SIMULATION OF THE SATELLITE INTEGRATION AND TEST PROCESS

by

JOHAN C. DENECKE

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Signature of Author...
Department of Aeronautics and Astronautics
January 27, 1995

Certified by...
Professor Stanley I. Weiss
Visiting Professor of Aeronautics and Astronautics
Thesis Supervisor

Accepted by...
Professor Harold Y. Wachman
Chairman, Department Graduate Committee

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Abstract

Critical attention to satellite manufacturing fueled by changing market conditions and consumer demands for world class quality is stimulating satellite firms to change their current practices. Changes are often difficult, slow, and risky, and there exists a need for a test bed in which to evaluate changes and understand their relationships to the overall system. Simulation provides such a platform. It enables the process owners to characterize the process, validate its dynamics, and test "design" possibilities, ultimately choosing the most likely candidate based upon a number of performance criteria.

This thesis focuses on the use of simulation in the analysis of the spacecraft integration and test process. The challenge is to characterize this complex and non-generic process with the following goals in mind: identify current capacity, lower the cycle time, improve resource utilization, and balance the manufacturing flow.

These goals are achievable by using a structured simulation methodology including: data collection and analysis, simulation model creation, verification and validation, and model experimentation. The thesis approaching deals with the unique characteristics of the spacecraft integration and test process and addresses such hurdles as inherently non-generic processes with scant historical data. Emphasis lay in the utility of the model to improve a current situation and communicate those results to management. The completed model illustrates the changes required to achieve the above goals with quantifiable savings in cycle time, cost, and resource utilization. It is applied to an existing integration and test flow at the Hughes Aircraft Company.

Thesis Advisor: Stanley I. Weiss
Title: Visiting Professor of Aeronautics and Astronautics

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Chapter 1 Introduction

Satellite manufacturing practice today, propelled by changing market conditions, arrived at lowering cycle time and cost as important change metrics. This thesis explores simulation as an important tool related to manufacturing improvement. The thesis proposes a methodology for manufacturing simulation to address change required in the satellite integration and test process. The emphasis is on the utility of simulation in a low volume, long cycle time, highly variable production system. The benefit of this simulation comes from understanding, improving, and managing of systems based upon a nine month internship at Hughes Aircraft Company where a simulation product was developed and is currently being implemented.

1.1 Statement of the Problem

The satellite industry faces a number of challenges due to the changing nature of the aerospace industry. The dismantling of the Soviet Union has left the U.S. defense industry with an uncertain future. The loss of the military threat (the Soviets) and a growing budget deficit has forced the government to cut spending for military contracts. With the days of lucrative cost plus contracts numbered, the government demands that the satellite industry do more with less.

In contrast, the commercial space sector holds promise. The growth of the telecommunication sector generates demand for instant video, voice, and data communication around the world using satellite technology. The profit potential entices a wide variety of companies. Among the customers, there are two critical success factors: time to market and cost. A one to two year jump on the competition could significantly impact market share and the reward for success is substantial.

The new environment makes it a buyer's market. Satellite manufacturers eager to replace lost government business, promise low cost and quick development time. The competitive market drives the prices down. Furthermore, the competition forces the industry to innovate new products and product capability quicker.

In response to the changing business climate, the industry is looking externally and internally for competitive advantage. Externally, Martin Marietta and Lockheed merged to take advantage of economies of scale, a significant threat to the competitors such as Hughes Aircraft Company. Hughes faces an interesting set of choices. A business alliance seems unlikely considering its recent business successes. The Hughes HS601 satellite has won 50% of all new commercial satellite orders in the last 18 months.[1] Instead, Hughes will look for internal change to retain its competitive advantage. It needs to cut costs and cycle time while insuring perfect product quality.

The key objectives for the changing industry are to reduce cycle time, cut costs, and improve product quality. The challenge is to change the slow, hand-crafted process to a well oiled manufacturing system. The satellite manufacturing characteristics of a long cycle time, low volume, and highly variable production system complicates the effort. Understanding how to improve is difficult. A majority of process experts have focused views lacking an overall system perspective. Furthermore, the culture requires cost justification for capital investments. As a result, creative thinking which promises substantial improvement is often stifled.

Product and process complexities provide the main barrier to improvement or comprehension by any one individual. Typically, the manufacturing process spans multiple sites and multiple suppliers. The assembly and test process alone may use several buildings, multiple equipment resources and manpower resources. Process planning lacks the capability for informed decision making. Process data is scarce and the planning systems too slow for instantaneous feedback. The primary model used for these situations is the opinion model: he who screams the loudest wins the fight.

Product and process variability further complicate the situation. Product complexity and new unproved technology decrease both hardware quality and impact the

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[1] Howard Banks, "GM's hidden Treasure,' Forbes. August 1, 1994.

satellite schedule and cost. Satellite integration and test receives the majority of these problems. The quality is tested into the product at the expense of cycle time and cost. Process variability complicates the situation further. The system has an inherent flexibility to change the order and duration of tasks. Activities have a preferred order but may have to change depending on the customer preferences, the product type, or resource availability.

The complexity of the situation requires a sophisticated modeling tool that can incorporate the characteristics of the process, answer the important questions regarding resources and improvement, and communicate results to process experts and decision makers.

1.2 Goal of the research project

The goal of this research project is to study the feasibility of simulation as a tool for cost and cycle time reduction in the satellite integration and test process. The emphasis is on developing a robust simulation methodology for a low production environment. The Hughes Aircraft case study illustrates the use of the simulation methodology.

The research was conducted in the Space and Communications Group of Hughes Aircraft Company in El Segundo CA. The project spanned a nine month period starting December 1993.

The simulation model contains company sensitive information. This fact forces the author to limit the scope of results presented in chapter 5 (the Hughes case study). The focus is on three functional areas of the integration and test: bus and payload module integration, environmental test, and final systems test. The actual data in the model is normalized to emphasize relative relationships without exact figures. The emphasis is on demonstrating the utility of simulation and nature of the results obtained. Furthermore, the intent is to showcase the low volume simulation methodology without the statistical detail required to perform some of the advanced calculations. These calculations have been documented in the field of probability and statistics. The author will describe the theory, how to reference the material, and the details for any unique applications of these concepts.

1.3 Structure of the thesis

The seven chapters of this thesis are intended to give a clear picture of simulation's use as a modeling tool for the spacecraft integration and test process. The first three chapters introduce the reader to the process in question, the modeling tools currently used, and proposes simulation as a requirement for successful process improvement and management. Chapter 2 exposes the reader to the satellite integration and test process. The overview covers the basic process characteristics and needs, and is followed by a vision of the factory of tomorrow. Chapter 3 addresses the process needs in terms of simulation and the currently available modeling tools. The comparison of the process and the available tools yields simulation as the required tool for accurate modeling.

Chapter four reveals the secret of simulation: the modeling methodology. This road map covers the entire effort from understanding the customer needs to interpreting and communicating results. Chapter five exemplifies this methodology for integration and the environmental test process at Hughes Aircraft Company. Chapter six examines different applications of simulation for manufacturers, computer networks, service systems, and business processes. The thesis concludes with research findings and conclusions in chapter 7.

1.4 Research Findings

Simulation is a capable modeling technique for complex systems requiring a high degree of accuracy. Its flexible characteristics allow the modeler to represent complex situations. The stochastic nature of simulation applies well to manufacturing situations where the uncertainty impacts the processes.

The thesis develops a simulation methodology to guide the modeler through a simulation project. The nature of simulation places high demands on the modeler since one has to understand the process, collect data, perform statistical analysis, program a computer model, interpret results, and present a information effectively. A structured methodology is a required tool for simulation success.

Simulation proves an applicable tool for satellite integration and test. It can model the unique product and process characteristics (discussed in section 2.7) and the results obtained from the model can be made flexible to the modelers intentions. One can examine cost, cycle time, and quality issues and their impact upon the process. For the case studied, the primary bottlenecks of the system were found to be manpower (system test engineers and mechanical technicians) and equipment (system test equipment (STE)) resources. The constraints limited the system to a maximum capacity of 14 S/C a year. Furthermore, process flow variability in the form of late payload deliveries and unit removals were found to have a two to one process impact. For every day delayed, the total cycle time was elongated by two days.

Simulation, however, has a number of pitfalls that may impede the modeler. These pitfalls include not understanding customer needs, inadequate data, excessive model complexity, obsession with graphics rather than results, poor model interpretation, and inadequate buy in by the user community and management. These issues will be addressed in chapters 3, 4, and 5.

Chapter 2 The Satellite Integration and Test Process

The character of satellite manufacturing uniquely distinguishes it from other industries. Like the first car production, satellites are hand-crafted to specific customer needs. Attempts have been made to standardize designs but unlike Henry Ford's mass production scheme, satellite mass production has not been viable in recent history. As such, the process suffers from the cost, schedule, and quality problems associated with custom manufacturing.

This chapter will discuss the differentiating characteristics of satellite manufacturing as applied to the satellite integration and test process. The goal is to educate the reader about the product (the satellite) and to give insight into the satellite integration and test process. The emphasis is on the problems commonly encountered in the process. The last section discusses the needs/requirements of the process for competitive manufacturing in the twenty-first century.

2.1 The Product

A satellite can offer a variety of products/services from space. These services include audio/video transmissions, two way voice communication (telephone) earth observation such as weather sensing, scientific missions like monitoring ozone levels in the atmosphere, and government missions like high resolution imagery for military intelligence, sensing of missile launches, etc. Two differentiating characteristics of satellites from other industries are the advanced state of the technology and reliability and survivability requirements.

Satellites utilize state-of-the-art technology to satisfy mission requirements. As a result, satellites become expensive and difficult to manufacture. The advanced mission requirements force manufactures to often use unproved technology in their product. The envelope is continually pushed in order to provide more power to communication equipment, better optic equipment for advanced sensing, and propulsion systems to increase life on-orbit and lower launch mass..

The satellite has stringent survivability requirements placed upon it due to the launch and upper atmosphere environments. The initial event is launch, shocking the product with high acceleration and vibration loads. Once in space, the satellite is exposed to radiation and the upper atmosphere environment. Radiation may be in the form of trapped radiation in the Van Allen Belts, solar particle events like solar flares, and galactic cosmic rays. The upper atmosphere affects the spacecraft by generating aerodynamic drag, heat, and corrosive effects due to highly reactive elements such as atomic oxygen.[2] Thermal heating due to ultraviolet radiation and solar cycle variation (solar flares, etc.) have the greatest effect on spacecraft lifetimes.

The combination of state-of-the-art technology and an hostile operating environment accumulate into an exotic and complex product. Furthermore, space has a major drawback, the difficulty and cost of repairing defective products demand extensive testing to verify quality. On orbit failures may spell disaster for a satellite supplier.

2.2 Process Origin

The satellite integration and test process has roots from the government and defense industry. The nature of the business created a culture (business climate) that focuses on technology and performance. It slowly reacts to changes and its culture is resistive to change. The new competitive environment is changing the industry but the old thinking prevails, hindering real progress.

Origin

The U.S. Navy manufactured the first American satellites in the late 1950's. The defense establishment quickly realized the potential for spying on its enemies and communicating among itself. Payload cost was a secondary issue. These "spy" satellites were instrumental to national security and received high priority. Ronald Reagan continued this paradigm with the announcement of the star wars program (missile defense

[2] Wertz, James R. and Wiley J. Larsen, Space Mission Analysis and Design, pp 193.

system). The cost plus programs allowed developers to absorb schedule and quality hits. Product performance and quality were the key drivers often at the expense of cost and schedule. Engineers often designed technically sophisticated systems without regard to manufacturability. Engineering elegance took the spotlight and the manufacturing floor sometimes had the character of a hobby shop for engineers to realize their creations.

The commercial customer had low buying power in the early stages. The highly specialized product allowed for a few manufacturers with similar product development philosophies. The low business volume did not warrant change in the satellite manufacturing practices.

Cultural Impact

The traditional paradigm of an engineering shop provides a substantial barrier to change. The engineering shop fosters a product performance focus at the expense of manufacturing, assembly, and testability. Furthermore, engineering functions may separate into fiefdoms with their own rules of engagement. As an example, the payload area regarded itself as the heart and soul of the product. In addition, the process did not require the payload business unit to be responsible for quality defects discovered during integration and test. Unit failures during I&T (Integration and Test) received separate funding from the enterprise. "Accountability was a joke."[3]

From Old to New

The current business climate is changing the focus to a trinity of values: cost, quality, and lead-time. Lower defense spending and uncertain budgets has oriented the military customer toward the new values. The advent of the global communication/entertainment revolution has transformed the commercial market to be the primary market of satellite services in the next century. Time to market and cost are the primary values. Quality is a universal constant.

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[3] I&T Systems Engineer, Hughes Aircraft Company.

2.3 Top Level Systems Perspective

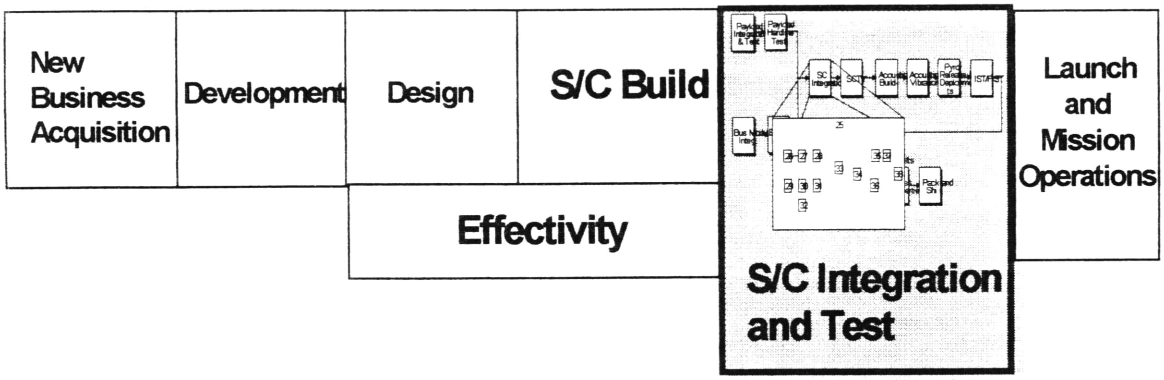

Figure 2.1 The Satellite Development Process

Satellite integration and test is one component of the product development process. As such it represents approximately half of the total product cycle time from contract start to launch. It can be considered an indicator of overall process performance since all the components come together and are tested for quality. Inconsistent designs and poor hardware quality impact this area in terms of elongated cycle times, ballooning costs, and frantic contention for resources. Section 2.4, 2.5, and 2.6 discusses the process in more detail including its unique process characteristics.

2.4 Satellite Integration and Test Process Goals

The goal of satellite integration and test process is to deliver a functional satellite to the launch pad that will perform according to specifications with perfect quality at a low cost. Recent market developments have changed priorities: cost and lead-time are equivalent to quality in terms of priority.

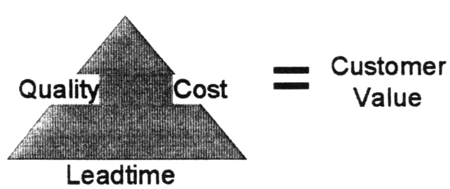

Figure 2.2 Customer Value Diagram

The new trinity approach is forcing the culture to change from an engineering hobby shop to manufacturing plant. Concepts such as total quality, continuous improvement, lead-time reduction, and informed decision making have to be embraced by the floor not just preached by the process leaders.

2.5 The Satellite Integration and Test Process

The S/C (spacecraft) I&T (integration and test) operation is the heart and soul of the satellite factory. It is the culmination of the design, engineering, and planning effort into assembled hardware. The entire process spans from 300 -500 days and require the use of multiple buildings and specialized facilities such as thermal vacuum chambers. A number of different satellite products may share the facilities. For instance, the Hughes production facility can assemble and test multiple satellites simultaneously. Hughes has two main commercial product lines, its 376 spinners and 601 three axis stabilized satellites. Each product line has unique product and process requirements including specialized routings and resources.

The satellite factory has a number of unique resources to its disposal. The most formidable are the large testing chambers required for environmental testing and antenna pattern testing. Other resources include specialized fixtures to transport the S/C, specialized testing equipment (Standard Test Equipment - STE), and several different manpower resources.

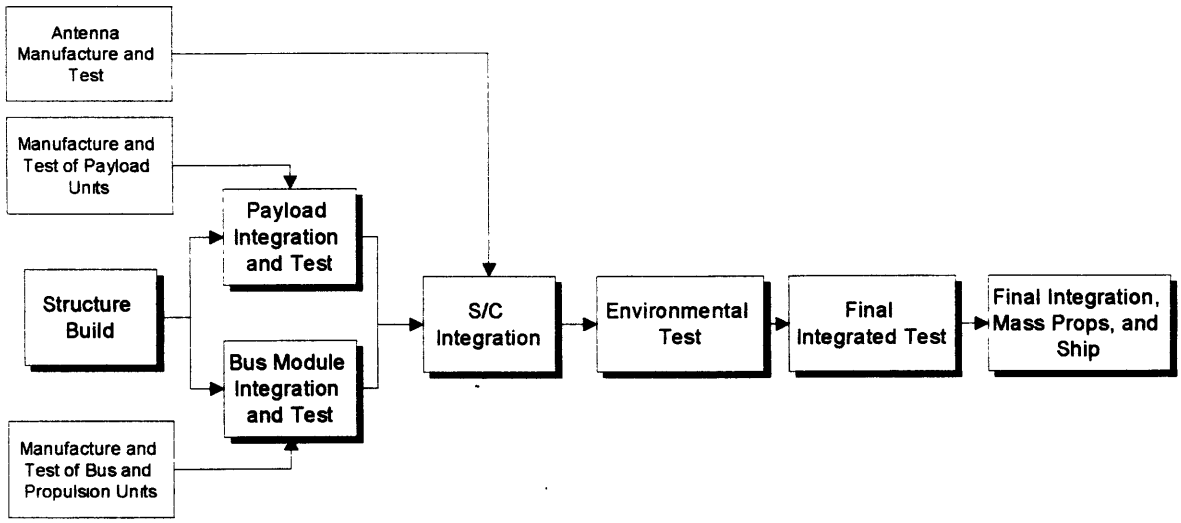

Figure 2.3 Satellite Integration and Test Process

The following sections outline the process in some depth to familiarize the reader with the process. The journey starts at the structural build area. The S/C is assembled from piece component parts into one structure (see figure 2.3). The S/C then gets separated into two parts: the payload and bus module. This separation allows the satellite integration teams to work in parallel installing the communication/observation payload and the bus units reducing the required cycle time.

Payload and Bus Integration and Test

The bus and payload modules take separate paths for the integration and test of their subsystems. The bus module travels to the propulsion area where the propellant tanks, fuel lines, thrusters, and pressure transducers are installed and tested. Upon completion, the bus units/electronics such as attitude control system (ACS) are installed and tested. The payload is sent to payload integration and test area. Here the structural shelf awaits the arrival and integration of the communications units. The payload and the bus module are thoroughly tested to verify system functionality prior to the next step, environmental testing. All the testing is done using Standard Test Equipment (STE). STE's are integral to the testing of the S/C since they furnish the power to the bus/payload, issue the commands, and measure the output.

Spacecraft Integration

The two halves are now joined and prepared for environmental testing. This activity includes installing the antenna, the batteries, and thermal blankets. An extensive quality inspection is usually required to give proof of workmanship prior to testing. As a note, all the integration activities are performed by hand by trained technicians. Automation has not found a home in S/C I&T due to the low volume and varied nature of the product.

Environmental Testing

Environmental testing simulates the harsh reality of space in order to weed out product deficiencies. This procedure consists of three major tests: thermal vacuum, acoustic, and vibration. Each test requires its own facilities and manpower. Experts work seven days a week three shifts a day to screen for deficiencies and prepare the product for final integrated test. Not surprisingly, this area bares the brunt of product defects resulting in increased cycle times and testing requirements.

Final Integrated Test

Following environmental exposures, the S/C is subjected to comprehensive performance testing, bus/payload interface verification tests, and some subsystem level tests. The Anechoic chamber, STE, and the roll-over fixture are the major resources required at this stage. A roll-over fixture rotates the S/C from a vertical to horizontal position. This enables the antennas patterns to be tested in the anachoic chamber (A6 Chamber).

Final Activities until Shipping

The last two activities are final integration and mass properties determination. Final integration fits and tests the solar arrays and deploys the antennas. Mass properties measure the mass and the moment of inertia of the S/C. The S/C is now packaged into a specialized container and awaits shipping to the launch date.

Resource Requirements

The number of resources requiring management attention adds to the process complexity. Table 1 shows a top level summary of the resource requirements per activity. The table displays 14 primary resources: 5 facility, 5 equipment, and 4 manpower. Effective resource utilization presents a continual challenge.

Table 1.1 Process Resource Requirements

Phase	Facilities	Equipment	Manpower
S/C Build	Floor space	Main Tool	Mechanical Techs Engineering Support
Propulsion I&T	Boom Room	S/C Cart	Propulsion Techs Engineering Support
Bus Module I&T	Floor space	Roll-over Fixture, Standard Test Equipment (STE)	Electrical Techs, Mechanical Techs, System Test Engrs Engineering Support
Payload Module I&T	Floor space	Payload Fixture, STE	Electrical Techs, Mechanical Techs, System Test Engrs Engineering Support
S/C Integration	Floor space	S/C Cart	Mechanical Techs Engineering Support
Environmental Test	Thermal Vacuum Chamber	STE	Mechanical Techs, System Test Engrs
	Acoustic Chamber	STE	Mechanical Techs, System Test Engrs
	Vibration Table	STE	Mechanical Techs, System Test Engrs Engineering Support
Final Integrated System Test	Anechoic Chamber	Roll-over Fixture, STE	Mechanical Techs, System Test Engrs Engineering Support
Final Integration	Floor space	Roll-over Fixture	Mechanical Techs Engineering Support
Mass Properties	Mass Measurement Facility		Mass Properties Engrs

2.6 The Satellite Integration and Test Process Characteristics

Satellite Integration and Test has five distinguishing features:

- Low volume production with long lead-times
- High reliability requirements
- Uncertain reliability of hardware
- Customized product

- Flexible in production sequences

In isolation, each one of these features presents a formidable challenge to any process manager. In combination, they render the process almost incomprehensible.

