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Understanding the Enterprise Value of Test: Characterizing System Test Discrepancies in the Spacecraft Industry

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Abstract

The goal of this research is to characterize the distribution and time impacts of spacecraft discrepancies found at the system level of integration and test, as well as understand the implications of those distributions and time impacts for the spacecraft enterprise as a whole. If discrepancies can be better understood, they can potentially be reduced or even eliminated. Reducing discrepancies will result in cycle time reduction and cost savings, as well as increased product quality and reliability. All of these potential outcomes are indications of successful progress toward becoming a lean organization.

Data on discrepancies at the system level of integration were gathered from spacecraft manufacturer databases, while interviews with key program managers and engineers provided perspective and insight into the data. Results are based on 224 spacecraft representing at least 20 different programs or product lines, and encompassing 23,124 discrepancies. The spacecraft date from 1973-1999, and represent different spacecraft manufacturers as well as a mix of commercial and government spacecraft.

Spacecraft discrepancies are analyzed in this work on the basis of ten categories: the spacecraft mission, the spacecraft subsystem where the discrepancy occurred, the date of the discrepancy occurrence, the discrepancy report open duration, the immediate action taken to fix the discrepancy (disposition), the root cause of the discrepancy, the long-term corrective action prescribed to prevent the discrepancy from happening again on future spacecraft, the labor time spent on the discrepancy, and the cycle time lost due to the discrepancy. Statistical measures of central tendency, correlation and regression are presented for the data as a whole population of spacecraft and by the two subpopulations of communications mission spacecraft and non-communications mission spacecraft. This statistical analysis forms the basis for research findings at the enterprise level that indicate the state of long-term organizational learning and improvement from test discrepancies in the spacecraft industry. Recommendations to enterprise stakeholders for increasing the value derived from system-level integration and test follow from the enterprise-level findings.

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Chapter 1.

Setting the Stage

1.1. Overview of Monograph

The goal of this monograph is to present the results of the Lean Aerospace Initiative research into characterizing the distribution and flow time of spacecraft discrepancies at the system level of integration and test, and understand the implication of those discrepancies for the enterprise as a whole.

Chapter 1 introduces the issues and gives an overview of the methodology and findings of the research. Chapter 2 explains the spacecraft development and testing process, and presents a value stream analysis for test. Chapter 3 contains a detailed methodology and analysis approach for the discrepancy distribution research. Chapter 4 presents the central tendency analysis results for the discrepancy distribution research. Chapter 5 presents the correlation relationship analysis for the discrepancy distribution research. Chapter 6 discusses the methodology and analysis results for the discrepancy flow time research. Chapter 7 concludes the monograph with recommendations on how to effectively use integration and test in creating a lean enterprise.

1.2. Background: The Lean Paradigm

This background section summarizes the origins of lean and the Lean Aerospace Initiative. It then discusses the Lean Enterprise Model (LEM) and how this research on spacecraft system-level integration and test fits into the LEM. A further discussion of lean thinking and the concepts of value and value stream analysis are discussed in Chapter 2.

1.2.1. Origins of Lean

Lean began as a manufacturing approach, and was first described in the United States in a book by Womack, Jones and Roos called *The Machine That Changed the World*. This book was born out of research conducted through the International Motor Vehicle Program (IMVP) at the Massachusetts Institute of Technology. IMVP applied the word lean to describe a revolutionary manufacturing approach in contrast to the conventional mass production approach. Lean included the concepts of Total Quality Management, Continuous Improvement, Integrated Product Development, and Just-In-Time inventory control[1].

Several years later, lean was broadened to include the entire product development process in a second book by Womack and Jones called *Lean Thinking*. That book made the case that lean is more than just manufacturing. The essence of lean was a way to specify value in a process or product as seen by the end user, identify and convert waste into value, and perform tasks more and more effectively. Lean is thus a way to "do more and more with less and less" – less human effort, less inventory, less time, and less cost – "while coming closer and closer to providing customers with exactly what they want."[2] Numerous case studies in the book showed the benefits of the lean paradigm applied throughout the entire enterprise. The lean paradigm continues to develop and evolve, as more and more industries change the way they do business through the use of lean principles. Application of lean to the aerospace business coalesced in the formation of the Lean Aerospace Initiative, a collaborative research consortium.

1.2.2. The Lean Aerospace Initiative

The Lean Aerospace Initiative (LAI) is an active research partnership among the U.S. government, labor, the Massachusetts Institute of Technology (MIT), and defense aerospace businesses. Formally launched in 1993, the initial research focused on the aircraft sector. Following very positive results, LAI expanded its research focus to include the space sector in 1998. Work in the research partnership now involves both aircraft and spacecraft sectors. This monograph focused on spacecraft system-level integration and test discrepancy research is the first LAI product to solely address the spacecraft sector.

As a neutral broker, MIT facilitates research across different companies and fosters an environment of cooperative learning among competitors in the industry. Other research is underway in LAI specifically geared toward the space sector, including work on autonomy in operations, launch range capacity modeling, and launch vehicle upgrade optimization.

1.2.3. The Lean Enterprise Model

The Lean Enterprise Model (LEM) is a key original contribution by LAI. The LEM not only applies to aerospace businesses, but to other industries as well. The LEM consists of Meta-principles, Enterprise principles, Enterprise metrics, Overarching practices (OAPs), and Enabling practices. A graphic representation of the LEM[3] structure is shown in Figure 1.1.

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[1] Pomponi, Renata A. Control of Manufacturing Processes with MRP II: Benefits and Barriers in the Defense Aerospace Industry. MIT Master's Thesis (TPP), February 1995. p. 21.
[2] Womack, James P. and Daniel T. Jones. *Lean Thinking*. New York: Simon & Schuster, 1996. p. 15.
[3] Lean Aircraft Initiative. "Lean Enterprise Model" (unpublished model and handbook), Massachusetts Institute of Technology, Cambridge, MA. 14 November 1996.

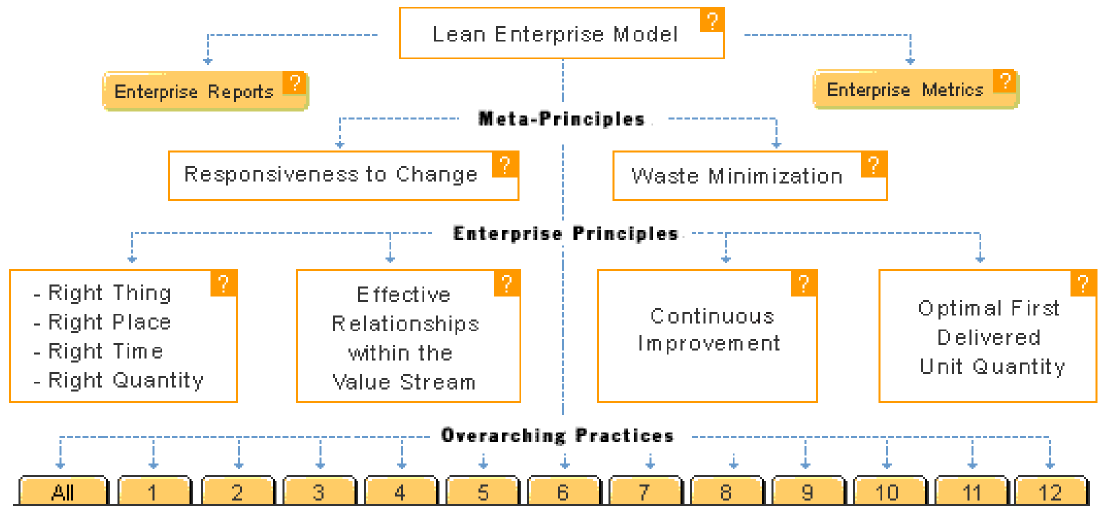

Figure 1.1: The Lean Enterprise Model structure

This spacecraft system-level integration and test discrepancy research draws upon several key principles in the LEM:

- Waste Minimization – Waste should be reduced and value maximized. Womack and Jones present a view of testing as a type of muda, or waste (see Section 2.4.2. They argue in an academic sense that if a product is truly made perfectly, no testing would ever be necessary, because the product was made perfectly in the first place. So hence, they classify testing as muda. Determining whether it is Type One or Type Two muda must be interpreted in the context of the industry in question. For the television manufacturing industry, television sets roll right off the production line and aren't even turned on and tested for functionality before they get sold to the customer. This is because the production process assures a near-perfect product, and testing is thus an unnecessary expense. But for the spacecraft industry, where the price of failure is too high, the technology is so complex and each spacecraft is unique in some way, testing is currently required to ensure a product that performs reliably to expectations. Still, Womack and Jones's protrayal of testing as waste defines a perfect process as an ideal to strive for, and when reached, testing transforms from a Type One muda to a Type Two muda. But without the goal in mind, however lofty and far-term it may be, less progress will be made towards it.
- Right Thing – The lean principle of "right thing" as applied to integration and test means that the parts delivered to the integration and test activity should be the right parts, the assembly and test equipment should be the right equipment, and the instructions and procedures should be the right ones. A discrepancy is essentially a "wrong" thing. Understanding the discrepancies will help to make progress towards achieving the "right thing" principle.

- Continuous Improvement – Continuous improvement means that an organization constantly seeks ways to increase its value and eliminate waste. Active learning from, and correction of, mistakes is one obvious form of continuous improvement. If an organization is not studying its mistakes and making changes based upon those studies, it is not effectively engaging in continuous improvement.

1.3. Basic Terminology

Several key terms are used throughout this monograph. Their definitions are presented here for clarity. Other definitions will be presented elsewhere as appropriate.

- Discrepancy – a functional or structural anomaly, which may reveal itself as a deviation from requirements or specifications.
- System Integration and Test – the time from payload and bus module mate until spacecraft ship from the factory.
- Spacecraft – a vehicle designed to operate in space, including both the payload and bus (this research does not include launch vehicles or human-rated vehicles).

1.4. Motivation

As discussed above in the section on the Lean Enterprise Model, there are fundamental lean philosophies that motivate this research in general. More specifically, spacecraft manufacturers are extremely interested in looking at spacecraft system-level integration and test because:

- System-level integration and test takes substantial time and resources, and dealing with discrepancies is perceived as a large percentage of the integration and test activity.
- The cost of fixing discrepancies is believed to increase by an order of magnitude with each higher level of integration. Thus, discrepancies found at the highest level of system integration and test are the most costly to fix.

If discrepancies can be better understood, then perhaps they can be reduced or even eliminated. Reducing discrepancies will result in cycle time and cost savings, as well as increased product quality and reliability. All of these outcomes are greatly desired on the part of spacecraft manufacturers and customers alike.

1.5. Research Goals and Approach

Responding to the motivation described above, the goals of this research are threefold:

- Characterize the kinds and distribution of spacecraft discrepancies at the system-level of integration across the industry

- Estimate the labor time and flow time impacts of spacecraft discrepancies at the system-level of integration
- Investigate enterprise implications of integration and testing

The research approach utilized data gathered from spacecraft manufacturer databases to achieve the first goal of characterizing discrepancy distributions. Fortunately, spacecraft manufacturers are typically required by contractual terms to keep records of all discrepancies that occur during system-level integration and test. This creates a rich record of discrepancies that can be searched now with relative ease, as many spacecraft manufacturers have migrated their paper-based discrepancy reporting systems to electronic-based systems. However, all companies do not keep their data in the same format, nor do they all collect all the same data, which does pose some challenges to the researcher.

