffic controllers for two reasons. First, the demands of the hub and spoke system require controllers in the facilities remaining in the system. Secondly, controllers who work in the facilities that do close will migrate to the expanded population of Flight Service Stations. Figure 6-27 illustrates the changes in the number of maintainers over time. Two factors account for the behavior of the maintainer stock over time. First, accelerated retirements due to an aged population causes the downward slope beginning in 2010. Second, the decline in radar-based ATC equipment, depicted in Figure 6-32, causes a large reduction in the need for maintainers after 2012 despite the increase in GPS-based equipment in Figure 6-33.

The trend in facilities growth in Figure 6-28 through Figure 6-31 indicates an even greater expansion of Flight Service Stations in the second scenario, but a reduction in the growth of control towers. The FSSs portrayed in Figure 6-28 continue to serve the non-commercial air traffic and the expanding fleet of SATS aircraft. Each of the three types of control towers depicted in Figure 6-29 to Figure 6-31 face decline in their numbers. The GA Towers face the greatest decline as the SATS aircraft fill in for the loss of the GA portion of the aviation system. The radar-based ATC equipment depicted in Figure 6-32 undergoes significant reductions due to the resource management strategy that emphasizes GPS equipment. Conversely, Figure 6-33 shows the increase in ground-based GPS equipment that enables the GPS-based approach to ATC.

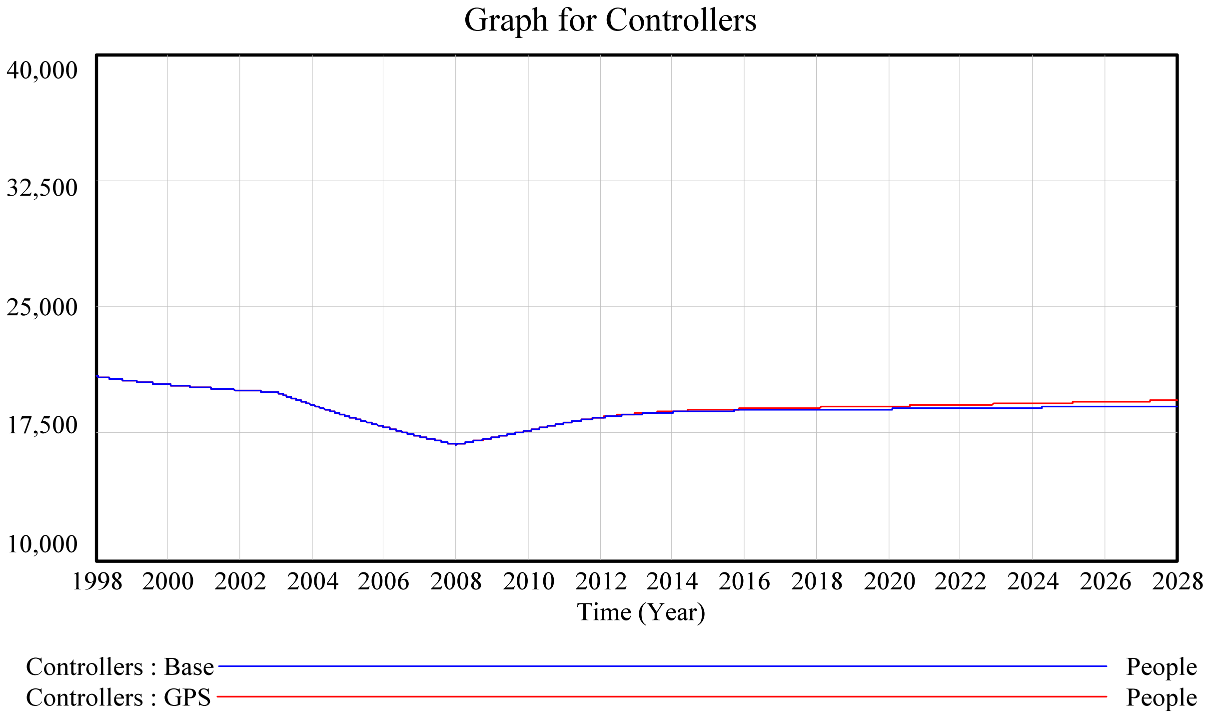

Figure 6-26: The GPS-based approach to ATC requires controllers to enable the Hub and Spoke system.

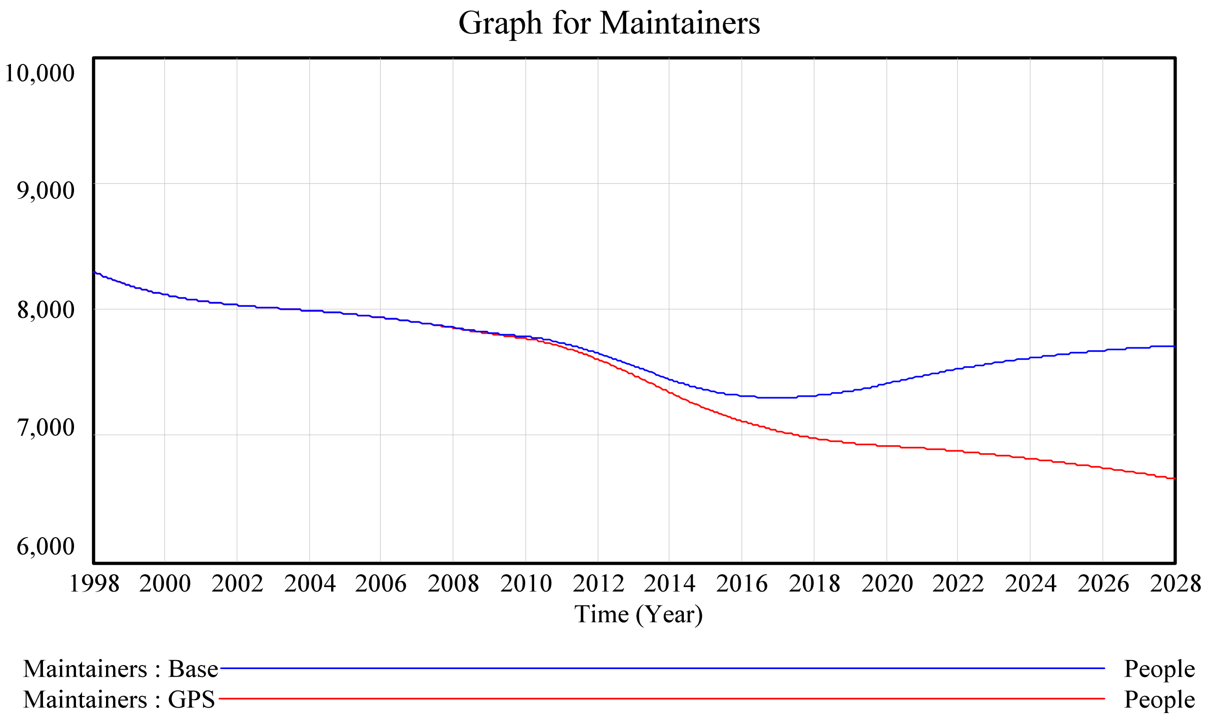

Figure 6-27: The reduction in radar-based equipment reduces the need for maintainers after 2012.

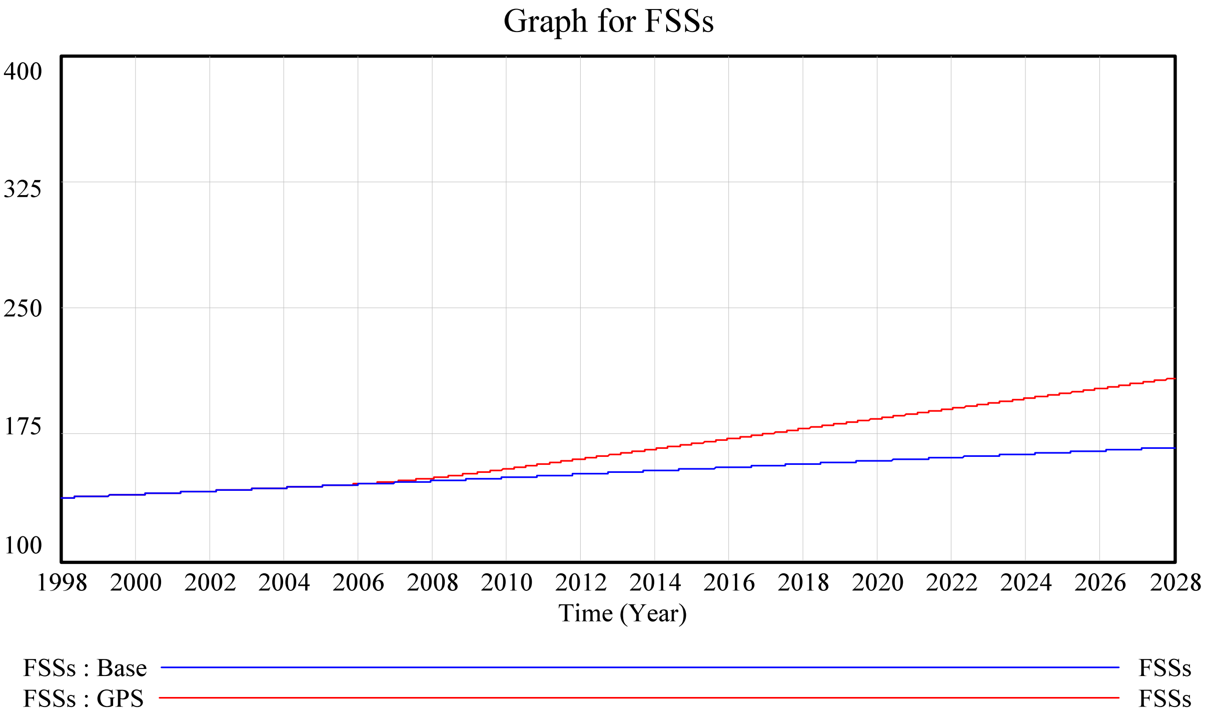

Figure 6-28: Flight Service Stations continue to serve a larger audience due to the expansion of SATS.

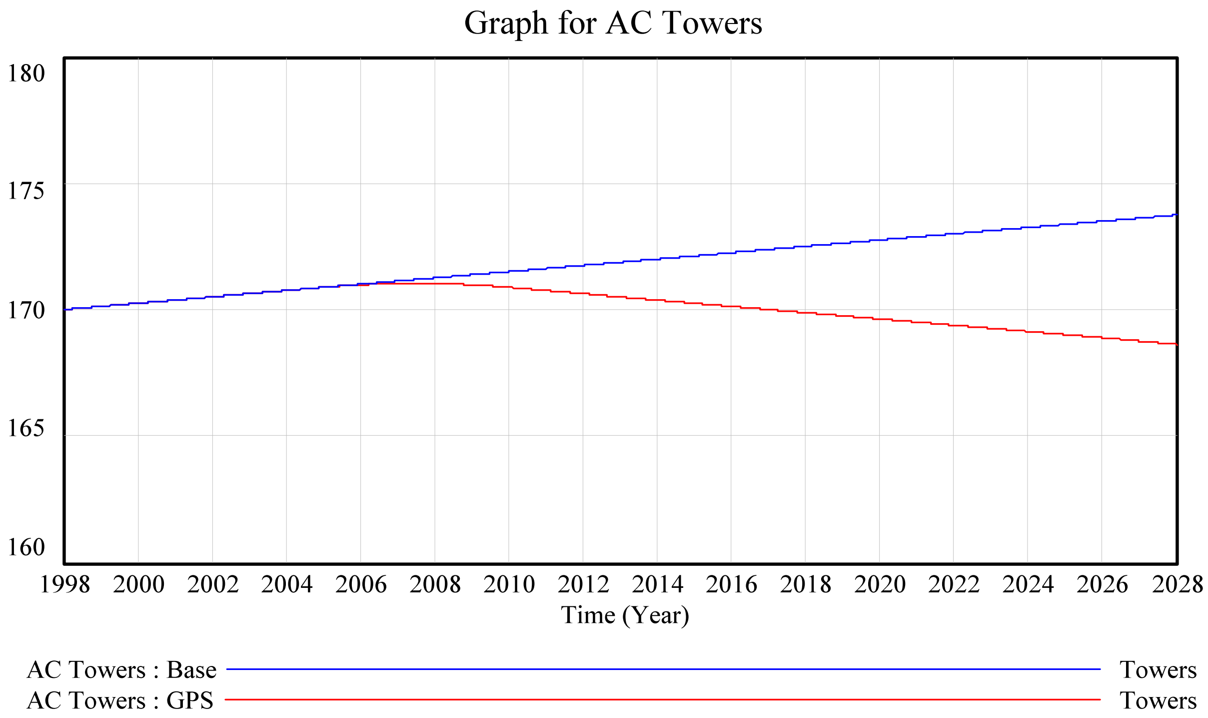

Figure 6-29: The change in resource management causes a reduction in the population of AC towers.

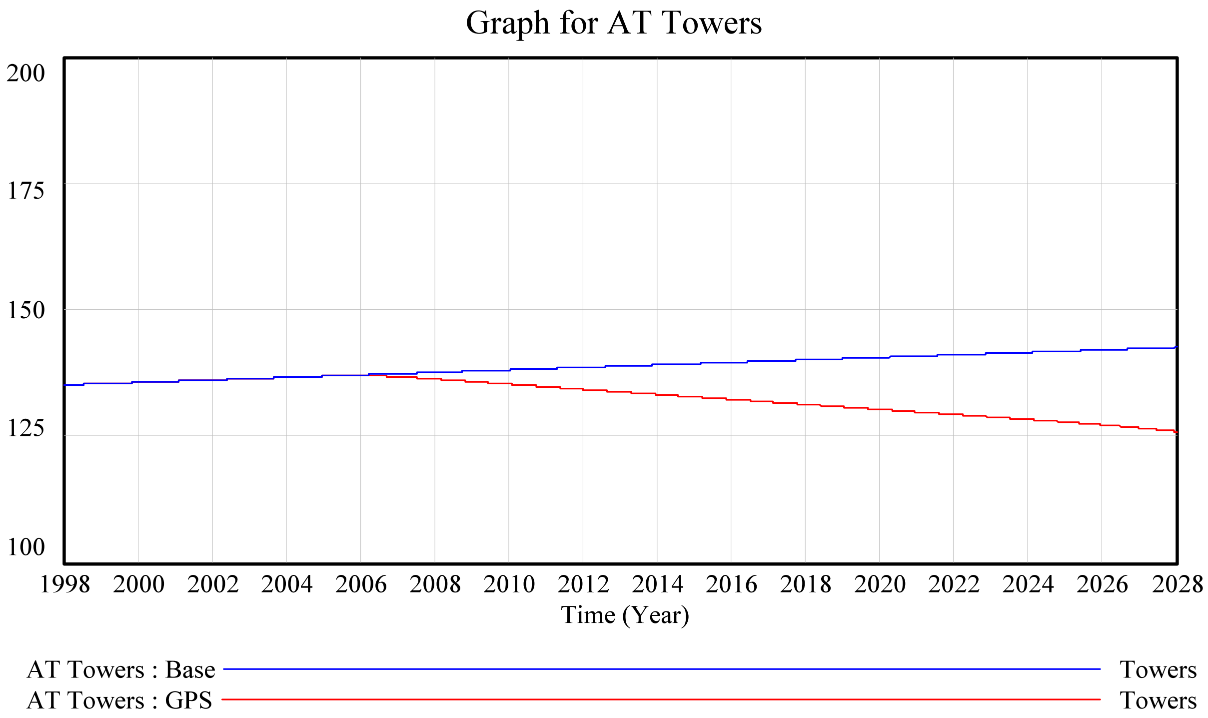

Figure 6-30: An emphasis on GPS-based ATC will reduce the requirement for control towers at AT airports.

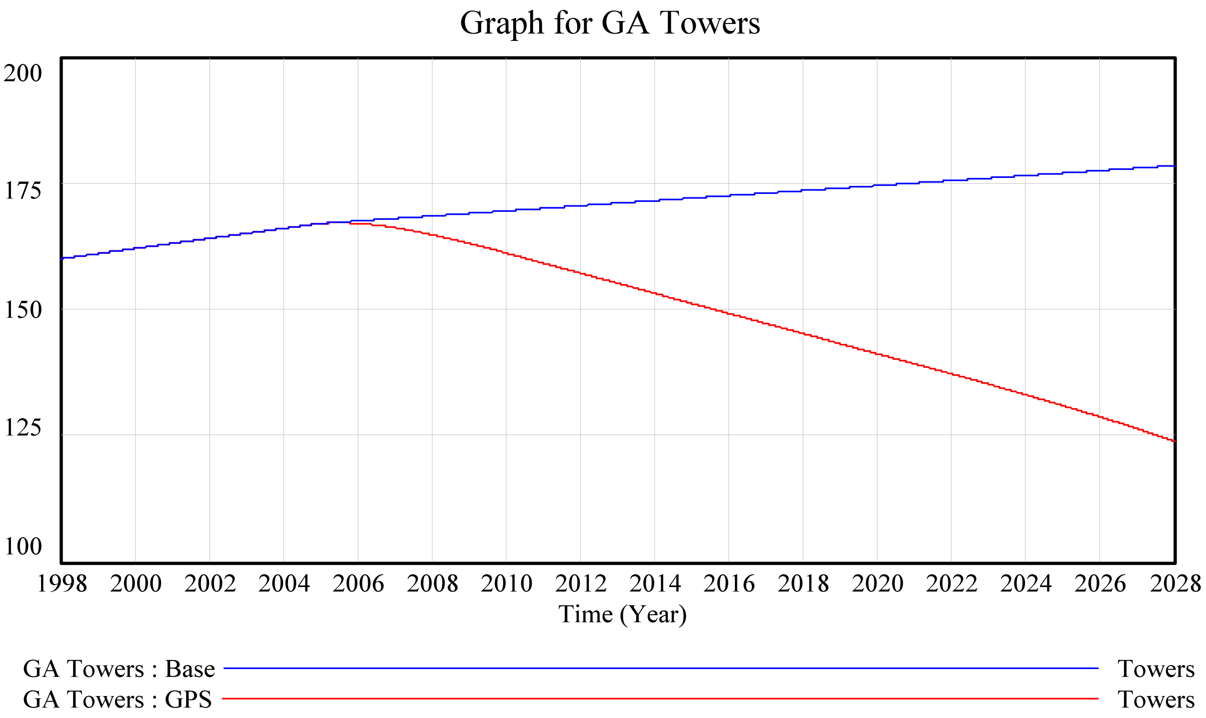

Figure 6-31: General Aviation control towers decline under the second scenario.