A low volume, highly flexible production system with customized products and unreliable hardware obscures any semblance of order on the factory floor. Variability is planned into the system since each S/C has unique product and process requirements. Assembly and test requirements may change dramatically depending upon the product features such as antenna size, communication equipment, and power requirements. The order in which activities are planned change between S/Cs depending upon who is in charge, what the customer wants, and the available hardware.

S/C high reliability requirements have several effects upon the I&T process. Testing composes close to 60-70% of the total I&T cycle time and requires large and expensive facilities. At Hughes, for instance, it costs the enterprise tens of thousands of dollars every time a S/C enters the thermal vacuum chamber. The system test engineers are sensitive regarding the testing requirements. Past history has taught them that anything that can go wrong will. The attitude is to test the quality into the hardware, consequently, the products are frequently over tested. The attitude is "too much testing may get you a slap on the wrist, an on orbit failure will get you fired".[4] Opportunity for improvement exists in this area but it is difficult to garner the necessary support.

Poor hardware reliability further complicates the situation. Careful planning may fall prey to hardware quality problems in the form of late component delivery or unit failures. The payload communication equipment can be up to three months late requiring dynamic rescheduling of the entire factory. Unit failures have the largest impact on the production system. A worst case scenario may require all S/C to remove a particular unit for rework. The entire factory scrambles to quickly resolve situations moving critical resources from other S/C programs and impeding their progress.

Resource competition is another source of variability in the system. Planned cycle times are often elongated due to the starvation of resources. Available resources may

[4] Systems Test Engineer, Hughes Aircraft Company

dictate the type of work done on the S/C. Complicated set up procedures are frequently discarded when bottlenecked resources such as Standard Test Equipment (STE) become available. Daily resource planning takes place where S/C programs battle for priority.

The nature of S/C customization provides an interesting set of challenges to the production system. As mentioned earlier, the product may have different routings, planned cycle times, and resource requirements. Furthermore, there is little opportunity to take advantage of learning curves. Few activities are repetitive. Most assembly activities require the technicians to study drawings carefully for information regarding the procedure and exact placement of the part. Testing activities are repetitive in nature but frequent hardware quality problems force deviation from current planning. To worsen the situation further, the traditional manufacturing process has teams following the S/C from initial structure build to final testing. This method negates any learning curve associated with repetition. Lessons learned in past projects have carried little meaning on the factory floor where the priority has been on getting the hardware tested and out the door.

Production flexibility manifests itself in two ways: ability to manufacture a wide variety of S/C products and the capability to respond to quality challenges. As mentioned earlier S/C may have different hardware and testing requirements forcing system flexibility. There are several different product lines such as spinners and three axis stabilized. Each product line requires different tooling fixtures and uses separate thermal chambers. In addition, quality problems require system flexibility in terms of flexible problem solving manpower and tools. The system must be flexible enough to absorb schedule hits quickly by adding additional manpower and shifts to accelerate the process. As mentioned earlier this flexibility can be at the expense of other ongoing S/C projects.

The process exhibits interesting dynamic behavior caused by product variability and resource contention. An example is the impact of resource ramping at the end of a program. Product and process variability invariably consume any safety margins built into the schedule. As the launch date approaches, a late S/C receives increasing priority and resources to speed the progress towards the deadline (see figure 2.4). As a consequence, upstream S/C are starved of required resources. Cycle times increase and several other programs become late.

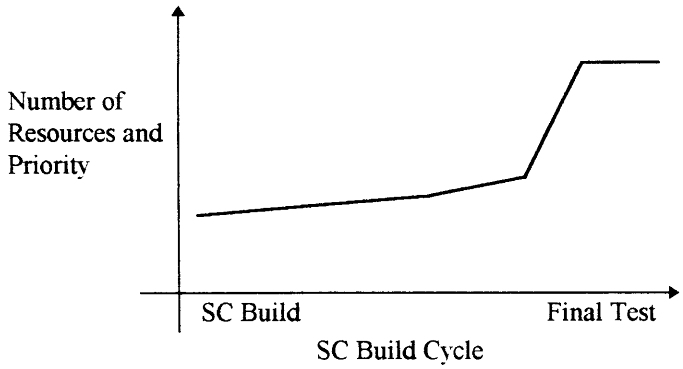

Figure 2.4 Resource and Priority versus Production Phase

The vicious cycle continuous as these programs receive additional resources starving upstream activities. This type of behavior can only be controlled through variability reduction and effective process management.

2.7 Process Management

The nature of S/C I&T provides interesting challenges for process management. Figure 2.5 illustrates the competing forces and their primary needs. Traditionally, management has relied on scheduling tools and expert advice to plan the process and resolve conflicts. There is a change towards informed decision making and a production analysis capability to better service the needs of the customers.

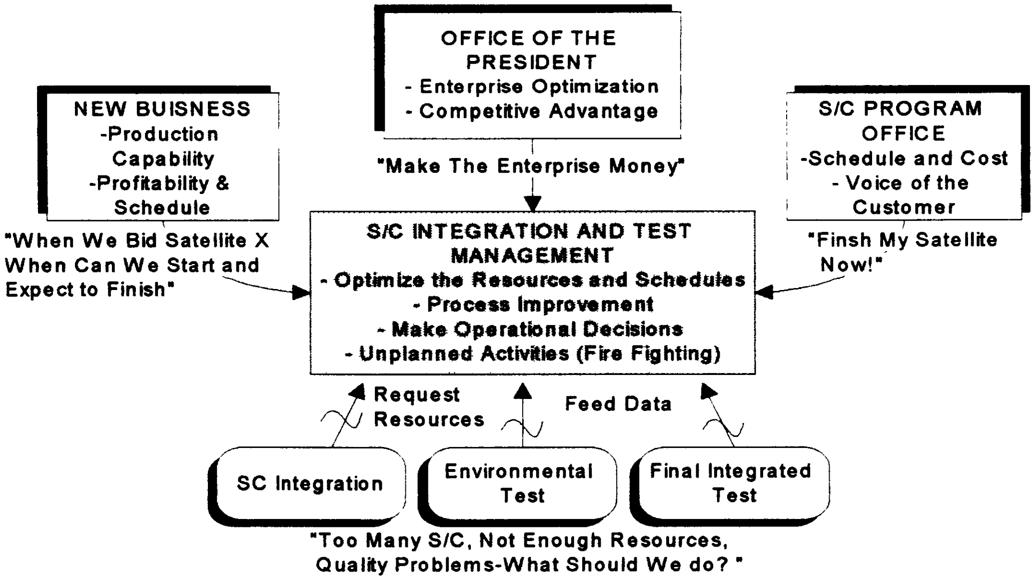

Figure 2.5 Integration and Test Management Customers

Traditional management tools like project scheduling have met little success in S/C I&T. The previously mentioned product and process variability rendered scheduling tools ineffective since they require continual, almost daily updating. Without effective enterprise work flow and resource management, the factory floor was reduced to individual S/C programs fighting for resources at every activity. The infamous "the one who screams the loudest gets the prize" management system became the norm. Opinion was the primary basis for decisions.

Current activities are attempting to take an enterprise view for work flow and resource scheduling. User friendly scheduling tools are allowing for daily updates of status and resource requirements across S/C programs. Short term planning on the factory floor is becoming viable. Long term planning is still difficult since variability is bound to invalidate even the most carefully constructed plans. The need is for quick scenario evaluation and dynamic rescheduling of S/C. Problems arise frequently in the process and there is no analytical method for evaluating the impact of different courses of action. The response time for current scheduling tools is still too slow for real time decision making.

2.8 Requirements World Class Satellite Integration and Test

Process Requirements Summary

World class manufacturing has its roots in a stable and predictable process that fosters creativity in problem solving and continuous improvements of its core processes. The process has to be clearly understood by its constituents. Performance metrics have to be simple and paint the total cost, schedule and quality picture of the process. Lastly, product planning has too be in accordance with process capability and resource constraints. A primary driver of the current problems is product and process variability. The variability obscures the process and destroys any careful planning. Lessons learned are often related to product failures which are unlikely to occur again. Process learning takes the back seat to product related fire fighting (work-arounds to solve problems).

The Road to World Class

The first step to world class is to increase process predictability by reducing product related quality defects. The quality related issues have been documented and targeted since the beginning of satellite production; the key is to identify the primary quality related drivers and attack them. Reality, however, is that management will not provide a concerted effort unless the proper cost benefit trade off can be performed and real benefits quantifiably identified. Such numbers are difficult to generate since no current tool can analyze the macro level impact of quality related defects in individual process centers. The need is to identify, analyze, and communicate the proper direction to management.

The next important step entails the installation of a production analysis capability within the organization which functions to accurately predict and plan the resource needs of the production facility. A number of tools exist that aid this effort. Scheduling tools manage day to day activities and resources. Material resource planning (MRP) and manufacturing resource planning (MRPII) supply the process with the intensive detail required to coordinate and track the bill off material as the raw material is shaped into parts which then are needed for assembly onto the S/C. A top level accurate production planning tool is lacking that can quickly analyze different factory loadings and product routings in terms of profitability, resource requirements, cycle time, and schedule risk associated with the occurrence of variability. Chapter 3 gives the reader an opportunity to discover simulation as a tool meeting the above requirements.

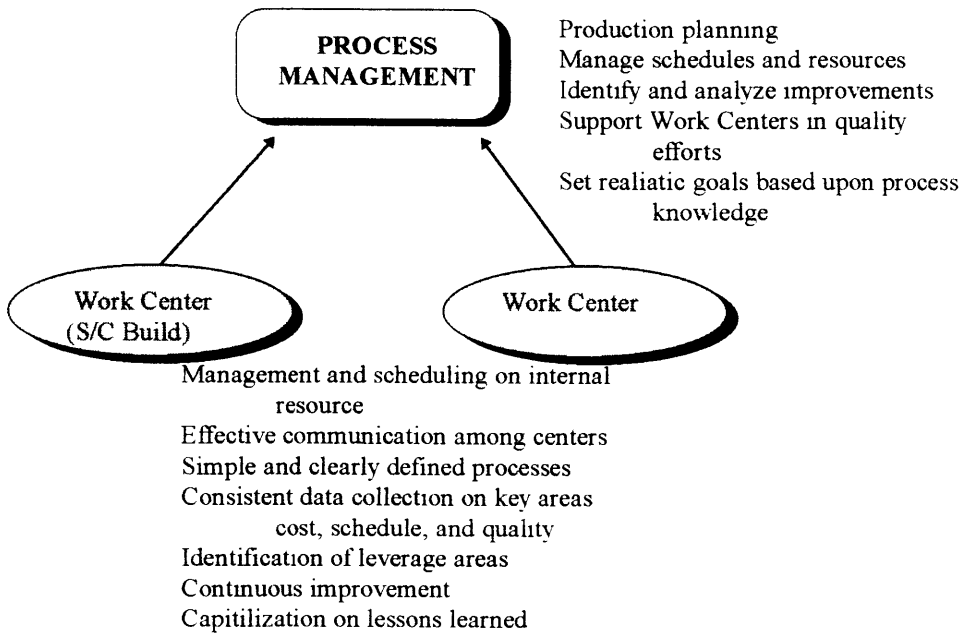

Figure 2.6 Management and Workcenter Interaction

The final thrust towards world class manufacturing is to integrate the tools and the process to a fluid entity that quickly reacts to changes, actively identifies areas of improvements and has a synchronous flow of product and supporting information. This vision requires an integrated view of the process, its constituents, and information. The above diagram (figure 2.6) illustrates one view of how to integrate these concepts.

Chapter 3 Applicability of Simulation

Simulation plays an important part in world class manufacturing. Beginning with an explanation of simulation, this chapter examines the applicability of simulation and its benefits to the satellite manufacturing process. Simulation has particular benefits for satellite integration and test. First and foremost, the complexity of the S/C I&T process can be modeled. Second, simulation provides the ability to explore the long lead-time and low volume nature of satellite manufacturing. Third, the result of this exploration is an improved understanding of the process and its drivers. Fourth, simulation can be used to identify improvements in terms of cost, cycle time, and resource conflicts. Lastly, simulation has potential as a capacity planning tool. These features distinguish simulation from other modeling methods. The chapter ends with a discussion of the limitations of simulation especially in regard to satellite integration and test. Simulation does not provide all the answers, but it can move the users closer to the solutions.

3.1 What is Simulation?

Simulation is a modeling technique for mimicking operations of real world facilities or processes on a computer. This technique translates the real world into a systems model through a set of mathematical and logical assumptions/relationships. Mathematical assumptions represent quantifiable information such as cost and cycle time equations. Logical assumptions drive system performance in terms of events and as scheduling, priority setting, and rule creation. The resulting model can be used for experimentation.

Simulation numerically exercises the model step by step as inputs arrive and are processed through it. The outputs measure the system response/performance. The environment is flexible, placing few limitations on what can be modeled. Simulation flexibility comes at the cost of complex models and long model development times. Simulation has been referred to as the method of last resort when simplified assumptions prove unfeasible for reducing the system to a set of analytical equations.

3.2 Simulation Benefits

As opposed to simpler techniques, simulation is limited only by the imagination of the modeler. This freedom enables simulation to model processes with few restrictions. For example, satellite integration and test was previously perceived as a process too complex for accurate modeling. Traditional modeling techniques could not incorporate the unique characteristics as discussed in section 2.6. Simulation, however, was able to model satellite manufacturing including its unique features. Other simulation benefits include: collecting data, characterizing the process, exploring improvement ideas, and managing the process.

Data Collection

Data collection provides benefits in terms of process characterization and understanding. For example, the start of a simulation project requires an extensive data collection process. This process will uncover the process and its inter-relationships. Furthermore, the data collection effort often locates previously hidden information. Such information may be in the form of the frequency and impact of quality defects. People working on the floor are often aware of such problems but do not have access or time to collect the information.

Understanding the Process

Simulation allows the user to explore the process and to increase his/her understanding. The dynamic model allows the user to view the process in a number of different ways. The user can follow the product flow visually or examine a number of metrics such as cycle time and resource utilization. Simulation teaches the process and product flow from a unique top level perspective. This feature is especially important for satellite manufacturing due to the long cycle time and the multiple resources involved. Simulation can display slow interactions that normally can not be observed such as the impact of resource prioritization on cycle times. Furthermore, workcenter interactions can be understood through simulation. One problematic workcenter interaction is sub-optimization - workcenters are encouraged to improve their process without an understanding of impact on other workcenters. Simulation can help prevent improvements that sub-optimize the overall process.

Identifying Opportunities

With an understanding of the manufacturing process, the user can identify areas for improvement. The modeler may examine the process for bottlenecks and capacity limits in order to identify opportunities. The user can analyze each scenario (opportunity) from different perspectives: performance evaluation, cost/benefit justification, and risk analysis. This capability is especially important for S/C I&T since management is often reluctant to invest in the manufacturing processes without proof of gains.

Scenario evaluations may also consider a number of factors at the same time. A scenario with the best cost benefit may compare poorly in terms of cycle time or resource utilization. One may balance a number of different metrics to find an alternative with the greatest amount of improvement potential.

Creative Thinking

Process participants may also benefit from the freedom of expression allowed by simulation. Creative thinking is stimulated in a non judgmental and risk free environment. Simulation can evaluate new creative ideas in terms of performance metrics without the cost and risk of implementation. For example, the idea of remote satellite testing has potential but requires a heavy investment. Current methods require the testing equipment (STE) to move between S/C. This movement is costly in terms of lost cycle time during the move and quality problems. Remote testing fixes the test equipment in one area with distributed accessed by each satellite. This change reduces equipment setup time, quality related issues associated with moving the testing equipment, and may allow for an increased level of parallel component testing. Simulation can incorporate these changes and explore the differences in the new process. Savings documented by simulation can then be presented to top level management in terms of cost and benefit to the enterprise.

Operational Tool

Simulation can be used as an operational tool for production planning. It can analyze and manage product schedules, identify potential resource conflicts, determine contingency plans, and analyze possible work-arounds for crisis situations. Current management methods for schedule routings and manpower forecasting are time consuming and resource intensive. Furthermore, the lead time required to conduct the analysis may prohibit its use. Simulation, however, allows for quick and accurate capacity planning, thereby enabling management to plan effectively. For instance, current manpower forecasting is done with scheduling programs. These programs can take a week to finish one scenario. Process management is therefore forced to base their decisions on a limited set of scenarios. Simulation allows management to explore a variety of likely business scenarios and plan accordingly. Furthermore, simulation provides information previously unavailable such as detailed cost and cycle time estimates and resource utilizations. The capability to manage the process with data prevents problems by anticipating process needs.

In summary

The simulation benefits are summarized in figure 3.1. The wishbone diagram illustrates how simulation can impact product quality, process quality, informed scheduling, cost analysis, crisis management, and continuous improvement. Each category has a number of elements that can be modeled. For process quality one can look at resource utilizations, facility, equipment, and manpower bottlenecking, process flexibility, and equipment reliability (mean time to failure and mean time to repair).

Another important area is cost analysis. Management of the manufacturing profitability can be facilitated by simulation. Due to large S/C costs, the satellite customer usually agrees to a phased payment plan. The production facilities are compensated for milestones such as finishing thermal vacuum testing. As can be imagined, these milestones impact program profitability and factory interactions. A S/C might get a short term prioritization to meet its cost milestones at the expense of other S/C. Simulation can model both the payment milestones and how to the balance payment, schedule, and effective factory operations.

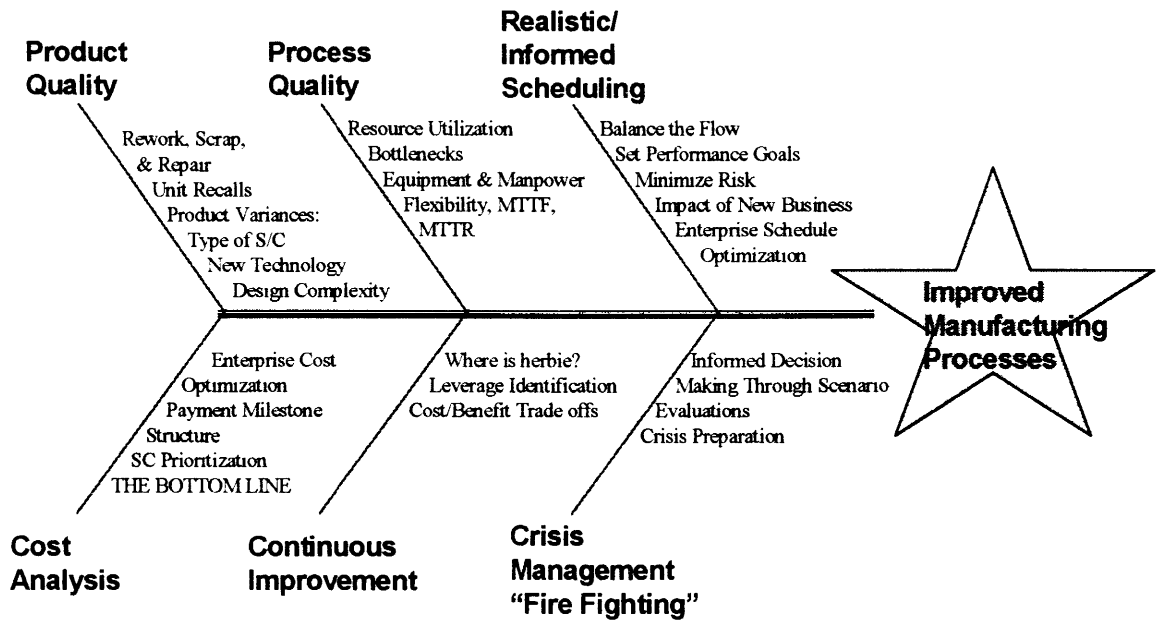

Figure 3.1 Simulation Capability Wishbone

In summary, simulation is experimenting with a model. It is a problem solving tool. It can engender creative attitudes and a zeal for trying new ideas. Simulation can predict outcomes for possible courses of action. It can account for the effects of variances occurring in a process or system. Simulation, therefore, promotes total solutions while uniting expertise, knowledge, and information.

3.2 Simulation Customers

Simulation caters to a number of different customers. In satellite manufacturing, the four main customers are top level management, new business, program managers, and factory operations. Top level management has an enterprise perspective, with a primary concern of the bottom line profitability and overall system performance. Issues such as factory capacity, profitability, and process/product capability are continually monitored.

New business requires information regarding factory loading, capacity, and profitability. The program office concerns itself about individual spacecraft. It continually manipulates cost, schedule, and resources to meet the launch schedule and profitability.

Factory Operations gets the job done on the factory floor. They manage resources, schedule work, and deal with day to day operational decisions. The below figure demonstrates the interaction between these customers. As discussed in the benefits section, simulation is an effective tool in supplying customers with the information required for decision making.

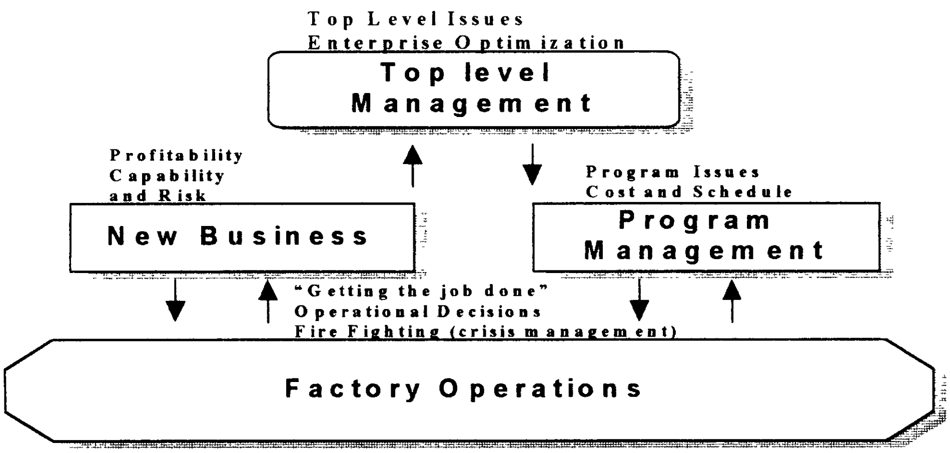

Figure 3.2 Simulation Customer Diagram.