The research approach utilized expert interviews to achieve the second goal of estimating the costs of discrepancies. Time spent by employees on discrepancies is used as a surrogate for cost in this research. Currently, companies participating in this research reported that they did not maintain detailed enough records of the time employees spent on discrepancy discovery and resolution to be of use in this research. As a result, expert interviews had to be conducted with people who had extensive experience in discrepancy discovery and resolution. The interviewees provided estimates of the time they spend on discrepancies.

A large data set was amassed, including over 23,000 discrepancies from over 200 spacecraft representing at least 20 commercial or government programs/product lines. The data included a mix of different spacecraft manufacturers, and a mix of different mission types as well as government and commercial spacecraft. In addition, over 50 substantial interviews were conducted.

Finally, statistical analysis provided insights into the central tendency behavior and correlation of the characteristics and costs of discrepancies across the spacecraft industry. This analysis led to findings at the enterprise level, and ultimately to recommendations for the spacecraft industry.

1.6. Overview of Findings

This ambitious research is the first of its kind to examine spacecraft testing discrepancies from an entire enterprise perspective, and clearly further analysis and validation of the findings presented here will shed additional insights. The analysis for this research was performed first on the entire set of spacecraft as a whole, and then again on the subsets of communications spacecraft and non-communications spacecraft. Six key findings resulted:

- Problems with test equipment, defined as any non-flight equipment used in integration and test (I&T), comprise a large percentage of discrepancies reported during system-level I&T. Test equipment problems are clearly waste in the system-level I&T process.

- Test Equipment and Employee/Operator error together cause nearly half of the discrepancies. Particularly on commercial spacecraft product lines, these are the two resources that may be reused on subsequent spacecraft to come through the factory. Thus there is potential for large returns on investment in these two areas.
- The corrective action prescribed most often is "No corrective action," reported in 24% of the discrepancies. This indicates missed opportunities for improvement in the enterprise.
- A significant percentage of subsystem discrepancies were discovered during system-level testing. If the goal is to drive testing to the lowest level possible, then opportunity exists for improvement. However, finding these subsystem problems at system-level test may be the most cost-effective method available, though no evidence has presented itself either way.
- Cycle time and labor time impact of system-level I&T discrepancies appears large, but currently these metrics are not tracked in adequate detail.
- Organizations are passing up opportunities to capitalize on problems they have spent significant time and resources to find.

In summary, there appears to be inadequate long-term organizational learning and improvement from test discrepancies in the spacecraft industry. Though discrepancies on a spacecraft in system test are rectified and the spacecraft is made fit to fly, less attention appears to be focused on preventing the cause of that discrepancy from occurring again on future spacecraft. It also appears that various aspects of the spacecraft industry are not yet fully aligned with addressing and solving problems using long term, cross-program, enterprise-wide solutions. Solutions optimized for the enterprise, not the program or spacecraft, are needed for the true long-term growth and prosperity of the enterprise.

1.7. Summary of Recommendations

Out of the findings from this research, several recommendations emerge on how to make test a valuable enterprise enabler. A complete discussion of these recommendations is presented in Chapter 7.

- Align incentives in the broadest sense with fixing discrepancies and problems for the long term.
- Establish an enterprise culture that truly values the continuous improvement philosophy.
- Collect the discrepancy cost data necessary to enable cost-benefit trades on fixing problems upstream to prevent discrepancies from occurring downstream in system-level integration and test.
- Establish an inter-organization working group to develop compatibility standards for discrepancy data collection to enable periodic cross-industry assessments.

The analysis of test discrepancies should not be limited to evaluating which tests precipitate which kinds of problems or which tests can be eliminated. Rather, the analysis of test discrepancies in the largest sense can provide an effective indicator of improvement in the entire enterprise, across multiple programs and over various periods of time. Lean enterprises look for information indicators that can be used beyond a single product development. Analysis and use of information from spacecraft system test discrepancies can be a significant enabler on the journey to lean.

Chapter 2.

Spacecraft System Development and Test

2.1. History of Spacecraft Development

"Dreams of space flight go back well before the 1950's. In Russia, Konstantin Tsiolkovsky published the Principles of Rocket Motion in 1903. In America, Goddard published his treatise on rocketing in 1919. Both of these seem to have been inspired by Jules Verne and dreamed of using the rocket as a means of getting to space."[4] "On July 29, 1955 the U.S. announced that it intended to launch a satellite during the International Geophysical Year set to start on July 1, 1957. The next day, the Soviet Union announced that same goal. The Soviets rushed ahead based on using the R-7 rocket that was the basis for their ICBM. On August 3, they successfully fired their first ICBM. On October 4, 1957 the same rocket put up the Sputnik spacecraft and the world was never the same again."[5]

Seven years before Sputnik, the Rand Corporation issued a report that set the first U.S. Space Policy. The report focused on the primary function of spacecraft as future tools of strategic and meteorological reconnaissance. "On March 16, 1955 the U.S. Air Force established a secret program project called WS-117L to develop a strategic satellite system. [6]…[T]he Eisenhower administration policy was to push to develop military reconnaissance satellites, establish the right of overflight , and minimize the amount spent on the military industrial complex. The concept of being first into space was not a high priority for Eisenhower. In essence the two adversaries (the U.S and the U.S.S.R.)were fighting two different battles. The U.S.S.R. was fighting for prestige and recognition, the U.S. for objective military advantage."

Sputnik was a sharp slap to American pride. But the Soviet launch did establish the concept of the freedom of international space that was critical to the development of a U.S. space program. The response to Sputnik clearly surprised Eisenhower. The U.S.

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[4] Hastings, Daniel E. "History and Policy in the Fifties", Class notes from Space Policy Seminar, MIT Course 16.899, Spring 2000, p. 1.
[5] Ibid, p. 2.
[6] Ibid, p. 3.

public demanded a strong response to the Soviet's beating the Americans to space. Space then became a U.S. public priority. NASA was formed and human space flight became emphasized. However the concept of spacecraft reconnaissance did not go away. It disappeared into a secret, compartmentalized world that set the pattern for the way unmanned spacecraft were developed for the next 30 years.[7]

Spacecraft quickly evolved. They started as small radio transmitters that weighed a few pounds and had little value except to prove the ability to launch objects into low earth orbit and communicate with them. They soon developed into sophisticated reconnaissance collectors that could be two stories tall and weigh up to 5 tons. By the late 1980's, spacecraft had evolved from primarily military reconnaissance and scientific data collectors to an important component of the U.S. commercial telecommunications structure.

From the beginning, failure of a spacecraft was not an option. Not only are development costs high, but much of the technology developed is one-of-a-kind and a failure of a spacecraft means the mission is delayed for years. Another factor is that there is no capability for launch on demand. Launch dates are planned years in advance and if a spacecraft fails to be launched and operate successfully it may be years before another launch manifest is obtained. These factors generated a culture where prelaunch testing of spacecraft takes on an importance greater than almost any other product except perhaps pharmaceuticals.

Spacecraft are not developed with an eye to future production. Except for a few specific cases (Global Positioning System, Iridium, and Globalstar) each spacecraft has unique features and is often a completely new design. Unlike aircraft or automobiles, spacecraft do not go through a two-step process in which a development prototype is developed and tested and following that the production version is designed and built. In spacecraft, the development unit is typically flown. This adds to the pressure to develop a meaningful prelaunch test and verification program.

2.2. Spacecraft Development Process

Though spacecraft share many product development similarities to other complex products, there are certain characteristics about spacecraft that make them stand apart from other complex products.

- A typical lot size for spacecraft is 1. Large lots sizes for identical spacecraft are considered to be around 6-8. The largest lot size produced prior to the start of this research in 1999 was 77 spacecraft for the Iridium constellation.
- Spacecraft are assembled primarily by hand, with extensive touch labor. This large human-in-the-loop factor greatly increases the chances that discrepancies will occur during assembly, integration and test.
- Spacecraft range in cost from about $100M up to $1B and more per spacecraft.

[7] Paragraph content extensively drawn from Hastings, Daniel E. "History and Policy in the Fifties", Class notes from Space Policy Seminar, MIT Course 16.899, Spring 2000.

- Typical order to delivery cycle spans 24-36 months for commercial programs, 24-84+ months for a government program.
- As contrasted with aircraft, spacecraft are operated in a "no return" environment. This results in risk-averse customers that usually dictate extensive testing and verification.

Space systems are mainly developed using a waterfall or gated process. User needs are determined and translated into a system specification. System requirements are flowed down and allocated to the spacecraft. The system architecture and preliminary design of the major components and their subsystems are reviewed and approved at a Preliminary Design Review. At this review the requirements baseline and the functions that the system must perform are approved and put under configuration management. Analyses showing that the design can meet requirements are an important step in the total test and verification process. The next major milestone or gate is the Critical Design Review. At this point analysis is complete and the detailed design specifications are approved. In addition, all the processes required to build the spacecraft are in place. The test program is detailed with plans and procedures. Test equipment is defined and designed as required.

Generally the spacecraft bus and the payload are developed separately, often by different organizations. They are not physically integrated until system-level integration and test. A graphic of the spacecraft development process is shown in Figure 2.1, and illustrates how various stages of integration proceed. First, units that will become part of the finished spacecraft are assembled and tested. These units are assembled into subsystems, which are also tested and reviewed. These subsystems are then assembled onto the payload and bus modules. The payload module performs the mission-specific function of the spacecraft, such as remote sensing, communication, position/navigation, etc. The bus module performs housekeeping functions common to most all spacecraft, including thermal control, attitude control, etc. Many of the major components of the bus and payload are procured from suppliers who in turn procure components from second and third tier suppliers. Because of this, there are usually multiple PDRs and CDRs which build upon one another prior to the spacecraft PDR and CDR. The payload and bus module are assembled and tested in parallel. When these two modules are mated, the activity of system integration and test begins. After system integration and test, the spacecraft is packed up and shipped from the factory to the launch site. This research focuses exclusively on the final stage of product development conducted in the factory – the system integration and test stage.

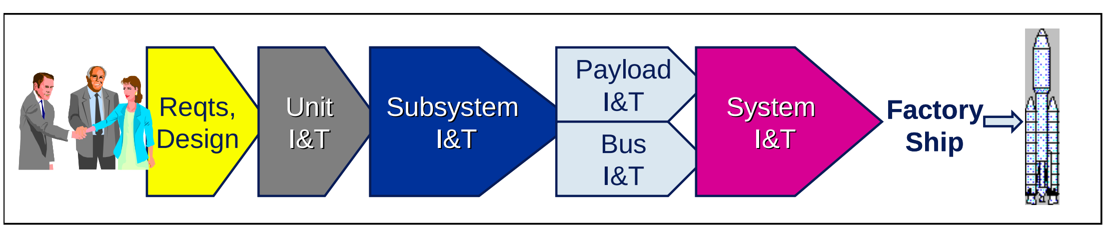

Figure 2.1: Spacecraft development cycle.