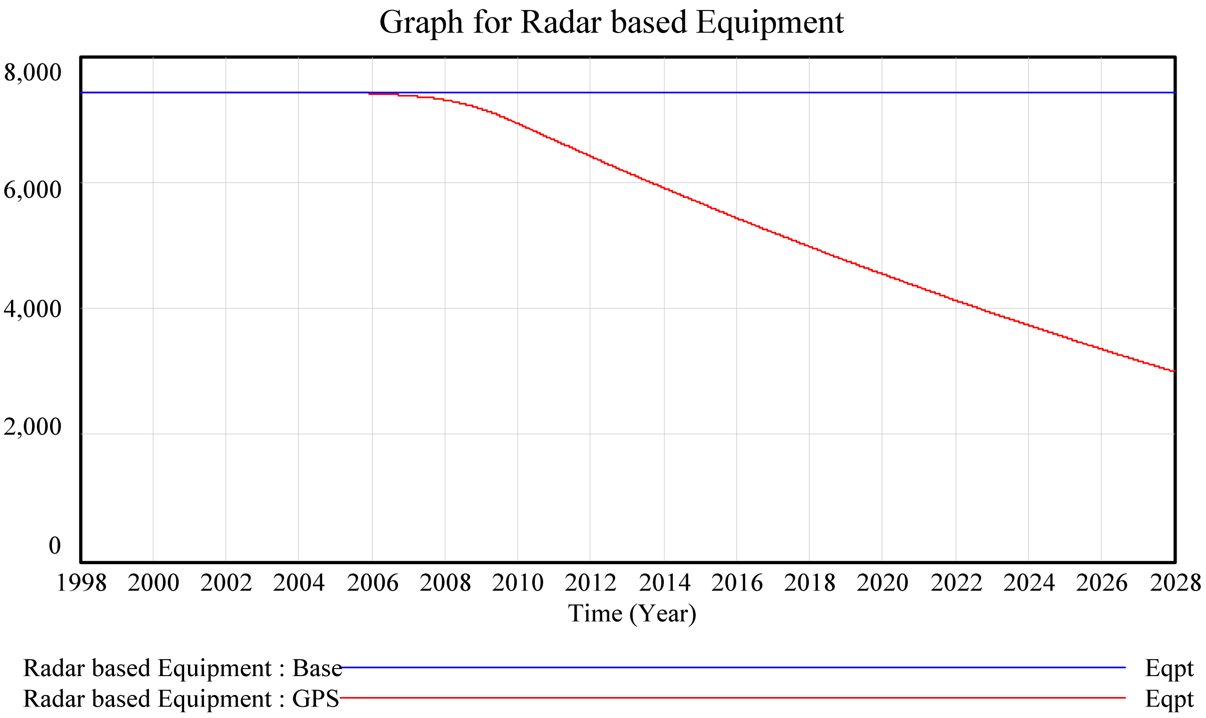

Figure 6-32: The change in resource management causes a decline in the pool of radar-based equipment.

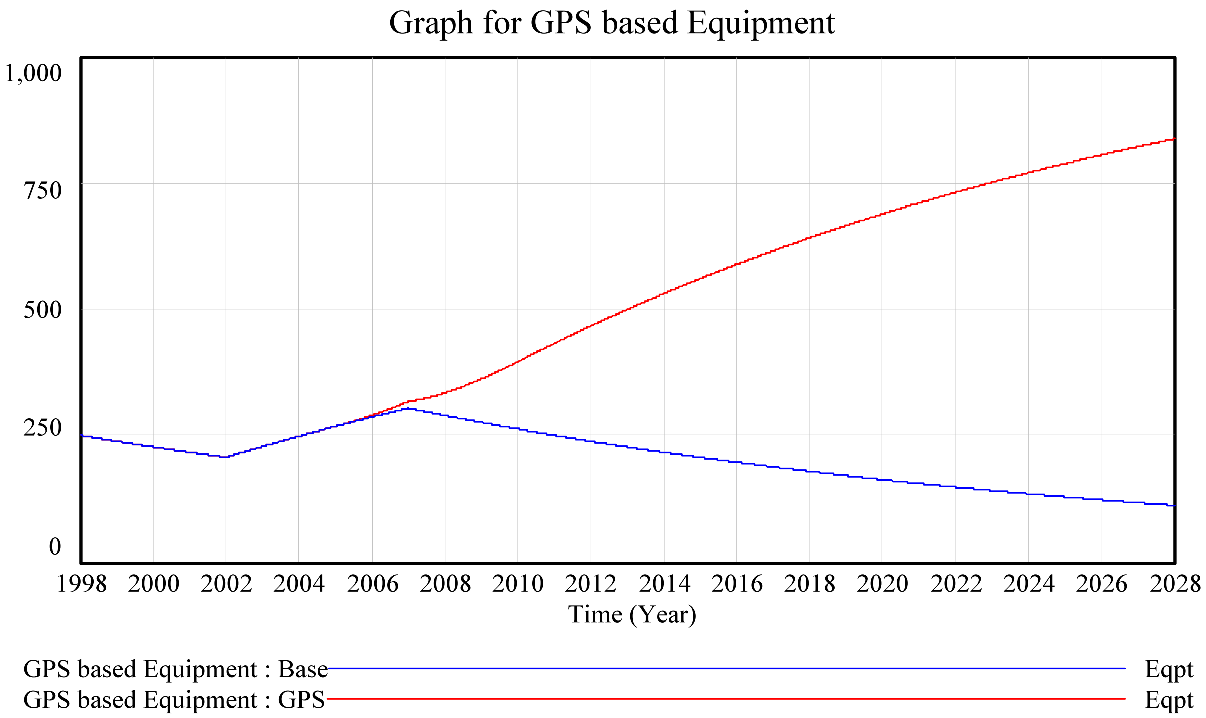

Figure 6-33: The GPS-based equipment pool expands under the second scenario.

The model addresses two other key parts of the ATC system: aircraft and airports. Figure 6-34 to Figure 6-37 describe the populations of AC, AT, GA, and SATS aircraft. The growth of AC aircraft in Figure 6-34 peaks around 2010 as a result of the reduction in capabilities of the radar-based ATC system caused by the resource management strategy used in the second scenario. The reduction in the AC population after 2010 is a significant negative effect of the second scenario that may make the resource management approach unacceptable to policy makers. Large declinations in the population of AT and GA aircraft also begin after approximately 2010 as depicted in Figure 6-35 and Figure 6-36. The number of SATS aircraft, depicted in Figure 6-37, grows rapidly due to conversions of AT and GA aircraft into SATS aircraft, enabled by the growth of supporting GPS infrastructure in the second scenario.

Figure 6-38 and Figure 6-39 capture the changes in the population of SATS and non-SATS airports. The non-SATS airports in Figure 6-38 continue to decline in number due to the normal demise of public use airports. However, many of the airports converted from non-SATS airports into SATS airports. The growth in SATS airports in Figure 6-39 during the second scenario enabled the establishment of the SATS as a viable transportation system.

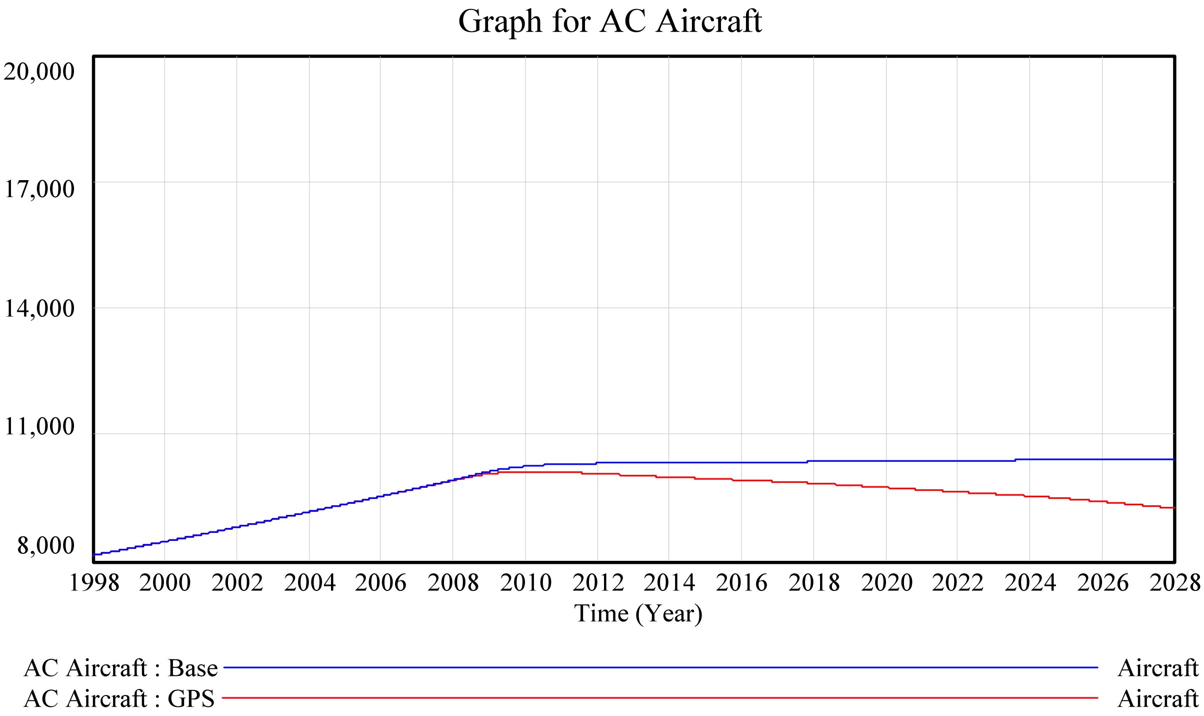

Figure 6-34: Feedback from the GPS-based system further restrains the growth in the number of AC aircraft.

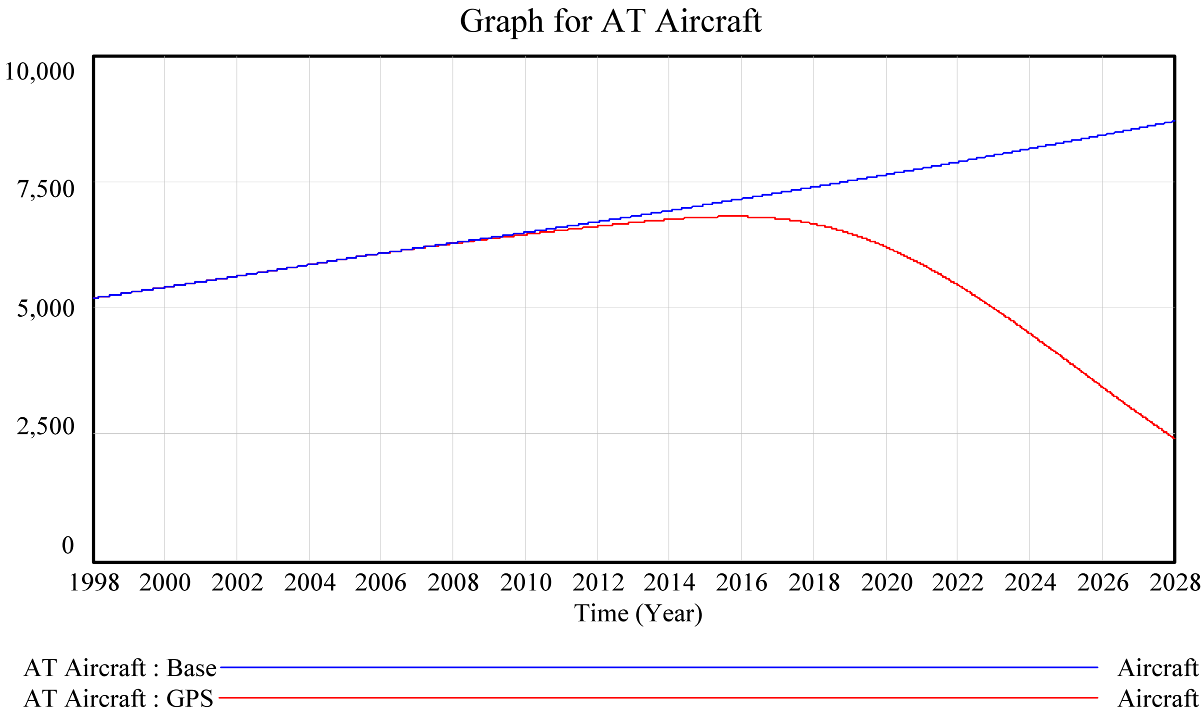

Figure 6-35: The population of AT aircraft growth declines with the onset of SATS.

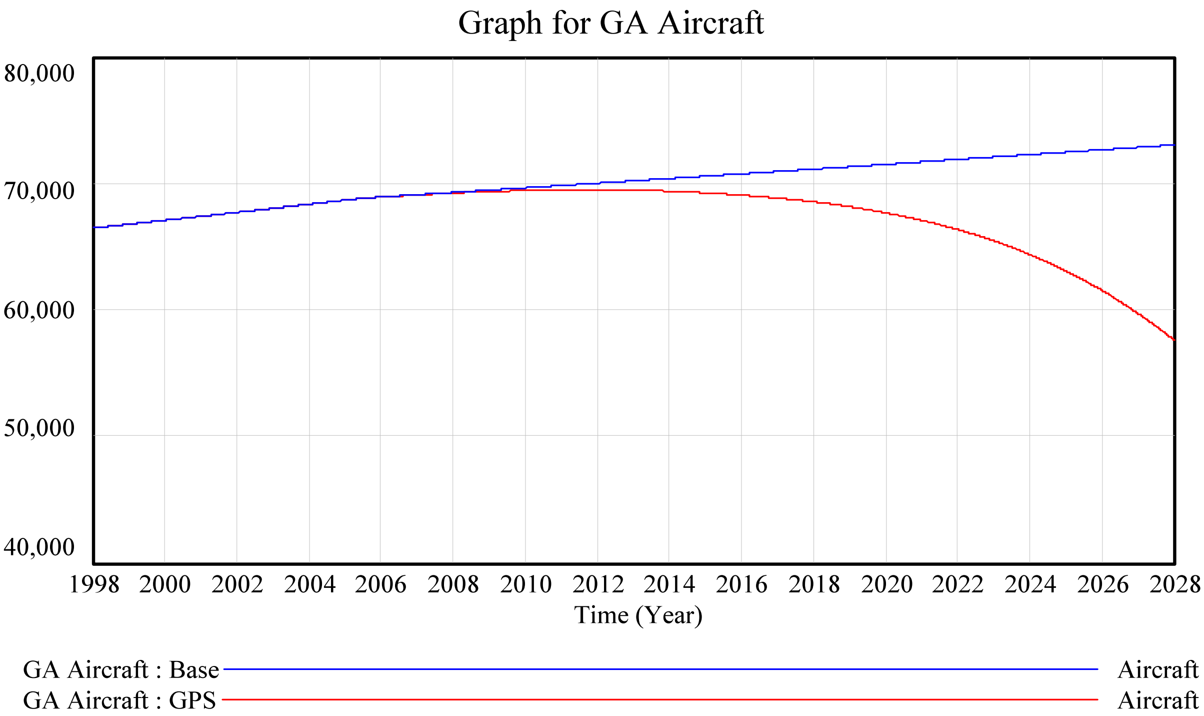

Figure 6-36: The system converts many GA aircraft into SATS aircraft.

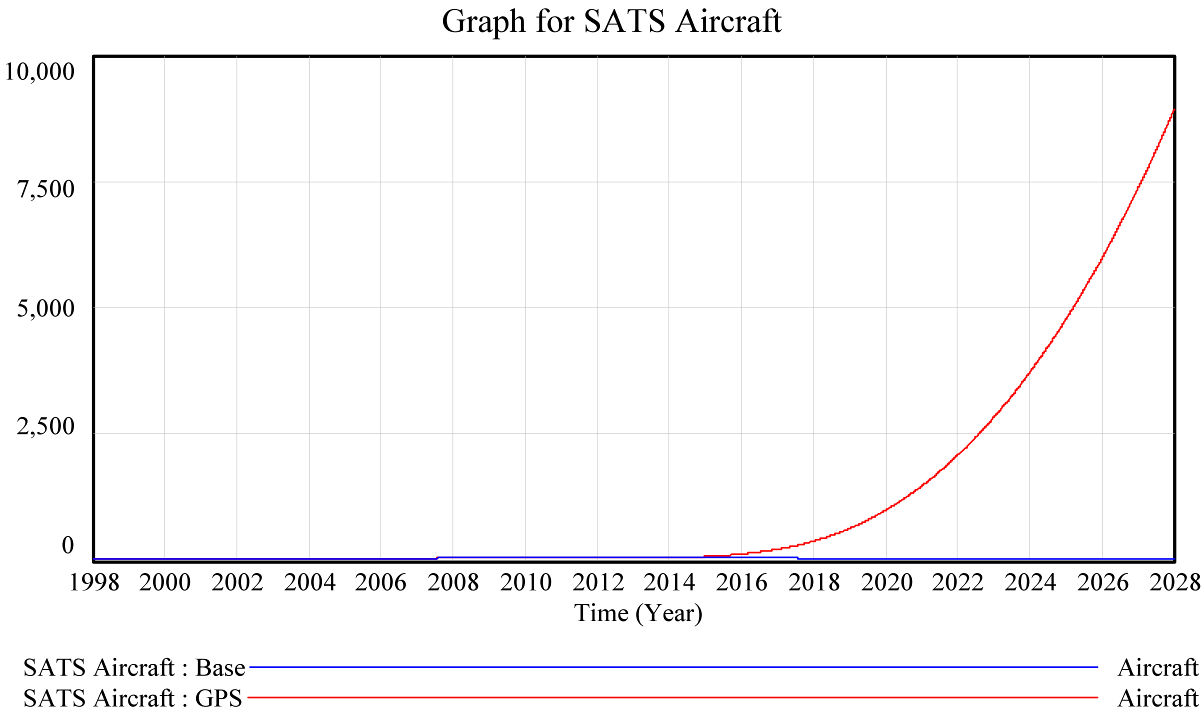

Figure 6-37: The growth of SATS airports enables the entire SATS program.

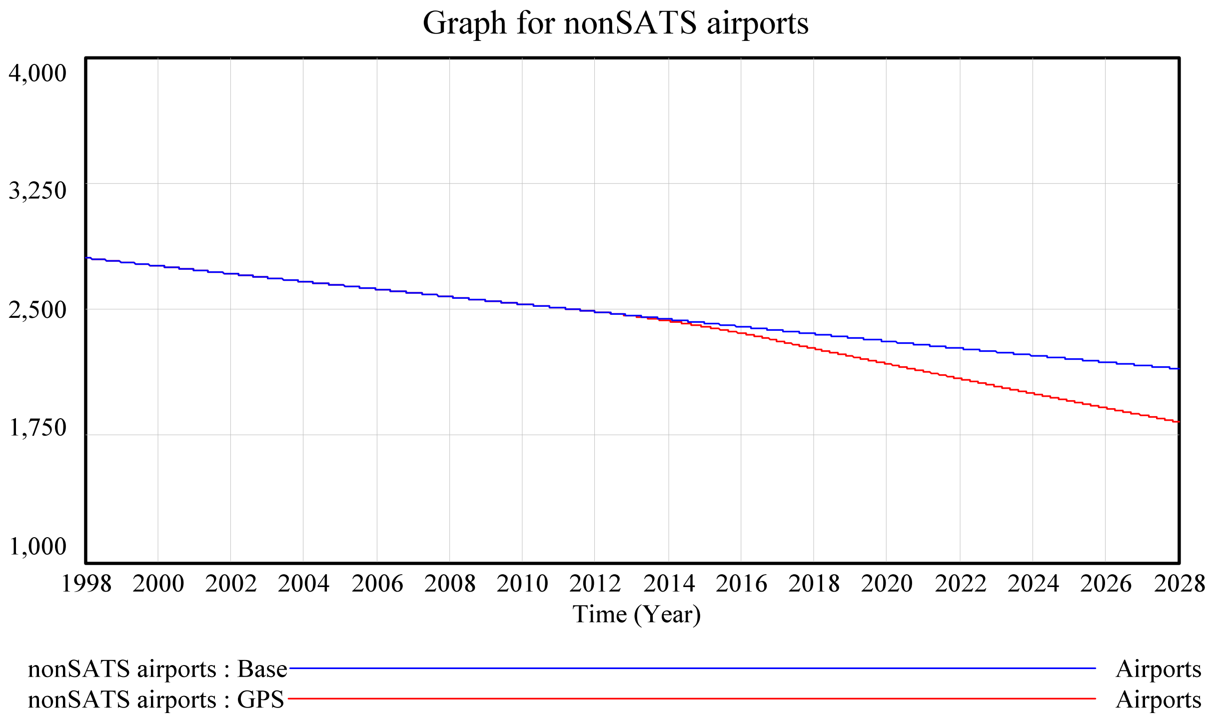

Figure 6-38: Non-SATS airports decline at a rate of approximately two per month.