Another benfit lies in the quest for continuous improvement. High level management traditionally sets the goals and dictates the improvement metrics, typically cost reduction. Simulation adds value by identifying the areas requiring attention and setting numerical performance targets. For example, excessive cycle time reduction at a bottleneck activity is wasteful. The bottleneck simply moves to another activity. Simulation can characterize the amount of reduction needed and the next likely bottleneck. The improvement effort, therefore, can utilize its resources effectively by attacking relevant problems and not waiting for them to appear. Goldratt refers to this game as "where is herbie?"[1] The goal is to anticipate herbie's next location before "he" arrives.

3.4 Modeling Techniques

[1] Elihaya Goldratt. The Goal, pp. 65.

Simulation is one of a number of applicable modeling techniques in the study of processes. The modeling field include different techniques with corresponding applications. Models are an efficient means for studying complex phenomena. Model value arises from observing and quantifying system behavior which may be unobtainable from observing the real system. Knowledge can be obtained quickly and at a lower cost than in real life. A number of different modeling methods may be used to characterize a system as shown in figure 3.3.

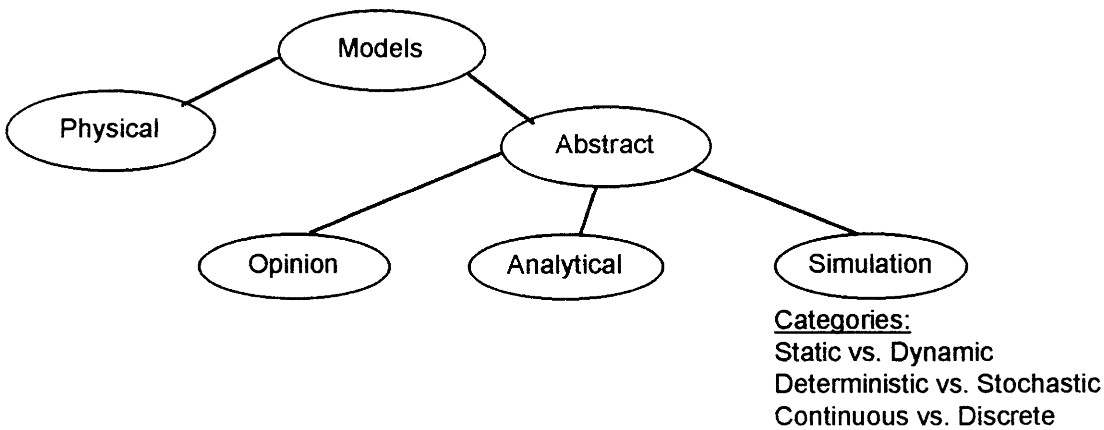

Figure 3.3 Modeling Techniques

Physical vs. Abstract Modeling

Models can be divided into two main categories: physical and abstract. Physical models are the easier to understand since they are typically reduced scale replicas of real systems. For example, wind tunnel models show the aerodynamic characteristics of proposed aircraft designs. Architectural designs model the structure and the floor plans giving the end user a visual appreciation of the proposal. Physical models are used for limited sets of applications where the construction is feasible, cost effective, and results can not be obtained accurately in other ways.

Abstract models represent the system through symbols and mathematical relationships or through a set of internalized personal experiences. Internal experiences are in the form of mental and verbal models (opinion models). Human beings create opinion models on a regular basis as information is understood and retained. Mathematical models are explicit representations of actual systems. They use the language of mathematical symbols to describe the system. These models are advantageous since they can be manipulated more easily than opinion or physical models. Their logic structure is explicit and assumptions can readily be traced to corresponding consequences.[2] Furthermore, results obtained through mathematical models do not require the costs of building an actual system or replica. Mathematical models are either analytical with exact solutions or simulation with inclusion of experimental data where available.

Opinion vs. Analytical vs. Simulation Modeling Techniques

Opinion, analytical, and simulation modeling have specific applications depending on system complexity. Opinion modeling is the most common modeling technique and is usually a cause of friction in organizations. Human nature naturally drifts towards opinion modeling as personal experiences are incorporated into mental models. These mental models may then clash against each other during decision making. Satellite integration and test have traditionally been subjected to opinion clashes during resource and priority decisions. Opinion models are limited by the human ability to understand complex situations and relationships.

Analytical models may be used to characterize simple processes or relationships. Analytical techniques includes the use of algebra, calculus, probability theory, etc. to find closed form solutions to problems. The results are numerically exact. Few real systems have exact solutions that can be easily computed. A simple example such as computing the distance traveled from velocity and time estimates may be impossible analytically depending on the number of forces and the nature of the forces acting upon the system. Furthermore, analytical methods usually require a number of simplifying assumptions that restricting their applicability and use.

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[2] Jay Forrester, Industrial Dynamics, pp 50.

Simulation models numerically exercise the models through a set of inputs and logical and mathematical rules. The outputs can then be measured to deduce the system response/performance. Simulation has been referred to the method of last resort when simplifying assumption prove unfeasible to reduce the system to a set of analytical equations. The complexity of real world problems quickly lead to simulation as the preferred solution method.

Given a mathematical model to be studied through simulation, there are a number of different dimensions to be classified:

Static vs. Dynamic

A static simulation is a representation of a system at a particular time, or one where time plays no role. Examples of static simulations are Monte Carlo Models. Dynamic simulation represents a system as it evolves over time. The satellite integration and test process requires a dynamic simulation since time and the timing of events play an important role in the model.

Deterministic vs. Stochastic

A deterministic simulation does not contain any probabilistic components. The model output is predetermined once the inputs are known and the logical rules governing the model specified. Deterministic models characterize the expected performance of system.

A stochastic simulation model contains probabilistic elements that generate uncertainty in the model. The output of a stochastic model is a probabilistic estimation and has to be treated as an estimate of the true character of the system. Stochastic models may have surprising results. For example, take a comparison between using deterministic versus stochastic value for the arrival rates into a machining center. The system consists of one machine with a cycle time of 0.99 minutes and a part arrival rate of once a minute. This system does not experience any delays or queuing since the machine works faster than arrival rate. However, if one adds uncertainty through an exponential distribution for the arrival rates with an average of 1 minute, the system experiences an average part delay one and a half hours. Stochastic variation plays an important role in simulation modeling.

Continuous vs. Discrete

There are two types of simulation: discrete event and continuous simulation. Continuous simulation evolves the model over time. Fluid flows frequently require continuous simulations to describe the gradual nature of system changes.

Discrete event simulation focuses on a model as it evolves discretely over time. The discrete points in time represent events occurrence. An event is defined as a transaction changing the state of the system instantaneously. The model may also contain logic statements controlling the behavior of the model. For example, in figure 3.4 a factory part arrival examines the queue in front of machine one. If the queue is above 4 pieces, the piece is routed to another part of the factory. Logic statements may include a probability of occurrence.

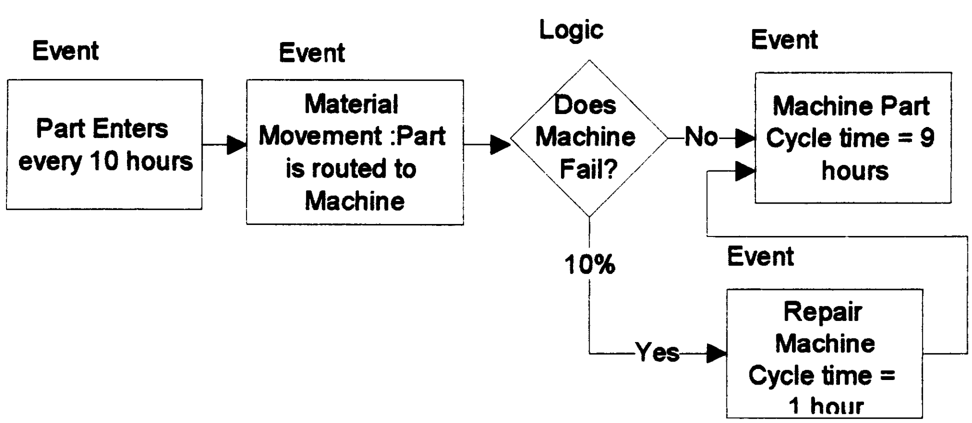

Figure 3.4 Example of a Discrete Event Process: Job Shop

A number of these flows may be assembled to create larger models. Models may contain a number of variables that determine the routing, activity duration's, and resources required for each task. In addition, variables may also track performance metrics such as cycle time, cost, variability in the system, etc.

Continuous simulation models state changes as occurring "gradually" over time. Fluid flow into a storage container is an example of continuous simulation. The fluid level changes continuously over time until container saturation. A discrete event simulation may model the situation as one activity with a certain cycle time depending on fluid flow rate and container size. Any further discussion is going to center around discrete event simulation because of its direct application to the satellite process.

3.5 Simulation Limitations

Simulation has a number of generic limitations stated below.

- Each run of a stochastic model produces estimates of a model's true characteristics for a particular set of input parameters. As a result, multiple independent model runs and statistical output analysis are often required to draw conclusions from the model.
- Simulation is better at scenario comparisons than system optimization since the stochastic nature of simulation may indicate different optimization solutions for every run.
- Simulation models are time consuming and expensive to develop.
- The quantitative nature of simulation produce numerically impressive results that may be misleading. A tendency exists to trust the model beyond what is justifiable. If a model is not a viable representation of reality then the results are meaningless or misleading.

The nature of satellite integration and test further limits the simulation results. The random nature of hardware failure may significantly change between model runs. Cycle times can be 50-70% higher in certain runs if a number of delays and failures are encountered. It is important to note that the simulation provides likely answers, not actual predictions. Simulation accuracy, however, increases as the frequency and impact of variability decreases.

Simulation is effective as a tool for process understanding. In this context, simulation becomes a risk analysis tool since it can analyze the best, worst, and most likely cases. Management can then choose to be conservative or optimistic while understanding the possible consequences.

The S/C integration and test simulation is constrained by the availability of data. Traditionally, metrics have not been a priority in this area. The data collected is often incomplete or biased. This constraint changes the variability in the system. Conservative assumptions are required for the frequency and impact of variability. On a positive note, simulation can identify which metrics have the greatest impact on the process and data collection efforts can focus their energy on those.

Chapter 4 Simulation Methodology

This chapter details the steps required for a successful simulation project. The intent is to give the reader an overview of the process without exhaustive detail. The bibliography notes some texts that may be of use for the advanced modeler.

Seven steps are required for simulation as illustrated in figure 4.1. The first and critical phase is understanding the needs of the customer and setting realistic expectations. With a defined purpose the modeler or modeling team collects process data, generates the process flow diagrams, and translates the information into a simulation model. The completed model is then verified for proper functionality and validated by the user community. An important step, since user buy in and understanding often determine the success of the model.

With a functioning model, the experimentation phase begins. This phase tests the model for interactions between different elements, examines bottlenecks, identifies areas for improvement, and evaluates scenarios through statistical output analysis. Lastly, the model results are compiled and presented to management. The figure 4.1 outlines the simulation modeling process. Note the iterative nature of the process. Simulation often requires the modeler to rethink his/her understanding of the process especially as the model begins to show results.

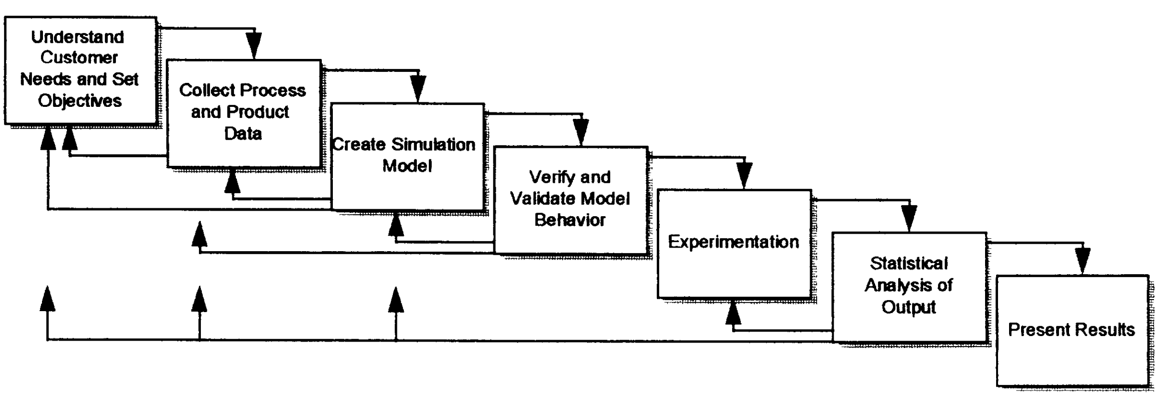

Figure 4.1 Simulation Methodology Diagram

4.1 Goals and Objectives

Defining the problem is the critical step in any simulation project. A number of questions that have to be answered first regard the goals, the process, and the role of simulation. These answers translate into model requirements. The author recommends a rigorous model definition methodology, including a definition of the process, the interfaces, the assumptions, and the required model functions.

The definition phase consists of interviews with customer and key personnel. Discussions should focus on the problem and form of the deliverable. The following questions need answers:

What constitutes the problem?

What are the objectives?

What are the assumptions?

What are the system constraints?

What are the metrics for measuring system performance?

What are the model deliverables?

A set of top level requirements for the project's success is specified during these discussions. Common requirements are for cycle time reduction and/or justification for capital equipment expenditure.

In addition, there are a number of model related questions that should be considered at this point.

What is the purpose of the model?

How should the model communicate?

Will the model be used for a one time improvement effort or as a permanent management tool?

The users may require the model to incorporate certain types of resources or model interactions. The above questions are important to answer early since they allow the modeling effort to focus quickly on the key objectives.

Model requirements and deliverables should be documented and signed by the involved parties. Consensus between the modeler and the customer is critical to project success.

Systems Definition Methodology

Systems definition encourages the use of a number of tools to define the project: functional flow, functional block, and quality function deployment diagrams. The intent is to clarify the process being studied and create consensus among the team. Furthermore, a clear initial system definition allows for a focused data collection effort.

Functional flow and block diagrams map the process and its boundaries. Functional flow diagram depicts the activities required to perform an objective. A top level functional flow diagram for the satellite integration and test process (S/C I&T) is shown in figure 5.1.

Functional block diagrams examine the interaction between different functions. For example, the S/C I&T process interacts with engineering, program office, new business, quality assurance, etc.. The functional block diagram illustrates the information flow between the above mentioned functions and specify their interactions. Figure 5.2 depicts the S/C I&T functional block diagram.

Quality function deployment (QFD) maps the customer preferences/needs to the computer model functionality. Furthermore, QFD can prioritize the model functionality as dictated by customer preferences, an important road map for setting prioritizing model goals. Figure 4.2 is an example of a generic quality function deployment for a manufacturing situation. The customer needs are evaluated by assigning the dependency high, medium, low, or NA for each model functionality. The functionality can be exploded to subcategories for more detail. The QFD diagram aids in prioritizing model features and identifies system requirements. Section 5.1 shows an extensive quality function deployment for the S/C integration and test process.

Customer needs \ Model Characteristics	Product Characteristics	Process Characteristics	Resources Modeled	Process Metrics	Variability Capture	Data Link to Schuling Tool
Identify cycle time reduction	□	●	□	●	□	NA
Manage manpower resources	□	●	●	○	□	NA
Bottleneck Analysis	□	●	●	○	○	NA
Balance Production Flow	●	●	●	○	□	NA
Permanent Management Tool	●	●	●	□	□	●

Strong Dependency	●
Medium Dependency	□
Weak Dependency	○
Not Applicable	NA

Figure 4.2 Top Level Quality Function Deployment

4.2 Data Collection

The data collection process uncovers the required data for a meaningful simulation model. The collection process begins with macro level perspective and focuses on detailed data where necessary. The effort is especially sensitive to process driver such as constraining resources and hardware quality problems, such areas may require additional investigation of data.

With the process data, a series of process flow diagrams are generated to visually depict the process and prepare the data for simulation. The process flows include the product movement, the activity durations, and the use of resources. In parallel, the data is also evaluated statistically to derive probability distributions for cycle times, quality defects, and delayed hardware delivery.

The simulation data is available through several different sources: process experts, existing databases, and observation. A common problem is the lack or bias of data in the production environment which can be dealt with through observation or through assumption of process behaviors.

4.2.1 Data Sources

Available data sources consist of process experts, data bases, and observation. Interviews provide perspectives from management to the hands-on worker. Interviews may focus on process flows, resources requirements, cost, planned vs. actual cycle times, and decision rules. Several interviews may be required to refine the process information.

A number of existing databases may contain information on process quality, scheduling information, lessons learned, etc. Bias of data is likely due to inadequate data collection procedures, missing data, lack of cause and effect, or personal bias. Questionable data may still be used to set boundaries and understand general process behavior. Data should only be used when it is bias free or when the limitations are clearly understood.

Process studies may be necessary to gain information about the behavior of the system. A process study may be in the form of time and motion studies. Rare events may be fabricated to study the impact on the process.

4.2.2 Macro to Micro

Efficient data collection begins at the top level and proceeds to detail where necessary. Data collection begins with an evaluation of the goals and requirements set in the systems definition phase. For example, certain resources or processes may be of greater interest requiring additional detail. Abstraction is a central concept as the modeler seeks to minimize the required data while maximizing the data utility. Initially, complex tasks should be simplified to a single activities of a certain duration and a certain number of resources. With further analysis, certain tasks may have larger impact on the process that others, requiring additional detail.

Most systems have one or several key drivers whose impact is orders of magnitude greater than other factors. These factors require detailed data collection.

Apart from key drivers, other common model data requirements include product routings, cycle times, resources, cost, and variability. Items such as shared resources may require further data regarding the allocation rules. For example, a late satellite may steal resources from other areas to make a delivery date. Furthermore, resources may be shared with other areas that are beyond the scope of the modeling effort. Data needs to be collected regarding the availability of these resources and abstracted.

4.2.3 Process Flow Analysis

Process flow analysis utilizes functional flow diagrams to visually characterize the processes and prepare the data for simulation. The author recommends a symbolic analysis where different shapes have distinct functions. Material movement is represented by arrows, storage by triangles, and activities by rectangles (see figure 5.7). This representation allows the modeler to understand the flows and communicate with factory personnel. In addition, the process representation may identify opportunities for improvement through waste reduction. Waste can be identified as inspection, inventory, material movement, material handling, correction, over production, and waiting. The symbolic representation visually identifies material movement, inventory, and inspection.

4.2.4 Variability Characterization

Variability characterization represents the occurrence of uncertainty in a system. Uncertainty can take the form of hardware failure or out of tolerance parameters, equipment failure, unavailable resources, sick personnel, late hardware delivery, product priority changes, etc. The choice of how to represent these variables may drive the model behavior and should be done carefully. The availability of data significantly aids this process but in reality such data may be difficult to obtain and validate. There are two ways of treating this situation: collect sufficient data to perform curve fitting or assume a distribution and test its validity. The latter is a feasible method for situations where data is scarce.

Probability Distributions

Table 2 Common Applications of Probability Distributions

Distributions	Arrival Rates	Activity	Quality Defects	Scarce Data
Exponential	x	x	x	
Gamma	x	x	x	

Normal			x	
Weibull		x	x	
Lognormal		x	x	
Triangular				x
Uniform				x
Binomial			x	
Geometric	x		x	
Poisson	x		x	

Table 2 illustrates common applications for a number of continuous and discrete probability distributions. Arrival rates, activity durations, and quality defects represent common applications of probability distributions. Discrete distributions are used in situations where integer values are inappropriate. For example, the number of unit failures on a S/C is discrete while the time until such failures is continuous. The modeler is charged with the task of picking the distribution and its parameters.

Choice of Probability Distribution

The choice of probability distributions requires three steps: choice of a distribution family, estimation of parameter values, and determination of distribution accuracy. The choice of distribution family is done according to previous knowledge or according to various heuristics (guidelines). Previous knowledge may be in the form of known system characteristics. For example, normal distributions are not applicable to activity durations since negative values are possible.

Heuristics can be used to examine data properties such as minimum and maximum values, the mean, the variance, the skewness, and the symmetry, to narrow the set of possible choices. With the narrowed set of choices, the modeler chooses a distribution, estimates its parameters, and tests the fit.

Parameter estimation aims to associate numerical values to the distribution parameters that correspond with the data. Several methods address this issue: maximum likelihood estimators, least squares estimators, unbiased estimators, and the method of moments. Law and Kleto [1991] recommend the use of maximum likelihood estimators for their desirable properties and intuitive appeal. Maximum likelihood estimators set the assumed distribution parameters to maximize the fit. Theoretical derivation and examples can be obtained in Law and Kelton [Ref. 26] and Drake [Ref. 7].

The chi square "Goodness-Of-Fit" test can be used to distinguish between the likely distribution choices. The test provides a means for deciding whether a particular theoretical distribution such as the binomial is a close enough approximation to observed sample. One of the strengths of the "Goodness-Of-Fit" test is that it permits a variety of different hypotheses to be raised and tested. Theoretical derivation and examples can be obtained in Law and Kelton [Ref. 26] and Drake [Ref. 7].