2.3. Spacecraft System Tests

The concept of lower level reviews building to higher level reviews in the development and design process is carried over in the test program. This is shown in Figure 2.2. The philosophy is to construct a verification program that determines how each system level requirement is to be verified and at what level.

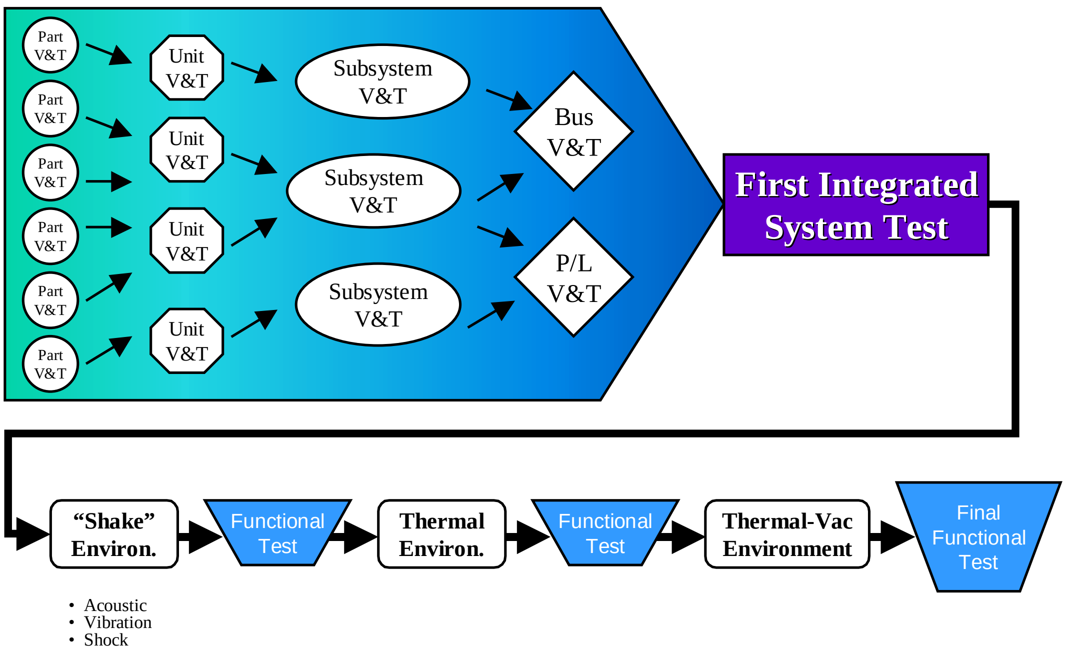

Figure 2.2: Generic Spacecraft Testing Flow.

Often it is necessary to combine analysis results from one component with test results from another component to show that a system requirement is met. Six different verification methods are described in Military Standard 1540, which governs the testing of space vehicles, and these are shown in Figure 2.3. They are analysis, qualification test, acceptance test, similarity, demonstration and inspection. The objective is to show that all system requirements are verified at the lowest level of analysis and test possible. Of course, there are requirements that cannot be verified at the component or subsystem level and can only be tested during spacecraft system testing. A major challenge of the systems engineering function is to ensure that the information presented both at the reviews and in the test planning is consistent and integrated among the many participants necessary to develop a complete spacecraft. It is very expensive to fix problems when the spacecraft is in final integration.

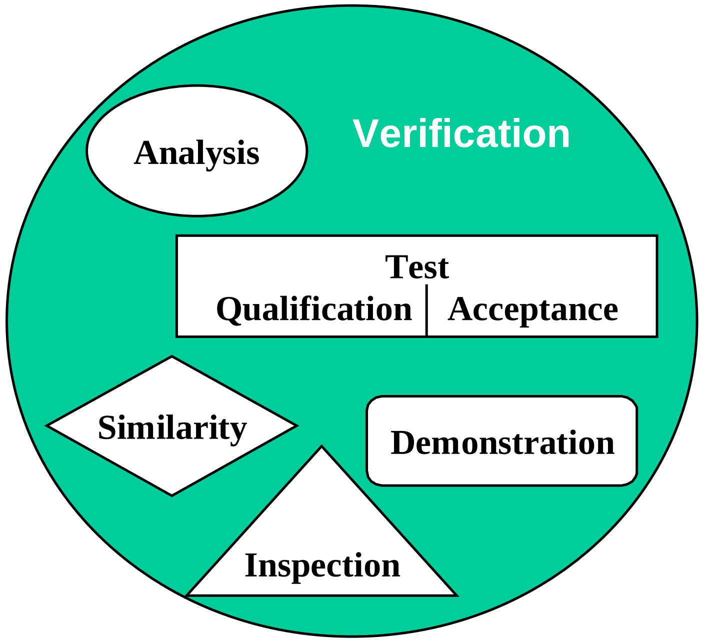

Figure 2.3: Methods of verification, taken from MIL-STD 1540.

The actual tests, test sequences and test levels carried out at spacecraft system-level I&T have been the subject of much study and evaluation. Starting in the 1960s and 1970s, Aerospace Corporation and others gathered and analyzed environmental test failure data from spacecraft. This was the basis for Military Standard 1540. The latest version, 1540C "Test Requirements for Launch, Upper Stage and Space Vehicles," was released in 1982. This document forms the basis for the current approach to spacecraft testing. As described in this Standard, the formal compliance tests for flight vehicle equipment start at the unit level of assembly and progress at each higher level of assembly until the entire launch system and the on-orbit system can be tested in their operational configurations. All of the spacecraft used in this research are tested according to this same basic philosophy. They differ though in terms of specific test sequences, environmental exposure conditions and duration, etc. as these are tailored for each spacecraft based upon its requirements.

Spacecraft system testing as prescribed in Military Standard 1540C has proven to be very successful in reducing the risk of on-orbit failure. But it is expensive and time consuming. In recent years, significant research has been undertaken to understand how to make tests more perceptive and optimize the test sequence. The Aerospace Corporation has played a leading role in this research by analyzing environmental test failures on government and commercial spacecraft. The NASA Jet Propulsion Laboratory and the NASA Goddard Space Flight Center have also been doing research into the physics of test failures and the ability of tests to catch specific failures. Several papers on these topics have previously been published by W. Tosney, A. Quintero, O. Hamberg, P. Barrett, S. Cornford, C. Larson, and A. Wallace.

The LAI test discrepancy research presented in this monograph takes a different focus from previous efforts that revolved around the perceptiveness of various environmental exposures. The focus of this monograph is on examining test discrepancy data to improve the value obtained for the enterprise from the testing activity. This ultimately leads to indications of how an enterprise can improve their spacecraft development process from one program to the next one by eliminating waste caused by discrepancies found during system-level integration and test.

2.4. Value Stream Analysis

Value stream analysis focuses on three key ideas of lean thinking: value, muda (waste), and value stream. It provides a way to line up actions involved in a process and determine which contribute value and which do not. For spacecraft test, the chief things that do not contribute value are the discrepancies that occur during test and set up / break down or related equipment associated with each test. However, these are the most difficult kind of waste to remove from the process. Hence, this research focuses on characterizing discrepancies so they can be better understood and someday reduced or ultimately eliminated.

2.4.1. Value Defined

Lean thinking begins with identifying the value of a product. Value is defined as a capability provided to a customer at the right time and at an appropriate price, as defined by the customer. For spacecraft, the ultimate customer is the user of the satellite. That may be government or commercial entities.

Specifically looking at a test, the capability that a test provides to the customer is verification and confidence that the spacecraft performs as expected. Adding in the other concepts of value – right time and right cost – the definition of value in a test can be stated as:

> *"Verification through accepted methods, in a timely manner and at the agreed cost, that the spacecraft performs as expected."*

Though each customer may have a different degree of verification needed due to its particular level of risk aversion, the definition of value remains the same.

2.4.2. Muda Defined

Muda, a Japanese word for waste, can be thought of as the opposite of value. More specifically, it is described as "any human activity which absorbs resources but creates no value." Taiichi Ohno, a Toyota executive, enumerated seven categories of waste commonly found in physical production. These seven muda are[8]:

- *Defects* in products
- *Overproduction* of goods ahead of demand
- *Inventories* of goods waiting further processing or consumption
- *Overprocessing* of parts due to poor tool and product design
- Unnecessary *movement* of people
- Unnecessary *transport* of goods
- *Waiting* for an upstream activity

In addition, Ohno described two different types of muda. *Type One* muda is those activities that create no value but are currently required by production technology or processes and so can't be eliminated just yet. *Type Two* muda is those activities that don't create value as perceived by the customer and can be eliminated immediately.[9]

In order to make an enterprise lean, Type Two muda is the first set of activities that should be eliminated, for it offers the most immediate payoff. Once Type Two muda has been removed, the way is clear to attack the remaining Type One muda. Type One muda typically requires more time and effort to eliminate than Type Two muda.

2.4.3. Value Stream Defined

For manufacturing products, the value stream is the set of all the specific actions required to design, build and deliver a specific product to the customer.[10] To narrow this into a testing framework, a test value stream would comprise all the activities required to take a product through a test, from test requirements definition and test plan development through test execution and data analysis.

For a spacecraft test, the activities that comprise a test value stream are:

- **Develop test plan and requirements**: This includes formulating detailed testing procedures and determining which requirements are to be verified by test; this also includes determining requirements for test equipment.
- **Set up test**: This includes setting up a test area, moving the spacecraft to the test area, instrumenting the spacecraft for test, configuring test equipment, etc.
- **Run test, take data**: This includes establishing any environmental conditions, putting the spacecraft through cycling required for the test, any test data gathering activity, etc.

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[8] Ohno, Taiichi. *The Toyota Production System: Beyond Large Scale Production*. Oregon: Productivity Press, 1988. pp. 19-20.
[9] Womack, James P. and Daniel T. Jones. *Lean Thinking*. New York: Simon & Schuster, 1996. p. 38.
[10] Womack, James P. and Daniel T. Jones. *Lean Thinking*. New York: Simon & Schuster, 1996. p. 311.

- **Take down test**: This includes removing test instrumentation from the spacecraft, moving the spacecraft off the test platform, returning the test chamber to some nominal condition, etc.
- **Analyze data, verify requirements met**: This includes all data processing and analysis required to determine that the spacecraft performed in the test as expected.

In addition, discrepancies frequently occur during testing. These situations introduce several other activities into a test value stream including:

- **Analyze discrepancy data**: This includes all data processing and analysis required to determine a discrepancy has occurred and identify the problem area of the spacecraft.
- **Determine root cause**: This includes all activities beyond identification of a discrepancy that are necessary to determine root cause of the discrepancy.
- **Fix discrepancy**: This includes rework needed on the spacecraft, or test equipment, or elsewhere to fix the discrepancy.
- **Rerun test, take data**: This may include setting up the test again either partially or completely, establishing needed environmental conditions, gather all test data, etc.