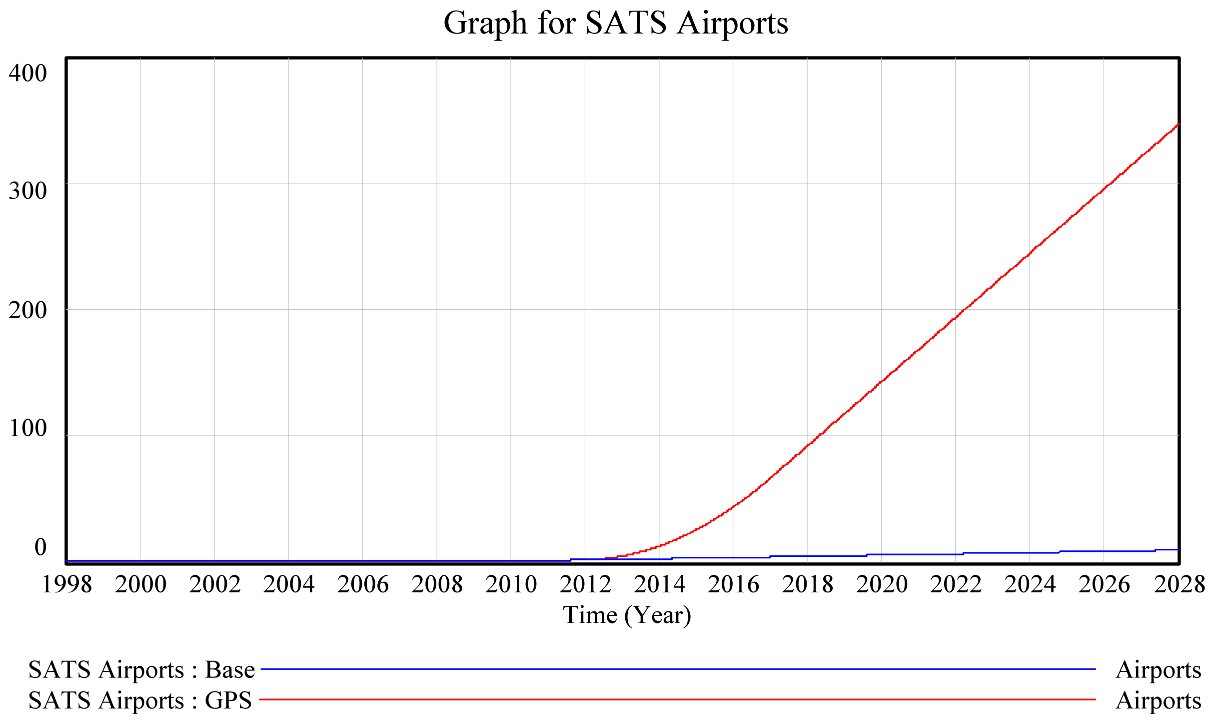

Figure 6-39: The growth of SATS airports enables the entire SATS program.

6.3.2 Analysis of Scenario 2

The data generated from the second scenario indicates that the resource management strategy favoring GPS may be both unacceptable and infeasible. The second scenario is unacceptable to Congress because it eventually necessitates high expenditures of General Funds beyond the limits set by Congress. Table 6-3 contains the percentages of General Funds required by the second scenario. Congress will not accept requirements to transfer more than 20% of the FAA budget from the General Fund. The second scenario is infeasible because it creates a reduction in the populations of AC aircraft and radar-based ATC equipment. The reduction of AC aircraft reduces the capacity of the aviation system to serve the nation. The reduction of the number of radar-based equipment increases the likelihood that there will be accidents or delays in the NAS. Therefore, the second scenario represents an infeasible option because of the potential for delay, AC capacity reduction, and a decline in safety. The lack of radar-based ATC equipment serves as a surrogate measure of delay and safety.

Table 6-3: Congress will refrain from funding more than 20% of the FAA budget from the General Fund.

Account $M	2000	2004	2008	2012	2016	2020	2024	2028
Gen Fund	$0	0.623	1,441	1,985	2,541	3,639	5,030	6,744
FAA Budget	9,419	12,320	13,840	16,160	18,410	20,500	22,750	25,150
Gen Fund %	0.00%	0.01%	10%	12%	14%	18%	22%	27%

Despite the infeasibility and unacceptability of the second scenario, it shows that the system has the potential to generate revenue and create the conditions for the growth and maturation of the SATS. Figure 6-40 shows the conversion of public use airports into SATS airports. Without conversion to SATS, the airports would no longer contribute to the NAS. Similarly, Figure 6-41 shows the conversion of AT and GA aircraft into SATS aircraft. In both cases, the SATS consists of a modest proportion of the entire system. Although the ATC resource management devoting the maximum resources towards the GPS-based approach proved infeasible and unacceptable in the second scenario, the establishment of SATS in the second scenario indicates that a compromise solution may support SATS and provide adequate revenue for the ATC system. The third scenario in the next section represents a less extreme departure from the normal conservative culture of the FAA, which consists using GPS-based ATC to supplement the radar-based ATC system.

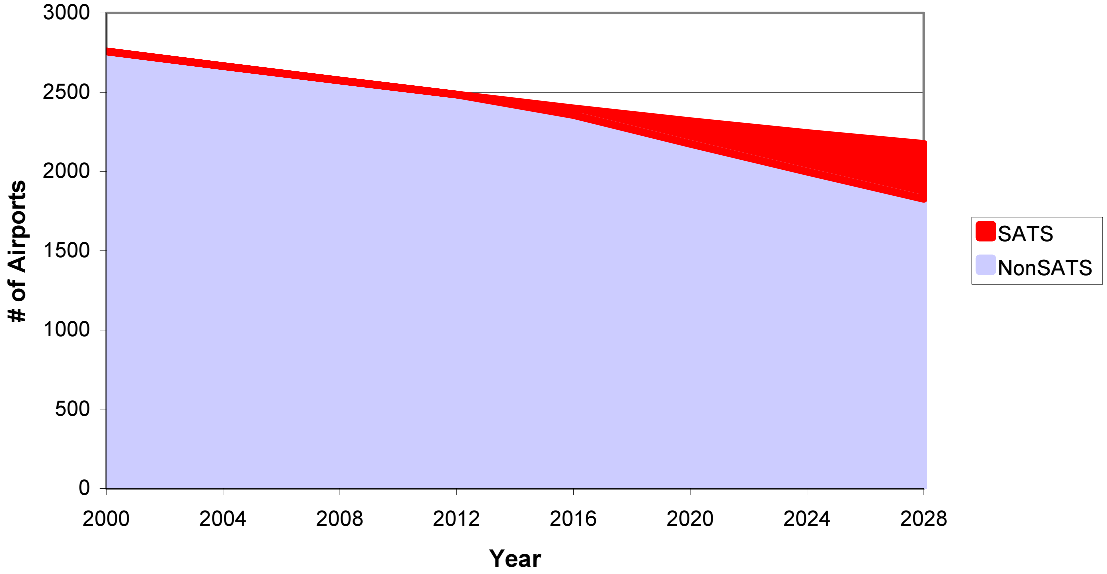

Figure 6-40: The conversion of non-SATS airports into SATS airports begins in approximately 2012.

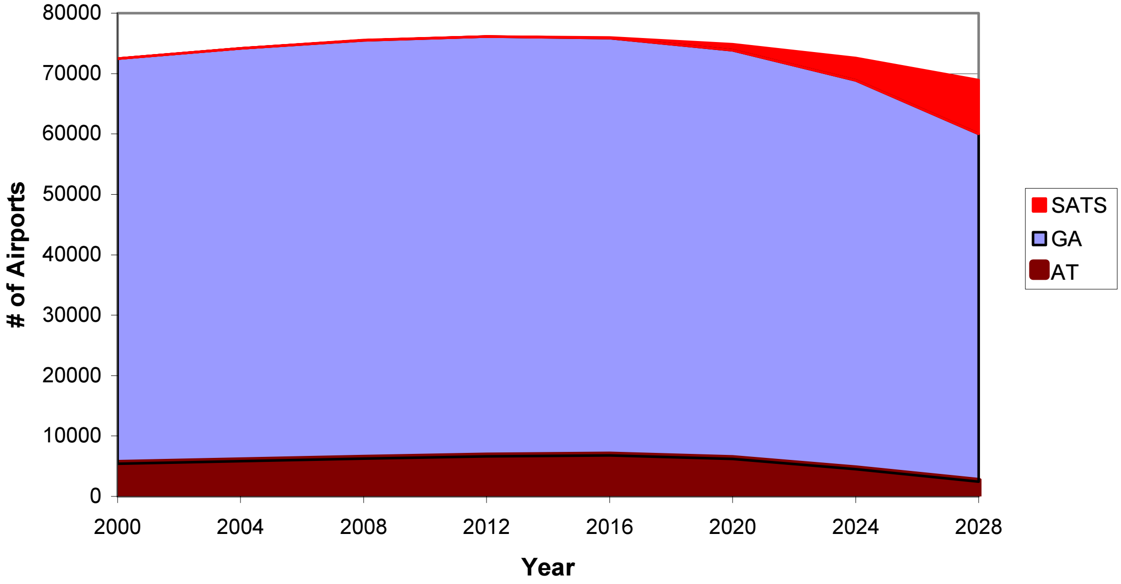

Figure 6-41: Many AT and some GA aircraft convert into SATS aircraft.

6.4 Scenario 3: Simulation and Analysis of the radar-based system supplemented by GPS

The third scenario represents a moderate change in the philosophy of ATC within the FAA that is more in keeping with the conservative culture of the organization. In this scenario, resources managers shift 25% of the resources away from the radar-based approach to the GPS-based approach to ATC. The resource shift occurs over a ten-year period from 2015 to 2025. From 2025 and beyond, the FAA continues to support the GPS-based approach to ATC with 25% of the funding that normally would have gone to continuation of the radar-based system. The resources support the radar-based system and also support installation and maintenance of GPS-based equipment and the conversion of airports into SATS airports. As in the previous scenarios, the simulation represents the 30-year time period from 1998 to 2028.

6.4.1 Simulation of the radar-based system supplemented by GPS

The simulation of the radar-based system supplemented by GPS demonstrated that the FAA will generally have sufficient resources to support its mission to provide air traffic control, and, the Small Aircraft Transportation System will have sufficient resources to grow at a modest rate. The third scenario represents a conservative compromise that places slight risk on future FAA revenue, but gives the SATS a chance to become established as a viable transportation system. As in the previous cases, Table 5-2 and Table 5-3 above contain the initial stock and parameter values used in the second scenario as well. All the stocks are endogenous to the system. The only exogenous variable, which is 25% for scenario 3, is the policy for the maximum percent of available funding resource managers should invest in the GPS-based ATC system. The resource managers linearly increase the transfer of funding from the radar-based approach to the GPS-based approach over the ten-year period from 2015 to 2025. Otherwise, all variables in the model are endogenous and reside in feedback loops. As explained in the previous scenarios above, the only major component of the model that is not endogenous is the Grants-in-Aid account. The third scenario represents a moderate change from past FAA resource management strategies; managers attempt to balance the radar-based approach to ATC with supplemental support from the GPS-based approach, which is necessary for the success of the SATS.

The figures below contain the same series of output used in the first two scenarios to describe the system's behavior. The first scenario is in blue, the second scenario in red, and the third scenario in green. In many cases the blue and green lines overlap. Again, the x-axis of each graph represents the time period 1998 through 2028 and the y-axis provides values for the stocks, parameters, or other metrics. The colored lines depict the growth or decline of system variables over time. Figure 6-42 through Figure 6-44 describe the flow of money through the major accounts of the budget. Figure 6-45 and Figure 6-46 show the flow of air traffic controllers and system maintainers. Figure 6-47 through Figure 6-52 depict the changes in the Facilities and Equipment stocks. Figure 6-53 to Figure 6-56 illustrate the growth or decline of the four aircraft stocks. Figure 6-57 and Figure 6-58 portray the adjustments in the growth or decline of non-SATS or SATS airports.

Figure 6-42 depicts the general pattern of growth exhibited by the AATF under the three scenarios. The third scenario aligns closely with the first. Figure 6-43 shows that the FAA budget growth pattern of the third scenario is almost identical to the budget from the first scenario. The budgets are similar because the delayed introduction of GPS funding until 2015 and the slow transition to the 25% funding level caused little change in the FAA budget. Figure 6-44 shows that the amount of funding the FAA required from the General Fund under the third scenario increased just slightly from the amount required in the first scenario to account for the shortfalls in the AATF. Congress will support the minimal increase in funding from the General Fund required under the second scenario. Thus, the future flow of revenue and resources makes the third scenario economically feasible.

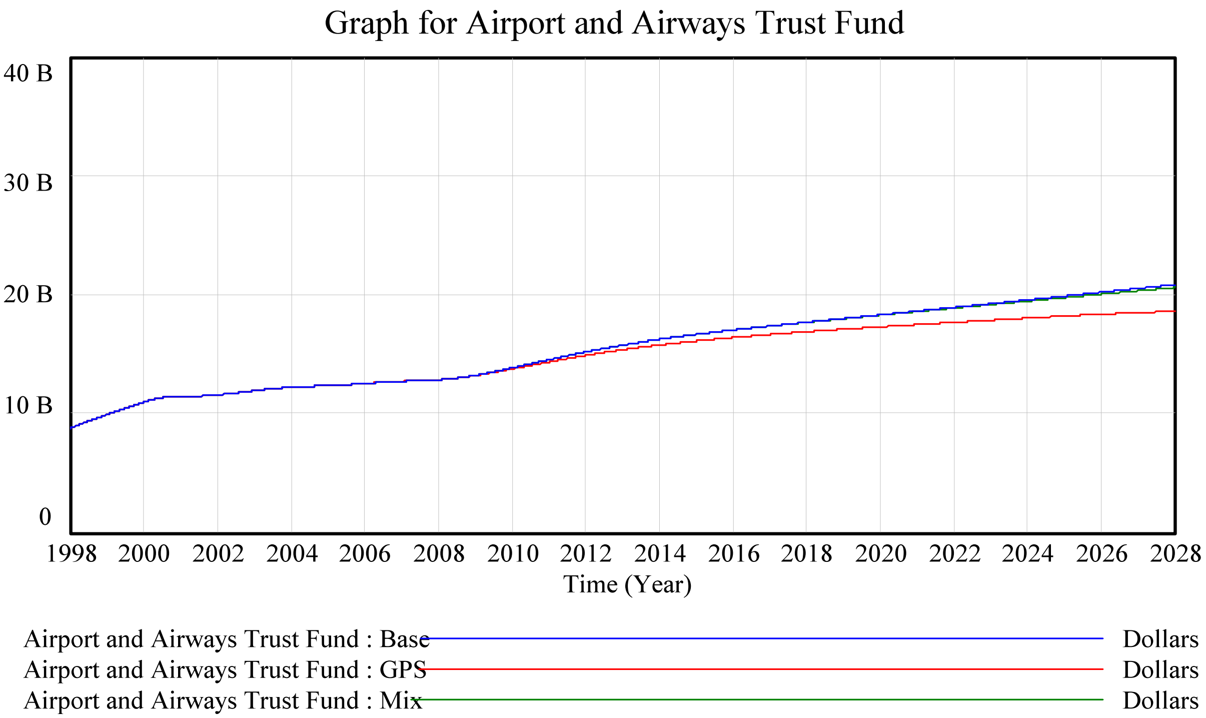

Figure 6-42: The third scenario aligns closely with the first.

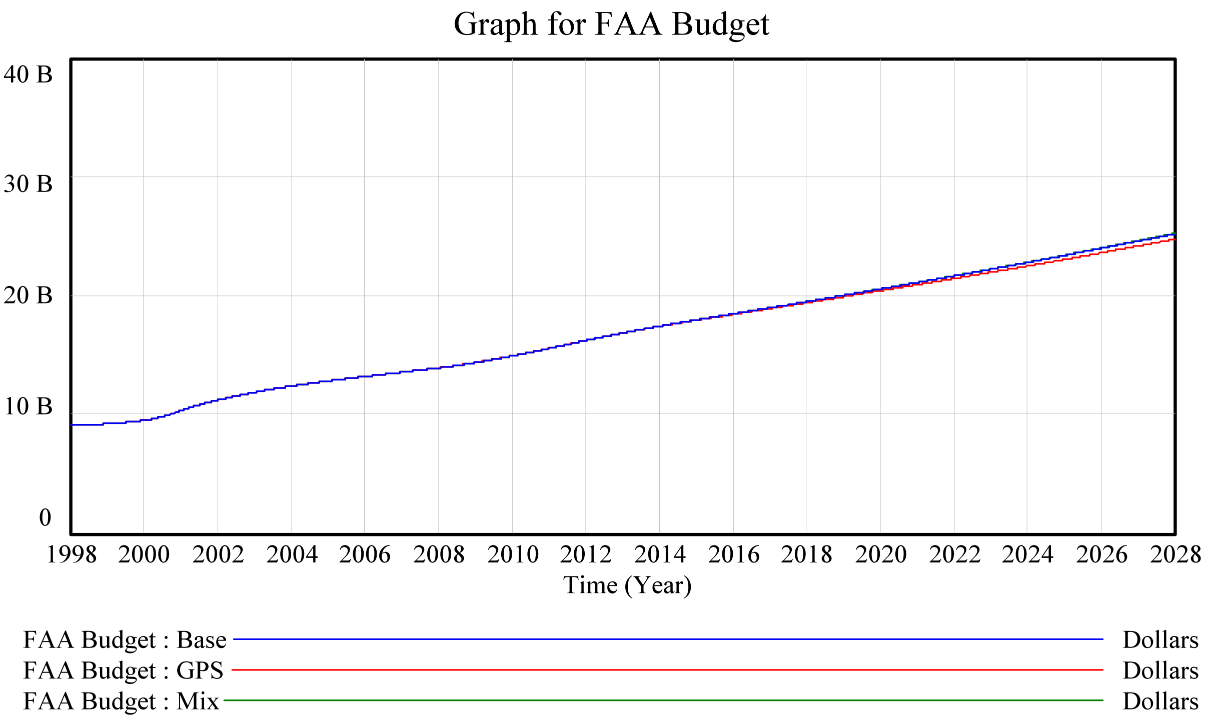

Figure 6-43: The Future FAA budgets of the first and third scenario are almost identical.