4.3 Simulation Modeling

Model construction translates the data into a computer model. This strategy focuses on maximizing model capability and accuracy while minimizing model complexity. The top level requirements are translated into to a second set of model requirements governing the nature of the model, its behavior, its inputs, and its outputs. The model construction strategy populates the model in an orderly fashion with a focus on model requirements. Layers of complexity are added, starting with the basic process flows and ending with decision logic. Documentation becomes an important issue as the model complexity grows.

4.3.1 Model Construction

The computer model is created in discrete steps representing layers of complexity as illustrated by figure 4.3. Each layer is added separately and verified for proper functionality. The author subscribes to a hierarchical modeling structure that begins with a top level model and proceeds to detail where appropriate. This section outlines the modeling approach regarding model construction, product flow representation, variability characterization, and decision logic additions.

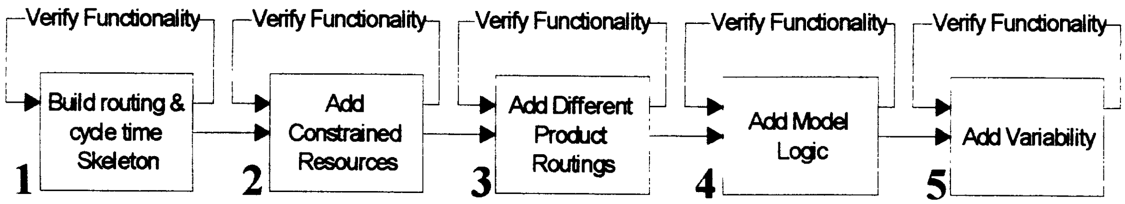

Figure 4.3 Model Construction Diagram

Figure 4.3 illustrates the 5 model building steps. The modeling steps are:

1. Initial construction of a skeleton model comprised of a single representative product routing and deterministic cycle times. Upon completion, the model functionality is verified.
2. The second step entails the addition of resources to the model. Resource may consist of manpower, equipment, or facilities. Defer resource related rules such as prioritization of resources based on product types or "hot" orders till step four.
3. The third step adds the different product routings to the model. Routings are a significant step in model complexity and needs careful verification.
4. The fourth step adds generic model logic such as product prioritization, shifts for manpower resources, work-arounds, and exception scenarios.
5. Lastly, variability is added to the model in terms of cycle time, quality, and equipment reliability probability distributions. Additional model logic may be required associated with hardware and equipment work-arounds.

Model complexity has to be actively managed at every stage of the building process. Complexity obscures model behavior and may be costly in terms of implementation time. Additional layers of detail and logic statements have to debugged this can be a painfully slow process. Model complexity also obscures the results documented by the model. If the model can not be adequately explained due to the number of possible interactions, the modeling effort may be in jeopardy.

4.3.2 Documentation

Model documentation is a required activity for any modeling endeavor. Documentation should translate how the real world is represented by the model. As such, the documentation needs to include the process, the model representation, the assumptions, the inputs, the outputs, the model functionality, the variability characterization, etc. It should be a road map how the model was built and the assumptions and trade-off's made along the way. The user should understand what the model is capable of doing and how to use it to get results. Large complex models require substantial documentation to track the model functionality and how the model is structured to achieve this functionality.

4.4 Model Verification and Validation

Model verification and validation accomplishes three things:

1. Proves model adherence to top level specifications,
2. Shows the model ability to mimic the real world by comparison to actual data,
3. Validates the model with the user community.

4.4.1 Verification

Model verification is an ongoing activity throughout the building phase. The layered modeling approach requires the builder to check model functionality at each layer. The final system checkout is a test that confirms the model behavior to predicted results. These tests should isolate each product group and compare the expected cycle time, cost, and resource utilization with predicted values.

In conjunction with these tests, the model is compared to macro data. Model verification may be process dependent. For instance, satellite production is difficult to verify due to the low volume production and the high product variation. Theoretical times and actuals may differ greatly due to singular events such as unit removals or late payload deliveries.

4.4.2 Model Validation

Model validation requires the user community to approve the simulation model. Approval can be obtained several different ways: hands on demonstration of the model, comparison of model against actual data, and detailed demonstration of the process flows and the model logic. Accurate model documentation is helpful in the communication of the model functionality. It is important to involve as many of the involved parties as possible at this phase to create user buy-in.

4.5 Model Experimentation

The primary objectives of model experimentation are to satisfy the model requirements, to gain understanding of process dynamics, and to identify opportunities for improvement. Simulation requires a structured model analysis methodology to efficiently gain the required insights into system performance. Simulation is not an optimizing algorithm such as linear programming. It does not calculate best solutions to a problem. The model yields probabilistic solutions and can provide various solutions dependent upon the scenario considered. The author recommends three analysis categories:

- Designed experimentation for parameter sensitivity analysis.
- Performance analysis for identification of system capacity and constraints (bottlenecks).
- "What if" scenario evaluations for specific process improvement scenarios.

Prior to experimentation, the modeler needs information regarding the number of model replications per experiment and the model warm up time required. A replication is a run with the same model input parameters as the previous run. The stochastic nature of simulation requires several replications to minimize stochastic variation in the data. Figure 4.4 illustrates the test flow.

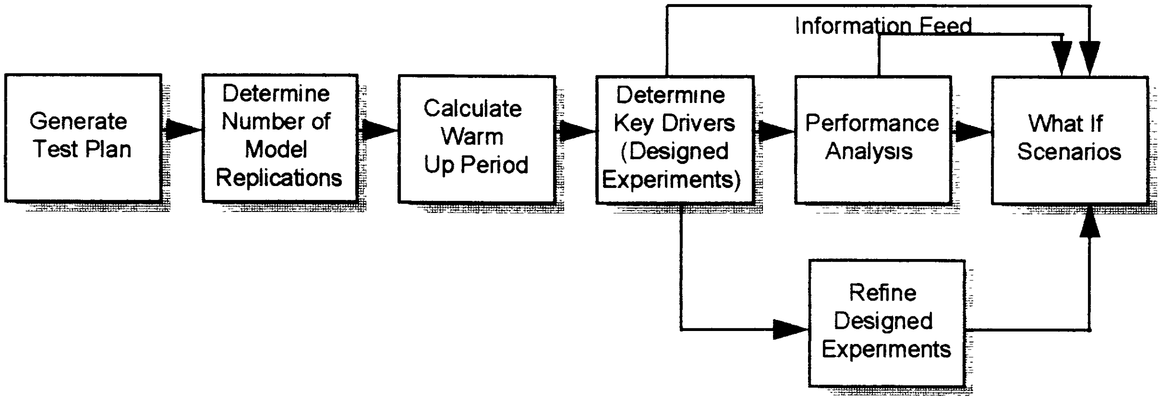

Figure 4.4 Experimentation Test Flow Diagram

Model experimentation may vary between modelers and processes. For instance, the satellite integration and test process is particularly concerned with capacity limits and resource constraints. Therefore, the experiments are designed to identify capacity and resource constraints. Furthermore, a situation may require analysis rigor beyond the scope of this thesis. For example, process optimization using response surface methodology (RSM) is beyond the current scope. The author identifies these methodologies and appropriate texts for further study.

4.5.1 Model Replications

The statistical nature of a simulation modeling requires several model replications to reduce the impact of variances. The modeler needs to know the minimum number of model replications to run in order to achieve a certain confidence that the observed data reflects the actual. The observed values approach the true mean as the number of replications increase. As a rule of thumb three to five experiments are sufficient. See appendix A for a description of required analysis

4.5.2 Warm Up Period

The warm up period negates any effects of initial startup transients. Start up transients are primarily caused by the factory conditions at time 0. The process (factory) is empty when the simulation begins. The initial products do not experience resource shortages or other effects that may occur later on in the process when in steady state. Data collection should begin after the warm up period to minimize the effect of these transients. The warm up period can be calculated using moving averages on the output produced from a model replication. See appendix B for further explanation.

4.5.3 Designed Experiments

Designed experiments serve two functions:

1. Reduce the number of model inputs
2. Quantify the impact of primary factors (sensitivity analysis)

A common problem with simulation models is the number of possible inputs that can be modeled. In the testing phase, the modeler needs to know which factors are the most important. Furthermore, these drivers can be characterized in terms of impact upon important metrics such as cycle time and cost. The most commonly used analysis techniques for the above two problems are the full factorial and partial factorial experiments.

- Full factorial experiments examine the impact of several factors through an exhaustive set of factor combinations.
- Partial factorial experiment examine several factors with a reduced set of factor combinations.

Figure 4.5 illustrates the full factorial, and partial factorial experimental cases. The

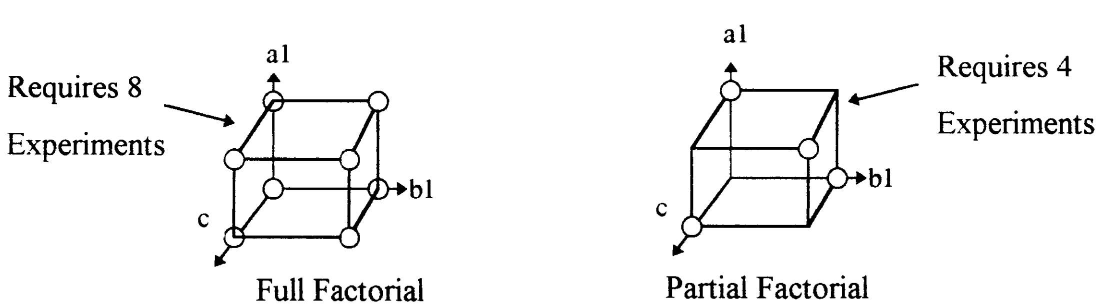

Figure 4.5 Experimentation Illustration

The author uses a partial factorial experiments to reduce the number of potential factors in the model. Once a set of important factors have been identified, the full factorial experiment can be used to quantify the impact of these factors. If the model is exceptionally large the modeler may need to use screening experiments to reduce the number of variables in the model. See Law and Kelton [Ref. 27] for discussion on factor screening.

Full Factorial Experiments

The full factorial experiment is an exhaustive test of all the variables. The intent is to identify the main drivers and interactive effects. The input parameters have two different settings: low and high. A test matrix of all the input parameters and possible setting combinations guide the modeler through a total of 2^k experiments where k equals the number of input parameters. An example of such a test matrix is given in appendix C. The accuracy of a full factorial is superior to other techniques but the required number of model runs may be prohibitive. A full factorial for five factors requires 32 experiments. The author recommends the use of partial experiments to limit the number of factors for the full factorial.

Partial Factorial Experiments

Partial factorial experiments allows the modeler to examine a large number of model parameters by reducing the number of required experiments as opposed to the full factorial experiment. The technique can be used to screen for main factors and interactive factors. With the screened factors, the modeler can then run a full factorial to obtain the accurate quantitative results.

The number of partial factorial experiments is 2^{k-p}, where k is the number of factors and p is the desired reduction of experiments. A p value of 1 cuts the number of experiments in half. An example of a five factor experiment with p equal to 2 is given in appendix C.

4.5.4 Performance Testing

Performance testing investigates the process limits in terms of capacity and bottlenecks. Process capacity is determined by increasing the process input rate until cycle times become extenuated beyond acceptable levels. This input rate is the maximum system capacity.

Bottlenecks are constraints which limit system capacity. A bottleneck hinders the capability of the process to handle the current volume of business. For example, an activity cycle time may be greater than the arrival rate, causing a build up of products waiting to be serviced. Transactions queuing in front of an activity is an indicator of a bottleneck. The modeler may visually search for bottlenecks during model operations or program in variables that track queue times in the model.

4.5.5 Scenario testing

Scenario testing is driven by the ability of the modeler and the user community to generate viable improvement scenarios. The modeler should carefully examine the process flows and product mix in the system to identify improvement opportunities. Furthermore, the key drivers and bottlenecks from the previous sections provide an initial starting point for improvement. With a set of scenarios, the model functionality is evaluated for any necessary changes. For instance, the model may need to be modified with new variables to measure the impact of certain choices. The final activity is to generate a test matrix and determine the number of required replications for each experiment.

The author encourages a thorough investigation of multiple scenarios. A frequent mistake is to judge the outcome on a single metric such as cost or cycle time. Situations exist where cost and cycle time solutions may contradict each other. A savings in cost may be at the detriment of cycle time which increases hidden costs such as storage, quality reduction, and maintenance.

Statistical analysis has several methods that evaluate the differences between choices. It is important to calculate averages, standard deviations and variances for an understanding of the data spread. Furthermore, techniques such as the Paired-t test and Bivariate test can be used to distinguish between choices.

4.6 Statistical Output Analysis

The data analysis phase extracts meaning from the model data. The experimental design factors are analyzed for the key drivers and scenarios differentiation. The nature of simulation cautions the modeler to draw quick conclusions. Stochastic variables drive the model, creating uncertainty to the accuracy of the data. The number of model replications alleviate this problem and the use of confidence intervals can further define the accuracy of the answers. Scenarios require the ability to distinguish between choices. The Bivariate and Paired-t test can be used for these situations.

First, the data from the experiments should be averaged and the standard deviations and variances calculated. All simulation packages should derive averages, standard deviations, and variances as part of the packages. These numbers can then be averaged among replications. The modeler can now calculate the results from the designed experiments, the performance testing, and the what-if scenarios.

4.6.1 Confidence Intervals

Confidence intervals determine the accuracy of the output. The observed value is given a certain confidence level (80-100%) of being in the proximity of the distribution's actual value. The confidence intervals establish the limits of this error. See Hamburg and Young for further details [Ref. 17].

Consider confidence limits for all output analysis and especially for scenario evaluation. Occasions where the confidence limits of two choices overlap are considered inconclusive. Design of experiments may consider confidence limits once the major factors have been identified.

4.6.2 Designed Experiments Analysis

Full Factorial Experiment

The full factorial investigates the impact of main effects and interactive effects on system performance. The main effect is calculated by averaging the high factor input settings subtracted from the low factor input settings. These numbers can then be compared to obtain the relative importance of each factor. The main factor calculations for a full factorial are illustrated in Appendix C.

Interactive effects express whether a given factor is impacted by another factor. Interactive effects may strongly impact system performance and cause non-intuitive model results. Interactive effects are important to document and my require further experimentation in the scenario section to fully understand the impact. Appendix C illustrate the calculation methods.

Partial Factorial Experiments

Partial factorial experiments are evaluated the same way as full factorials. An example of a five factor partial factorial is given in appendix C. The theory behind factorial experiments and other experimental design techniques is beyond the scope of this thesis. The information presented here provides the reader with an elementary understanding and ability to design these experiments. Further reading may be obtained in Kleijnen and Groenendaal [Ref. 25] and Law and Kelton [Ref. 27].

4.6.3 Scenario evaluations

Scenario evaluations primarily utilize the Paired-t test and Bivariate test to distinguish between choices.

A Paired-t test examines if the subtraction between the two choices is greater or less than zero. If the difference is significantly higher or lower than zero, then one can differentiate between the choices. If the difference is close to zero, the answer depends on the amount of variation in the stochastic data. The test requires the number of replications between the two choices to be equal. See Law and Kelton [Ref. 27] for a detailed discussion of this concept.

The Bivariate tests the differences between two means when the number of replications is not equal between the two alternatives. The test itself is similar to that of the Paired-t test and may be studied in Law and Kelton [Ref. 27].

4.7 Presenting Results

The final step of any simulation project is to collect the results and present them to management. The simulation results documented from the section 4.6 are compiled and compared to the project goals set in section 4. The results should then be documented including the assumption made that impact the results. This documentation is important if process experts question the validity of the results. With the information at hand the results can then be presented to management and process experts.

Chapter 5 Hughes Case Study

This chapter illustrates the simulation methodology applied to the satellite integration and test process. The Hughes case study is a limited representation of the actual model and some of the critical cycle time and resource data have been altered to remove company sensitive information. The author employs this chapter to demonstrate the utility of simulation in its multiple uses .

It is intended that this example will illustrate how simulation can be a beneficial tool for low volume variable manufacturing situation. It provides added value in understanding the process and its key drivers. It can examine capacity limits, bottlenecks, and scenarios. A scenario may be in the form of an improvement idea which can be evaluated in terms of performance measures such as cycle time. Lastly, it may be used as an accurate tool for process management.

5.1 Simulation Definition

Hughes Space and Communication's Motivation

The Hughes Space and Communication (HSC) simulation project stemmed from a need to better understand satellite production and reduce the total build cycle time - cycle time is considered strategically important for new customers. Furthermore, HSC business volume was at an all time high with over fifty percent more business than previous years. Management realized the need for accurate planning of workcenters and resources to meet the deadlines. In addition, the high volume created complications with customer confidence in HSC's ability to meet promised schedules. HSC needed a way to prove the capability of the factory to fill new orders on time. A simulation pilot program was one among several projects targeted to solve the above problems.

The Customer:

The primary customer and project instigator: Integration and Test (I&T) management.

Additional beneficiaries:

New Business

S/C Program Office

Office of the President

Project Goals

A series of interviews with management established the following project goals:

- Provide a better understanding of the process and its key drivers
- Reduce the production cycle time
- Provide cost/benefit analysis of improvement scenarios
- Investigate capability of simulation as a production analysis tool

The Process

The simulation model covers the satellite integration and test process from S/C integration to final system test. The following diagrams illustrate the top level process and the project boundaries. A number of interfaces have to be modeled regarding the product flow, the facilities, equipment and manpower resources.

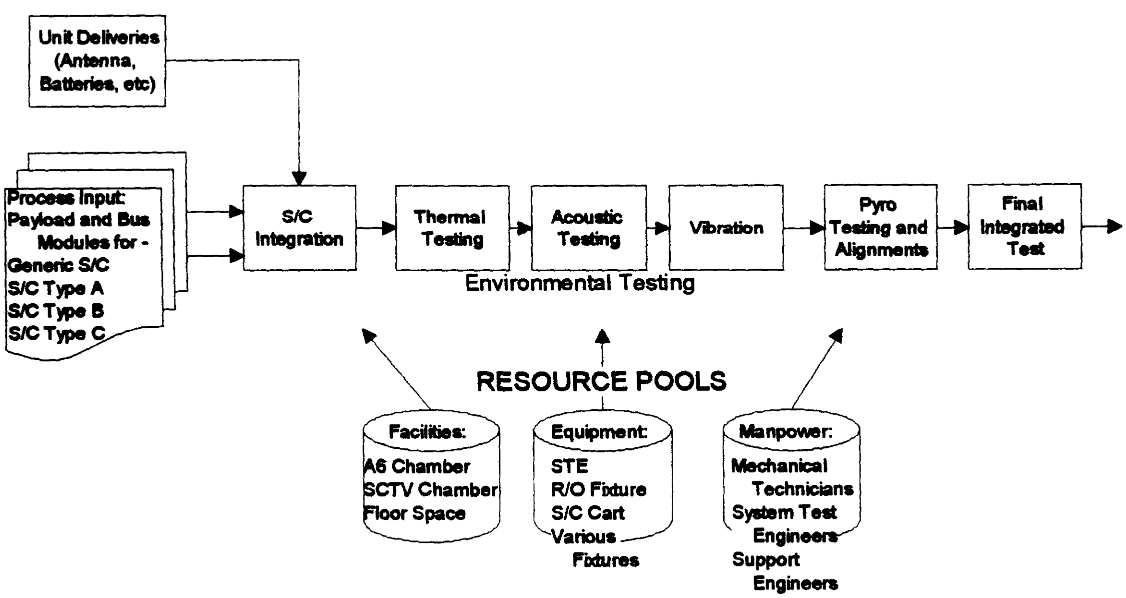

Figure 5.1 Top Level Functional Flow

The simulation project includes the following workcenters: S/C integration, environmental testing, pyro and alignments, and final integrated test. There are ten primary resources: three facilities, four equipment, and three manpower (see Figure 5.1). The model team made an assumption on the number of S/C types modeled. The product types can be categorized into four different product types: generic S/C, S/C type A, B, and C. These four product types may have different routings, cycle times, and resources requirements. Section 5.2 discusses these product differences in detail.

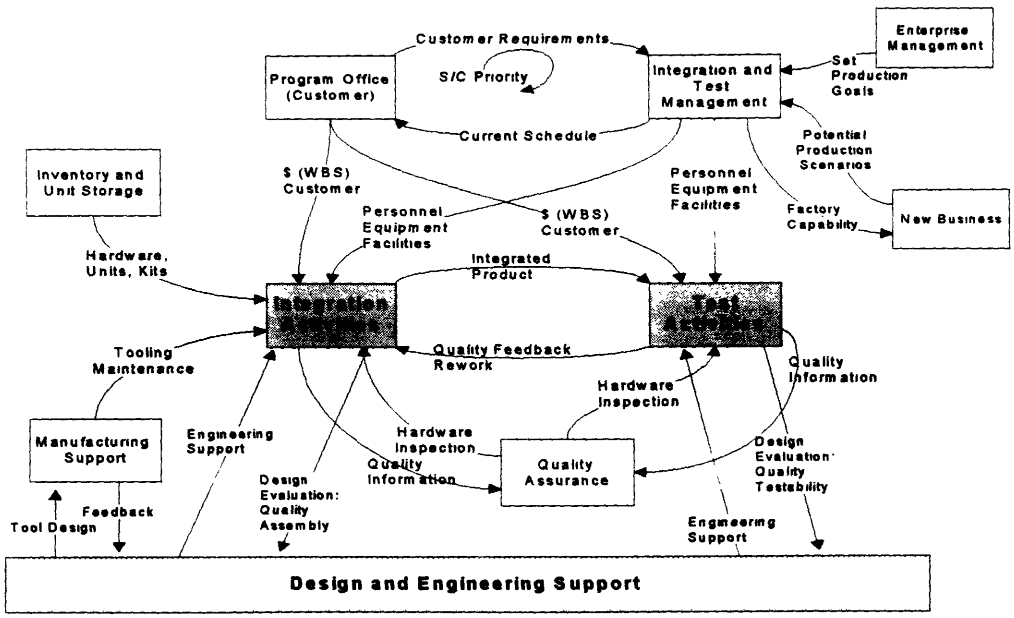

Figure 5.2 Top Level Functional Block

The functional block diagram (figure 5.2) illustrates the complex inter-relationships between the main functions of the S/C integration and test area. The modeling team will investigate the different relationships to determine their impact on the process and model them appropriately. The interaction loop between the I&T management and the program office is an important driver of the system since it impacts the number of resources allocated to any one S/C.