2.4.4. The Process of Value Stream Analysis

With the key concepts of value, muda and value stream in mind, one can analyze the value stream of the spacecraft testing process. Womack and Jones make a strong case for value stream analysis. They write: "Just as activities that can't be measured can't be properly managed, the activities necessary to create and produce a specific product which can't be precisely identified, analyzed, and linked together cannot be challenged, improved, and, eventually, perfected."[11]

Value stream analysis consists of three main steps. Using the example of spacecraft test, these are:

- *Step 1*: Define the value of test to the ultimate end customer.
- *Step 2*: Identify the test value stream by creating a map of the actions required to take a product all the way through a test activity, from test requirements development to test data analysis.
- *Step 3*: Based on the definition of value, determine which actions in the value stream are value-added, and which are not (these are muda of one type or another).

This analysis results in a mapped flow of truly value-added activities, as well as muda of one type or another, that comprises the testing value stream. With a clear mapping of

[11] Womack, James P. and Daniel T. Jones. *Lean Thinking*. New York: Simon & Schuster, 1996. p. 37.

where both value and muda occur in the stream, a lean enterprise can begin the process of converting muda into value.

2.5. Applying Value Stream Mapping to a Spacecraft Test

The first step in value stream analysis is defining value. The value of spacecraft test was previously defined as: "Verification through accepted methods, in a timely manner and at the agreed cost, that the spacecraft perform as expected." The definition contains three key elements: verification of meeting requirements, schedule and cost.

The second step is mapping the stream. The activities associated with spacecraft testing were outlined earlier. Figure 2.4 shows these activities assembled into a value stream map, which illustrates a sequential flow of actions from test plan development through posttest analysis of data. The map shown is generic, and attempts to encompass most kinds of tests performed. More specific value stream maps should be created by a lean enterprise for each type of test on each particular satellite it produces. The more detailed and specific the value stream map, the more useful for identifying muda for eventual conversion to value.[12]

The final step in value stream analysis is to examine each activity in the stream to determine how much value it adds to the process. Keeping in mind the definition of testing value given above, three activities are found to unambiguously add value:

- **Develop test plan and requirements**: The test plan and requirements ensure that the appropriate test is done with determined procedures in a timely manner and within budget.
- **Run test, take data**: Running the test generates data critically needed for verifying that the spacecraft meets its design requirements.
- **Analyze data, verify requirements**: Analyzing the test data verifies that the spacecraft indeed performed at its expected level.

The remaining activities in the value stream shown in Figure 2.4 do not unambiguously add value, considering the definition of value presented. Thus, they represent some kind of muda. Three kinds of muda are present here:

- *Muda of Waiting* – While the test is being set up and taken down, the muda of waiting occurs. Setting up or taking down the test equipment and the spacecraft does not contribute directly to adding value. In other words, it does not positively contribute to any of the three elements of the value definition: verification, schedule or cost. Put yet another way, the customer doesn't care that the test was set up and taken down – the customer only cares that the expected spacecraft performance was verified in a timely and cost-efficient manner.

[12] For examples of creating and using value streams, see Womack and Jones; also Rother, Mike and John Shook. *Learning to See*. Massachusetts: The Lean Enterprise Institute, 1998.

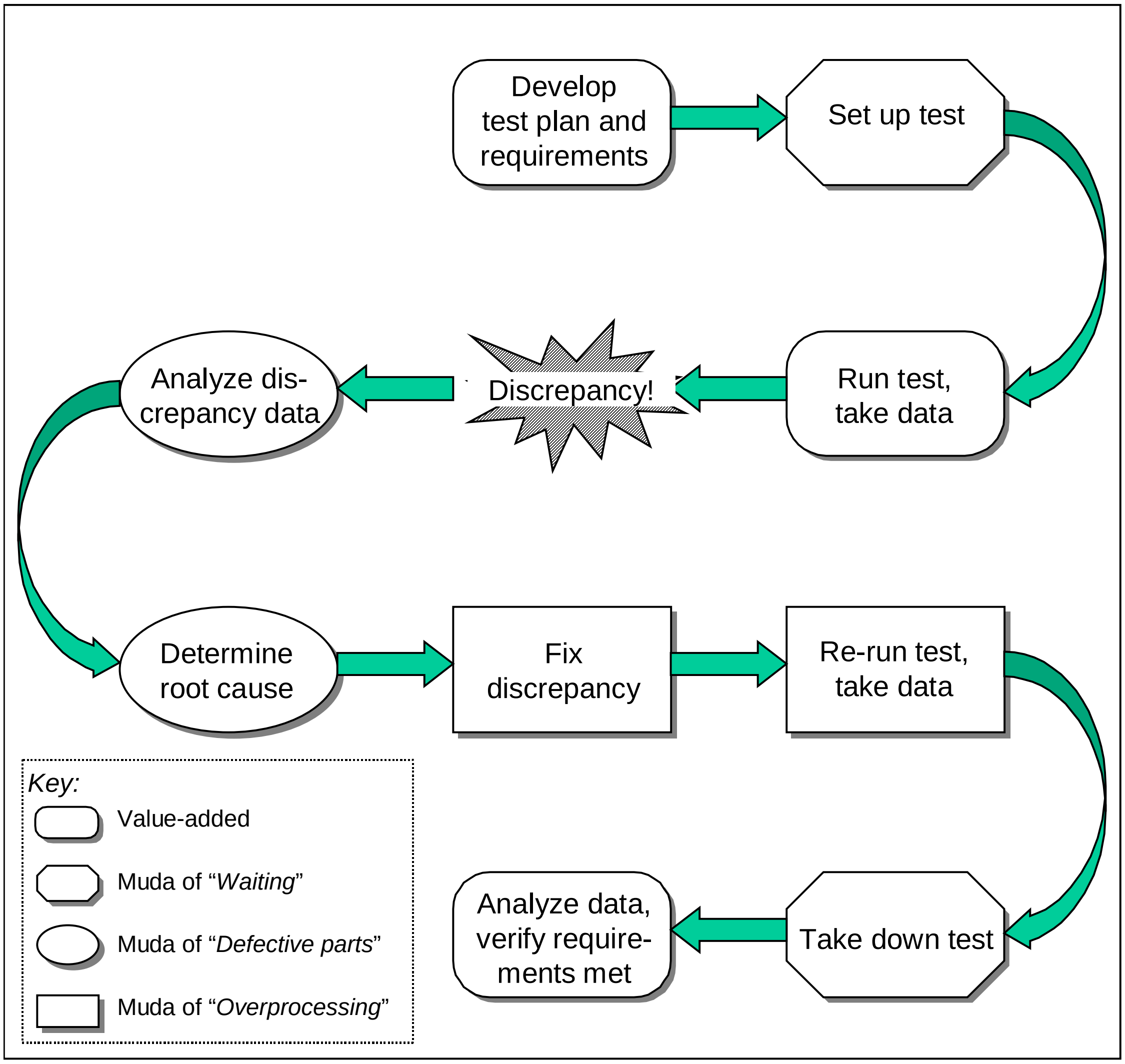

Figure 2.4: The value stream for a test.

- *Muda of Defects* – Defects introduced into the spacecraft during the manufacture and assembly process create discrepancies during test. These defects result in the creation of more work, specifically the activities of analyzing the discrepancy data and determining the root cause of the discrepancy. It is no question that these activities are necessary to fix the current problem and make the spacecraft fit for flight. However, if the defect were not present in the first place, these activities would be unnecessary, and thus are considered the muda of defects.
- *Muda of Overprocessing.* – Poor manufacturing and product design result in defects in the spacecraft, which require further processing in the form of rework and retest. The activities of fixing the discrepancy and re-running the test are examples of this kind of overprocessing muda in the value stream.

Muda can come in two types, as explained previously. Type Two muda creates no perceived value for the customer and thus can be eliminated immediately. Type One muda is those activities that are non-value-added but are required by the technology and manufacturing processes in place currently. Thus, they can't be eliminated just yet. Making a determination on Type One versus Type Two muda depends on the context of the situation. It is not possible to label the generic test value stream muda shown in Figure 2.4 as either Type One or Type Two. However, given a more detailed value stream for a specified spacecraft using specified testing facilities and processes, what muda is Type One and what muda is Type Two becomes obvious.

For example, fixing discrepancies due to a new technology is mostly a Type One muda. Today's technology and manufacturing processes don't permit construction of a defect-free spacecraft. Thus defects are present and test discrepancies need to be remedied. However, it is conceivable to envision a future where the manufacturing processes are so improved that defects are much less common, or perhaps eliminated almost entirely.

An example of Type Two muda would be putting the spacecraft onto a unique mounting platform for one test, moving it back to a transport platform to move it around the factory floor, and then placing the spacecraft on a different mounting platform for the next test. Clearly, the action of moving the spacecraft back and forth between platforms adds no obvious value to the product. Significant time and human effort can likely be saved by reducing the number of times the spacecraft has to be transferred between platforms. This problem can be addressed now, with the current state of technology and processes, and is thus considered Type Two muda.

2.6. The Enterprise Testing Value Stream

The value stream for a single test combines and interacts with the value streams of other tests, as well as other activities within organizations, to create the testing value stream for the entire enterprise. A conceptualization of the enterprise testing value stream is shown in Figure 2.5.

While individual test value streams are focused on verifying the performance of the current product to specifications, the larger enterprise testing value stream focuses on being a center of organizational learning for many different aspects of the entire enterprise. From the product development system, to the manufacturing system, the supply chain and even the testing system itself, the enterprise testing value stream evaluates all of these aspects with a view to analyze test data for the improvement of the entire enterprise. As an illustration, this research finds that 29% of discrepancies reported during system-level integration and test are related to test equipment. This provides feedback on how well the organization's testing system is functioning, and it shows that there is currently opportunity for improvement in this area. A successful enterprise is one actively engaged in continuous improvement. Striving to get the most out of the enterprise value stream signals a commitment to continuous improvement and puts organizations on the road to success and long-term prosperity.