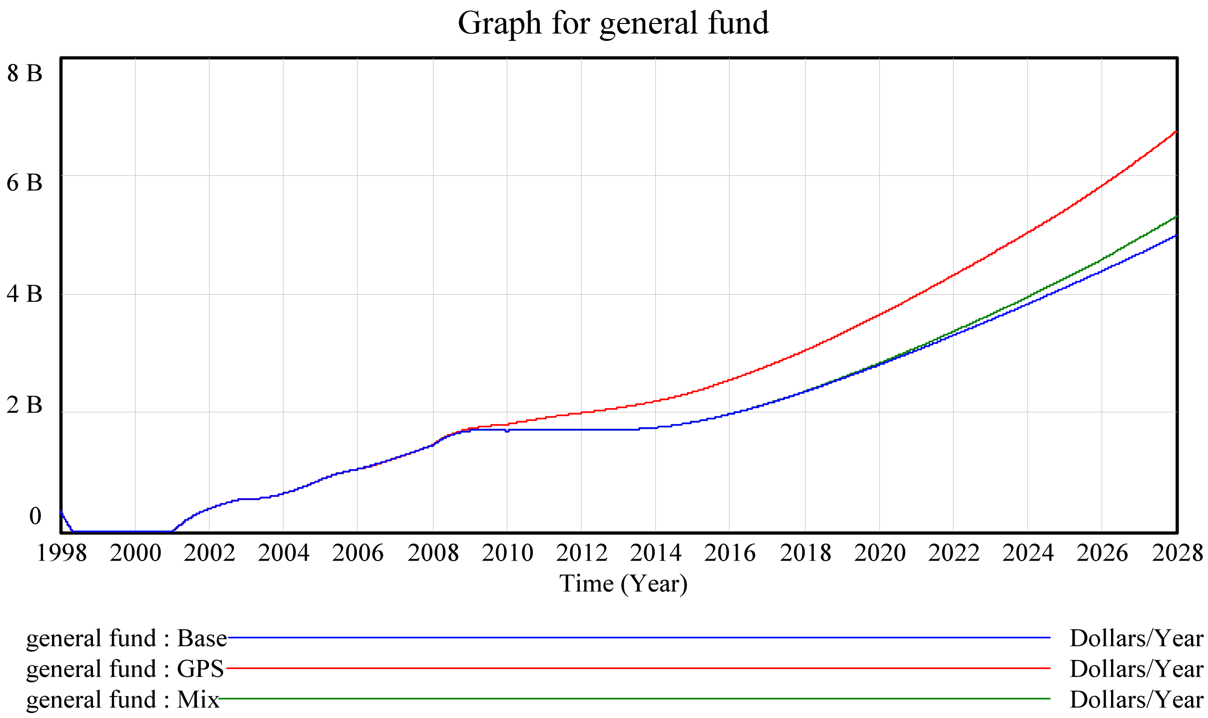

Figure 6-44: The minimal additional funding required by the third scenario makes it feasible.

The following charts describe the behavior of three other parts of the ATC system: the people, the facilities, and the equipment. Figure 6-45 shows that the radar-based and GPS-supplemented ATC system will not reduce the need for air traffic controllers. Figure 6-46 illustrates the changes in the number of maintainers over time caused primarily by retirements. The trend in facilities growth in Figure 6-47 through Figure 6-50 indicates an even greater expansion of Flight Service Stations in the second scenario, but a reduction in the growth of control towers. The FSSs portrayed in Figure 6-47 continue to serve the non-commercial air traffic and the expanding fleet of SATS aircraft. Each of the three types of control towers depicted in Figure 6-48 to Figure 6-50 face decline in their numbers. The GA Towers face the greatest decline as the SATS aircraft fill in for the loss of the GA portion of the aviation system. The radar-based ATC equipment depicted in Figure 6-51 undergoes significant reductions due to the resource management strategy that emphasizes GPS equipment. Conversely, Figure 6-52 shows the increase in ground-based GPS equipment that enables the GPS-based approach to ATC.

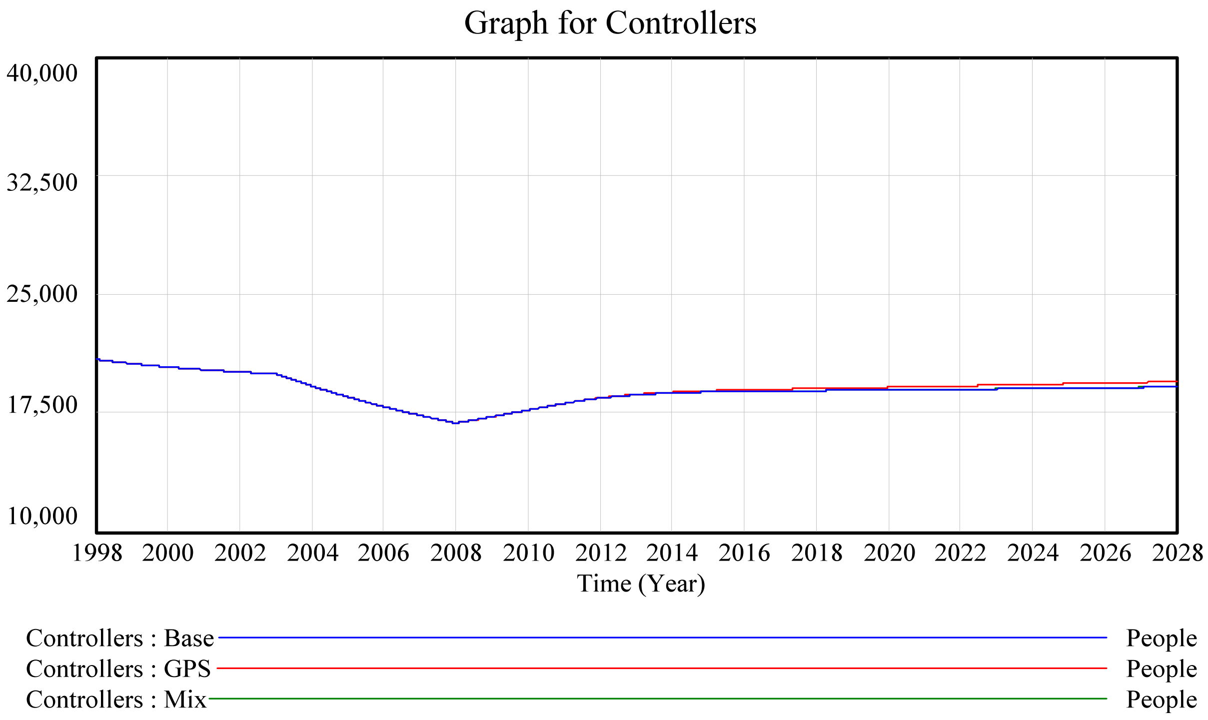

Figure 6-45: Each scenario requires controllers to support the Hub and Spoke system ATC facilities.

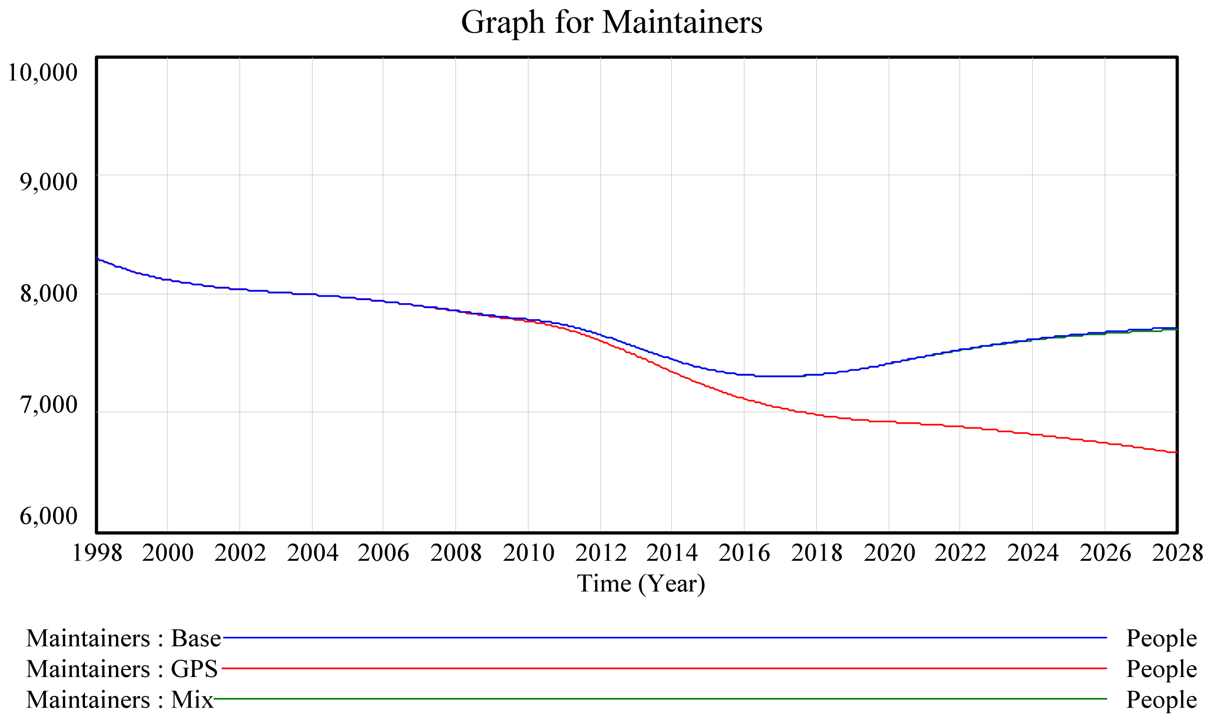

Figure 6-46: The first and third scenarios require the same number of maintainers.

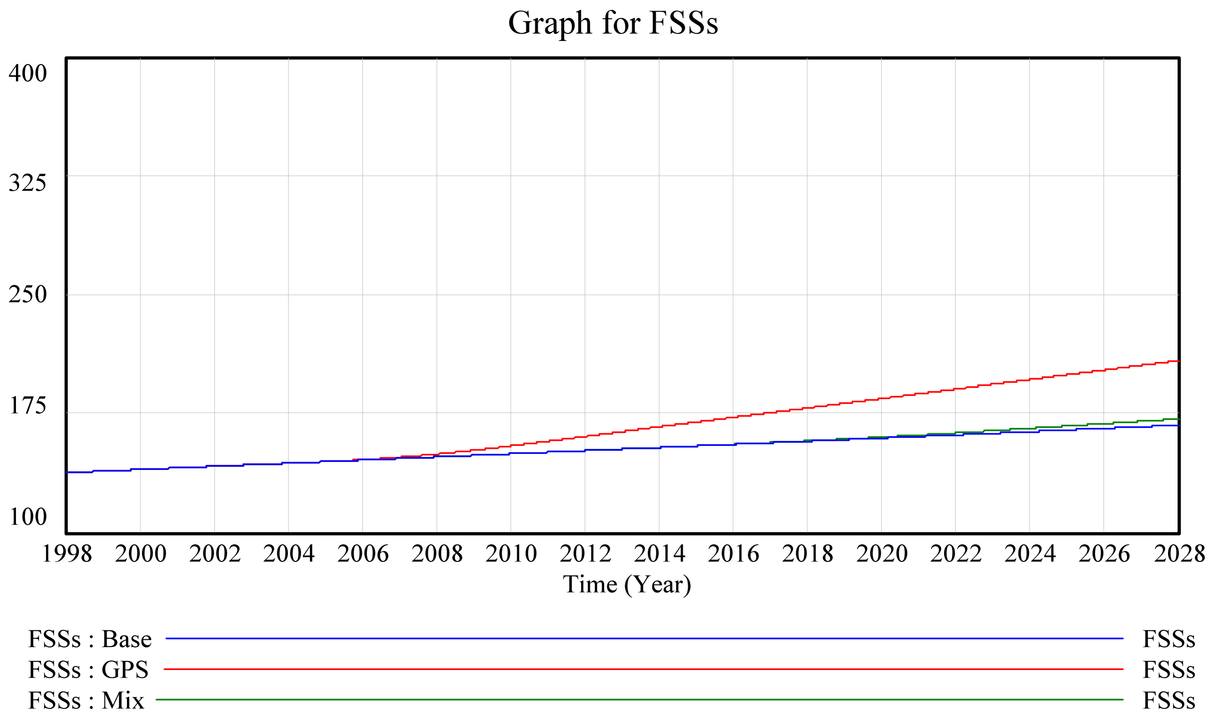

Figure 6-47: There is a slight growth in the number of Flight Service Stations in the third scenario.

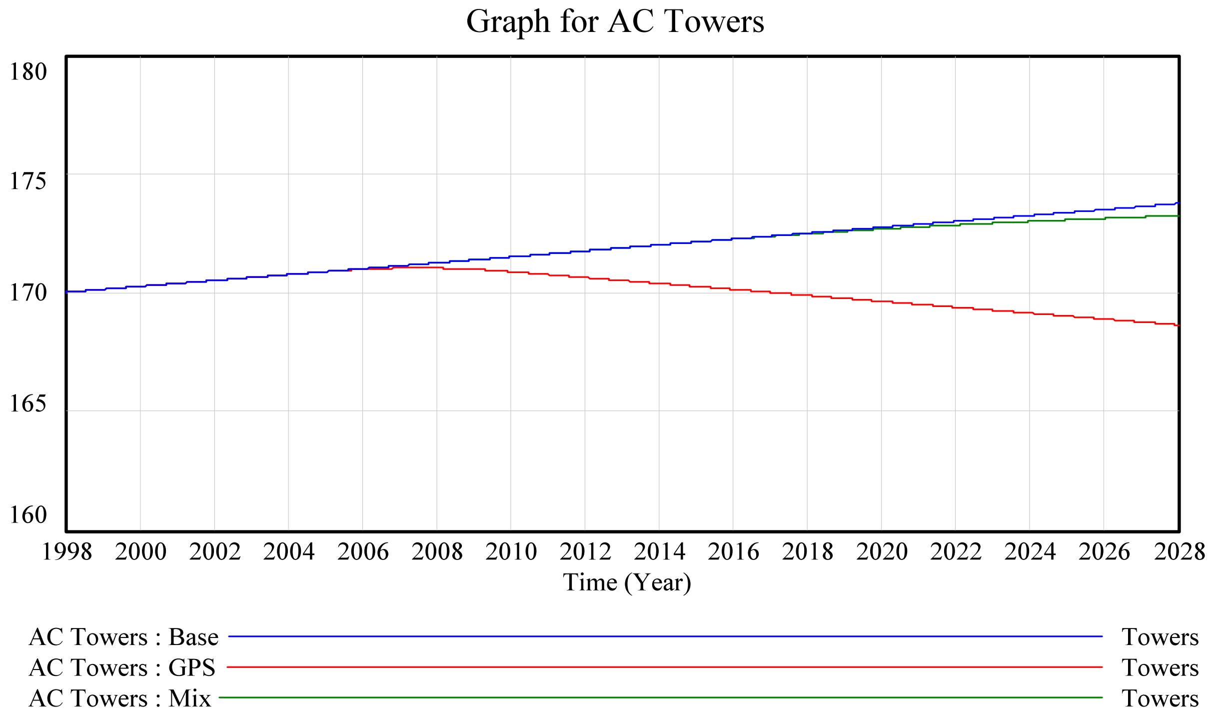

Figure 6-48: The third scenario causes a slight reduction in the population of AC towers.

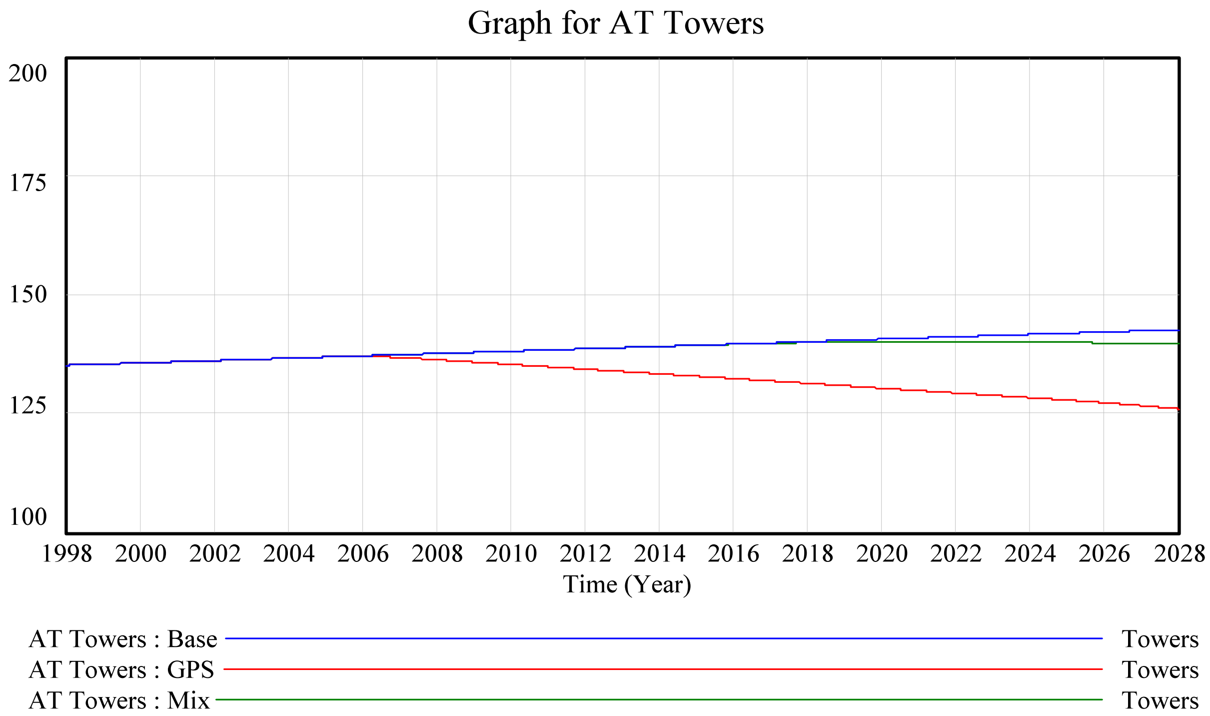

Figure 6-49: The third scenario causes a slight reduction in the population of AT towers.