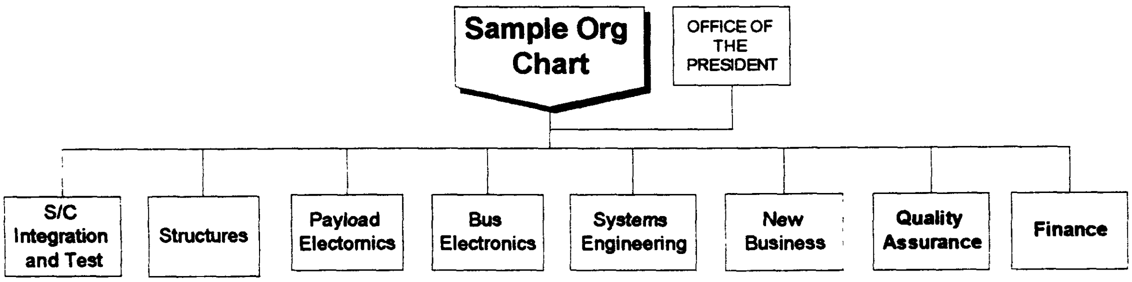

Figure 5.3 Sample Organizational Chart

The organizational chart (Figure 5.3) illustrates the number of different organizations involved in the process. It is important to understand the motivations of the involved parties prior to data collection. This knowledge may facilitate the interpretation of the different process views.

Requirements:

Satellite production's unique characteristics, as described in chapter 2, have to be accounted for and modeled to an adequate level. This includes:

- Modeling Features:

- Different product characteristics including - routings, cycle times, and resources.
- Resource competition and prioritization of S/C
- Characterization of quality related problems
- Unique process characteristics: such as work arounds for late antennas

- Model Input

- Different S/C types in any order and inter-arrival times
- Different Resource levels
- Type and amount of process variation
- Prioritization levels per S/C and workcenter

- Model Output:

- Measure cycle times and cost
- Measure resource utilization
- Monitor resource contention, queue length, time lost to queuing

- Dynamic display of information

Quality Function Deployment

The model requirements have been mapped to the customer needs in the quality function deployment on the following page (Figure 5.4). The purpose is to identify the important model features. Furthermore, the mapping can be used to see what characteristics are important to what customers. The diagram groups the customer needs into three categories: strategic decisions, S/C program decisions, and I&T management decisions. These needs are compared against the model representation of the S/C, the process, the resources, the variability, and the metrics. A ranking is given in terms of high (●), medium (❍), and low (❐).

The primary model characteristics were identified as:

- Customizable S/C routings, cycle times, and resources.
- Constraining resources: facilities, equipment, & manpower.
- Hardware Variability: Unit delivery uncertainty & unit removals.
- Metrics in terms of cost, cycle time, and resource utilization.
- Ability to load factory to any initial state

QUALITY FUNCTION DEPLOYMENT FOR THE GM HUGHES SATELLITE MANUFACTURING SIMULATION

CUSTOMER NEEDS		MODEL FEATURES: SC Reqmts		Process Characteristics			Resource Specification			Model Variability				Metrics Tracking					Scen Dvlp
		Customizable SC Routing, Cycle times, & Resources	Unique SC Characteristics - Priority, etc..	Rule Based Change Task Order, Duration, & Resources	Priority Based System-Impacts Process/Resources	Capability for Serial and Parallel Processes	Constrained Resources: Facilities, Equipment, and	Prioritize Resource Allocation	Number of Resources per Shift	Unit Delivery Uncertainity	Unit Removals	"File to Fit" Rework localized to workcenters	Variability in Task Duration	COST - Track Labor, Facility, Support Costs: per SC, per	Cycletime - Track number of days: per SC, per WC, per Task	Resource Utilization: Min, Max,& Ave - per Resource	Identify Bottlenecks - Queueing for Workcells & Resources	Cost & Cycletime Impacts of Quality	Load Factory to any Intial State
Strategic Decisions	**New Business Planning:**																		
	- Cost and Schedule Impact of New Programs	●	●		○	○	●	○	○	●	●	○	○	●	●	●			●
	Process Planning																		
	- What are realistic performance goals	●	○		○		●	●	●	●	●	○	○	●	●	●			●
Program Decisions	**Individual SC Optimization**																		
	- How do I best meet my payment milestones?	●	○			○	●	●	●	●	●	○	○	●	●				●
	- Given a current state, what is required to push the S/C out of the factory	●				●		●	●	●	●	○	○		●				●
	- What is the profitability of the program during SC I& T	●	○			○	●		●	●	●	○	○	●					●
	Enterprise Level View																		
	- How does my program interact in the factory and impact other programs	●	○				●	●	○	●	●	○	○	●	●	●	●		●
	- What Program gets priority given multiple choices?	●	○				●	●	○	●	●	○	○	●	●	●	●		●
I&T Management Decisions	**Toplevel Understanding**																		
	- What is the realistic system performance given the current factory loading	●	○			○	●	○	●	●	●	○	○	●	●	●	●		●
	- What resources will be impacted and to what degree given the current Waterfall schedule	●	○			○	●	○	●	●	●	○	○		●		●		●
	- What are the likely conflicts and what can I do to prepare for them	●					●	●	●	●	●				○	●	●		●
	Conflict Resolution																		
	- Which solution has the lowest impact on cost, schedule, and process risk	●					●	●						●	●	●			●
	Process Improvement																		
	- What is my current capacity?	●					●	●	●										
	- What are the key drivers of the system? -	●								●	●			●	●	●			
	- Where are my process/resource bottlenecks?	●								●	●					●			
	- What is the impact of process and delivery variability?	○								●	●			●	●	●	●		
	- What is the impact of unit quality?									●	●	●	●						
	- What is the impact on cost and cycle time if improvements are made in certain areas?	○	○				○	○	○	●	●	●	●	●	●	●			
	- Am I sub-optimizing?	●					●							●	●	●	●		

Figure 5.4 Hughes Simulation Quality Function Deployment

5.2 S/C I&T Data Collection Process

Strategy:

The data collection effort faced a set of unique challenges with the S/C integration and test process. The low volume nature of S/C production limited the set of available data. Furthermore, the data collected required a careful examination for biases and errors, for example, the majority of cycle time data, from scheduling databases, comprised of planned times and not actuals. The lack and inconsistency of data reduced the data accuracy and forced a number of assumptions on task cycle times, hardware quality problems, etc..

The data collection strategy addressed three critical elements established by the quality function deployment:

- Customizable routings, cycle times, and resources
- Constraining resources
- Hardware variability

The data collection procedures called for an initial understanding of the top level process (see figure 5.5). Any additional information such as quality problems could be identified during this process and characterized at a later date.

The top level view was accomplished through several interviews with the workcenter experts. Each workcenter was detailed to 10-20 activities with the associated cycle times and resources. A number of iterations were required to consolidate the information to representative format. This information was then reviewed with management for verification. Important processes, resources, or interactions were highlighted for further exploration.

Additional information requirements regarding cycle time, quality, and process characteristics were identified during this phase and parallel data collection efforts initiated. These efforts consisted of interviews, data base searches, and data validation. The data validation process proved critical due to unreliable information in data bases. Cycle times were often longer than recorded and quality issues lacked origin and process impact information.

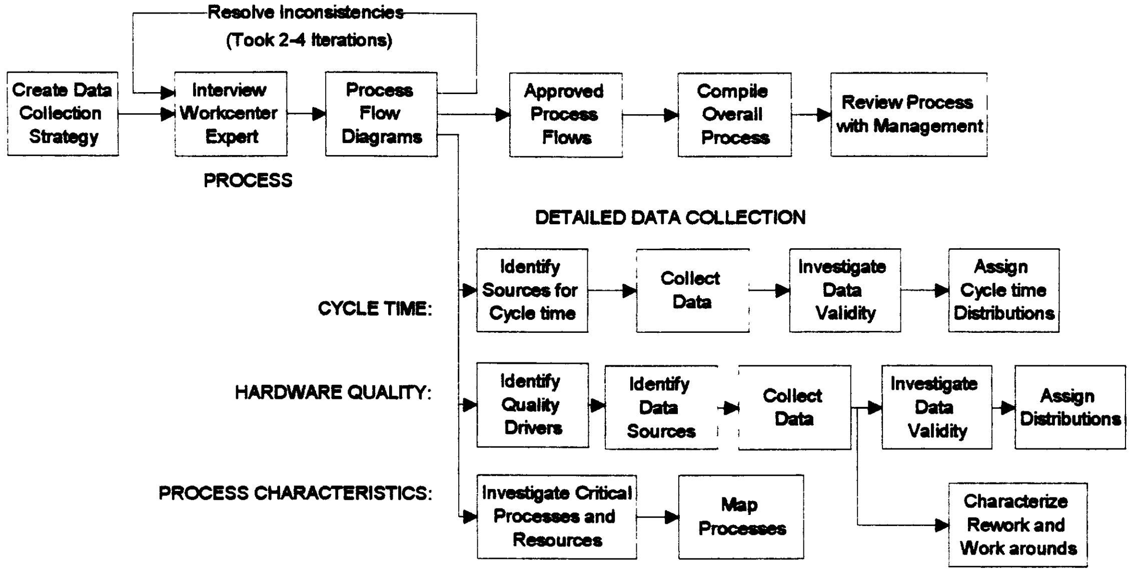

Figure 5.5 Data Collection Process

Data Sources:

- Interview with workcenter leaders to map processes ~ 10-20 tasks per workcenter
- Investigation of current data bases for cycle time and quality related information - S/C cycle times, Hardware delivery, Units Removed, etc.
- May Require Experimentation/Real time Data Collection

Process Characterization:

Process characterization is comprised of a series of process flows describing the product movement through the factory. Figure 5.1 illustrates the top level functional flow of the process. Each workcenter was mapped in detail displaying activity, cycle time, and resource information. Figure 5.6 is an example of the path for the generic S/C type in S/C integration.

The author adopted a process modeling methodology with a symbolic representation of the process flow. Activities, inspections, material movements, and inventory stores are represented with different icons as shown in figure 5.7.

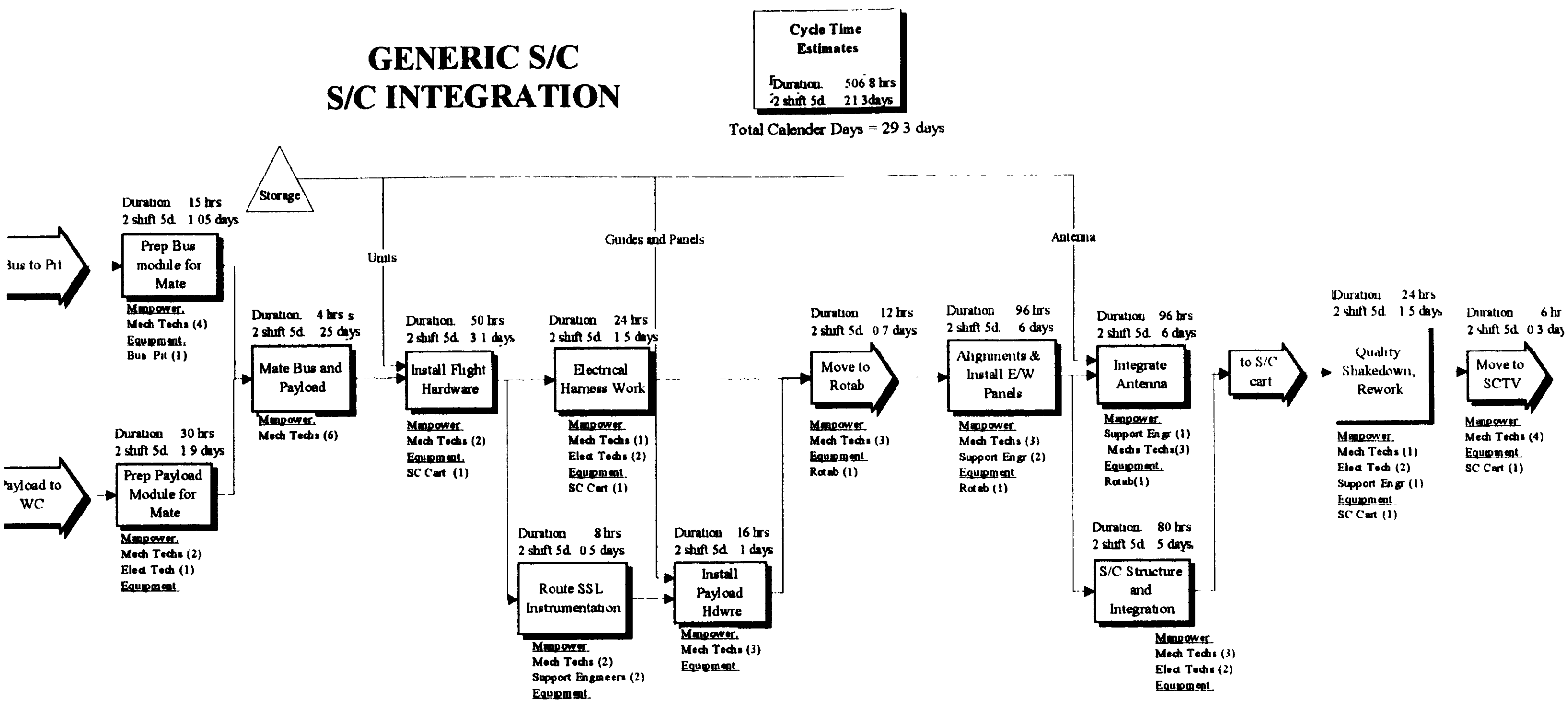

Figure 5.6 S/C Integration Process Flow

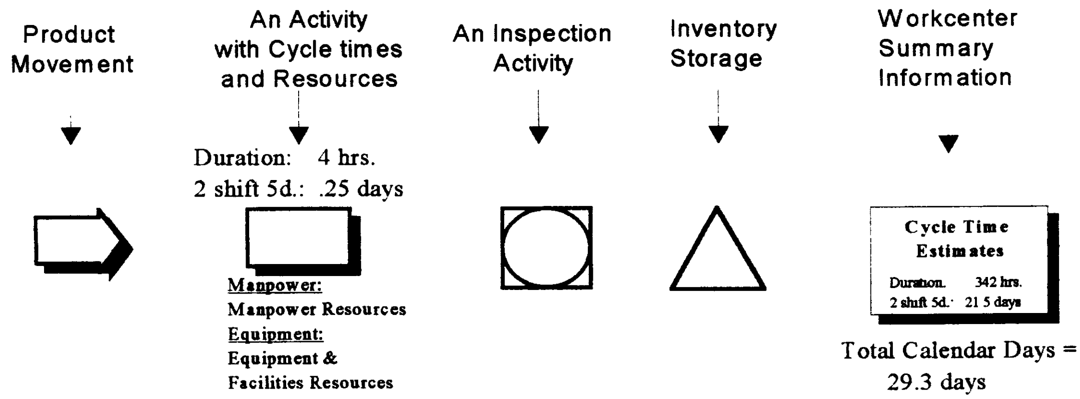

Figure 5.7 Icon Representation of the Process Flow

Situations were identified that did not follow or change the generic process flows. These situations required further detail to model accurately. Antenna delivery work arounds is an example of such an occurrence. The antenna has three different integration options depending on the delivery date. If the antenna is less than 5 days late, the S/C waits for the integration. If the antenna is between 5 and 15 days late, the S/C continues with its planned activities and integrates the antenna at the end of the workcenter prior to the S/C Thermal Vacuum testing. If the antenna is greater than 15 days late, it gets integrated prior to acoustic testing. The options are displayed below in Figure 5.8.

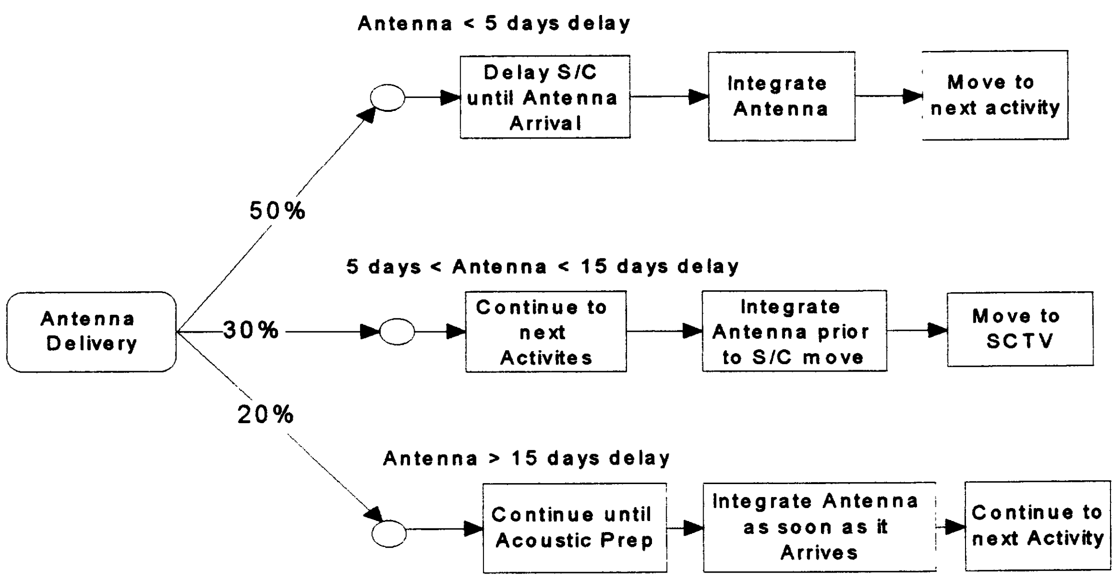

Figure 5.8 Antenna Delivery Work Around

Variability Characterization:

The variability characterization consisted of understanding and assigning probability distributions to activity cycle times, equipment and hardware reliability, and hardware delivery. The data collection team was challenged by the lack and inconsistency of the available data. The strategy consisted of collecting enough data to find minimum, average, and maximum values for the data points. This data was then validated with process experts along with a set of likely probability distributions fitting the situation. A list of likely choices is given in section 4.2.5. The team narrowed down the choice further as described in the following sections.

Cycle time information was universally unavailable for detailed tasks. The process experts supplied information regarding the theoretical minimum and the observed average and maximum times. The author chose the use of triangular distributions to represent these tasks. The low throughput of satellite production discourages detailed cycle time collection. Any one activity has statistically a minor impact on the overall process due to its infrequent repetition.

Product variability was examined on three levels: workcenter rework, late hardware deliveries, and unit removals. Rework comprised approximately 10-25% of workcenter cycle times. Rework demonstrated an interesting dynamic behavior since certain workcenters were dedicated to discovering problems (testing workcenters) and others dedicated to installing equipment and fixing problems (integration workcenters). As a result, integration workcenters experienced significantly more cycle time variation than testing workcenters.

The payload was the primary driver of late hardware delivery. Fifteen valid data points described a triangular distribution for late payload delivery times. For the purpose of this case study, the data was fit to a triangular distribution with a minimum of 0 days, an average of 10 days, and a maximum of 30 days.

Unit removals were analyzed in terms of frequency and process impact. Ample unit removal data could be found in the quality organization database. The frequency of unit removals fit to an exponential distribution with a mean arrival rate of 30 days. Unit removals could be split into two categories: single S/C removals and multiple S/C removals. Eighty percent of the removals were single S/C unit removals. Multiple S/C removals had a significant impact on the production process since they required all the satellites to be reworked.

5.3 Model Construction

The model construction followed the guidelines outlined in section 4.3. This methodology was facilitated by the hierarchical nature of the simulation tool SES Workbench. SES Workbench is an object oriented modeling tool with abstract symbology to characterize the process. Figure 5.9 shows the basic process flow and how the model decomposes into multiple layers of detail. A series of networks were created to simulate the process. The model construction was iterative in nature. The initial approach proved inadequate to model the different product routings and the model had to be restructured for flexible product routing.

The hierarchical modeling nature of the SES tool allows the modeler to start with a high level abstraction of the process and explode into detail where necessary. The top level constructs are called submodels and are used to model workcenters. Each workcenter was detailed to adhere to the process flows. Separate model logic regarding resources, hardware variability, and model logic was added in layers as described in the methodology chapter.

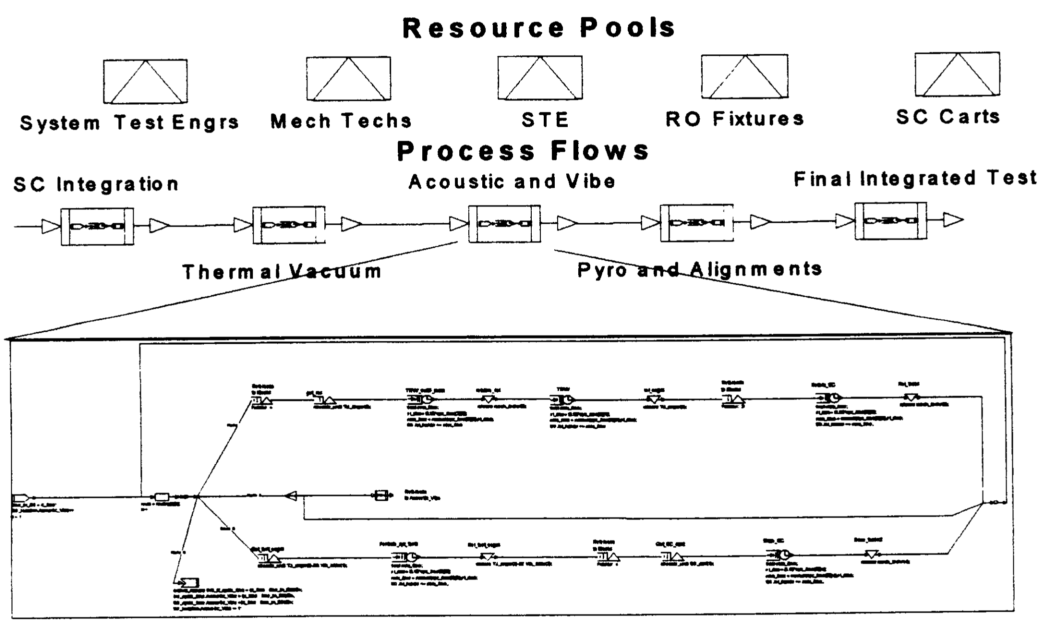

Figure 5.9 SES S/C Integration and Test Model Representation

Model Features

The model consists of a number of critical elements that adhere to the model features identified in the quality function deployment (QFD) (see section 5.1). These critical elements are: flexible product routings, multiple resources, hardware reliability, and model logic.