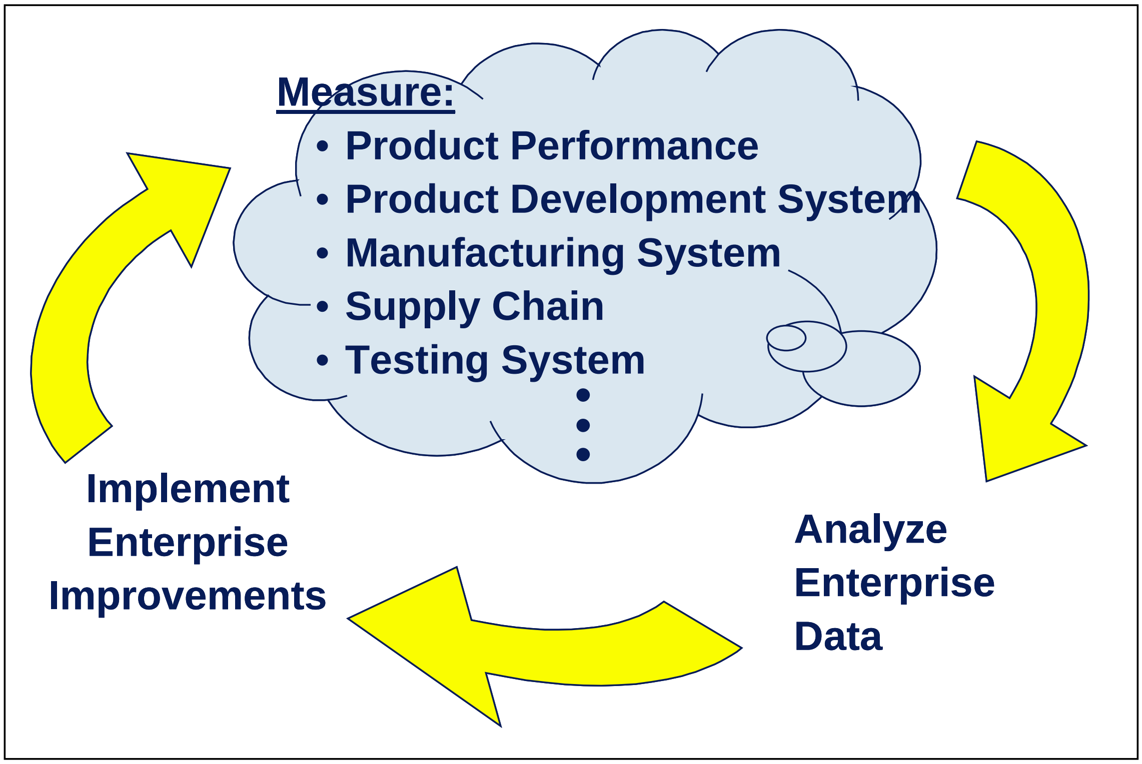

Figure 2.5: The enterprise testing value stream.

Chapter 3.

Discrepancy Distribution Research: Methodology and Analysis Approach

3.1. Introduction

The goal of the discrepancy distribution research is to characterize the distribution of various aspects of system-level integration and test (I&T) discrepancies, including affected subsystem, environment that precipitated the discrepancy, root cause, disposition, corrective action and open duration of the discrepancy. This chapter explains the research design for investigating the distribution of system-level (I&T) discrepancies. Key questions are presented, data needs and data collection are discussed, and potential sources of error are listed. A brief overview of statistics used in data analysis is also presented. Finally, barriers encountered in the research and ideas for enabling further research in this area are discussed.

3.2. Key Questions

Two key questions that succinctly explain the research were formulated to help guide the research process. These are:

- What kinds of discrepancies are being found during spacecraft system-level integration and test?
- What distribution, patterns and correlations exist?

3.3. Data Types and Collection

To answer the key questions above, data on system-level integration and test discrepancies were collected from several spacecraft manufacturers engaged in system-level I&T. A spacecraft customer normally requires the manufacturer to maintain paper or electronic records of each discrepancy reported during system-level I&T. Those records were the basis for obtaining the information on discrepancies required for this research.

For each discrepancy reported at the system level of integration for a particular spacecraft, the following information (to the extent it was available) was provided by participating spacecraft manufacturers based upon archived discrepancy reports they maintained.

- Spacecraft pseudonym (to protect proprietary concerns, yet enable the ability to distinguish between spacecraft)
- Spacecraft order in production (if the spacecraft was part of a constellation or block build or product line)
- Spacecraft mission area (the primary functional mission area of the spacecraft, such as communications, weather, etc.)
- Discrepancy report open date (year only) and open duration
- Subsystem, or part of the spacecraft testing setup, the discrepancy was written against
- I&T activity taking place at time of discrepancy occurrence
- Description of the discrepant behavior observed
- Root cause of the discrepancy
- Immediate fix action needed to make the current spacecraft functional again (also called disposition)
- Long-term corrective action that was prescribed to prevent the problem from happening again on future spacecraft

To put into context and supplement the information contained in the discrepancy reports, interviews were also conducted with members of spacecraft I&T teams. They were asked to describe the discrepancy lifecycle, from discovery through corrective action, explaining what happens at each step.

3.4. Characterization System

Many spacecraft manufacturers use their own internal code system to record much of the information about discrepancies. For example, many spacecraft manufacturers have a finite code list for causes of discrepancies. Each time a discrepancy is investigated and a root cause determined, the root cause is assigned one of several codes describing the nature of the cause. This coding, or "binning", of each root cause facilitates analysis.

Since each spacecraft manufacturer's code was different, it was necessary to create a master code scheme, or characterization system, into which to map the company-specific codes. This characterization system is derived from existing spacecraft manufacturer codes, DoD military standards documents, and interagency working group products. The master code scheme was limited in granularity by the individual companies' internal code schemes. For example, if Company A used only eight categories in their code for cause, the master code scheme for this research was necessarily restricted to a maximum of eight categories for cause. Every effort was made to maintain as many separate categories in the master code scheme as possible. However if Company A combined cause codes X and Y into one category, the master code scheme would have to require causes X and Y to be grouped together in one category.

Spacecraft manufacturers were provided with a description of the characterization system and asked to map their own codes into it. The spacecraft manufacturer mapping was then reviewed with the researchers for potential interpretation issues to ensure the best mapping possible of individual company codes to the master characterization system.

The characterization system is divided into six areas: Mission Area Categories, Activity or Test Categories, Subsystem Categories, Disposition Categories, Root Cause Categories, and Corrective Action Categories. These six areas are each broken down into several bins to describe subcategories of the data. These are each described in detail below, and summarized in Figure 3.1.

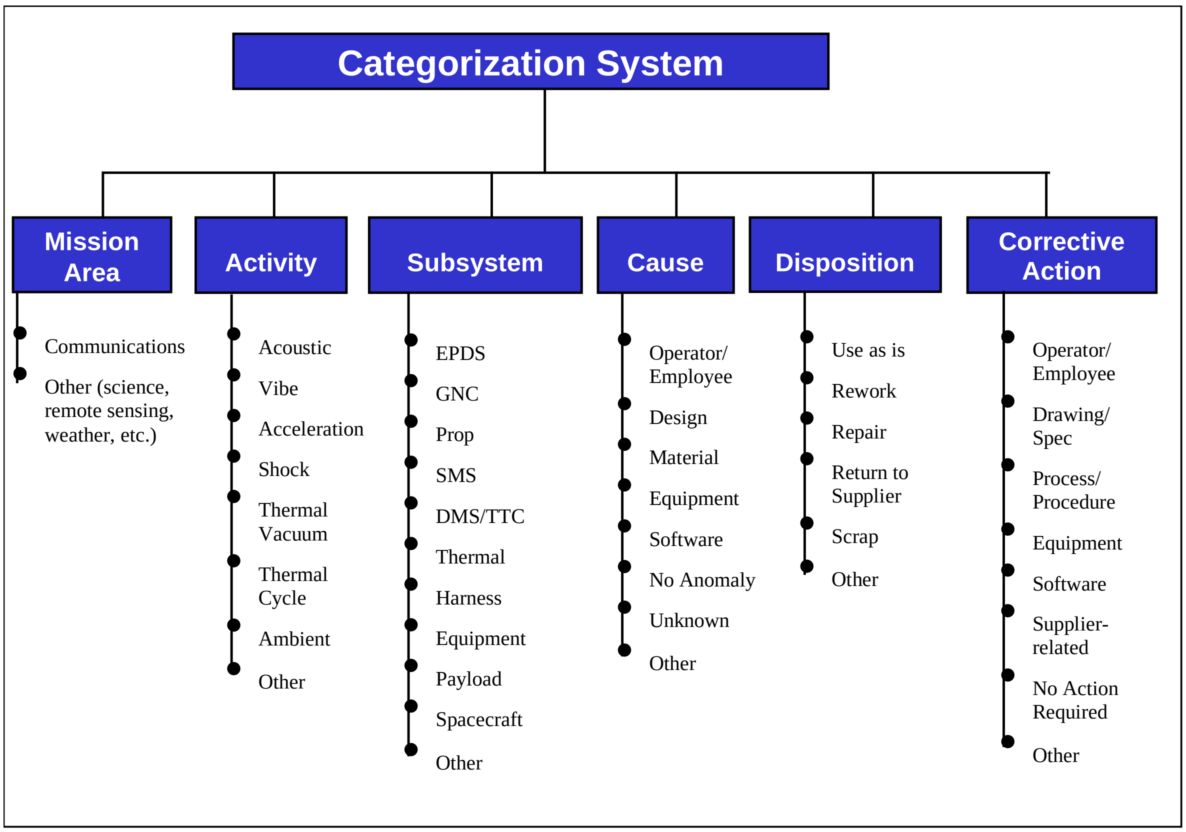

Figure 3.1: Graphical representation of categorization system of test discrepancy data.

3.4.1. Mission Area Categories

These categories describe the primary mission area of the spacecraft on which the discrepancy occurs. The bins are:

- **Communications (Comm) –** any spacecraft whose primary mission is to provide communications, including direct broadcast, relay satellites, telephony, etc.
- **Other –** all other missions, such as weather, remote sensing, early warning, navigation, etc.

3.4.2. Activity or Test Categories

These categories describe the spacecraft system I&T activity that was happening at the time the discrepancy occurred. The bins are:

- **Acoustic Test (Acoustic) –** includes setup and post environment activities, as well as the acoustic test itself and immediate post-environment functional tests.
- **Vibration Test (Vibe)–** includes setup and post environment activities, as well as the vibration test itself and immediate post-environment functional tests.
- **Acceleration Test (Acc) –** includes setup and post environment activities, as well as the acceleration test itself and immediate post-environment functional tests.
- **Shock Test (Shock) –** includes setup and post environment activities, as well as the shock test itself and immediate post-environment functional tests.
- **Thermal Vacuum Test (TV) –** includes setup and post environment activities, as well as the thermal vacuum test itself and immediate post-environment functional tests.
- **Thermal Cycling Test (TC) –** includes setup and post environment activities, as well as the thermal cycling test itself and immediate post-environment functional tests.
- **Ambient Integration and Test Activities (Ambient) –** Any activity taking place from payload and bus mate up to spacecraft ship that is accomplished in an ambient environment and not included in the categories above. This includes initial and final functional tests, as well as other functional tests not associated with environmental exposure.

3.4.3. Subsystem Categories

These categories describe the subsystem or part of the spacecraft that the discrepancy was written against.[13] The bins are:

- **Electrical Power and Distribution Subsystem (EPDS) –** EPDS's primary function includes the generation or collection through solar panels, regulation, storage and distribution of electrical/electronic power throughout the vehicle. Other names: Electrical Power System (EPS), Power Subsystems, Power.

[13] Many subsystem category descriptions taken from Quintero, A. H. *Space Vehicle Anomaly Reporting System (SVARS) Electronic Data Interchange (EDI) Template.* California: The Aerospace Corporation, 1996. p. 26.