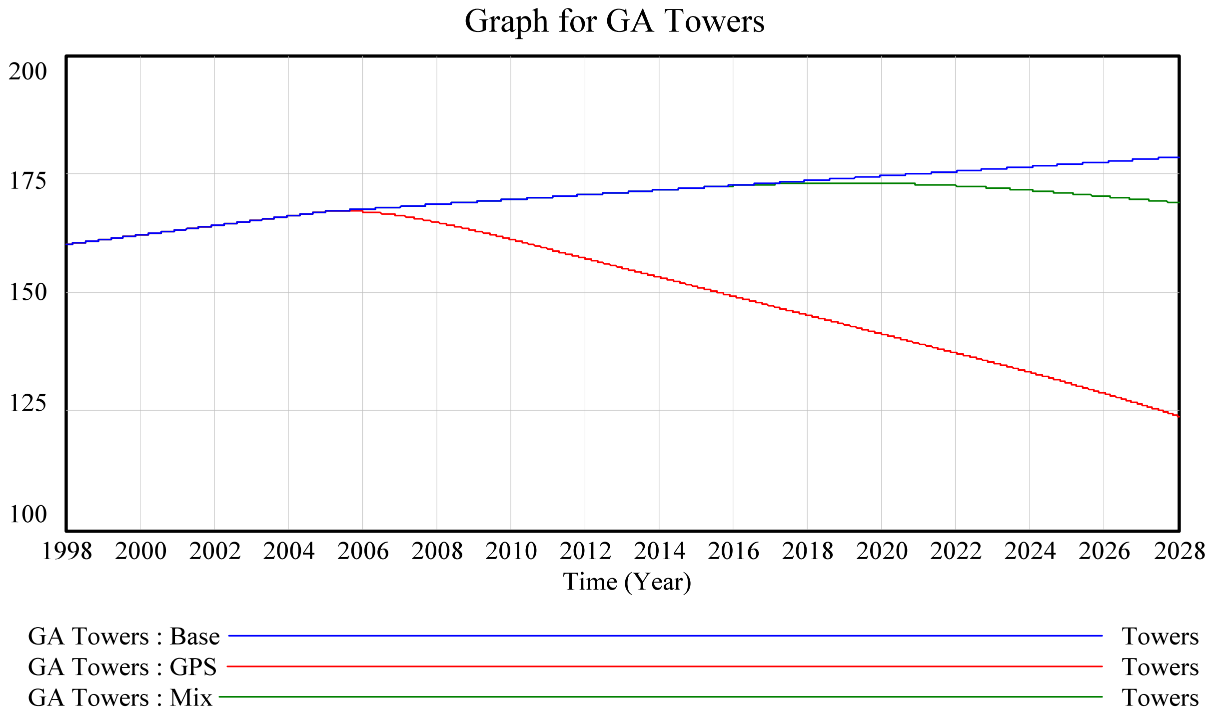

Figure 6-50: General Aviation control towers decline slightly under the third scenario.

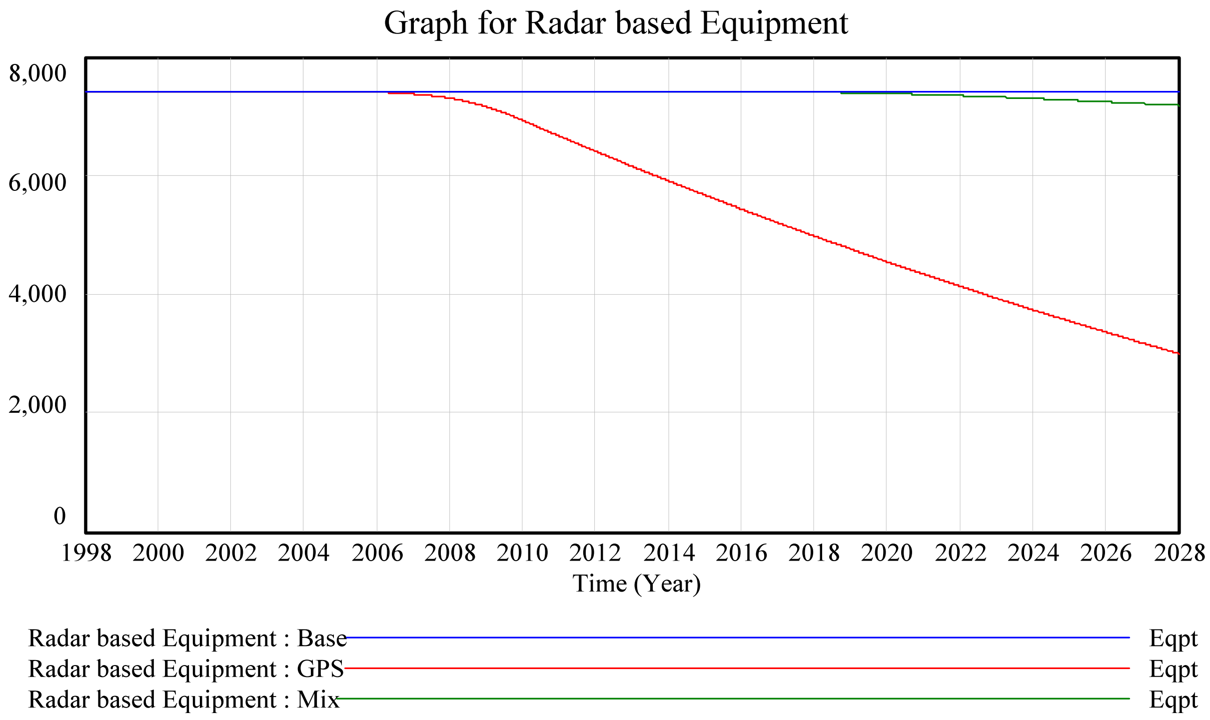

Figure 6-51: The population of radar-based equipment remains high throughout the third scenario.

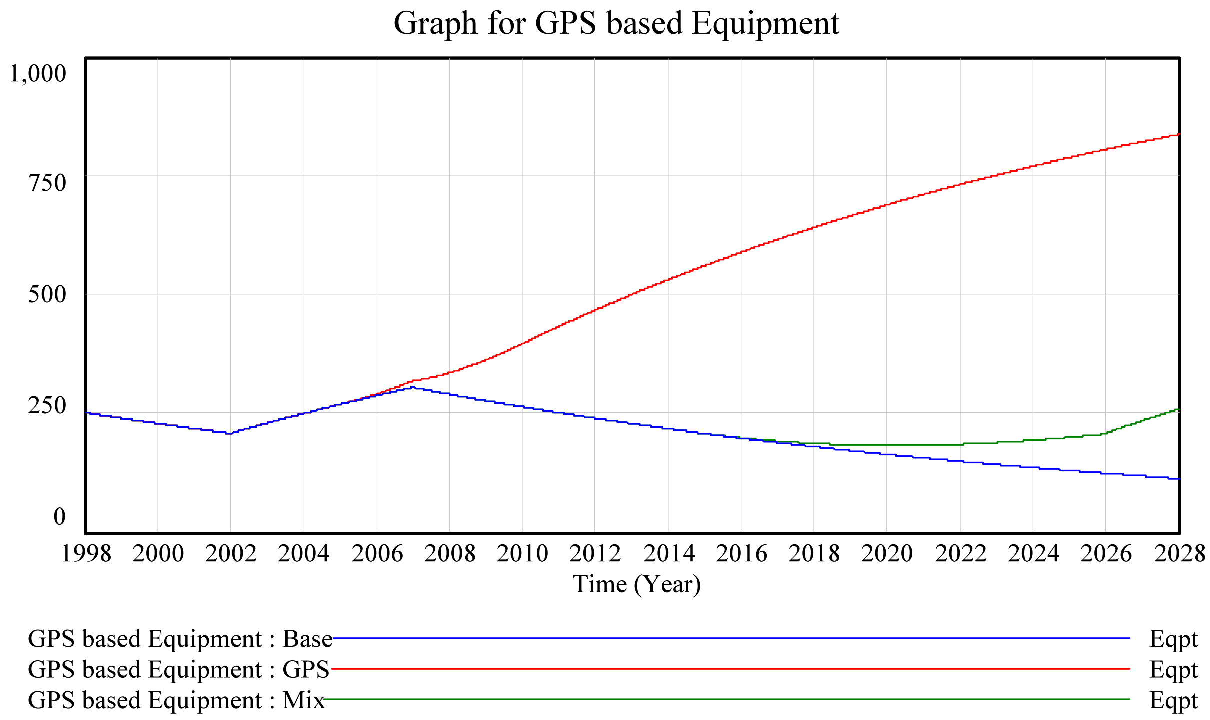

Figure 6-52: The GPS-based equipment population provides minimal support for SATS.

The model addresses two other key parts of the ATC system: aircraft and airports. Figure 6-53 to Figure 6-56 describe the populations of AC, AT, GA, and SATS aircraft. The growth of AC aircraft in Figure 6-53 plateaus around 2010 as in the first scenario due to inherent capacity constraints in the system. There is a slight reduction in the AC population after 2025 that has a small effect on revenue for the ATC system. Similarly, there are small declinations in the population of AT and GA aircraft also beginning approximately 2025 as depicted in Figure 6-54 and Figure 6-55. The number of SATS aircraft, depicted in Figure 6-56, grows rapidly due to conversions of AT and GA aircraft into SATS aircraft, enabled by the mild growth of supporting GPS infrastructure in the third scenario. However, the third scenario delays the growth of SATS by about five years, compared to the aggressive second scenario.

Figure 6-57 and Figure 6-58 capture the changes in the population of SATS and non-SATS airports. The non-SATS airports in Figure 6-57 continue to decline in number due to the normal demise of public use airports. After 2015, many of the non-SATS airports converted into SATS airports. The growth in SATS airports in Figure 6-58 during the third scenario enabled the relatively small-scale establishment of the SATS as a transportation system comprised of about 200 airports and 500 aircraft by 2025.

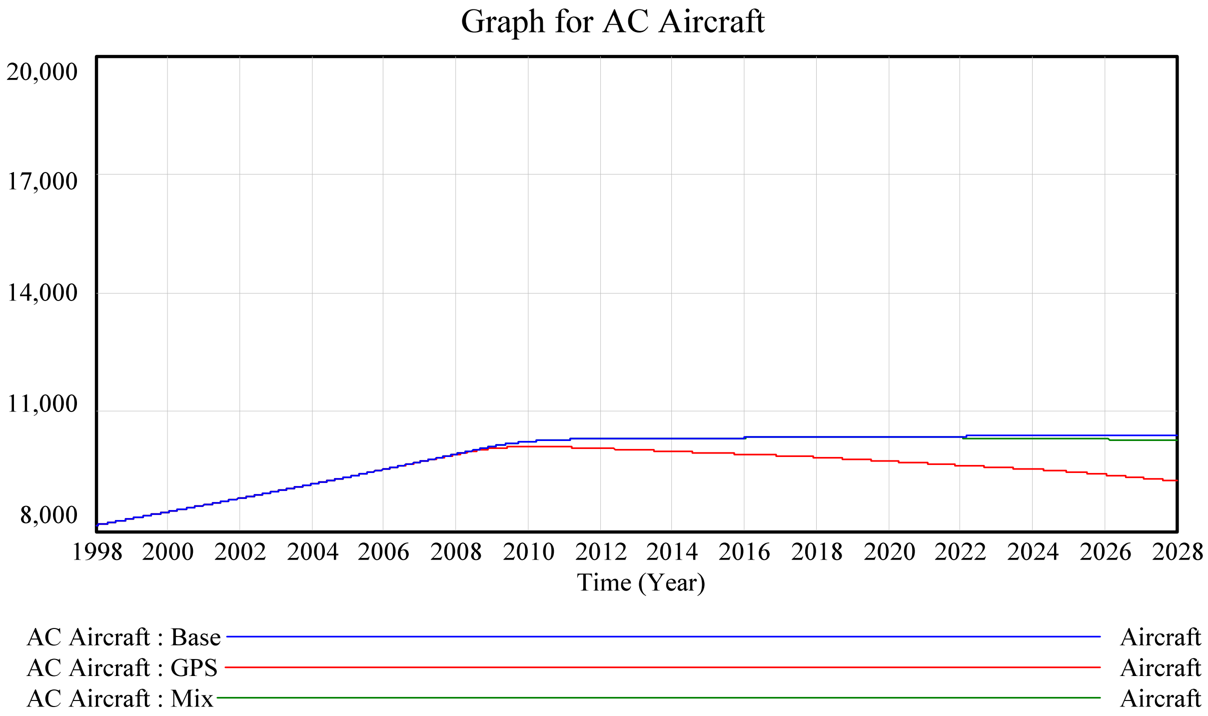

Figure 6-53: The third scenario maintains a steady population of AC aircraft.

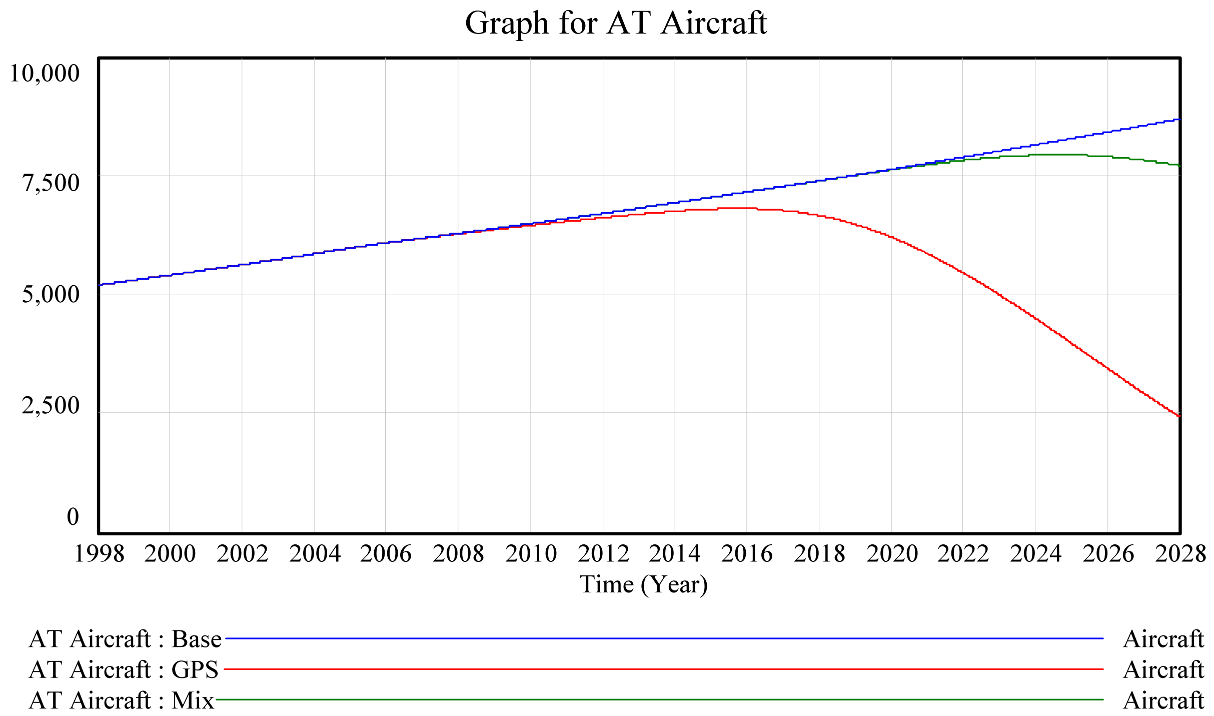

Figure 6-54: The population of AT aircraft declines slightly with the onset of SATS after 2020 in the third scenario.

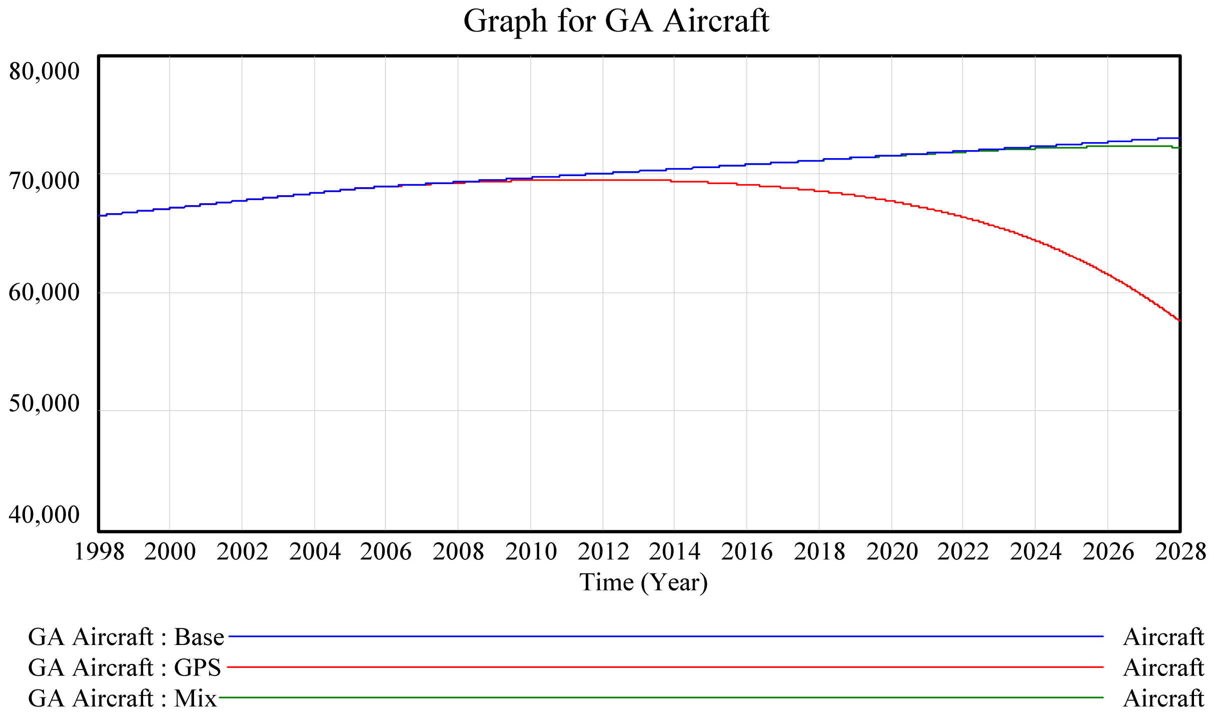

Figure 6-55: Only a small number of GA aircraft convert into SATS aircraft after 2024 in the third scenario.

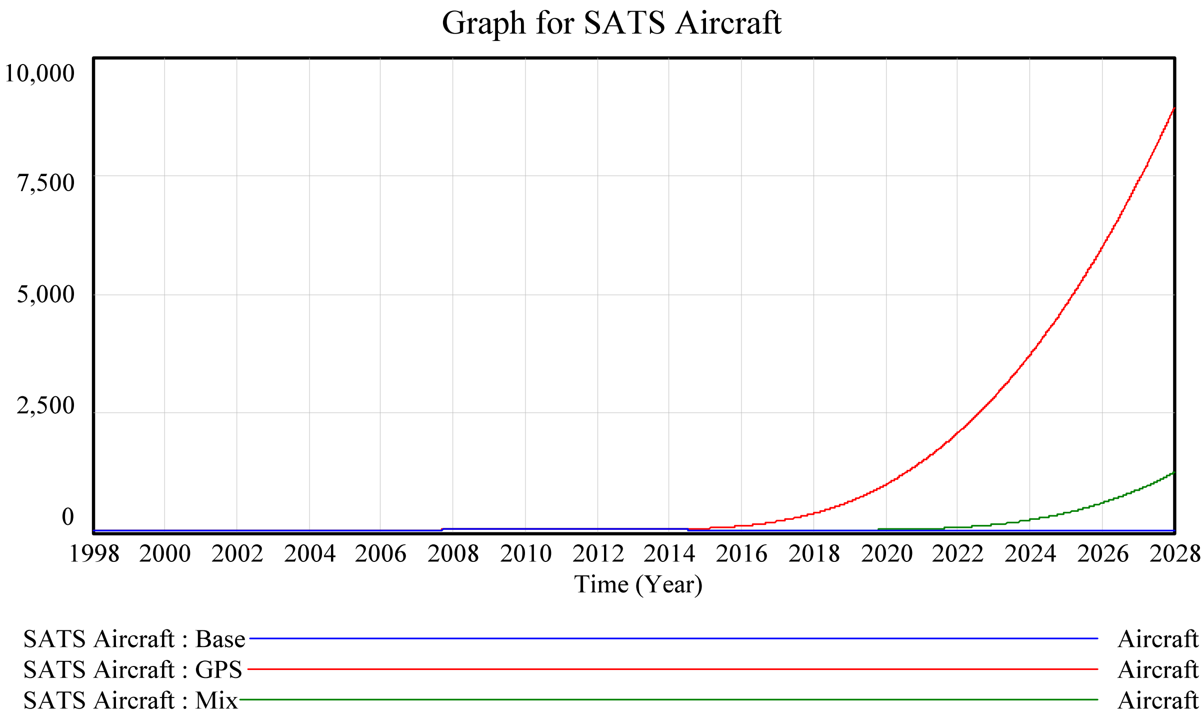

Figure 6-56: The third scenario delays the growth of SATS airports until five years after the second scenario.