A flexible routing schema allows for multiple SC types with different routings and task durations. Each S/C receives a routing sheet specifying its path and its task durations.

The number of resources modeled are limited by the modelers imagination within model complexity constraints. The case study contains two facilities resources (SCTV Chamber, A6 Anachoic Chamber), four equipment resources (STE, RO Fixtures, S/C Carts, Vib Table) and four manpower resources (System Techs, Mechanical Technicians, Electrical Technicians, Engineering Support).

The model represents variability on a Macro, Mini, and Micro level. Macro level variability are hardware unit removals and late payload and antenna deliveries. Mini level represents workcenter rework. Lastly, micro level variability encompasses task duration uncertainty.

Model logic represents the different S/C manufacturing characteristics other than hardware variability and long production cycle times. This logic includes prioritization of S/C with respect to program importance and stage of the manufacturing process. Furthermore, late antenna deliveries have multiple paths as stated in section 5.2.

Simulation Representation

The SES Workbench software is an object oriented programming tool that allows the modeler to assemble a sequence of flows representing the process. The most common objects are shown in figure 5.10. Each object has a specific function such as requesting the use of a resource, performing a task, and releasing the resource. Submodels in SES allow for hierarchical modeling. Each submodel may represent a workcenter which includes a number of individual tasks. Figure 5.11 is a reduced example of a submodel used in the S/C integration and test model.

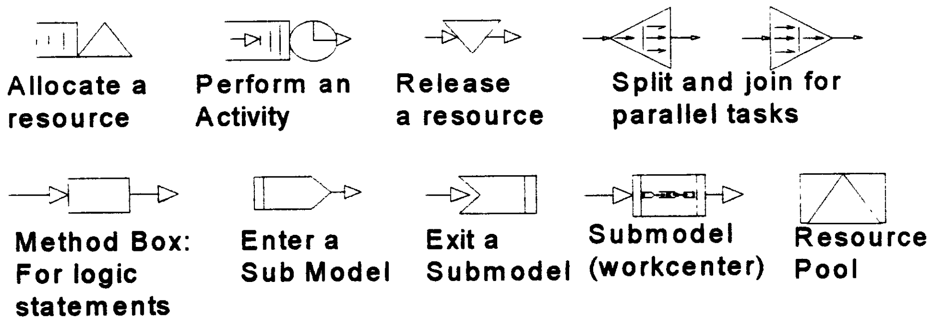

Figure 5.10 SES Workbench Model Constructs

Figure 5.11 shows the construction of a representative workcenter (the actual model construction contains significantly more detail.) A flexible routing schema facilitates the use of multiple S/C types. As shown below, the S/C can be routed to any step once it arrives at the "Routing Logic" object. The model flow proceeds as follows: The S/C travels from workcenter 1 to 2. At workcenter 2, the S/C arrives at "Enter Workcenter" and proceeds to the "Routing Logic" node. At this point, the logic statement determines the appropriate S/C routing depending on the S/C type. The S/C may "Install Antenna", "Test Antenna", "Install Flight Hardware", or "Move S/C. Once a task is completed and the resources released, the S/C returns to the "Routing Logic" node and proceeds to its next scheduled task.

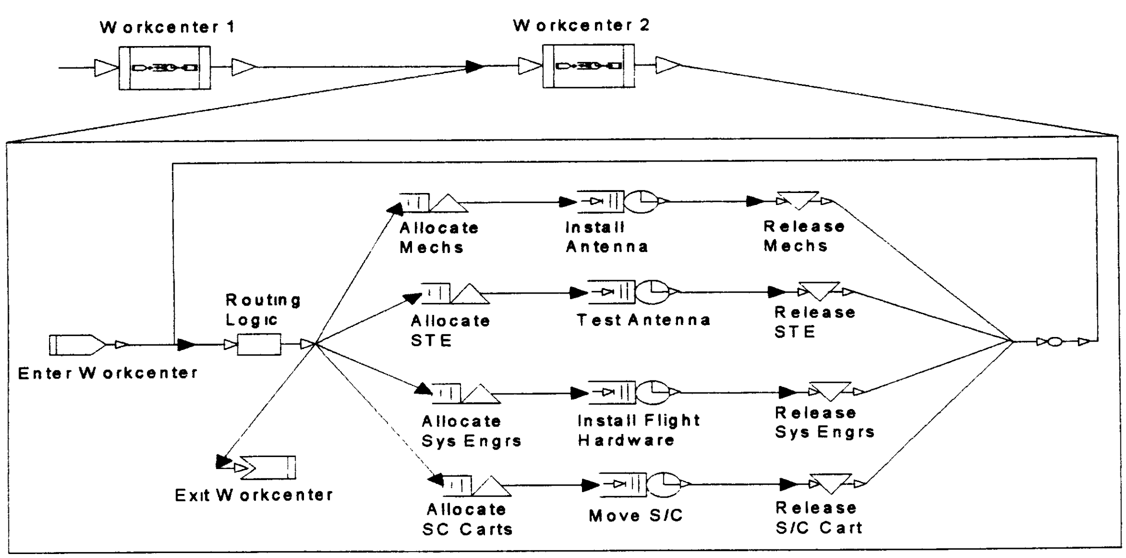

Figure 5.11 Example Workcenter SES Construction

5.4 Experimentation

The experimentation phase follows the procedures set in chapter 4. The purpose of the case study is to demonstrate the power of simulation and its applicability to satellite integration and test. As such, the author attempts to demonstrate a limited set of possible experiments without drowning the reader in detail.

Resource contention is an important driver of the process. The satellite integration process has the potential for fluid bottlenecks. Fluid bottlenecks are performance constraints that migrate in the process. Resources such as manpower and movable test equipment do not have a set location but may be found throughout the process. The designed experiments will examines the effects of these constraints. The capacity and bottleneck analyses explore the impact of these constraints on factory throughput. The what if scenarios examine the impact variability reduction on cycle time and resource constraints.

Number of Model Replications

The model requires 5 replications for each experimental data point. Appendix A contains the details of the calculations required for this value.

Warm-up Period

The simulated model time to steady state was calculated as 15,000 hours. A single run was used to estimate the required warm up time. Appendix B contains the details of these calculations.

Designed Experiments

The designed experiments characterize the impact of multiple factors. In our case the main driver is resource contention. Other cases may examine the impact of changes in workcenter cycle times. The author uses the partial factorial to screen important factors and interactive elements. A full factorial experiment accurately quantifies their impact.

Partial Factorial

The partial factorial experiment examines the impact of STE, system test engineers, mechanical technicians, R/O fixtures, and S/C carts with a fixed arrival rate of fourteen generic S/C a year. The testing matrix is contained in appendix D and the results are displayed in section 5.6.

Full Factorial

The factors identified in the partial factorial experiment are examined further in the full factorial experiment. The test matrix is contained in appendix D and results are displayed in section 5.6.

Performance Testing

Performance testing consists of capacity testing and bottleneck analysis. Capacity testing examines the impact of varying input rates on the cycle time and resource utilization. The arrival rate of the S/C is increased from 8 S/C a year to 17 S/C a year. The resulting cycle times and resource utilization are recorded and graphed. Special attention is given to the critical resources as identified by the partial and full factorials.

The result is an understanding of the system capacity and the limiting constraints. where cycle time elongation indicates the capacity impact. Furthermore, this analysis leads into the bottleneck analysis. The limiting resources identified are the bottlenecks.

The bottleneck analysis fixes the input rate and varies the constraining resources to reach a satisfactory process performance level. The process is iterative in nature as resources are varied, their impacts assessed, and the next step calculated. The performance measures are the cycle time and the resource utilization. The resource with the highest utilization is the bottleneck. The bottleneck is eliminated by increasing its resources. The model is run again and next bottleneck identified. Appendix D shows the test matrix used.

Scenario Evaluation

One proposed scenario is to be evaluated: variability impact on cycle time and resource constraints. The variability study includes the impact of unit removals and late payload deliveries on the process. As stated in chapter 2, this variability accounts for a majority of the problems. The intent is to quantify the impact of this variability in order to justify further improvements in these areas.

The scenario consists of three phases. Phase 1 examines the impact of reducing late payload deliveries. Phase 2 examines the impact of reducing the occurrence of unit removals. Phase 3 examines the combination of these two phases and looks at the total improvement. The primary indicator of process performance is the S/C cycle time and resource utilization. Appendix D contains the test matrix.

5.5 Output Analysis

Designed Experiments

Partial Factorial

The partial factorial is analyzed according to the guidelines set in section 4.6. High and low values are plotted (figure 5.12) to show the set of possible values. The test was used to identify the primary drivers and interactions.

Figure 5.12 shows the resulting plot with the primary effects, system test engineers and mechanical techs, circled. System test engineers and mechanical technicians have an impact on the order of 25 and 10 cycle time days respectively. The interacting factors show an interesting phenomenon. The STE (standard test equipment) has a strong interactive impact with the manpower resources, yet a negligible effect in isolation. The author decided the interactive impact of the STE warranted further examination in the full factorial experiment. The full factorial experiment consists of the STE, system test engineers, and mechanical technicians.

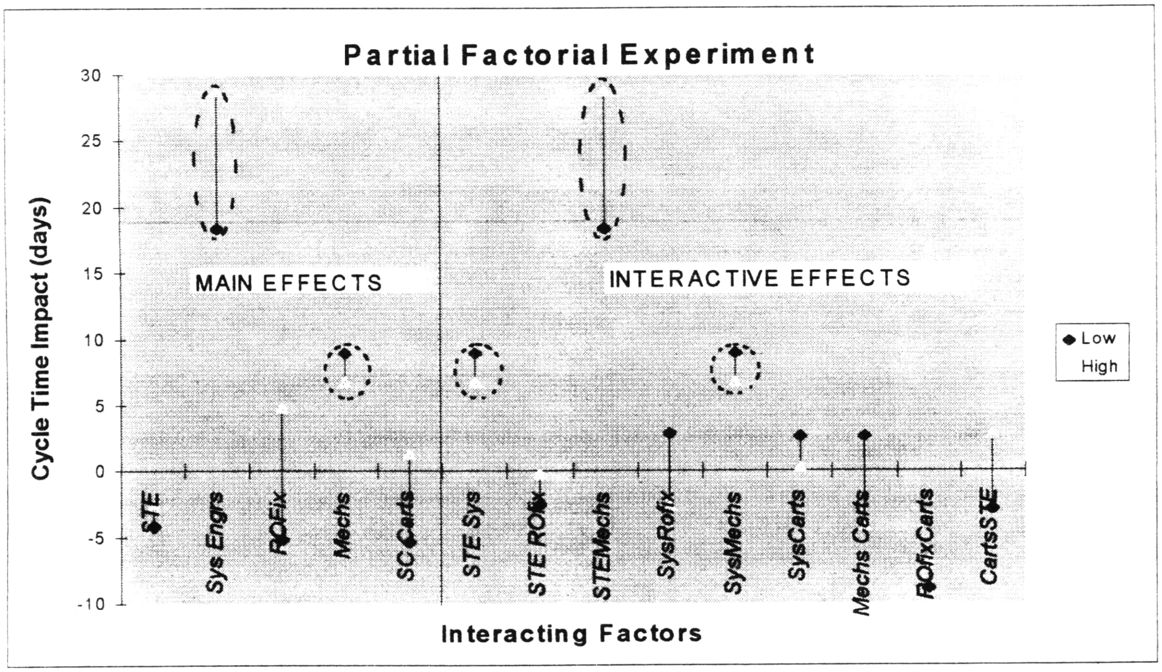

Figure 5.12 Partial Factorial Experimental Output

Full Factorial

The full factorial experiment characterized the impact of STE, system test engineers, and mechanical technicians as shown in Figure 3.13. The two primary drivers were confirmed as system test engineers and mechanical technicians. Standard Test Equipment had negligible effect on the experiment. It is important to note that these values may change as the factory loading changes. A higher input rate may increase the impact of certain resources. In Figure 5.14 the STE utilization is below that of system engineers until the arrival rate is above 14 S/C a year. Above 14 S/C a year, the system test engineers are waiting for the equipment to arrive and they are available for other jobs.

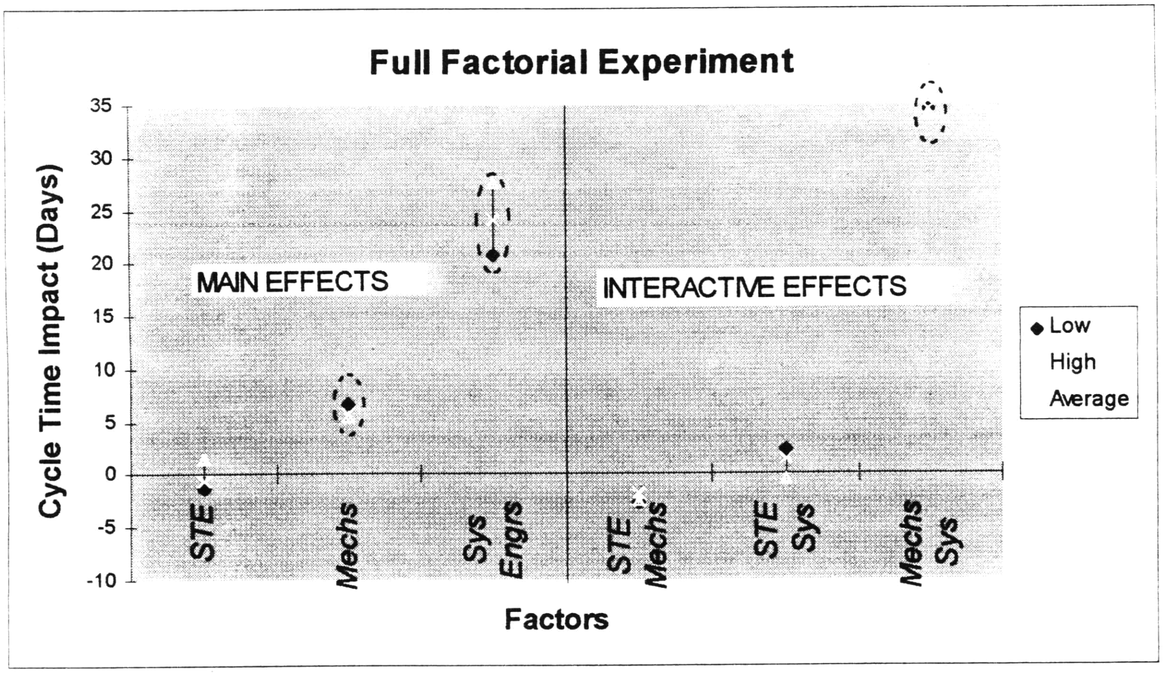

Figure 5.13 Full Factorial Experimental Output

Capacity Analysis

The capacity analysis examines the impact of S/C arrival rate on cycle time and system constraints. As identified in designed experiments, the system constraints are STE, system test engineers, and mechanical technicians. Figure 5.14 plots the results. At 14 S/C a year, the system test engineers and STE resource utilizations cross. As discussed in the previous factorial analysis section, the system test engineers are idle, waiting for equipment. Cross over points are important since they change the dynamics of the process and may require a prioritization of resources on the factory floor.

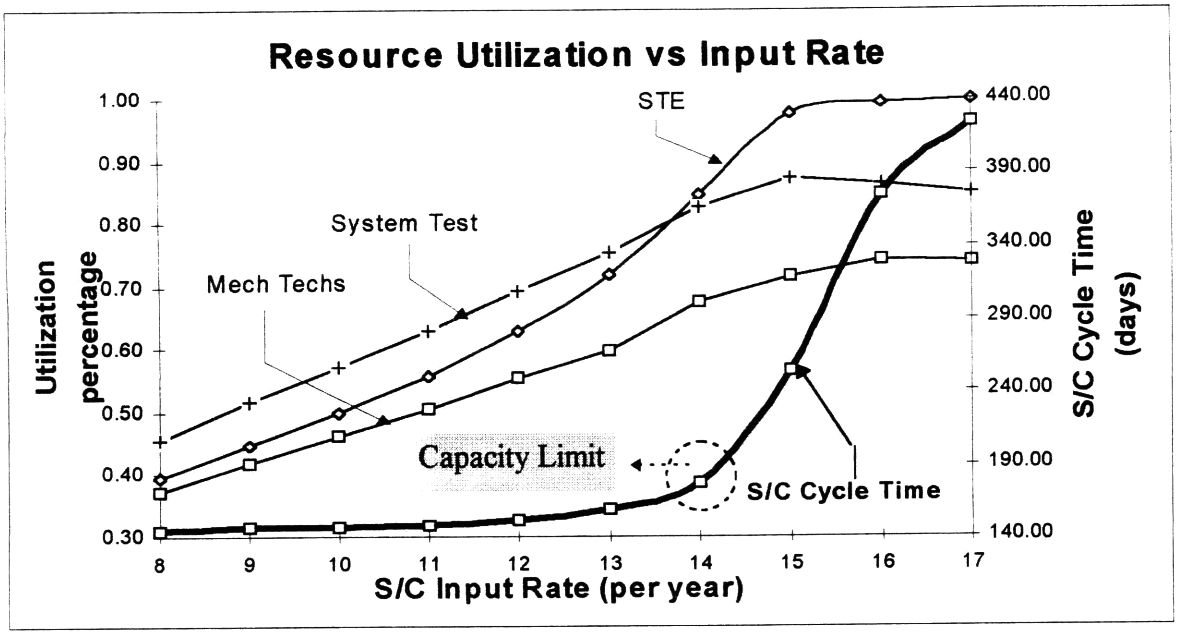

Figure 5.14 Capacity Analysis Graph

Bottleneck Analysis

The bottleneck analysis attempts to remove the constraining resources to maximize the system performance. The constraining factors for the S/C integration and test process are its equipment and manpower resources. The following initial conditions are placed on the model.

Table 3 Bottleneck Initial Conditions

Arrival Rate	STE	System Test	Mech Techs	R/O Fixtures	SC Carts
14 S/C a year	4	14	10	2	5

Each model run is evaluated in terms of resource utilization and the most frequently used resource is incremented. This procedure is repeated until an acceptable level of system performance is attained. Figure 5.15 show the resource and cycle time estimates for each scenario. The scenario starts on the right hand side with STEs as the constraining resource. An additional STE is added the new model response is measured. The STE resource is incremented once again since it continues to be the most frequently used resource. This process continues until an acceptable cycle time performance of 160 days is achieved. The x-axis names the constraining resource for each model run. The final system performance represents a 247% cycle time reduction and requires an additional 2 STEs, 4 system test engineers, and 2 mechanical technicians.

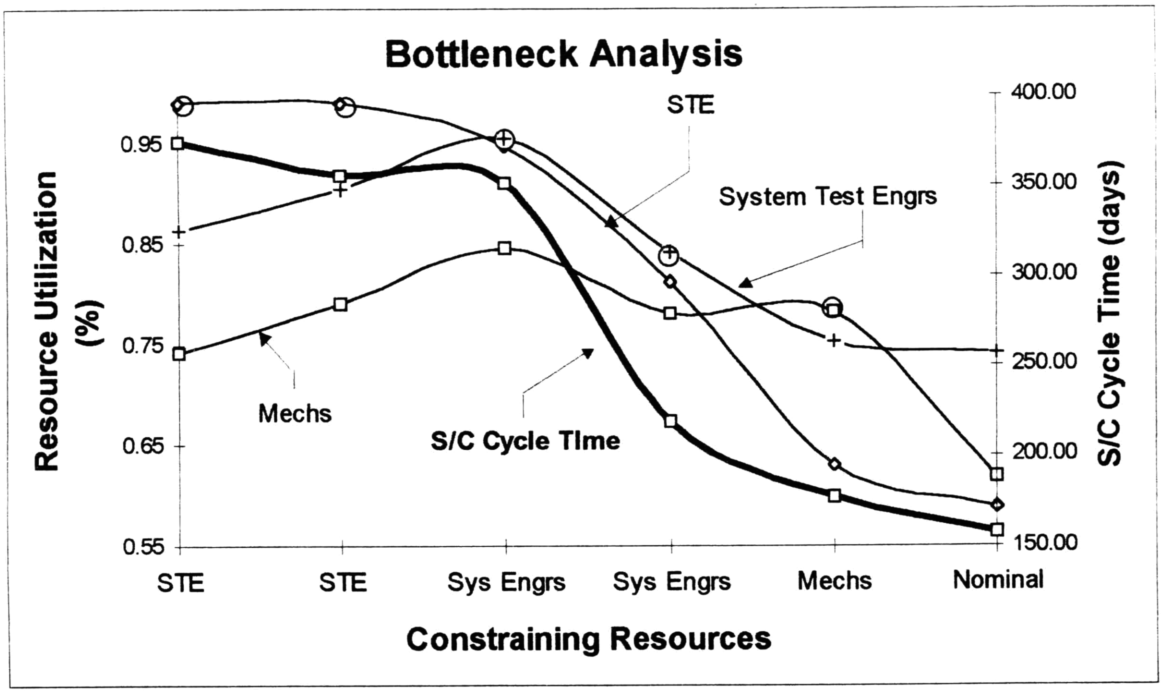

Figure 5.15 Bottleneck Analysis Graph

Scenario Evaluation Analysis

The proposed scenario is the impact of variability reduction on the process. Two major drivers were identified: unit removal and payload delivery variability. The results can be viewed in figures 5.16 and 5.17.