- **Guidance, Navigation and Control (GNC) –** The GN&C's primary function provides determination and control of orbit and attitude, plus pointing of spacecraft and appendages. Other names: Attitude Control Subsystem (ACS), Attitude Determination and Control Subsystem (ADCS).
- **Payload –** The Payload subsystem's primary function provides mission specific capabilities to the space vehicles' functionality. Payloads have various capabilities such as communication, navigation, science, imaging, radar, and others.
- **Propulsion (Prop)** – The Propulsion subsystem's primary function provides thrust to adjust orbit and attitude, and to manage angular momentum. Other names: Reaction Control Subsystem (RCS).
- **Structures and Mechanisms Subsystem (SMS) –** The SMS's primary function provides support structure, booster adaptation, and moving parts. Other names: Structural, Structures and Mechanisms.
- **Combined Data Management Subsystem and Telemetry, Tracking and Command (DMS/TTC) –** The DMS's primary function distributes commands and accumulates, stores, and formats data from the spacecraft and payload. Other names for the DMS: Command and Data Handling (C&DH), Spacecraft Computer System, Spacecraft Processor. The TT&C's primary function provides communications with ground and other spacecraft. A basic subsystem consists of receivers, transmitters, and wide-angle antennas. Uplink data consists of commands and ranging tones while downlink data consists of status telemetry, ranging tones, and may include payload data. Other names: Communication subsystem. [These subsystems were combined because not all spacecraft manufacturer data made a distinction between the two.]
- **Thermal –** The Thermal Control subsystem maintains equipment within allowed temperature range. Other names: TCS, Environmental Control Subsystem (ECS).
- **Wiring and Cabling (Harness) –** Wiring (harness) and cabling that is not considered part of a particular subsystem called out above.
- **Equipment –** Test equipment or ground support equipment of any type.
- **Other –** Discrepancies that are traceable down to a subsystem level, but the subsystem does not fall into one of the above categories.
- **Spacecraft –** Discrepancies that cannot be traced down to a particular subsystem called out above, or discrepancies that were chosen (for any reason) not to be traced down to a particular subsystem.

3.4.4. Root Cause Categories

These categories describe the root cause of the discrepancy. The bins are:

- **Employee/Operator –** discrepancies caused by a person incorrectly executing a procedure, bumping an object, etc. For example handling errors, manufacturing errors, operator error, workmanship, etc.
- **Design** – discrepancies caused by incorrect design of spacecraft or procedures; includes bonding/encapsulation, drawing/layout and design characteristics. Also a planned procedure executed as planned and determined to be planned incorrectly, etc.
- **Material –** discrepancies caused by defective material, parts, etc. ON the spacecraft
- **Equipment –** discrepancies caused by defective test equipment, GSE, etc. that is NOT on the spacecraft
- **Software** – discrepancies caused by software, either on the spacecraft or on the ground equipment
- **No Anomaly** – discrepancies written up in error, or determined later not to be anomalies, etc.
- **Unknown** – discrepancies whose cause is unknown or unable to be determined, etc.
- **Other –** discrepancies which don't fit into the above 7 categories. Examples might include, but are not limited to, unplanned events such as roof leaks or facility environmental control malfunction.

3.4.5. Disposition Categories

These categories describe the disposition of the discrepancy, that is, the immediate action that is required to make the current discrepant spacecraft functional again. Note how this differs from corrective action below. The bins are:

- **Use as is –** discrepancies which are dispositioned to use the anomalous item in its present state, not requiring any changes.
- **Rework** – discrepancies which are dispositioned as rework to the original blueprint.
- **Repair** – discrepancies which are dispositioned as repair, either standard or unique. Repair leaves the spacecraft different from the original print.
- **Return to Supplier** – discrepancies which are dispositioned to return the anomalous part to the supplier.
- **Scrap –** discrepancies which are dispositioned as scrap, meaning the anomalous items will be thrown away because they can no longer serve their designed purpose.
- **Other –** discrepancies which don't fit into the above 4 categories for disposition.

3.4.6. Corrective Action Categories

These categories describe the corrective action prescribed. A corrective action is a long-term action that will prevent the discrepancy from occurring again on future spacecraft. Note how this differs from disposition above. The bins are:

- **Operator/Employee** – a corrective action involving an operator or employee; e.g. training, counseling, notifying supervisor.
- **Drawing or Spec** – corrective action involving drawings or specifications that need to be changed, corrected, modified, etc.
- **Process/Procedure** – Corrective action involving processes or procedures that need a change, certification, recertification, etc.
- **Software Change** – Corrective action involving software (either on the spacecraft or on ground support equipment) changes, corrections, modifications, etc.
- **Equipment** – corrective action involving testing, manufacturing, assembly, etc. equipment that needs to be repaired, replaced, recalibrated, corrected, etc.
- **Supplier-related** – corrective action involving a supplier or subcontractor.
- **No Action Required** – it is determined that no corrective action is needed, for whatever reason.
- **Other** – corrective actions which don't fit into the above 7 categories.

3.5. Data Profile and Validity

Over 23,000 discrepancies from over 200 spacecraft representing at least 20 commercial or government programs/product lines were analyzed in this research. The data included a mix of different spacecraft manufacturers, and a mix of different mission types as well. The mission type breakdown and the government/commercial program breakdown are shown below in Figure 3.2. The data is ¾ commercial communications missions, and ¼ other types of government missions. Start dates of system integration and test for the data ranged from 1973-1999. A distribution of start dates is shown in Figure 3.3. As seen in the figure, the bulk of the data are from 1990-1999.

The following information was sought on each discrepancy that occurred at the system level of integration and test for each spacecraft:

- Spacecraft pseudonym
- Spacecraft order in production
- Spacecraft mission area
- Discrepancy report open date (year only) and open duration
- Subsystem, or part of the spacecraft testing setup, the discrepancy was written against
- I&T activity taking place at time of discrepancy occurrence

- Description of the discrepant behavior observed
- Root cause of the discrepancy
- Immediate fix action needed to make the current spacecraft functional again (also called disposition)
- Long-term corrective action that was prescribed to prevent the problem from happening again on future spacecraft

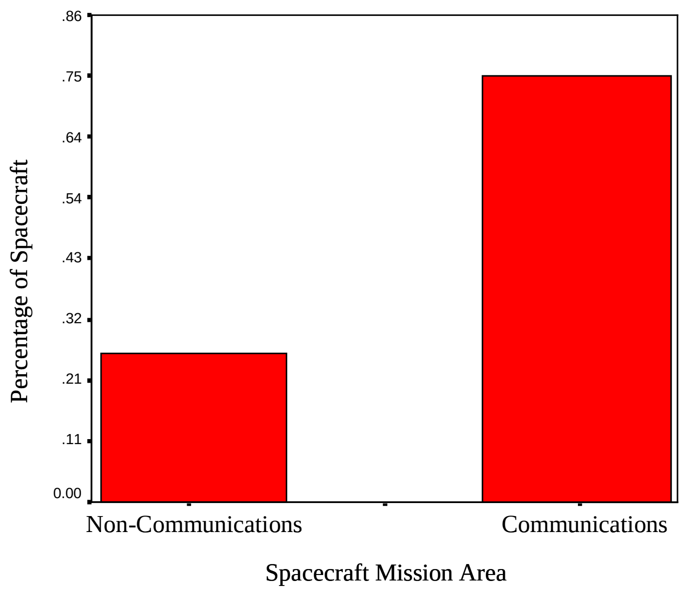

Figure 3.2: Distribution of spacecraft by mission area.

However, the data obtained for some spacecraft was incomplete from the perspective of containing all the above information that was sought. For example, some discrepancies reported did not contain information about the close date, and thus duration information on that discrepancy was unavailable. If a certain category of information (such as duration) was unavailable for more than 50% of the discrepancies reported on a given spacecraft, that category was treated as missing data and not included in the analysis.

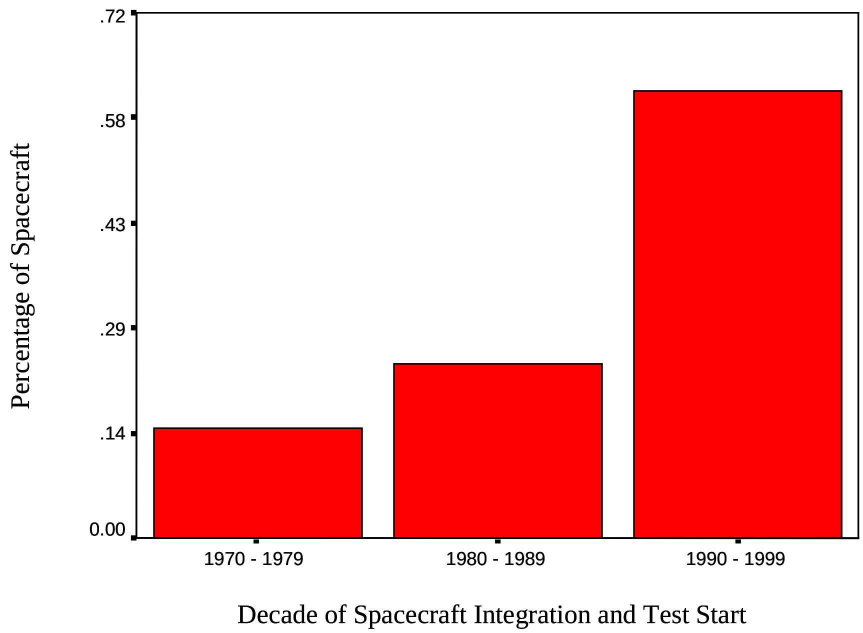

Figure 3.3: Distribution of spacecraft by decade of integration and test start date.

In addition, if a spacecraft manufacturer provided data for a spacecraft that they speculated was incomplete from the point of view of not containing all the discrepancies reported during system-level I&T, these spacecraft were not used in the analysis. Several spacecraft manufacturers did report that, for instance, they were migrating to a new automated reporting system at particular points in history, and believed that certain spacecraft undergoing system-level I&T around that timeframe were not accurately or completely contained within the records provided for this research. Hence, they were not used in the final analysis.

3.6. Unit of Analysis

The unit of analysis used in this research is the spacecraft. All data are presented for each category as a percentage of the total discrepancies that occurred in that category on a given spacecraft. Thus, the numbers are normalized, which protects proprietary concerns. It also effectively weights all spacecraft evenly regardless of the total number of discrepancies reported. This is important, because the reasons behind different numbers of total discrepancies per spacecraft can be considered an artifact of organization and corporate culture. It is important to eliminate this bias from the analysis.