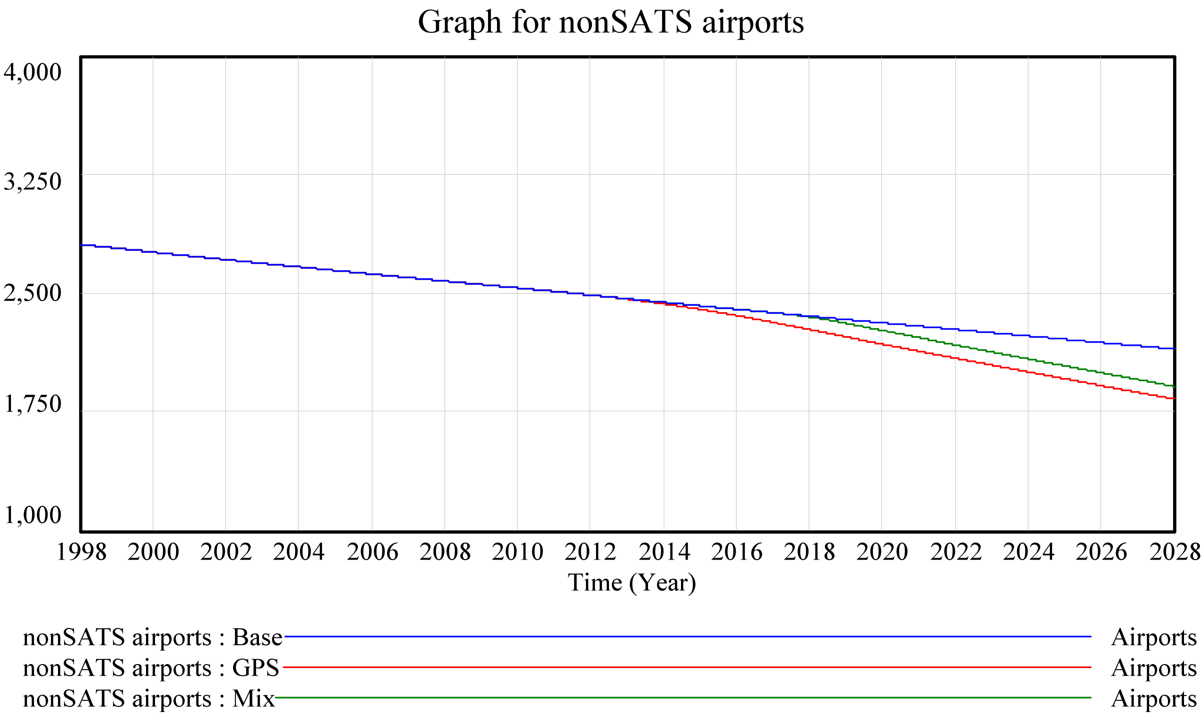

Figure 6-57: The third scenario invokes a slightly accelerated decline of non-SATS airports after 2018.

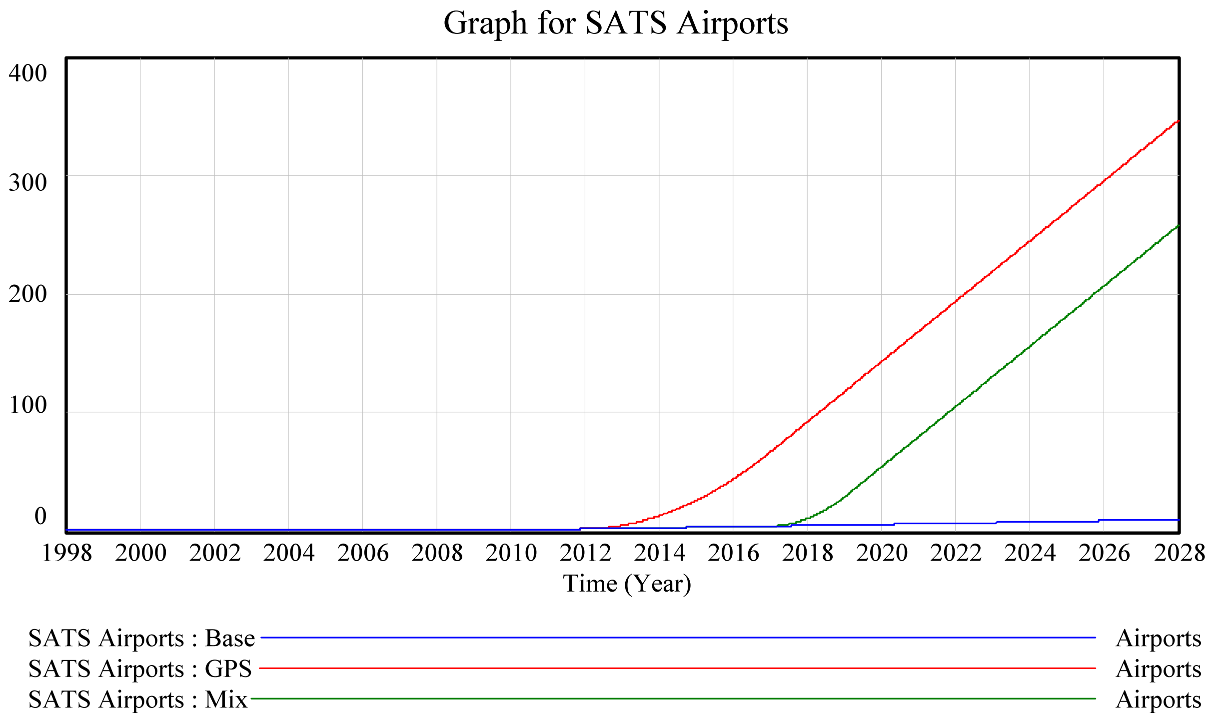

Figure 6-58: The third scenario shifts the growth of SATS airports five years later than the second scenario.

6.4.2 Analysis of Scenario 3

The results of the ATC Resource Management Model for the third scenario showed that the ATC system will continue to function almost as it has in the past, with minor exceptions in the distant future. The minor exceptions to normal behavior patterns appear to foreshadow the changes indicated in the second scenario. The third scenario is the only scenario of the three containing high revenue rates and growth in SATS airports and aircraft. Thus, the third scenario offers the SATS the best opportunity to establish itself and survive as a transportation system. Additionally, the third scenario includes a viable radar-based ATC system that generates the revenue needed to supply the AATF with the funds needed to operate the radar-based ATC system and establish SATS.

The behavior of the SATS and non-SATS airports over time may provide additional support to the growth of the SATS. Table 6-4 below provides an eighteen-year overview of the ratio of non-SATS IFR aircraft per public use airport. The data in the bottom row of Table 6-4 shows a range of 21 to 32 non-SATS IFR aircraft for each public use airport. The number of public use airports available for IFR aircraft is approximately 52% of the total number of public use airports, as discussed previously in Section 4.10. As the number of public use airports diminishes and the number of non-SATS IFR aircraft increases, the ratio of aircraft to airports begins to escalate as illustrated in Figure 6-59. In the third scenario, the ratio climbs above 40 non-SATS IFR aircraft per public use airport by the year 2026.

Concurrent to the increase in non-SATS aircraft per public use airport, the number of SATS aircraft per SATS airport remained relatively low in the third scenario. Figure 6-60 depicts the ratio of SATS aircraft per SATS airport from 1998 to 2028. The graph shows that all scenarios experience a ratio of up to 40 SATS aircraft per SATS airport when the SATS is in its infancy between 2008 and 2020. At that time, the SATS aircraft population virtually equals the SATS aircraft to SATS airport ratio because there is only one SATS airport until 2012 all three scenarios. The denominator grows slowly under the third scenario until about 2018 when the rate of new SATS airports begins accelerating as depicted in Figure 6-58 above. After 2020, when the non-SATS aircraft to airport ratio climbs above 35, the SATS aircraft to SATS airport ratio is less than 10. The potential "crowding" at non-SATS airports may serve as an incentive to transition to the SATS aircraft and system.

Table 6-4: The number of IFR aircraft per public use airport ranged from 21 to 32 between 1980 and 1998.

Airports & Aircraft	1980	1985	1994	1995	1996	1998
Public Use Airports	4,814	5,858	5,474	5,415	5,389	5,352
Adjusted Public Use (52%)	2,503	3,046	2,846	2,816	2,802	2,783
GA IFR nonSATS Aircraft	81,102	69,590	56,694	56,895	61,896	66,453
AT IFR nonSATS Aircraft			3,800	4,100	3,900	5,190
Total IFR type Aircraft	81,102	69,590	60,494	60,995	65,796	71,643
IFR Acft per Pub Use Airport	17	12	11	11	12	13
IFR Acft per Adjusted Pub Use Airport	32	23	21	22	23	26

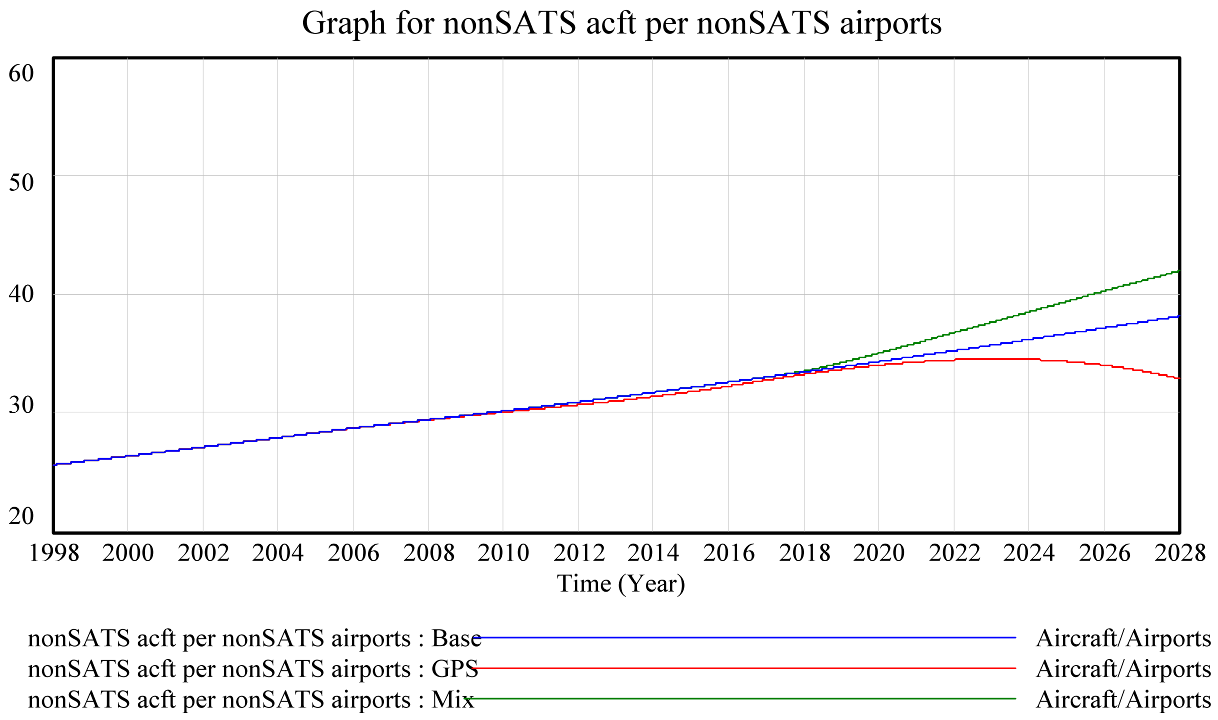

Figure 6-59: The ratio of non-SATS aircraft to airports exceeds historical ranges after 2015.

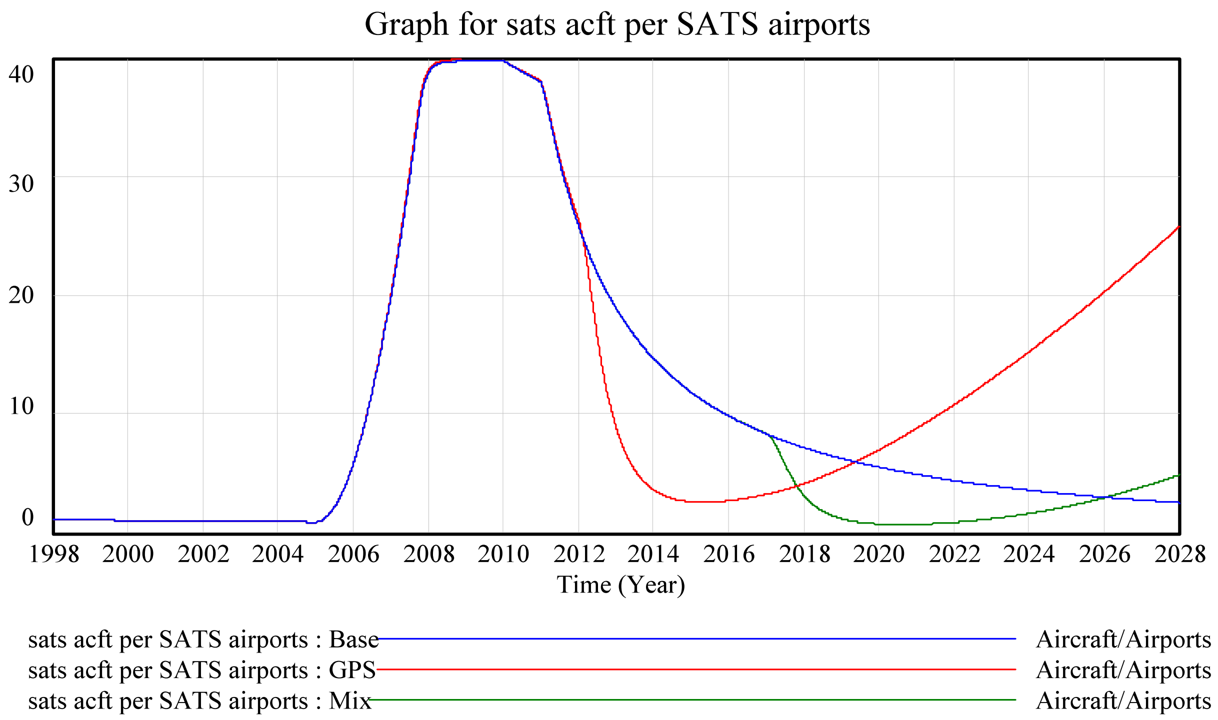

Figure 6-60: The ratio of SATS aircraft to airports remains low beyond 2020.

6.5 Summary of Simulation, Analysis, and Results

The three scenarios provided a glimpse of the future potential for the SATS. Each scenario created a slightly different view of the future according to the resource management strategy used to operate the ATC system. The discussion below describes the role of each scenario and highlights the results of the simulations used to answer the research questions.

6.5.1 Research Question 1: Future levels of support for SATS under radar-based ATC

The radar-based ATC scenario served as a base case from which to evaluate the current trends in ATC. The scenario included a handful of SATS aircraft and SATS airports; however, there was no management emphasis to provide resources to create the infrastructure needed to support SATS. The purpose of this scenario was to determine system behavior if the managers at the FAA chose to ignore the potential requirements of the SATS system and continue the current radar-based method of conducting air traffic control.

The model created dynamic system behavior that captured growth in AATF revenue, FAA budgets, facilities, and aircraft. The model illustrated the reduction of FAA employees, caused by controller and maintainer retirements, and the system's compensation through feedback to the hiring and training functions. The model also described the decline of SATS aircraft and systems as well as the continued decline in public use airports. The research showed that the radar-based ATC system would not support a small fleet of SATS aircraft. Further analysis of the behavior of the system indicated that the lack of SATS airports and ground-based GPS equipment prohibited the establishment of the Small Aircraft Transportation System.

6.5.2 Research Question 2: Future levels of support for SATS under an aggressive transition to GPS-based ATC

The GPS-based ATC scenario provided the opportunity to evaluate a major philosophical change in the manner of ATC conducted by the FAA. However, a major constraint on the GPS-based ATC scenario was to provide a moderate level of support to the many AC, AT, and GA aircraft that continued to utilize the radar-based ATC system. Management emphasis was to provide resources to create the infrastructure needed to support an aggressive expansion of GPS-based ATC, which supported the introduction and expansion of SATS aircraft. The purpose of this scenario was to determine system behavior if the managers at the FAA chose to endorse the SATS program while providing minimal support to the traditional radar-based ATC system.

The model demonstrated dynamic system behavior using the GPS-based approach that proved to be unacceptable and infeasible. However, the research also showed that the accelerated development of a GPS-based ATC system would support the establishment and maturation of a system of SATS aircraft and airports. Further analysis of the behavior of the ATC system indicated that the decline of AC aircraft caused an unacceptable reduction in system revenue. Additionally, the large reduction of radar-based equipment in the system created the potential for increased accidents or delays in the ATC system.

6.5.3 Research Question 3: Future levels of support for SATS under a radar-based ATC system supplemented by GPS

The final ATC scenario provided the opportunity to evaluate a hybrid ATC system that supported the radar-based approach while directing moderate amounts of resources towards GPS. Management emphasis was to provide resources to maintain the infrastructure needed for radar-based ATC while slightly accelerating the expansion of GPS-based ATC. The purpose of this scenario was to determine system behavior if the managers at the FAA chose to rely primarily on radar-based ATC, and, chose to provide a level of support to GPS related investments to give the SATS program the opportunity to come into being.

The model demonstrated dynamic system behavior that appeared very similar to the first scenario, yet provided sufficient marginal investments to elicit favorable trends for the SATS. The research showed that by supplementing radar-based ATC with GPS-based infrastructure, the system could produce over 250 SATS airports by 2028; beginning with only a dozen SATS airports in 2018. Additionally, the research showed that the supplemental approach would create a population of over 1,200 SATS aircraft by 2028; beginning with only 30 aircraft in 2020. Further analysis of the behavior of the system indicated that the ratio of aircraft to airports would encourage the transition to SATS aircraft due to the "overcrowding" of non-SATS aircraft.

All three scenarios provided evidence useful for drawing conclusions about the future behavior of the ATC system. The data shows that SATS will thrive under the second scenario, grow slowly under the third, and never come to fruition under the first. Additionally, the data shows that the AATF will support the ATC system under the first and third scenarios, but not the second. Chapter 7 provides further discussion of the outcome of the scenario analysis above.

Chapter 7: Conclusion

The FAA Operational Evolution Plan (FAA, 2002c) serves as the overarching document that addresses the desire to expand NAS capacity and improve efficiency in accordance with changing technology and adjustments in system priorities. However, the plan does not address SATS, a potentially significant technological change to the NAS that may alter national aviation priorities. The OEP focuses primarily on the larger airports around the nation that serve the commercial airlines. The findings of this dissertation show that the transformation of several hundred small airports in the US public use airport population can facilitate the growth of a viable Small Aircraft Transportation System that complements the commercial airliner dominated radar-based ATC system.