Unit removals are measured in terms of frequency of occurrence. As the time until a removal increases, the number of removals per year decrease. Figure 5.16 illustrates the impact of unit removal on cycle time and resource utilization. Unit removal reduction is beneficial from 20 till 45 days between removals. Beyond 45 days the cycle time benefit levels off. A reduction goal can be set analytically knowing the impact on the process.

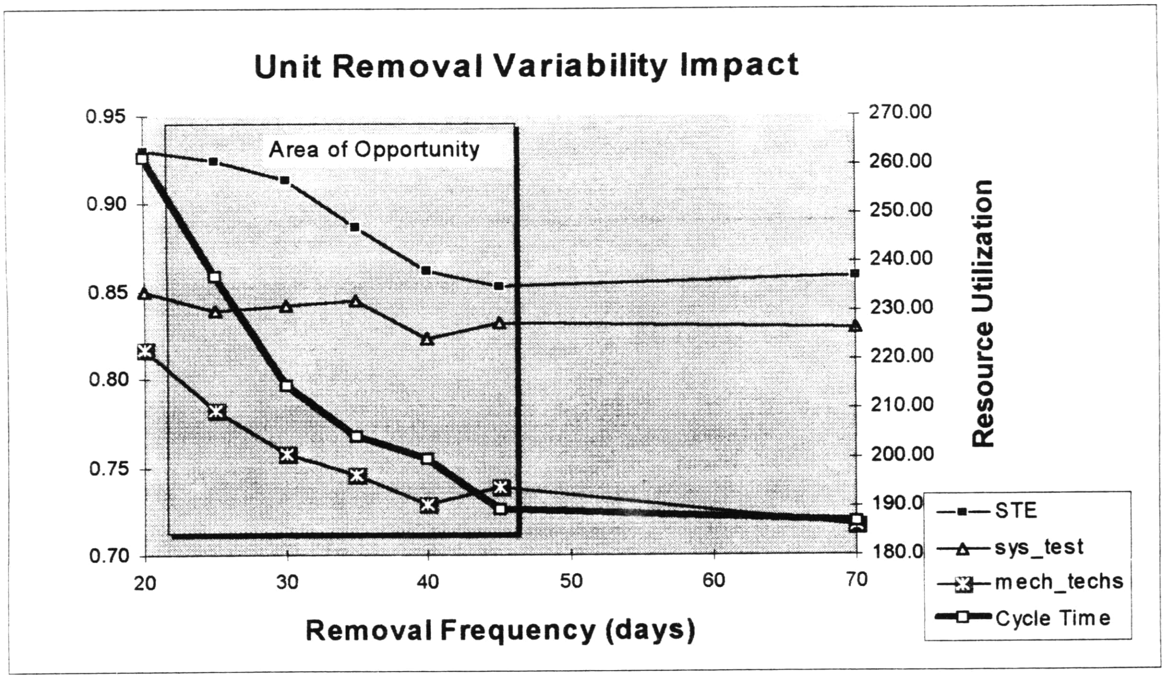

Figure 5.16 Unit Removal Variability Impact

Payload delivery variability impacts the process in several ways: uneven factory loading, higher resource utilization, and longer cycle times. The impact of payload delivery uncertainty is quantified in figure 5.15. The cycle time reduction is approximately linear with delivery variability. However, for every day of delivery reduction, the S/C cycle time reduction is 1.75 days. One would expect a one for one relationship, but the uncertainty creates an uneven factory flow. Resource conflicts are attenuated by uneven flow since effective allocation can not be planned. The cycle times increase in proportion to the late payload delivery and the additional resource conflicts.

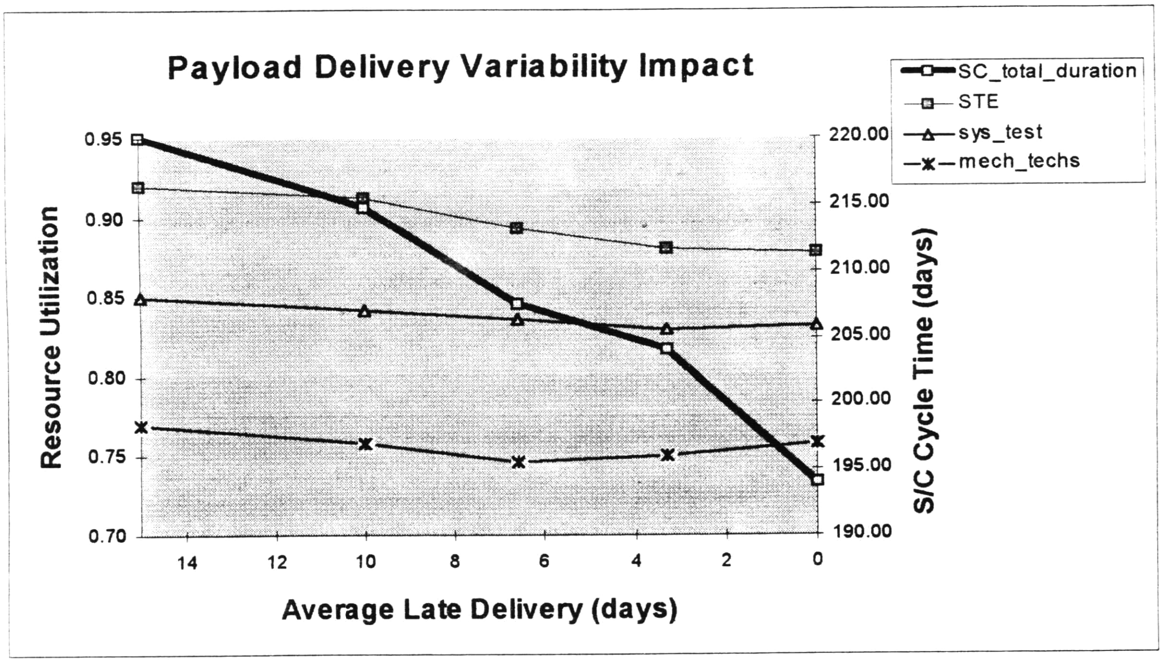

Figure 5.17 Payload Delivery Variability Impact

5.6 Operational Tool

Simulation can operate as a tool to benefit decision making. It provides capacity planning and process performance information in a timely fashion. The two primary benefits are:

- Quick response time
- Accurate capacity planning

The following discussions represent an overview of simulation planning and not a detailed discussion. For more information refer to Rosenwinkel and Rogers "Simulation-Based Finite Capacity Scheduling" [Ref. 34].

Simulation has a quick response time in comparison with other planning tools. Traditional planning tools are slow and resource intensive. The simulation plots presented in this chapter required 4 minutes of model runs and 20 minutes of data manipulation. The modeler could present in excess of 16 such scenarios a day. A significant advantage over traditional tools which may take weeks for similar scenarios.

Simulation is an accurate capacity planning tool. Traditional planning tools, such as MRP systems, assume an infinite production capacity. This assumption may inaccurately model the system behavior since the system is not constrained by bottlenecks or resource interactions. With simulation, modelers may choose between infinite capacity and finite capacity planning. This allows for an interesting process perspective. An infinite capacity model run can examine the "best case" scenario and establish maximum resource levels. A finite capacity model run can then display the realistic system performance in terms of cycle time and resource utilization. The modeler can compare the two scenarios and identify potential solutions for over-utilized resources and uneven production flows. Simulation provides more information for decision making.

The following sections show the comparison between finite capacity and infinite capacity planning. The impacts are evaluated in terms of equipment utilization (STE), workcenter capacity (SCTV), and total S/C cycle times.

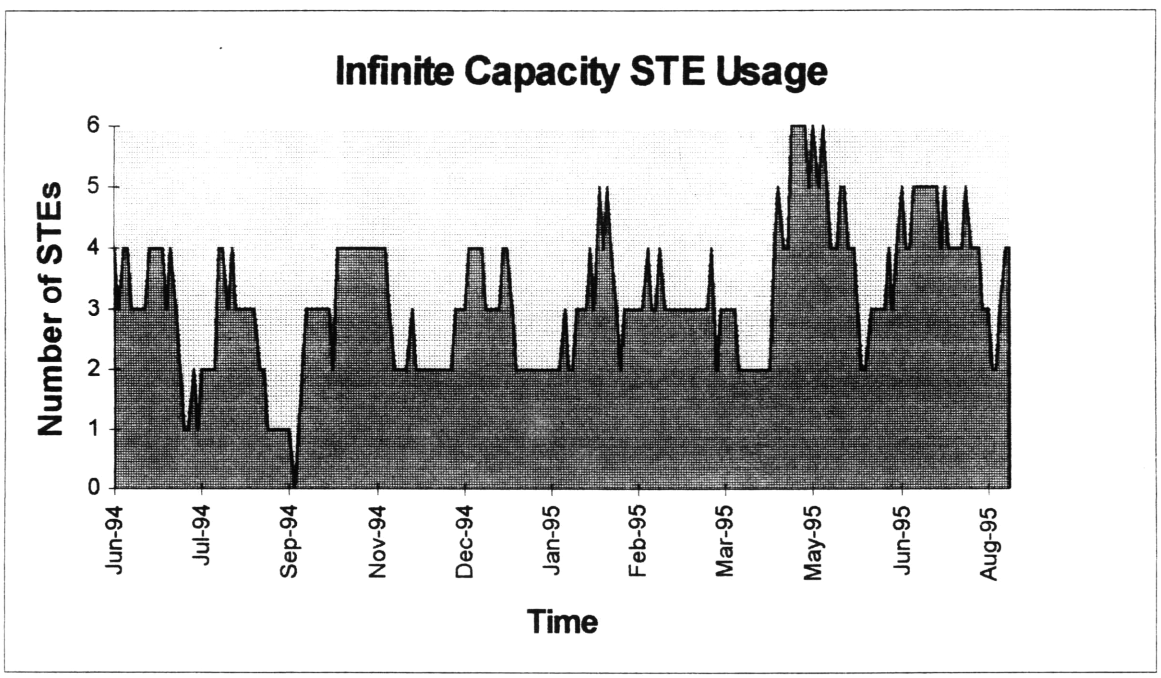

Figure 5.18 Infinite STE Resource Usage

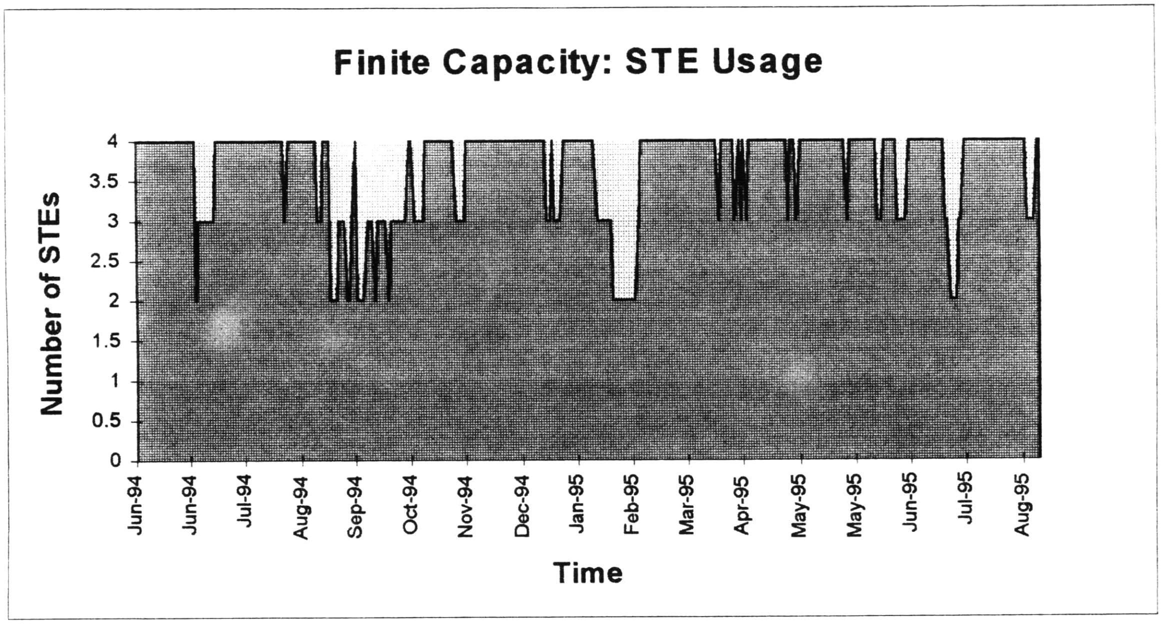

Figure 5.19 Finite STE Resource Usage

STE resource utilization changes dramatically between figures 5.18 and 5.19. Figure 5.18 illustrates a varied STE usage with a spike of 6 STEs in May 95. The average STE use from July 94 to May 95 is approximately 3.3. The finite capacity diagram (figure 5.19 tells a different story. The four STEs are utilized close to 100% compared to 80% for the infinite capacity. The delays caused by resource contention has changed the dynamic behavior of the process. The timing between events as S/C are delayed may significantly alter the of resources required at any on time. This timing is illustrated further in the following workcenter capacity diagrams.

Simulation can also display workcenter capacity information. Figures 5.20 and 5.21 show the difference in planned workload between the infinite and finite capacity cases. The expected workloads are significantly different. The finite case predicts a work spike from Nov.-94 to Jan-95. The workcenter has to process 4 S/C during this time. The infinite capacity cases predicts business as usual with two S/C requiring work. Which view is correct? Reality is probably a combination of both views due to the high variability of satellite production. The Nov. 94-Jan 95 time frame can be labeled as a potential problem and a number of contingency scenarios can be prepared ahead of time. In this application, simulation serves as a risk management tool.

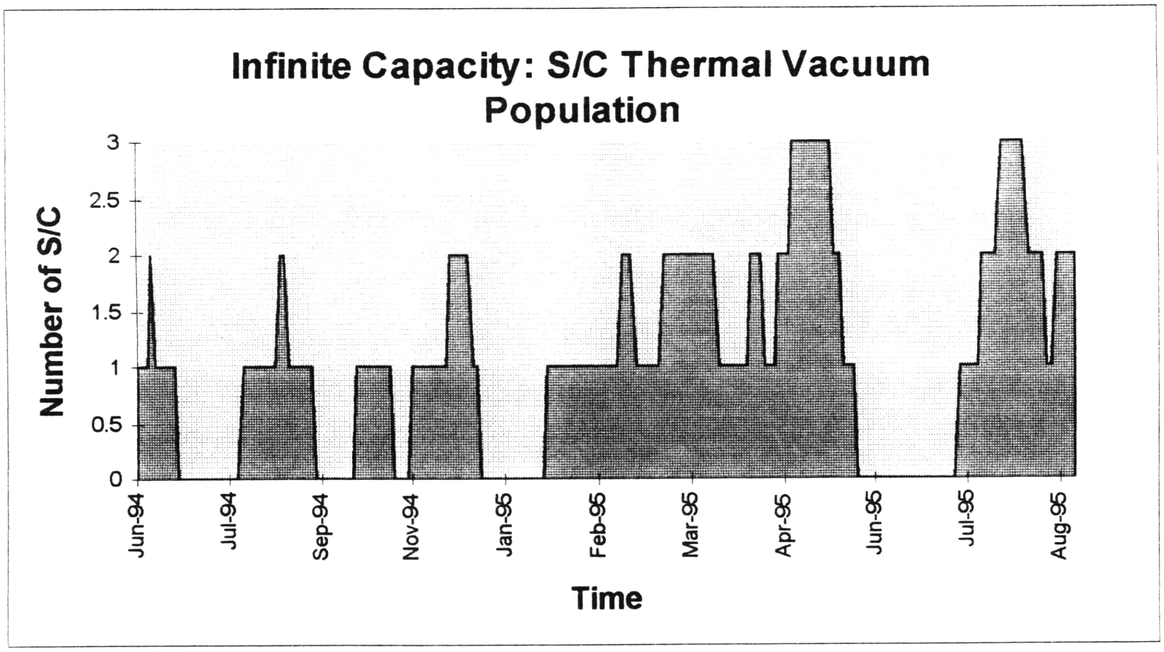

Figure 5.20 Infinite Capacity Thermal Vacuum S/C Workload

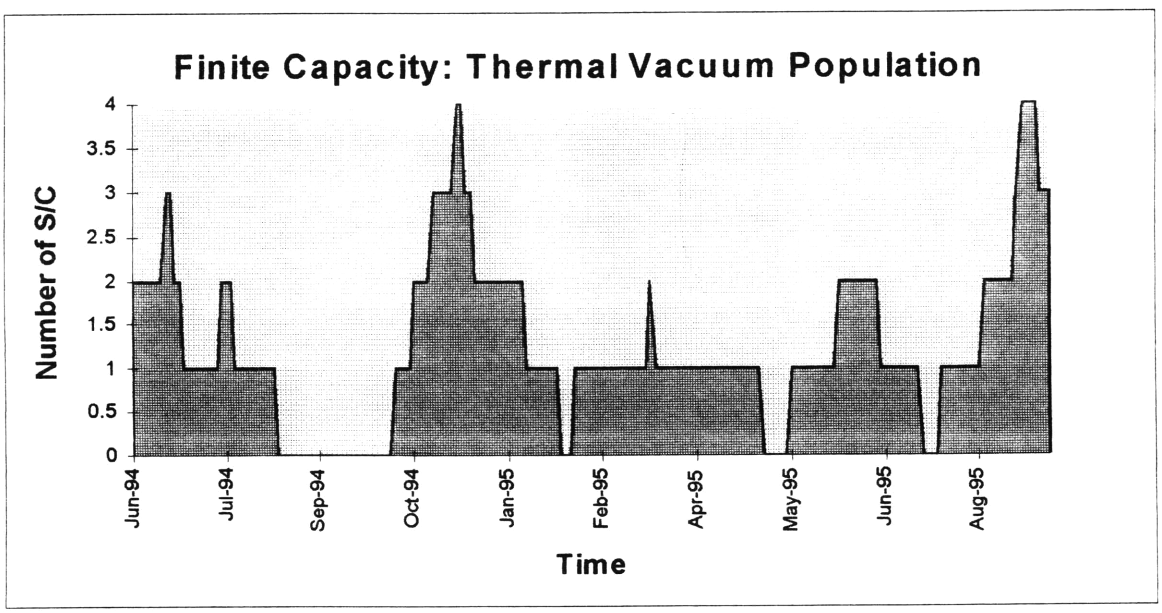

Figure 5.21 Finite Capacity Thermal Vacuum S/C Workload

Top level system performance can also be compared over time. Total S/C cycle time is plotted for the finite and infinite cases. Figure 5.22 illustrates the differences in cycle time for the two cases. The impact can be measured in cycle time elongation or delivery delay. The infinite capacity cycle time is elongated by ~30 days resulting in a delivery delay of 30 days. Notice the upward trend in the finite capacity case. This is primarily due to a increase in the number of contracts in 95. The model scheduled 6 contracts in 92, 10 contracts in 93, 11 contracts in 94, and 12 contracts in 95. Infinite capacity planning does not incorporate the impact of the increase in business volume.

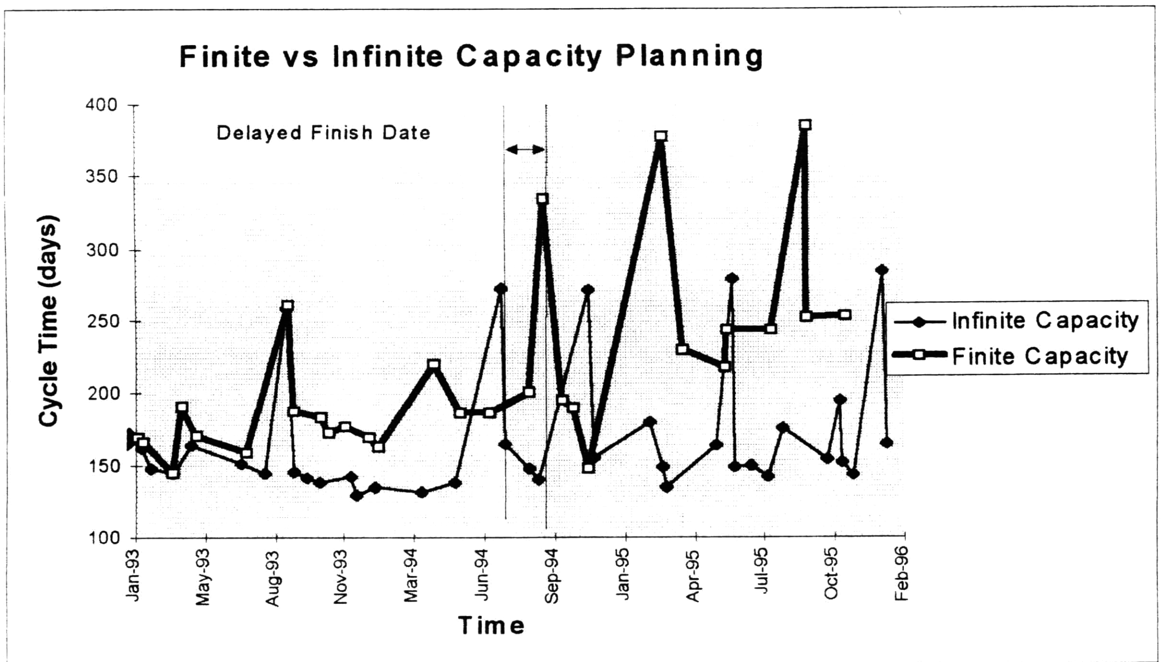

Figure 5.22 Cycle Time Plot for a Fabricated Schedule

This section provided a top level overview of simulation's use as an aid in decision making. It provides benefits in terms of quick response time and data accuracy. The author suggests further readings in Rosenwinkel and Rogers "Simulation-based finite capacity scheduling: a case study" [Ref. 4] and Kaye and Sun "Data manipulation for the integration of simulation with on-line production control" [Ref. 23].