To get a more intuitive idea of using the spacecraft as the unit of analysis, examine Figure 3.4. Figure 3.4 shows a research data sheet for a sample spacecraft. The spacecraft pseudonym, order in production, mission area, and discrepancy report dates

Spacecraft Psuedonym	#00136	**Open Year**	1989
Order in Production	1	**Open Duration**	67 Days
Mission Area	Communications		

Activity [% Discrepancies]

Acoustic	Vibration	Acceleration	Shock	Thermal Vacuum	Thermal Cycle	Ambient	Other
1	0	0	0	34	5	60	0

Subsystem [% Discrpeancies]

EPDS	GNC	Propulsion	SMS	DMS/TTC	Thermal	Harness	Equipment
5	2	5	1	0	3	0	32

Payload	Spacecraft	Other
31	20	1

Disposition [% Discrepancies]

Use As Is	Rework	Repair	Return to Supplier	Scrap	Other
45	26	24	0	0	5

Root Cause [% Discrepancies]

Operator/ Employee	Design	Material	Equipment	Software	No Anomaly	Unknown	Other
28	13	3	24	11	6	11	4

Corrective Action [% Discrepancies]

Operator/ Employee	Drawing/ Spec	Process/ Procedure	Equipment	Software	Supplier-Related	No Action Required	Other
16	9	13	19	8	1	31	3

Open Duration [% Discrepancies]

0-30 Days	31-60 Days	61-90 Days	91-120 Days	121-150 Days	151-180 Days	>180 Days
50	23	12	5	2	1	6

Figure 3.4: Example data sheet for a notional spacecraft.

and duration are listed at the top. Beneath that, the categories of Activity, Subsystem, Disposition (immediate fix action), Root Cause, Long-term Corrective Action, and Open Duration are listed. Each of the categories contains a list of the bins they contain. Underneath the bin name is an entry containing the percentage of discrepancies in the category that occurred in that bin. Using percentages in this way, the data is normalized to protect proprietary concerns.

Future analyses could certainly be performed focusing on the discrepancy as the unit of analysis. This would of course provide different insights, and could be performed to compare the insights gained using the discrepancy vice the spacecraft as the unit of analysis.

3.7. Overview of Statistics Terminology

The analysis of spacecraft system-level I&T discrepancy distribution data draws upon statistical measures of central tendency and correlation. The sample mean or average usually represents the central tendency of a population. The correlation, or degree of association of two variables, tells how independent the behavior is of two variables. Understanding these measures of a population helps in making predictions about their future behavior, and is thus a necessary part of the research. This section presents a brief overview of statistics terminology that will be used in this monograph. For further information on statistics, see *Statistics for the Social Sciences* by Rand Wilcox.

3.7.1. Measures of Central Tendency

Measures of central tendency are intended to represent the typical object under study. Specifically, central tendency refers to a central or middle point in the data being studied. The two measures of central tendency used in this research are the sample mean and the sample median.

3.7.1.1. Sample Mean, Sample Mean Standard Error

The sample mean is the best-known and most-studied measure of central tendency. The sample mean is equal to the sum of the measurements in a data set, divided by the number of measurements contained in that data set. The sample mean is not a very resistant measure of central tendency, because small changes in many of the values or large changes in only a few values have relatively big effects on its value.[14]

The sample mean standard error is used to assess the precision with which the population mean is estimated from the sample. It is computed by taking the sample standard deviation and dividing it by the square root of the sample size.[15]

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[14] Entire paragraph drawn from Wilcox, Rand R. *Statistics for the Social Sciences*. San Diego: Academic Press, 1996. p. 15.
[15] *SPSS Base 10.0 Applications Guide*. Chicago: SPSS Inc, 1999. p. 24.

3.7.1.2. 95% Confidence Interval of the Sample Mean

Sample mean standard error is used to construct a confidence interval such that 95% of the intervals constructed in the same way from many random samples of the same size will include the population mean. The 95% confidence interval is constructed by computing

$$\text{Mean} \pm t_{0.975}(df) \times \text{Standard Error}$$

where the value of t is found in a table of percentiles of the t distribution, and the table is entered using *(n-1)* degrees of freedom.[16]

3.7.1.3. Sample Median

The sample median is the middle number when all of the data in a set are put in order and the number of data is odd. The sample median is the average of the two middle numbers when all of the data in a set are put in order and the number of data is even. The sample median is a very resistant measure of central tendency, meaning that small changes in many of the data or large changes in only a few data have a relatively small effect on its value. It is often applied as a measure of central tendency when the data set has a large number of outlier, or extreme, values that would significantly influence the sample mean.[17]

3.7.2. Measures of Correlation

Correlation is defined as the degree of relative correspondence between two sets of data. The correlation between variables X and Y, for example, can be interpreted as the ability to predict or explain the behavior of variable X based upon variable Y's behavior. Correlation indicates a relationship between variables, but does not indicate a direction of causality of that relationship.

3.7.2.1. Spearman's Rho

Spearman's Rho is one measure of association based on ranks, useful for examining correlation between variables that do not follow a normal distribution. Since the data gathered on spacecraft discrepancies do not follow a normal distribution, Spearman's Rho will be used as the measure of correlation. Other measures of association commonly used are Kendall's Tau-B and Pearson's Gamma. These are more commonly applied to variables that are normally distributed, and hence will not be used in this analysis.

Spearman's Rho measures the extent to which two variables have a monotonic relationship. Two random variables, X and Y, are said to have a monotonic relationship if Y has a strictly increasing or strictly decreasing relationship with X.[18]

For this research, a two-tailed significance less than 0.01 was used. All correlation indicated in these analyses will have a significance less than 0.01 unless otherwise noted.

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[16] *SPSS Base 10.0 Applications Guide*. Chicago: SPSS Inc, 1999. p. 28.

[17] Entire paragraph drawn from Wilcox, Rand R. *Statistics for the Social Sciences*. San Diego: Academic Press, 1996. p. 14-15.

[18] Wilcox, Rand R. *Statistics for the Social Sciences*. San Diego: Academic Press, 1996. p. 382.

3.7.2.2. Least Squares Regression

Least squares regression derives a linear rule or expression that predicts a variable Y given a variable X using an equation of the form

$$\hat{Y} = b_1 X + b_0$$

such that

$$b_1 = \frac{\sum (X_i - \overline{X})(Y_i - \overline{Y})}{\sum (X_i - \overline{X})^2}$$

$$b_0 = \overline{Y} - b_1 \overline{X}$$

where $\hat{Y}$ is the predicted or fitted value, *X* is the given predictor value, $\overline{Y}$ and $\overline{X}$ are the means of *X* and *Y* variables respectively, and X_i and Y_i are the i^{th} observations of variables *X* and *Y*. Using this regression equation ensures that no other linear regression line will give a smaller sum of squared residuals for the data being examined. In addition, this regression equation makes no assumptions about the distribution of *X* and *Y*.

The coefficient of determination, or the proportion of variation among the *Y* value that is explained by a linear prediction rule involving *X*, assesses how well a linear regression equation performs. The coefficient ranges from zero to one, with values close to one indicating a better fit than values closer to zero.[19]

3.8. Potential Sources of Error

Research is always confounded with potential sources of error. By understanding these possibilities, the research results in the following chapters can be viewed in the proper context.

The discrepancy data used in this research is obtained from spacecraft manufacturer-maintained records of discrepancies. These records are accurate to the best of the spacecraft manufacturer's knowledge, and were assumed to be accurate for the purpose of this research. However, the initial discrepancy reports upon which the records are based were created by people, and are thus subject to some inaccuracies and mistakes that are just a fact of life in a fast-paced environment. The data were reviewed for such mistakes, and inaccurate data were discarded before analysis. As an example, several discrepancies were listed as having report close dates happening chronologically before report open dates. Obviously, this is a mistake. For these discrepancies, the open and close date, as well as the open duration, were treated as missing data for the purpose of analyses.

Another potential source of error arises in mapping the spacecraft manufacturer-specific codes to the characterization system described above. This was done with the aid of experts at the spacecraft manufacturer who were familiar with the their coding system.

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[19] Entire section drawn from Wilcox, Rand R. *Statistics for the Social Sciences*. San Diego: Academic Press, 1996. p. 307-315.

Working with the above definition of the characterization system, they mapped their own codes into the characterization system. The mapping was reviewed to minimize interpretation problems and reduce this as a source of error.

3.9. Barriers Encountered

Proprietary concerns, lack of standardization, and incomplete data were the chief barriers encountered in this research.

Proprietary concerns by spacecraft manufacturers will always be a challenge for researchers. These proprietary concerns are valid ones, and can be addressed by using pseudonyms, normalizing results, and having spacecraft manufacturers periodically review the research to identify potential downstream proprietary issues. Though the research may accept a somewhat lower level of fidelity as a result, this is necessary to accomplish any research involving real-world data. An example of this arose in collecting mission area information for spacecraft used in this research. It was originally requested that spacecraft manufacturers indicate that the spacecraft fell into one of six mission categories: communications, early warning, navigation, space science, remote sensing, and weather. However spacecraft manufacturers felt that this data, combined with an indication of the time period the spacecraft was being produced, would lead to a link between a specific spacecraft manufacturer and specific data in the research results. This would compromise the research participant’s anonymity and proprietary requirement. A compromise was formulated that broke down mission area into only two categories: communications and other. While this protected the proprietary and anonymity concerns, the coarser categorization prohibited investigating correlation based upon the six original mission area categories desired.

A lack of standardization across spacecraft manufacturer discrepancy reporting systems dictated that time needed to be spent learning about and understanding each one. In addition, terminology associated with discrepancy reporting systems is not standardized across companies, resulting in the need to create a "Rosetta Stone" of sorts for discrepancy reporting terminology. This manifested itself in the characterization system described previously.

Finally, incomplete discrepancy records provided a challenge in assembling a comprehensive, cross-company set of discrepancy information. For many reasons, ranging from the records no longer existed, to a person forgot to enter certain information, to a spacecraft manufacturer was changing over its discrepancy reporting system, incomplete data was provided. This is another reality of real-world data, and was dealt with by not including missing data points in the analysis.

3.10. Enabling Future Research

Research into characterizing the distribution and patterns of discrepancies can be greatly enabled by the use of a common discrepancy reporting framework and terminology. While many spacecraft manufacturers have internal reporting systems that are common throughout their company, these are not common across spacecraft manufacturers. A cross-company discrepancy analysis is extremely time-consuming without some level of standardization across the industry.

Chapter 4.

Discrepancy Distribution Research: Results of Central Tendency Analysis

4.1. Chapter Introduction

Measures of central tendency are intended to represent the typical object under study. Specifically, central tendency refers to a central or middle point in the data being studied. The sample mean or average is perhaps the best-known and most-studied measure of central tendency, and will be the focus of this chapter. Also well known is the sample median, which is the middle number when all of the data in a set are put in order. Understanding these tendency measures of a population helps in making predictions about their future behavior.

This chapter discusses the observed sample means for several categories of system-level integration and test (I&T) data, including:

- **Activity** – Describes the spacecraft system-level I&T activity that was taking place at the time the discrepancy occurred.
- **Subsystem –** Describes the subsystem or part of the spacecraft or test equipment that the discrepancy was written against.
- **Root Cause –** Describes the determined root cause of the discrepancy.
- **Disposition –** Describes the immediate action that is required to make the current discrepant spacecraft functional again, called a disposition. Note how this differs from corrective action below.
- **Corrective Action –** Describes the long-term corrective action prescribed to prevent the discrepancy from occurring again on future spacecraft. Note how this differs from disposition above.
- **Open Duration –** Describes the time in days a discrepancy report remained open. Typically a discrepancy report is opened upon discovery of the discrepancy and closed upon resolution of the discrepancy and prescription of a corrective action.

For a detailed review of the bins into which each category is subdivided, please see Chapter 3.