7.1 Major Findings

The most significant contribution of this research was the insight and understanding gained of how several resource management strategies and the presence of SATS aircraft may impact the future US Air Traffic Control system. In particular, the dissertation answered the fundamental research question: what air traffic control resource management strategy will support the future needs of the Small Aircraft Transportation System and create adequate tax revenue to fund the Federal Aviation Administration? The research showed that a radar-based ATC system, conservatively supplemented with GPS-based ATC capabilities, provided sustained revenue for the AATF and the opportunity for the creation of a Small Aircraft Transportation System.

The System Dynamics modeling and simulation methodology used to obtain the results contributed to the body of knowledge in two ways. First, the methodology provided a macro level view of the effects of feedback between the AATF and the ATC system. Second, the methodology provided insight into the role of SATS aircraft in the dynamic behavior of a future ATC system. The System Dynamics process guided the modeling effort. The process included procedures to verify and validate the System Dynamics model. A product of the process was a software tool that ATC resource managers could use to aid decision-making and understanding.

The ATC system performance results created by using the System Dynamics model provided the data needed to answer the research questions.

7.2 Research Questions

The research questions stemming from the fundamental research question above helped shape the scenarios addressed by the model in chapter 6 and led to understanding of the potential future behavior of the ATC system. The first insight gained is that the continuation of the current ground and radar-based ATC system will not create the conditions for the SATS to succeed. The data generated by the model for the first scenario showed that SATS would be nothing more than an experiment. The second insight gained is that too much emphasis on GPS-based ATC will jeopardize the SATS because the lack of radar-based ATC will cause a decline in AATF revenue. To create a viable SATS and maintain an adequate source of revenue, there must be a balance between radar-based ATC and GPS-based ATC. Thus, the third insight gained is that a future radar-based ATC system, supplemented by a ten-year transition period to GPS, will provide adequate revenue to operate the ATC system and will set the conditions for the successful establishment of the SATS. The second insight is counterintuitive, but makes more sense in light of the third insight. The insights lead to actions resource managers at the FAA should consider undertaking to shape the future ATC system.

7.3 Future FAA Resource Management Strategies

The focus of this effort was on the relationship between the GPS-based ATC system required to support a network of SATS aircraft and the FAA resource management strategies that would create the conditions for the existence of such a system. The System Dynamics modeling process highlighted the challenges faced by managers who would have to reduce their level of support for the existing radar-based ATC system in order to expand GPS. The results of the research showed that it is possible to support both systems and meet the requirements of the Airport and Airways Trust Fund. The results supported a strategy of choosing a conservative migration of up to 25% of the funding available in the Facilities and Equipment account over a ten-year period. The recommended strategy caused both Grants-in-Aid investments in SATS airports and the expansion of the SATS aircraft population, resulting in an operational SATS.

Managers at the FAA should also consider several other proposals regarding future resource management and the SATS. First, the FAA should integrate SATS into the Operational Evolution Plan (FAA, 2002c). The US Congress and NASA support SATS. The FAA should not ignore the possibilities and potential of the SATS. The system may benefit the FAA. For example, SATS could reduce requirements for Air Traffic Controllers at a time when there may be controller shortages due to retirements. Second, the FAA should use the ATC resource management model to observe how the ATC system will behave after they implement policy decisions related to SATS. Managers can determine which parts of the system they may have the most leverage in order to restructure it to create more favorable outcomes.

The FAA managers should take action in several areas. First, they should write an Operational Evolution Plan for the SATS to address specific requirements for SATS aircraft. Second, they should collect and process data to determine how GPS systems influence ATC. In particular, they should determine how the reliability of the system may influence the need for Air Traffic Controllers. Third, they should assess the impact of various tax rates on the AATF to determine if SATS aircraft should fall into a unique tax category. Fourth, they should analyze the future required distribution of resources among the major accounts of the FAA budget. Finally, they should consider the impact of other emerging ATC technologies they may be more advantageous than GPS.

Historically, restructuring the FAA has been a slow and methodical process due to the conservative culture of the organization. The understanding created by System Dynamics modeling may serve as an impetus to accelerate change with confidence. The findings of this research indicate that the SATS faces a "limits to growth" system archetype depicted below in Figure 7-1. Risk averse ATC resource managers can apply the archetype and the ATC Resource Management Model to understand that SATS will grow continuously with increased funding for GPS-based ATC. However, the constraint caused by the radar-based system upon the revenue from AC aircraft clearly balances the growth of SATS. Tracing causality through the archetype makes it easy to understand how SATS can grow or decline.

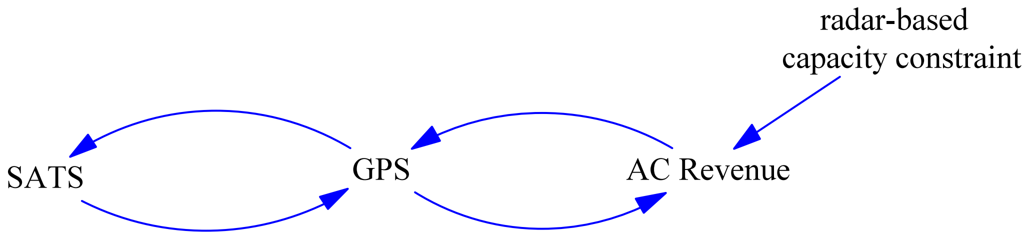

Figure 7-1: The radar-based constraints limit AC revenue, GPS infrastructure, and ultimately, SATS.

7.4 Future Considerations for SATS Proponents

Those who advocate the creation of a Small Aircraft Transportation System should also consider several proposals. First, recognize that a healthy conventional airline industry provides the bulk of the revenue needed to create and sustain a SATS. Second, understand that to be successful, SATS must develop slowly over a long period of time. Third, the longer it takes to establish SATS, the more mature the technology will be to enable the concept. Fourth, advocates of SATS should ensure the development of SATS airports is a consideration as part of the National Plan of Integrated Airport Systems (NPIAS) to secure future Airport Improvement Program (AIP) funding for potential SATS airports. Finally, SATS may face other disruptions and challenges, such as passenger security restrictions, pilot shortages, or in-flight route constraints to protect national interests.

The future of SATS is uncertain. The FAA does not recognize the system as a future requirement to consider because the aircraft is not yet technologically feasible. However, there is significant effort among industry, government, and academia to create a SATS for the US. Although research funding exists for the program for several more years, its success will require a long-term balance of resources to establish SATS and maintain a high level of AC revenue for the AATF. Advocates for SATS will have to provide an honest assessment of the technological feasibility of the system, and communicate the resource requirements to stakeholders. Ultimately, those who provided the seed money, the US Congress, may be called upon to provide more money for research or make adjustments in aviation taxes to support the program.

7.5 Future Research

This research successfully developed a System Dynamics model of the principal components of the US air traffic control system. Future research may provide useful expansions and extensions of the System Dynamics modeling approach. By developing stocks and flows associated with the hub and spoke system, future researchers could expand the model to gain greater insight on the flow of passengers through the system and how their feedback influences the system. Additionally, an expanded model could be a useful tool to determine the impact SATS may have upon the number of small aircraft utilizing the large hub airports. Researchers could investigate how SATS may increase or reduce problems of congestion, parking shortages, gate shortages, and wake vortex incidents.

Future research could extend the System Dynamics model of the ATC system by generalizing it to other similar systems. The Federal Highway Trust Fund creates revenue based on motor vehicle gasoline taxes. Department of Transportation managers may wish to implement resource management strategies that impact revenue and non-fossil fuel vehicles. Extending the ATC Resource Management Model to other domains may help managers understand systems so they can make appropriate interventions with confidence.

7.6 Summary

The Small Aircraft Transportation System offers exciting opportunities on many fronts. The technological challenges of developing a low-cost, yet highly capable means of airborne transportation is being addressed by the aviation industry. Several academicians are addressing the challenges of airspace management and Air Traffic Control under an approach that leads to the notion of free flight. Program leadership and management emanates from NASA research centers. However, the FAA has not taken the initiative to support the SATS concept. The research in this dissertation attempts to bridge a gap that exists between the FAA and the communities and groups who support the SATS program. The research shows that an ATC system that supports SATS is feasible, however, the FAA must join with the stakeholders to create the conditions to make the ATC piece of the SATS a success.

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Appendix 1: Glossary

AATF - Airport and Airways Trust Fund

AIP – Airport Improvement Program

ARTCC – Air Route Traffic Control Center

ASDE – Airport Surface Detection Equipment

ATADS -

ATC – Air Traffic Control

ATM – Air Traffic Management

ATS – Air Traffic Services

CAA - Civil Aeronautics Administration

DOT – Department of Transportation

FAA - Federal Aviation Administration

FAST – Final Approach Spacing Tool

GPS – Global Positioning Satellite

IFR – Instrument Flight Rules

NAS - National Airspace System

NASA - National Aeronautics and Space Administration

NATCA – National Air Traffic Controllers Association

NPIAS - National Plan of Integrated Airport Systems

OEP - Operational Evolution Plan

RTCA - Radio Technical Commission for Aeronautics

SATS – Small Aircraft Transportation System

TMA – Traffic Management Advisor

TRACON – Terminal Radar Approach Control

US – United States

VFR – Visual Flight Rules

Appendix 2: Control Tower Rankings

The following table provides the average annual number of control tower operations for the four types of control towers.

LOCID: Control tower location identifiers.

FTYPE: Type of control tower; B – radar, C – limited radar, D – non-rader, E – VFR, F – Contract VFR

AC Avg: Average annual control tower operations between 1990-2001 for Air Carrier aircraft

AT Avg: Average annual control tower operations between 1990-2001 for Air Taxi aircraft

GA Avg: Average annual control tower operations between 1990-2001 for General Aviation aircraft

MIL Avg: Average annual control tower operations between 1990-2001 for Military aircraft

Rank: Quantitative order for the LOCID and type aircraft.

LOCID	FTYPE	AC Avg	AC Rank	AT Avg	AT Rank	GA Avg	GA Rank	MIL Avg	MIL Rank
ORD	C	697,445	1	142,618	10	33,144	252	2,235	163
DFW	C	592,092	2	204,886	2	34,398	238	790	
ATL	B	573,176	3	170,984	4	21,868	351	2,851	140
LAX	C	479,061	4	207,493	1	32,992	256	6,767	53
PHX	C	341,817	5	83,538	27	88,060	53	7,541	43
DEN	C	334,389	6	139,584	11	25,728	315	1,245	
STL	C	317,303	7	120,166	15	32,878	257	6,763	54
DTW	C	316,170	8	107,729	19	66,435	91	1,494	
EWR	C	314,068	9	101,631	21	19,742	373	317	
SFO	C	313,477	10	83,428	28	25,458	317	2,483	152
MIA	B	305,824	11	134,656	12	72,108	84	6,399	60
IAH	C	278,943	12	79,484	31	31,400	269	887	
MSP	C	269,328	13	108,681	17	77,014	74	3,057	136
LAS	C	262,693	14	66,697	40	90,302	46	17,734	10
CLT	B	260,800	15	131,052	14	62,298	99	4,136	101
LGA	C	256,314	16	79,812	30	18,056	390	312	
PIT	B	253,528	17	149,139	9	23,760	333	6,792	50
BOS	C	247,846	18	202,506	3	32,674	260	632	

PHL	B	240,593	19	133,287	13	50,036	148	4,225	99
JFK	C	223,698	20	107,859	18	14,729	416	614	
SEA	C	216,978	21	157,397	8	7,374	450	225	
MCO	B	210,534	22	88,040	23	29,322	287	5,223	76
CVG	B	190,803	23	160,698	6	19,708	374	1,376	
MEM	B	189,679	24	100,978	22	60,228	107	5,519	72
DCA	B	180,299	25	76,089	33	55,452	119	6,370	61
SLC	C	174,877	26	85,687	24	79,278	69	4,303	97
BWI	B	162,830	27	80,726	29	33,496	245	2,191	165
SAN	C	143,128	28	52,552	49	18,912	382	3,793	113
CLE	B	142,965	29	105,403	20	31,635	268	3,098	133
OAK	C	138,986	30	53,382	47	149,157	12	686	
MCI	B	132,136	31	49,317	50	14,187	421	990	
TPA	B	128,766	32	78,289	32	44,685	170	1,929	180
MDW	C	125,517	33	60,636	42	76,166	76	1,955	178
HOU	C	120,756	34	16,590	140	113,798	24	644	
SJC	C	117,401	35	25,874	95	96,741	40	574	
IND	B	115,017	36	72,272	37	50,980	140	2,097	170
BNA	B	114,714	37	73,375	36	65,315	95	5,042	80
PDX	C	114,274	38	119,459	16	45,326	166	10,509	28
RDU	B	113,305	39	75,864	35	69,284	86	6,012	66
IAD	B	111,876	40	167,178	5	57,185	116	6,776	52
FLL	C	110,668	41	54,774	46	74,153	80	955	
MSY	B	102,887	42	29,202	84	25,973	310	1,965	176
DAL	C	94,232	43	30,944	73	96,379	41	1,282	
ONT	C	94,135	44	29,308	83	25,416	318	303	
SDF	B	92,124	45	36,849	61	33,672	244	4,525	93
SAT	B	81,352	46	32,974	69	107,240	33	7,202	46
MKE	B	81,018	47	67,662	39	43,155	177	5,178	77
ABQ	B	77,858	48	35,902	63	63,218	98	23,076	4
SJU	C	77,643	49	84,152	25	26,916	302	3,470	121
AUS	B	77,538	50	18,449	130	86,366	56	5,556	71
CMH	B	75,257	51	67,734	38	52,505	135	1,398	
SNA	C	73,625	52	22,423	106	243,821	2	444	
SMF	E	73,148	53	33,958	68	26,225	308	1,388	
DAY	B	69,191	54	38,613	58	40,958	193	1,909	183
BDL	C	67,036	55	53,381	48	41,750	185	7,921	34
RNO	B	65,163	56	20,490	118	50,578	145	5,073	79
ELP	B	57,418	57	10,359	209	54,188	124	4,801	85
BUR	C	56,812	58	38,436	59	87,096	55	602	
PBI	B	55,674	59	29,530	81	105,847	34	1,389	
BUF	B	52,454	60	39,796	54	38,290	212	3,345	128
JAX	B	51,961	61	33,964	67	28,294	295	8,246	32
TUL	B	49,215	62	16,042	147	75,028	77	21,065	7
OKC	B	48,367	63	11,697	192	60,757	105	25,972	2
GSO	B	46,575	64	25,121	98	52,172	136	850	
OMA	C	45,334	65	29,015	86	51,314	138	889	

TUS	C	43,137	66	11,005	200	93,531	45	23,788	3
ROC	B	41,923	67	43,785	51	43,163	176	2,121	167
ORF	B	40,750	68	23,617	101	59,263	110	3,972	105
RSW	B	39,728	69	14,205	160	10,020	441	1,344	
RIC	B	39,379	70	29,495	82	50,283	146	10,204	30
GEG	B	38,616	71	35,684	64	24,489	329	1,752	186
SYR	B	36,928	72	59,655	43	36,129	221	5,570	70
BHM	B	36,560	73	26,711	93	74,159	79	10,394	29
PVD	B	36,487	74	41,223	52	41,918	181	3,068	134
LIT	B	34,904	75	21,295	113	78,109	71	7,212	45
COS	B	31,428	76	11,928	190	54,763	122	16,681	12
BOI	B	31,280	77	29,671	80	61,448	104	11,946	23
DSM	B	30,137	78	27,994	92	55,197	121	4,041	102
ICT	B	26,449	79	18,274	131	98,807	39	2,084	171
ALB	B	26,220	80	65,277	41	42,852	178	4,632	90
GRR	B	23,843	81	34,945	65	52,633	132	1,167	
TYS	B	22,602	82	26,582	94	53,087	129	12,433	21
CHS	B	22,284	83	9,204	227	32,389	262	22,202	6
CAE	B	20,600	84	24,077	99	38,387	211	3,967	106
GUM	G	20,012	85	4,181		10,026	440	3,155	130
TOL	B	19,869	86	20,134	120	32,809	258	3,792	114
MDT	B	19,852	87	30,441	75	18,020	392	4,626	91
LBB	B	19,759	88	15,415	153	31,816	266	2,414	156
MHT	B	19,600	89	29,851	78	34,125	241	577	
GSP	B	18,394	90	19,827	122	18,587	385	1,454	
SRQ	C	18,100	91	13,303	177	94,767	44	2,065	172
JAN	B	17,688	92	17,428	134	22,817	343	7,889	36
ABE	B	16,824	93	20,159	119	50,961	141	2,492	151
MSN	B	16,651	94	15,754	149	53,829	125	6,158	64
HSV	B	16,601	95	10,346	210	28,396	294	4,786	86
PWM	B	16,008	96	31,249	72	35,672	225	1,550	195
SAV	B	15,480	97	9,354	223	40,973	192	6,782	51
FWA	B	15,358	98	22,703	104	34,692	235	3,824	109
CID	B	14,823	99	17,229	136	30,860	275	216	
MAF	B	14,471	100	9,243	226	21,605	354	6,278	62
PNS	C	14,266	101	21,931	109	33,870	243	20,752	8
CRP	B	13,803	102	14,355	159	32,306	264	13,377	20
LGB	E	13,511	103	4,153		192,219	4	1,320	
HRL	G	13,456	104	3,874		11,910	434	4,211	100
ISP	C	13,270	105	22,099	108	78,776	70	2,444	155
LEX	B	13,094	106	22,446	105	47,305	160	1,297	
SBN	B	12,957	107	21,172	114	26,375	305	169	
SHV	B	12,711	108	25,666	96	25,872	311	3,818	110
MOB	B	12,689	109	7,700	248	23,120	338	22,670	5
BTR	B	12,238	110	16,524	141	52,542	133	1,921	181
FSD	B	11,634	111	16,288	144	36,443	218	4,350	96
MLI	B	11,539	112	16,511	142	27,845	298	1,669	191