5.7 Result Summary

The S/C integration and test model was exercised to gain a greater understanding of resource and variability in the model. The primary resources were discovered to be system test engineers, mechanical technicians, and STE. Interestingly enough, the impact of these resources changed significantly with the throughput rate. The importance of test equipment (STE) increased with the S/C throughput and became the primary constraint above 13 S/C a year. Furthermore, simulation provided a useful aid for decision making. The accuracy and quick response time of simulation provided information previously unavailable to decision makers.

The capacity analysis discovered a process limitation at 14 S/C a year. Above this point the cycle times increased rapidly beyond acceptable levels. The primary constraints appeared to be STE and system test engineers. The author chose this break point for the bottleneck analysis.

For a satellite throughput of 14 S/C a year, the bottleneck analysis discovered 3 principle bottlenecks: STE, system test engineers, and mechanical technicians. The acceptable cycle time target was below 170 days. This performance goal required 2 additional STEs, 4 additional system test engineers, and 2 additional mechanical technicians. The variability analysis focused on the impact of unit removals and payload delivery. Both factors were found to have a dramatic impact upon S/C cycle times. Unit removals significantly impacts S/C cycle time at frequencies above one removal per 45 days. Improvements should focus from the current estimated removal frequency 30 days to once per 45 days. Any improvement beyond the 45 day mark shows little cycle time impact. Late payload deliveries attenuated the S/C cycle times. For every day late, the overall cycle time increased by 1.75 days.

The author recommends a strict focus on effective resource management of system test engineers, mechanical technicians, and system test equipment (STE). Process and product variability provide sizable opportunity for process performance. Unit removals and payload delivery should both be reduced by a factor of two for a manageable and predictable system.

Chapter 6 Simulation Applications

Simulation has uses beyond the current application. It is a matured tool that covers a spectrum of subject areas including manufacturing, computer and communication systems, service systems, military systems, and business processes. The following section briefly describes theses areas and gives examples of current projects taken from the Winter Simulation Conference in 1993 as noted in the bibliography.

6.1 Manufacturing

Simulation is most commonly applied to manufacturing situations. The applications are numerous including electronics manufacturing, material handling and distribution systems, inventory management, production planning and control, and real-time applications. The following sections site a number of examples to familiarize the reader with current studies.

Electronic Manufacturing

Common applications within the electronic manufacturing industry include surface mount assembly, PCB assembly lines, and semiconductor wafer fabrications. The references for the following examples can be found in the bibliography. Current examples: "Subsystem Decomposition in Simulation of a PCB Line" ,"Simulation Software for Surface Mount Assembly" , " Precise and Flexible Modeling for Semiconductor Wafer Fabrication" and "The Simulation of Integrated Tool Performance in Semiconductor Manufacturing."

Material Handling and Distribution Systems

Simulation provides in the pre-implementation of material handling and distribution systems. It is commonly used to understand material movement requirements, check material handling logic, and set requirements for automated systems (AS) such as automated guided vehicles (AGVs). Current examples: "Modeling Beverage Processing

Using Discrete Event Simulation“,” Generalization of an AS/RS Model in SIMAN/CINEMA” ,“Design and Cost-Effectiveness Analysis of Large-Scale AS/RS-AGV Systems,” and “A Simulation Model and Analysis: Integrating AGV’s with Non-automated Material Handling.”

Inventory Management Issues

Inventory management simulations deal primarily with inventory policies such as Just-In-Time, synchronous manufacturing, and pull systems. Pre-implementation is usually required due to the risks associated with inventory policy changes. Current examples: “Kanban Simulator Using Siman and Lotus 1-2-3”, “Modeling Just-In-time Production Systems: A Critical Review” , “Simulation of a Plant-Wide Inventory Pull System”, and “A Simulation of Synchronous Manufacturing at a Naval Aviation Depot.”

Production Planning and Control

Production planning and control simulations focus primarily on tools to aid and automate decision making on the factory floor. Such simulations allow for job scheduling, finite capacity planning, and crisis management. Current examples: “An Integrated Simulation and Shop-Floor Control System”, “ A Flexible Assembly Global Control Simulation,” , “Modeling and Control of Deadlocks in a Flexible Machining Cell”, “Generating Component Release Plans with Backward Simulation”, “Simulation-Based Finite Capacity Scheduling: A Case Study Control of Deadlocks in Flexible Machining Cell”, and “Generating Component Release Plan, Simulation-Based Finite Scheduling.”

Real-Time Applications

Real-time simulation applications addresses the need for quick decisions on the manufacturing floor. Simulation can provide quick accurate estimations of possible choices. Current examples: “Simulation for Real-Time Decision Making in Manufacturing Systems” and ”Exception Management on a Shop Floor Using On-line Simulation.”

6.2 Computer and Communication Systems

Computer and communication system simulation is a rapidly expanding application. Simulation provides pre-implementation answers regarding system response time, network capacity, congestion control, routing algorithms, survivability, system failure response, and user expansion impact. Current Examples: "A Simulation Model for Assessing Network Capacity", "The Telecom Framework: A Simulation Environment for Telecommunications", and "Simulation in Support of Software Development."

6.3 Service Systems

Health Care Systems

Health care systems is another growing application area for simulation, especially for critical care units. Critical care units inquire information regarding required staffing levels, bed levels, and patient processing times. Current examples: "Multi-Hospital Validation of Critical Care Simulation Model" and "Simulation Modeling of Prehospital Trauma Care."

Transportation Services and Systems

Simulation of transportation systems is becoming increasingly prominent due to city crowding and interest in intelligent vehicle highway systems (IVHS). Simulation can model traffic patterns, provide information regarding throughput and capacity, and visually represent the flow. Current applications: "Simulation of Streetcar and Bus Traffic", "Distributed/Parallel Traffic Simulation for IVHS Applications", and "A Simulation-Based Analysis of Parking System Performance."

6.4 Military Applications

Constrained budgets and increasingly complex weapons systems are forcing the military to validate weapon systems through simulation. These simulations can be categorized as infrastructure simulations, warfare simulations, and Combat (land, air, and sea) simulations. Current examples: " Defense Modeling and Simulation Office: Defining the Infrastructure", "Modeling Coalition Warfare: A Multi-Sided Simulation Design", "The Close Combat Tactical Trainer Program", and "Naval Modeling and Simulation Verification, Validation, and Accreditation."

6.5 Business Processes

Business process simulation models areas such as data and workflow analysis. Specific applications include corporate financial planning, enterprise modeling, and business process re-engineering. Current examples: "Using Symbolic Modeling in Business Re-Engineering", "Simulation as a Tool for Business Process Innovation", "General Purpose Enterprise Simulation with MASTER", and "Discrete Event Simulation for Corporate Financial Planning."

Chapter 7 Conclusions

Research findings

This thesis demonstrated the utility of simulation in a complex, flexible, low volume production system such as S/C integration and test. Special attention was given to the benefit of simulation for process improvement and process management. The research findings include:

- Simulation projects require a structured methodology
- Lack or bias of data does not invalidate the simulation model
- Simulation is capable of modeling the S/C integration and test process
- Simulation increases process understanding through identification of primary factors, capacity limits, and bottlenecks
- Simulation can quantify the impact of process uncertainty
- Simulation is a valuable aid in decision making

The complexity of simulation encourages the use of a structured methodology. Simulation modeling is a diverse field requiring knowledge about systems definition, data collection, process mapping, probability theory, statistical analysis, computer programming, and experimental technique. A structured methodology guides the modeler through the modeling decisions. For example, the thesis methodology requires the modeler to construct the model in layers to avoid unnecessary complexity.

Lack or bias of data does not invalidate the S/C integration and test (S/C I&T) simulation. S/C I&T lacked cycle time and quality data, constraining the modeler's ability to choose exact probability distributions for process variability. The lack of data limited the accuracy of the model but with educated choices the overall process behavior was modeled accurately. Furthermore, the stochastic nature of simulation is inherently more accurate than traditional deterministic methods for S/C I&T.

Simulation is capable of modeling a low volume, complex, and variable manufacturing system like S/C I&T. The model was able to incorporate unique satellite production features such as: low factory throughput, unreliable hardware, customized product, flexible production system. and production logic such as S/C prioritization.

Simulation increased the process understanding by identifying system drivers, capacity limits, and bottlenecks. The case study illustrates the use of simulation to identify keys system drivers (system test engineers, mechanical technicians, and System Test Equipment), the process capacity limit (14 S/C a year), and how to alleviate bottlenecks in the system.

Simulation can quantify the impact of system uncertainty such as late hardware delivery, hardware failure, and equipment failure. The case study quantified the impact of unit removals and late hardware delivery in terms of cycle time and resource utilization. The quantifiable impacts can then be presented to management as justification for process improvements in hardware reliability.

Simulation has been shown to be a valuable decision making tool. Simulation provides quick answers (relative to traditional tools) to capacity and what-if questions. Furthermore, simulation is more accurate than traditional manufacturing planning tools (MRP systems) since it incorporates stochastic variable and finite capacity resources. The case study validated finite capacity planning as sufficiently different from infinite capacity planning in terms of S/C finish dates, S/C cycle times, and resource utilization percentages.

Recommendations for Future Work

Future research opportunities exists in theoretical simulation research, real-time simulation research, S/C subsystem simulation, and other aerospace applications.

Theoretical Research -

The author recommends further study on the impact of large statistical variances on system accuracy. From a statistical perspective, how much risk is incurred by large cycle time variation and how does one plan effectively to incorporate these variances.

Real time simulation tool -

Further research is required to quantify the benefits of simulation in an operational environment. Specifically, one needs to identify the critical decision metrics, the required response time for answers, and the relationship of simulation to other tools/data bases such as scheduling programs. Furthermore, local decisions exception management, commonly referred to as fire-fighting, may benefit from simulation.

Subsystem Simulation -

The current model may be augmented with simulations of the individual subsystems. The current S/C I&T model can be used to identify problem subsystems and quantify improvement goals. A subsystem simulation may include a detailed model of the subsystem including high leverage (problem) units. For example, the payload subsystem may require a detailed simulation to reduce the payload delivery uncertainty.

Aerospace Applications -

The simulation methodology presented in this thesis has applications beyond S/C manufacturing to most Aerospace systems due to similarities in assembly and test processes. Furthermore, S/C manufacturing represents an extreme end of low volume manufacturing. As the production volume increases the simulation accuracy increases. Some examples may be: aircraft manufacturing, missile manufacturing, and other similar complexity products.

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Appendix A: Model Replication Calculation

This section covers the statistical procedures for calculating the number required model replications. The method centers around the confidence level required between the observed data and the actual. For example, one might want a 90% confidence level that the observed mean (X) is within a set difference (e) from the actual mean. For a = .10 there is a ten precent chance the difference between X and μ is greater than e.

The equation governing the calculation is described below:

$$N = \left(\frac{t_{n-1,1-\alpha/2} * S(n)}{e} \right)$$

N= The number of required Model Replications
S(n) = Standard deviation (S) based on n model replications
e = The amount of Allowable error between the Observed and Actual means
n = Number of Model replications
α = probability that the obsereved mean is e off tje actual mean.confidence limit
$t_{n-1,1-\alpha/2}$ = t-distribution value for n-1 degrees of freedom and modified confidence level

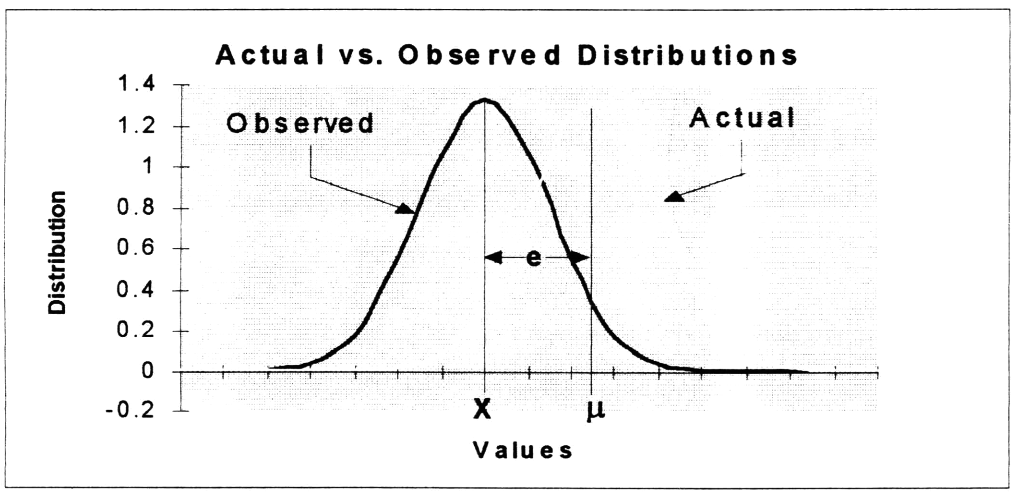

Figure A.1 Model Replication Illustration

Appendix B: Warm-up Period Calculation

This section covers the procedures required to calculate the length of the warm up period. A steady state modeling run is necessary for this calculation. Steady state implies that the model gravitaties to one certain value and does not deviate from it significantly. A steady state condition occurs at the point where the curve of the transient flattens out.

A graphical plotting of a weighted moving average is a recommended procedure for determining the model time required.[1] The below equation describes the calculation method.

$$\overline{Y}_i(w) = \begin{cases} \sum_{s=-w}^{w} \frac{\overline{Y}_{i+s}}{2w+1} \; for \quad i = w+1,\ldots,m-w \\ \sum_{s=-(i-1)}^{i-1} \frac{\overline{Y}_{i+s}}{2i-1} \; for \quad i = 1,\ldots,w \end{cases}$$

Y = Moving Average
m = total number of periods in each model replication
w = length of the sample "window" for the moving average. For i <= w, then the current period is averaged with the values from the (i-1) preceding periods and (i-1) following periods. For i>w, the current period is averaged from w preciding and following periods. Note w must be less than or equal to m/2.

The following is an example graph for w = 30.

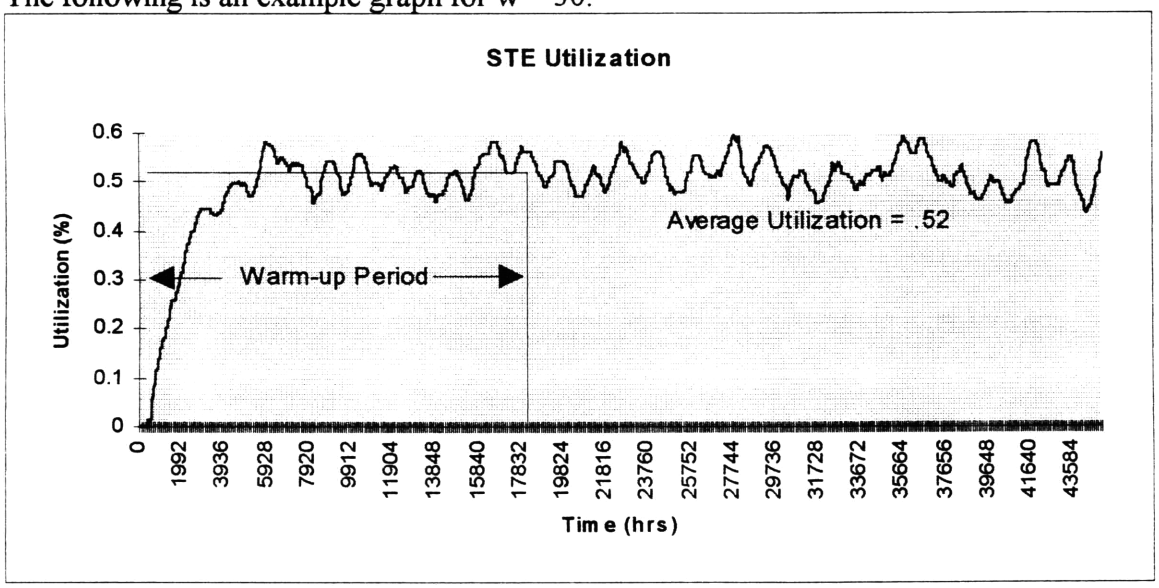

Figure B.1 Graph of Moving Average

[1] Thomas Gott and Jack Mott, Improve Quality and Productivity with Simulation, pp. 11.11-7.

Appendix C: Designed Experiments Test Matricies

The impact of factors A, B, and C (E_A, E_B, and E_C) are calculated by averaging the results (R_1, R_2, R_3, ...). The sign of each result is equivalent to the high value (+) or low value (-) of the experimental input factor. For example, EA is calculated by subtracting R_{1-4} from R_{5-8} and dividing by 4.

Table 4 Full Factorial Experiments

Test	Input A	Input B	Input C	OUTPUT
Experiment 1	-	-	-	Result 1 (R_1)
Experiment 2	-	-	+	Result 2 (R_2)
Experiment 3	-	+	-	Result 3 (R_3)
Experiment 4	-	+	+	Result 4 (R_4)
Experiment 5	+	-	-	Result 5 (R_5)
Experiment 6	+	-	+	Result 6 (R_6)
Experiment 7	+	+	-	Result 7 (R_7)
Experiment 8	+	+	+	Result 8 (R_8)

The following equations are used to calculate the primary effects:

$$E_A = \frac{((R_5+R_6+R_7+R_8)-(R_1+R_2+R_3+R_4))}{(4)}$$

$$E_B = \frac{((R_3+R_4+R_7+R_8)-(R_1+R_2+R_5+R_6))}{(4)}$$

$$E_C = \frac{((R_1+R_3+R_5+R_7)-(R_2+R_4+R_6+R_8))}{(4)}$$

The impact of factor interactions (E_{AB}, E_{BC}, and E_{AC}) are calculated by summing the results of all the experiments. The sign for each result is obtained by multiplying the signs for the interacting factors. The sign for R_1 in E_{AB} is (-)*(-)= +.

$$E_{AB} = \frac{(R_1+R_2-R_3-R_4-R_5-R_6+R_7+R_8)}{(4)}$$

$$E_{BC} = \frac{(R_1-R_2-R_3+R_4+R_5-R_6-R_7+R_8)}{(4)}$$

$$E_{BC} = \frac{(R_1-R_2+R_3-R_4+R_5-R_6+R_7-R_8)}{(4)}$$

Table 5 Five Factor Partial Factorial Test Matrix

Experimen	Factor A	Factor B	Factor C	Factor D	Factor E	Result
1	+	+	+	+	+	R_1
2	+	+	-	+	-	R_2
3	+	-	+	-	+	R_3

4	+	-	-	-	-	R_4
5	-	+	+	-	-	R_5
6	-	+	-	-	+	R_6
7	-	-	+	+	-	R_7
8	-	-	-	+	+	R_8

Appendix D: Model Scenarios for Case Study

Table 6 Partial Factorial Testing Matrix

Arrival Rate	STE	RO Fix	Mechs	Sys Engrs	SC Carts
12 a year	5	3	12	15	4
12 a year	5	2	12	15	5
12 a year	4	3	12	13	4
12 a year	4	2	12	13	5
12 a year	5	2	10	13	4
12 a year	5	3	10	13	5
12 a year	4	2	10	15	4
12 a year	4	3	10	15	5

Table 7 Full Factorial Testing Matrix

Arrival Rate	STE	Sys Engrs	RO Fix	Mechs	SC Carts
12 a year	4	13	3	10	5
12 a year	4	13	3	12	5
12 a year	5	13	3	10	5
12 a year	5	13	3	12	5
12 a year	4	15	3	10	5
12 a year	4	15	3	12	5
12 a year	5	15	3	10	5
12 a year	5	15	3	12	5

Table 8 Capacity Analysis Testing Matrix

Arrival Rate	STE	Sys Engrs	RO Fix	Mechs	SC Carts
8 a year	4	14	2	10	5
9 a year	4	14	2	10	5
10 a year	4	14	2	10	5
11 a year	4	14	2	10	5
12 a year	4	14	2	10	5
13 a year	4	14	2	10	5
14 a year	4	14	2	10	5
15 a year	4	14	2	10	5
16 a year	4	14	2	10	5
17 a year	4	14	2	10	5

Table 9 Bottleneck Analysis

Arrival Rate	STE	Sys Engrs	RO Fix	Mechs	SC Carts
16 a year	5	14	2	10	5
16 a year	6	14	2	10	5
16 a year	6	16	2	10	5
16 a year	6	18	2	10	5
16 a year	6	18	2	12	5

Table 10 Varibility Reduction Test Plan

Arrival Rate	STE	Sys Engrs	RO Fix	Mechs	SC Carts	Payload Variabili min	ave	max	Unit Removals (Exponential)
Phase 1									
14 a year	4	14	2	10	5	0 days	10	30	30 days
14 a year	4	14	2	10	5	0 days	6.6	20	30 days
14 a year	4	14	2	10	5	0 days	3.3	10	30 days
14 a year	4	14	2	10	5	0 days	0	0	30 days
Phase 2									
14 a year	4	14	2	10	5	0 days	10	30	30 days
14 a year	4	14	2	10	5	0 days	10	30	70 days
14 a year	4	14	2	10	5	0 days	10	30	110 days
14 a year	4	14	2	10	5	0 days	10	30	150 days
Phase 3									
14 a year	4	14	2	10	5	0 days	240	720	30 days
14 a year	4	14	2	10	5	0 days	160	480	70 days
14 a year	4	14	2	10	5	0 days	80	240	110 days
14 a year	4	14	2	10	5	0 days	0	0	150 days