SWF	G	11,518	113	13,408	175	49,130	153	6,403	59
ACY	B	11,481	114	16,145	145	33,090	253	12,278	22
BIL	B	11,373	115	32,159	71	35,644	227	670	
AMA	B	11,348	116	10,109	216	21,946	349	13,615	18
MYR	B	11,301	117	12,945	180	20,116	367	1,615	194
FAT	B	11,209	118	56,252	45	77,653	73	9,925	31
GRB	B	10,810	119	12,868	182	21,908	350	815	
HPN	C	10,527	120	39,242	57	110,552	29	287	
MWH	B	10,499	121	4,769	294	24,558	327	3,136	131
TLH	B	10,049	122	33,975	66	43,786	173	4,931	83
MHR	G	9,955	123	13,803	168	29,180	288	3,976	104
YIP	E	9,753	124	29,686	79	43,372	175	368	
CHA	B	9,187	125	15,648	151	50,761	144	3,794	112
BTV	B	9,040	126	39,542	56	30,921	274	6,756	55
ROA	B	8,931	127	28,609	89	29,515	286	949	
DAB	B	8,801	128	4,511	297	227,264	3	822	
CAK	B	8,630	129	19,576	124	54,689	123	4,915	84
PIA	B	8,572	130	20,922	116	30,216	280	6,725	56
ATW	G	8,554	131	12,643	185	22,825	342	32	
SGF	B	8,465	132	21,684	112	38,811	210	3,987	103
LAN	B	8,309	133	29,158	85	41,653	186	1,621	193
PSP	B	8,280	134	30,326	77	44,111	171	628	
BFI	E	8,267	135	36,594	62	191,848	5	2,117	168
MBS	B	8,186	136	10,220	215	20,579	360	506	
GTF	B	8,098	137	13,808	167	16,614	404	5,876	67
BGR	B	7,747	138	22,800	103	22,487	345	10,721	26
ASE	B	7,650	139	5,554	280	26,311	306	120	
RFD	B	7,490	140	11,970	189	43,857	172	1,156	
RST	B	7,417	141	3,231		24,973	321	1,390	
STT	C	7,342	142	58,716	44	21,634	353	1,919	182
PIE	C	7,203	143	5,472	281	78,094	72	8,049	33
MLB	G	7,130	144	2,509		88,667	51	613	
CWA	G	6,937	145	11,083	197	10,515	438	475	
SBA	B	6,894	146	41,153	53	71,910	85	1,011	
LNK	B	6,860	147	10,896	202	39,104	208	10,849	25
MFE	G	6,758	148	2,660		28,949	290	3,869	108
TRI	B	6,644	149	15,676	150	36,099	222	512	
FAR	B	6,551	150	11,117	196	34,271	240	4,442	95
CRW	B	6,496	151	25,291	97	36,228	219	3,949	107
GSN	G	6,466	152	23,652	100	8,797	446	450	
AZO	B	6,390	153	19,378	126	39,598	205	390	
EUG	B	6,122	154	22,266	107	49,110	154	1,542	196
MGM	B	5,994	155	10,533	205	31,899	265	17,086	11
AVL	B	5,941	156	13,827	165	34,687	236	1,810	185
AVP	B	5,833	157	15,418	152	25,275	319	1,292	
AGS	B	5,508	158	8,436	236	18,851	383	3,201	129
DET	G	5,066	159	7,638	249	65,218	96	406	

MSO	G	5,056	160	11,348	194	23,050	341	391	
FNT	B	5,044	161	17,344	135	31,191	271	353	
BZN	G	4,876	162	5,136	286	18,026	391	322	
DLH	B	4,795	163	6,566	264	20,565	361	5,237	75
FAY	B	4,658	164	10,364	208	23,222	336	6,916	49
MLU	B	4,544	165	9,929	219	29,164	289	2,808	141
ILM	B	4,453	166	13,783	170	30,769	276	2,463	154
STX	G	4,354	167	28,993	87	6,007		2,016	174
BIS	B	4,188	168	11,216	195	24,841	323	2,668	145
HTS	B	3,998	169	8,804	229	20,720	358	647	
XNA	G	3,925	170	19,793	123	5,629		819	
GCN	E	504		159,590	7	6,325		184	
ACK	E	67		83,929	26	46,199	162	756	
HYA	G	4		76,080	34	25,829	313	108	
LFT	B	1,181		39,707	55	35,578	229	2,102	169
HUM	G	0		37,936	60	17,343	397	381	
EYW	G	806		32,787	70	36,573	216	7,766	39
VGT	E	2		30,814	74	61,615	103	147	
TEB	C	113		30,371	76	185,589	6	368	
BFL	B	1,306		28,819	88	68,990	87	1,370	
EVV	B	1,674		28,535	90	32,399	261	767	
MRY	B	2,663		28,201	91	56,025	118	1,679	190
PSC	B	2,605		23,008	102	25,551	316	766	
CHO	G	592		21,888	110	32,364	263	1,357	
MVY	G	5		21,732	111	29,909	282	185	
SPI	B	395		20,970	115	42,524	179	5,266	74
BGM	B	2,648		20,764	117	14,244	420	546	
GJT	G	2,565		19,942	121	38,953	209	2,734	143
BLI	G	1,102		19,563	125	35,896	224	801	
PHF	E	2,364		19,375	127	53,438	127	15,507	13
AGC	E	15		19,146	128	73,529	81	604	
MFR	G	2,496		18,809	129	24,641	324	337	
PFN	G	2,664		18,079	132	33,166	251	2,357	159
TVC	E	2,619		17,736	133	40,083	200	2,642	146
APA	E	9		16,990	137	173,820	8	1,443	
CMI	B	1,206		16,953	138	39,817	202	518	
FMN	G	48		16,853	139	29,557	285	328	
BPT	B	25		16,439	143	17,220	399	1,378	
ALO	B	217		16,044	146	23,063	340	2,757	142
LCH	B	17		15,759	148	15,781	410	1,733	188
SBP	G	1		15,396	154	40,113	199	705	
RDD	G	67		15,164	155	35,161	232	777	
OXR	G	38		14,963	156	40,367	197	1,230	
ARA	G	129		14,797	157	8,600	447	6,160	63
PIH	G	166		14,383	158	17,380	396	223	
MFR	E	2,496		14,194	161	24,641	325	337	
ORL	E	0		14,181	162	118,569	21	965	

HLN	D	2,378		14,063	163	20,242	365	4,781	87
FSM	B	159		13,864	164	24,552	328	13,698	17
LRD	G	2,780		13,809	166	24,987	320	5,829	68
PTK	E	380		13,792	169	151,459	11	276	
RDM	G	141		13,742	171	15,845	409	354	
PPG	D	342		13,690	172	353		470	
YKM	G	432		13,554	173	16,084	408	1,388	
CPR	B	1,332		13,493	174	18,185	389	375	
APF	G	19		13,313	176	65,866	92	99	
SUX	B	1,823		13,175	178	22,295	347	3,461	123
RDG	B	88		12,948	179	58,204	114	1,373	
MOD	E	7		12,884	181	35,161	230	363	
BMI	G	1,148		12,767	183	19,866	370	306	
ABI	B	180		12,710	184	24,887	322	7,721	42
CRQ	E	11		12,616	186	144,056	14	3,805	111
EWB	G	4		12,336	187	20,431	363	166	
ELM	B	2,722		12,180	188	20,685	359	289	
LWS	G	77		11,923	191	22,249	348	379	
LYH	G	144		11,602	193	20,219	366	655	
TWF	D	158		11,066	198	20,530	362	871	
IDA	G	1,953		11,057	199	13,456	424	147	
FYV	G	811		10,956	201	12,643	432	162	
ACT	B	242		10,616	203	26,165	309	3,355	127
UCA	G	499		10,596	204	17,836	394	764	
SMX	G	79		10,512	206	29,907	283	381	
GPT	B	3,733		10,417	207	23,995	332	14,252	16
AEX	G	1,472		10,312	211	4,598		2,678	144
CSG	B	2,439		10,288	212	29,610	284	604	
MKG	B	65		10,273	213	40,166	198	2,362	157
TYR	G	5		10,257	214	41,910	182	146	
GNV	G	3,258		10,077	217	35,666	226	1,665	192
RAP	G	3,646		10,053	218	19,454	376	1,930	179
ERI	B	3,340		9,894	220	27,017	301	849	
ABY	G	204		9,697	221	15,546	412	1,204	
SUN	G	55		9,621	222	41,852	183	30	
MKC	C	97		9,276	224	84,839	62	830	
SFF	G	0		9,270	225	33,058	254	287	
EKO	G	1,693		8,988	228	9,684	442	82	
TUT	D	583		8,776	230	370		550	
EWN	G	0		8,716	231	13,606	423	1,000	
MGW	G	2		8,670	232	14,910	415	1,300	
BED	E	119		8,551	233	108,516	31	1,958	177
ITH	G	2,197		8,508	234	13,894	422	91	
MOD	G	7		8,455	235	35,161	231	363	
FLG	G	31		8,435	237	25,808	314	375	
PAH	G	58		8,305	238	20,025	368	687	
MEI	G	1		8,193	239	13,272	425	18,593	9

TXK	G	64		8,116	240	19,863	371	1,046	
FLO	B	1		7,967	241	21,748	352	1,725	189
YNG	B	1,766		7,866	242	30,961	273	6,609	57
LSE	G	2,118		7,840	243	15,758	411	516	
JAC	G	1,536		7,819	244	16,901	401	204	
MYF	E	5		7,795	245	130,209	18	267	
STS	E	66		7,789	246	85,401	61	556	
FXE	E	0		7,774	247	178,159	7	160	
CLL	G	70		7,637	250	27,711	299	7,091	47
SIG	G	2		7,501	251	48,320	156	2,928	138
HVN	G	805		7,483	252	28,489	293	200	
OPF	G	89		7,354	253	72,715	83	7,904	35
GFK	E	3,584		7,124	254	81,439	66	671	
CRG	G	0		7,113	255	58,662	112	11,004	24
PDT	G	12		7,067	256	18,554	386	1,366	
GGG	B	50		7,018	257	31,001	272	1,741	187
CKB	B	15		6,852	258	22,573	344	3,462	122
SJT	G	22		6,850	259	18,219	388	4,977	81
PUB	B	818		6,786	260	26,726	303	5,325	73
BKL	G	58		6,738	261	39,712	203	459	
IPT	G	13		6,633	262	17,015	400	194	
DBQ	G	75		6,624	263	17,858	393	76	
MYT	E	2,361		6,538	265	1,254		178	
CYS	G	321		6,449	266	11,254	437	3,444	124
CIC	G	23		6,339	267	26,256	307	419	
STP	E	3		6,332	268	86,266	58	6,555	58
LUK	G	1		6,329	269	65,581	93	440	
JVL	G	342		6,190	270	36,220	220	261	
TTN	G	1,690		6,107	271	68,296	89	3,762	116
ROW	B	201		6,092	272	19,098	379	10,600	27
DHN	G	552		6,085	273	19,165	378	15,107	14
PKB	G	4		6,009	274	16,396	406	3,000	137
PRC	E	229		5,965	275	108,867	30	512	
GRI	G	64		5,723	276	11,884	435	398	
LMT	G	1		5,696	277	16,850	402	5,608	69
GON	G	5		5,634	278	32,729	259	2,279	161
HOB	G	0		5,590	279	16,605	405	632	
BRO	G	1,949		5,438	282	31,222	270	2,499	150
JLN	G	19		5,397	283	19,905	369	199	
L15	G	0		5,237	284	4,730		13	
LAW	G	10		5,142	285	5,967		6,982	48
SDL	E	4		5,081	287	111,615	26	306	
MOT	G	2,117		5,019	288	8,394	448	289	
COU	G	290		4,935	289	18,634	384	635	
SAF	G	8		4,934	290	28,773	292	1,537	197
ORH	G	1,176		4,931	291	21,229	356	359	
MMU	E	5		4,867	292	140,488	15	717	

DEC	G	59		4,799	293	19,539	375	2,542	149
SAC	G	2		4,746	295	57,518	115	112	
BCT	G	0		4,703	296	45,139	169	208	
DVT	E	3		4,507	298	116,254	23	543	
GMU	G	0		4,506	299	48,629	155	267	
HIO	E	1		4,485	300	87,144	54	886	
VNY	E	4		3,358		321,959	1	436	
FTW	E	242		2,161		161,332	9	483	
ADS	E	10		2,862		151,958	10	106	
PDK	E	2		3,604		144,865	13	542	
RVS	E	5		87		138,637	16	58	
SMO	E	1		1,907		137,340	17	1,534	198
PWK	E	1		2,871		122,878	19	185	
SFB	E	2,819		381		119,562	20	180	
VRB	E	8		2,465		116,898	22	164	
CDW	E	2		1,198		113,032	25	168	
FRG	E	29		4,080		111,161	27	450	
CCR	E	271		2,281		110,722	28	403	
CNO	E	1		314		107,618	32	664	
DPA	E	13		1,209		104,016	35	208	
POC	E	1		846		102,433	36	166	
FFZ	E	40		1,573		100,545	37	2,598	148
TOA	E	0		71		99,323	38	301	
FCM	E	1		1,587		95,738	42	196	
TMB	E	1		475		95,004	43	777	
PNE	E	0		1,671		90,287	47	13,407	19
LVK	E	0		839		89,842	48	359	
HEF	E	1		1,762		89,403	49	534	
SEE	E	8		199		88,783	50	163	
SUS	E	61		2,942		88,112	52	229	
EMT	E	37		3,923		86,324	57	237	
PAO	E	30		79		85,723	59	51	
CMA	E	3		2,402		85,614	60	603	
LAL	G	2		531		84,017	63	1,505	
NEW	E	100		4,070		83,900	64	7,420	44
BJC	E	1		1,563		81,741	65	333	
DWH	E	0		443		80,541	67	736	
PAE	E	3,403		2,556		80,120	68	2,464	153
HWD	E	0		1,695		76,774	75	301	
FPR	E	4		2,085		74,318	78	150	
APC	E	3		292		73,239	82	336	
MIC	E	0		3,517		68,349	88	279	
RHV	E	1		529		66,545	90	24	
ILG	E	165		3,853		65,372	94	5,091	78
HFD	G	0		1,338		65,022	97	223	
ANE	G	0		3,601		61,950	100	458	
POU	E	0		3,891		61,799	101	293	

MTN	G	0		233		61,697	102	6,062	65
SQL	G	0		15		60,260	106	46	
CHD	G	0		1,206		60,205	108	51	
CPS	E	3		3,129		59,647	109	567	
PWA	G	0		409		58,717	111	145	
LNS	G	1		3,277		58,442	113	1,526	200
FTY	G	3		2,491		56,994	117	852	
LOU	E	4		1,876		55,371	120	178	
SUA	G	0		2,298		53,598	126	561	
OSU	G	1		2,094		53,259	128	287	
LZU	G	0		2,202		52,935	130	153	
ENW	G	8		826		52,675	131	112	
WHP	G	0		325		52,535	134	112	
ASH	G	20		14		51,467	137	36	
BTL	G	15		879		51,120	139	3,652	119
DXR	G	0		128		50,907	142	52	
GYR	G	88		36		50,877	143	85	
TIX	G	1		882		50,196	147	346	
ARR	E	1		236		49,687	149	611	
HWO	G	3		9		49,634	150	83	
HWO	G	3		9		49,634	151	360	
ISM	G	0		381		49,265	152	70	
MWC	G	15		276		47,810	157	46	
FUL	G	2		125		47,766	158	9	
CGF	G	1		3,630		47,635	159	88	
SNS	G	20		1,434		46,322	161	431	
LAF	E	82		4,074		46,166	163	47	
RYN	G	0		40		45,992	164	692	
RYY	G	1		506		45,603	165	635	
PMP	G	1		42		45,264	167	53	
RNT	G	266		1,529		45,195	168	183	
OUN	G	0		1		43,430	174	1,052	
AFW	E	3,205		2,049		42,049	180	1,848	184
TIW	G	0		1,418		41,850	184	390	
IWA	G	718		3,673		41,460	187	4,574	92
ARB	E	1		840		41,292	188	102	
INT	G	186		938		41,291	189	172	
FMY	G	0		3,265		41,166	190	156	
OWD	G	2		1,846		41,100	191	96	
SCK	B	233		3,320		40,920	194	3,410	126
UES	G	0		1,596		40,854	195	44	
OSH	G	510		2,296		40,697	196	616	
UGN	G	0		836		39,880	201	452	
TKI	G	0		43		39,648	204	47	
OJC	G	1		125		39,420	206	114	
CRE	G	0		2,233		39,162	207	885	
CXY	G	26		692		37,834	213	1,418	

BDR	G	17	2,259	37,376	214	226	
GEU	G	0	672	36,648	215	198	
GPM	G	0	1	36,561	217	46	
TOP	G	39	478	36,019	223	869	
CGX	G	0	2,244	35,582	228	210	
WJF	G	1	1,591	34,790	233	626	
WJF	G	1	1,591	34,790	234	529	
LWM	G	0	109	34,407	237	61	
BVY	G	1	274	34,280	239	78	
OLM	G	1	1,878	34,054	242	961	
SPG	G	0	2,662	33,492	246	312	
OGD	G	60	306	33,485	247	95	
RAL	G	0	401	33,481	248	126	
SLE	G	73	993	33,296	249	3,059	135
SLN	G	90	4,111	33,282	250	3,676	117
ALN	G	128	944	33,041	255	1,316	
JXN	G	3	495	31,644	267	182	
HGR	G	248	4,007	30,695	277	1,047	
HHR	G	8	1,726	30,627	278	108	
BAF	G	6	422	30,272	279	3,544	120
SSF	G	1	1,043	30,180	281	4,767	88
OWB	G	1,225	3,051	28,830	291	1,220	
RBD	G	3	61	28,232	296	152	
AHN	G	30	2,917	28,051	297	901	
TTD	G	0	3,125	27,083	300	424	
IXD	G	73	1,244	26,417	304	1,317	
MDH	G	13	645	25,851	312	165	
IFP	G	728	2,705	24,624	326	180	
HUF	B	3,391	2,861	24,281	330	4,960	82
MFD	B	24	3,379	24,126	331	4,749	89
MQY	G	182	1,751	23,675	334	3,667	118
TCL	G	41	1,445	23,411	335	7,750	41
BFM	G	1,698	3,935	23,122	337	7,753	40
MCN	G	697	3,527	23,075	339	1,530	199
HKY	G	6	3,404	22,477	346	385	
GYY	G	495	930	21,493	355	392	
VLD	G	15	3,244	20,968	357	3,427	125
TUP	G	15	3,415	20,262	364	2,245	162
HUT	G	1	1,685	19,849	372	2,146	166
TZR	G	0	420	19,346	377	81	
LEB	G	11	4,280	19,084	380	120	
ALW	G	1	4,362	19,028	381	138	
SDM	G	4	199	18,428	387	854	
SBY	G	2,896	4,451	17,756	395	976	
HKS	G	0	931	17,279	398	2,613	147
ISO	G	324	3,045	16,837	403	2,916	139
CGI	G	0	1,488	16,201	407	268	

PMD	G	624		2,288		15,313	413	14,914	15
JQF	G	0		2,880		15,112	414	47	
HLG	G	0		407		14,713	417	2,361	158
EGE	G	2,843		3,467		14,485	418	1,993	175
MWA	G	67		3,718		14,409	419	221	
MKL	G	7		3,964		13,266	426	1,242	
TVL	G	380		1,147		13,214	427	317	
LWB	G	219		2,619		13,170	428	467	
WDG	G	1,208		1,412		13,145	429	7,809	37
ADM	G	5		212		12,838	430	2,313	160
IAG	G	249		327		12,740	431	3,133	132
STJ	G	46		138		12,166	433	4,488	94
FOE	G	204		2,398		11,595	436	4,254	98
BMG	G	72		224		10,499	439	111	
GCK	G	26		4,160		9,354	443	466	
GLH	G	26		1,886		9,349	444	2,217	164
ADW	B	101		22		9,149	445	55,659	1
JEF	G	0		974		7,966	449	1,133	
KWA	B	913		1,103		3,254		7,780	38
CSM	G	0		0		3,249		3,782	115
ESF	G	60		4,061		3,124		2,051	173
ASG	G	0		934		5,913		8	
BAK	G	32		117		3,380		141	
DTN	G	0		13		6,827		1	
HND	G	0		1,445		1,420		7	
MIE	G	5		81		4,829		30	
SGR	G	0		422		5,809		19	

Vita

James J. Galvin Jr. is currently serving as a Lieutenant Colonel in the United States Army. After receiving the Ph.D. degree in Industrial and Systems Engineering from Virginia Tech, he will serve as an Operations Research Analyst to assist in the large-scale organizational transformation of the US Army. Lieutenant Colonel Galvin received a BS degree in Mechanical Engineering from the United States Military Academy in 1983 and the MS degree in Operations Research and Systems Analysis from the Naval Postgraduate School in 1991.