The observed sample means are presented first for the whole population of spacecraft used in this research. Then, observed sample means for two subpopulations are presented:

- Communications Spacecraft – a spacecraft whose primary mission is to provide communications. This includes fixed and mobile broadcast, relay spacecraft, telephony, paging, and other transmission of communication services.
- Non-Communications Spacecraft – a spacecraft whose primary mission is not communications, though the spacecraft may have some communications capability. These spacecraft might have weather, remote sensing in the broadest sense, early warning, planetary or space science, etc. as their primary mission.

Statistically significant differences between these two subpopulations are noted, and hypotheses about the differences are presented. The chapter concludes by highlighting important analysis findings that underpin the themes of this monograph and form the basis for the recommendations presented in the final chapter.

4.2. Activity Means Analysis

The data contained in the activity category describe the spacecraft system-level I&T activity or environmental test that was taking place at the time the discrepancy occurred. The activity category has seven bins. For a detailed description of each of these bins, please see Chapter 3. The seven bins with their short names in parentheses, are:

- Acoustic Test (Acoustic)
- Vibration Test (Vibe)
- Acceleration Test (Acc)
- Shock Test (Shock)
- Thermal Cycling Test (TC)
- Thermal Vacuum Test (TV)
- Ambient Integration and Test Activities (Ambient)

4.2.1. All Spacecraft Activity Means

Figure 4.1 shows the observed sample means of the seven Activity category bins for the set of all spacecraft. The 95% confidence interval upper and lower bounds on those means, as well as the medians, are also shown in the figure. On average over the entire population of spacecraft, the vast majority of discrepancies found in an environmental exposure are occurring during the thermal vacuum activity. The thermal cycling environment finds about 3% of all discrepancies discovered during system-level I&T, and the various “shake” environments of acoustic, vibration, acceleration, and shock combined find less than 3% of all discrepancies discovered during system-level I&T. The ambient environment accounts for nearly 2/3 of all discrepancies reported at the system level.

Environmental test chambers needed to create the environmental exposures are very large and expensive resources for a spacecraft manufacturer to maintain. Thus, there is great interest among spacecraft producers to use these resources in an effective manner. As the thermal cycling and "shake" environments account for a small percentage of discrepancy discoveries, they would be logical targets for further tradeoff studies. These tradeoff studies would examine the risks, costs and benefits of continuing the thermal cycle and shake environmental exposures vice eliminating those exposures in lieu of other countermeasures for discovering, or otherwise eliminating, the discrepancies currently found in those environments.

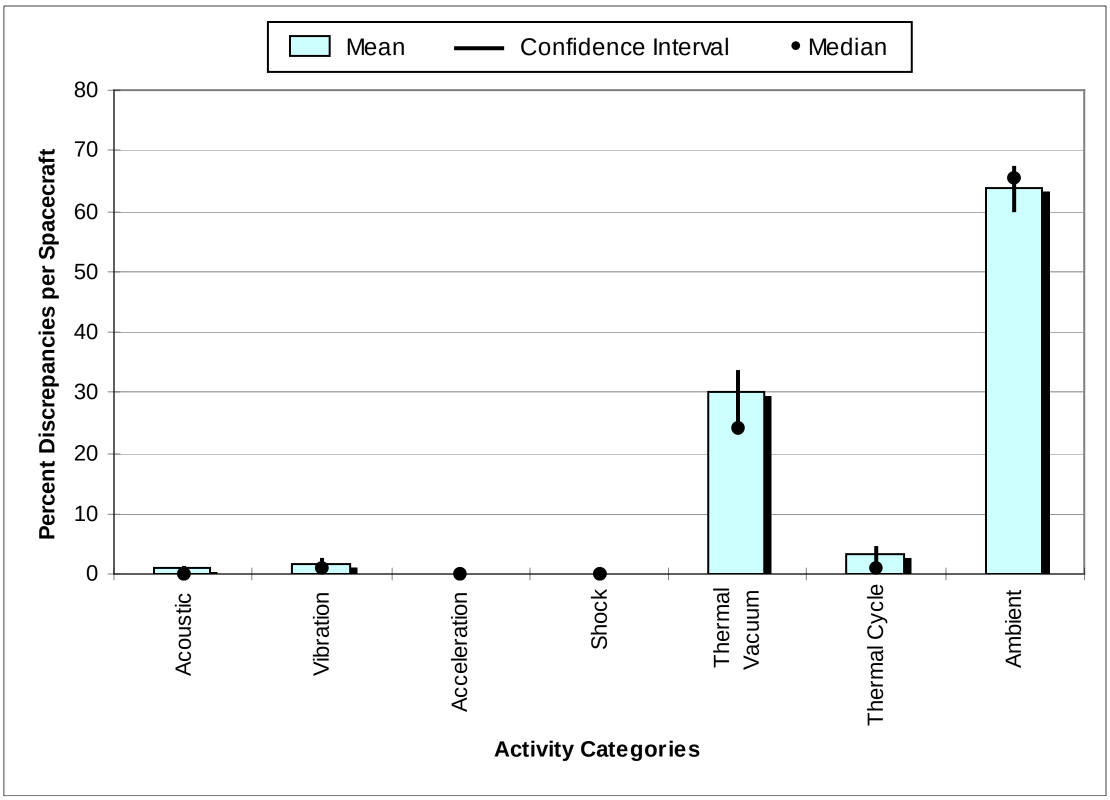


Figure 4.1: Means, confidence intervals, and medians for percent discrepancies per average spacecraft in each activity category.

4.2.2. Activity Means by Mission Area

Figure 4.2 shows the observed sample means of the seven Activity category bins for the subpopulations of communications mission area spacecraft and non-communications mission area spacecraft. The 95% confidence interval upper and lower bounds on those means, as well as the medians, are also shown in the figure.

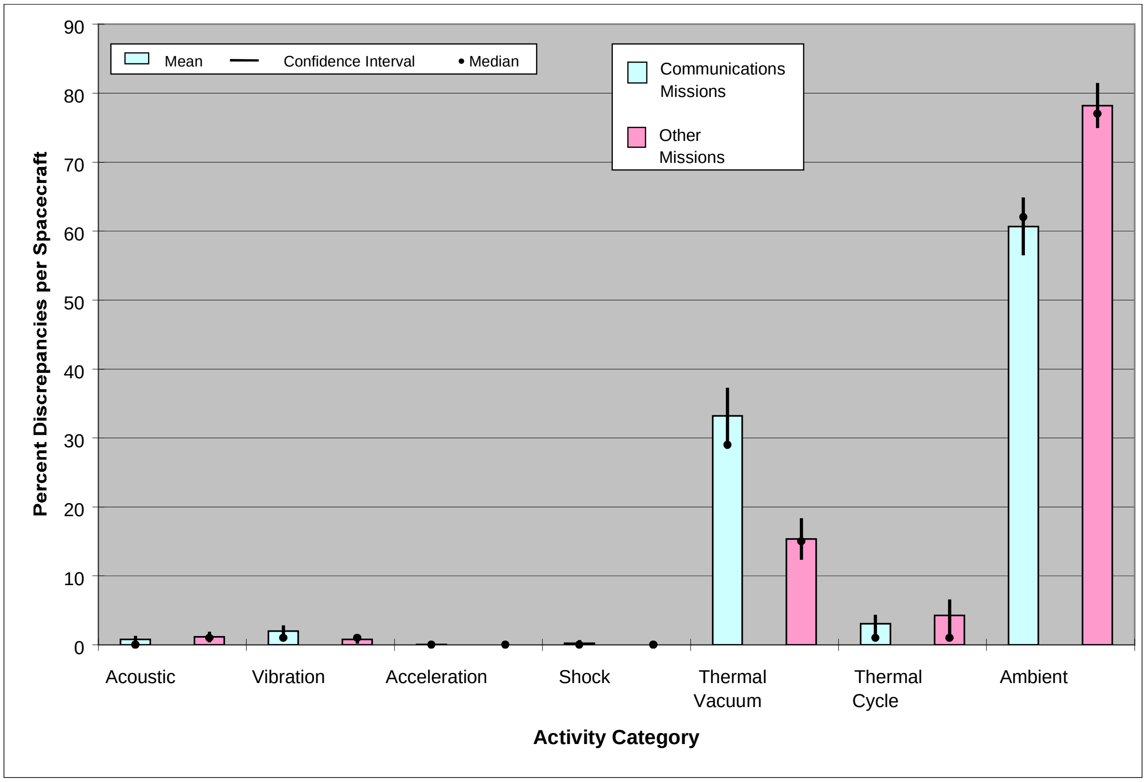


Figure 4.2: Means, confidence intervals, and medians for percent discrepancies per average spacecraft in each activity category, broken out by mission area.

Statistically significant differences in the means of the two subpopulations show up in the Thermal Vacuum and Ambient category bins. A statistically significant difference occurs when the range of the confidence interval surrounding a mean for one population does not overlap with the range of the confidence interval surrounding a mean for the other population.

The percent of discrepancies discovered during Thermal Vacuum activities is 33% for communications spacecraft versus 15% for non-communications spacecraft. In addition, the percent of discrepancies discovered during Ambient activities is 61% for communications spacecraft versus 78% for non-communications spacecraft. Interview data and feedback from industry reviews of this research suggest the difference in these two category bins may be owed to the different aspects of testing philosophies, sequences, and cycles employed by the two different subpopulations.

Data were not able to be collected on test sequences for each spacecraft in the research data set, and thus no conclusions can be drawn about the effect of test sequence on discrepancy occurrence.

4.3. Subsystem

The data contained in the subsystem category describe the subsystem or part of the spacecraft or test equipment that the discrepancy was written against. The subsystem category has eleven bins. For a detailed description of each of these bins, please see Chapter 3. The eleven bins with their short names in parentheses, are:

- Electrical Power and Distribution Subsystem (EPDS)
- Guidance, Navigation and Control (GNC)
- Payload
- Propulsion (Prop)
- Structures and Mechanisms Subsystem (SMS)
- Telemetry, Tracking and Command (TTC) / Data Management Subsystem (DMS)
- Thermal
- Wiring and Cabling (Harness)
- Equipment
- Spacecraft
- Other

4.3.1. All Spacecraft Subsystem Means

Figure 4.3 shows the observed sample means of the eleven subsystem category bins for the set of all spacecraft. The 95% confidence interval upper and lower bounds on those means, as well as the medians, are also shown in the figure. On average over the entire population of spacecraft, Equipment accounts for the largest percentage of discrepancies written against a particular subsystem with a mean of 30%. The payload subsystem and the spacecraft are the next largest percentages of discrepancies, at 17% each. The remaining 36% of discrepancies are distributed between the remaining traditional subsystems of the spacecraft, with no single subsystem accounting for more than 9% of the total discrepancies.

Figure 4.4 shows an aggregated version of Figure 4.3, displaying the distribution of discrepancies on an average spacecraft at the system level of integration, by aggregated subsystem category area the discrepancy was written against. As shown in the graph, 36% of the discrepancies found at system level test are written against subsystems, and 29% of the discrepancies are written against test or support equipment. The remaining 35% of the discrepancies are written against system level problems.

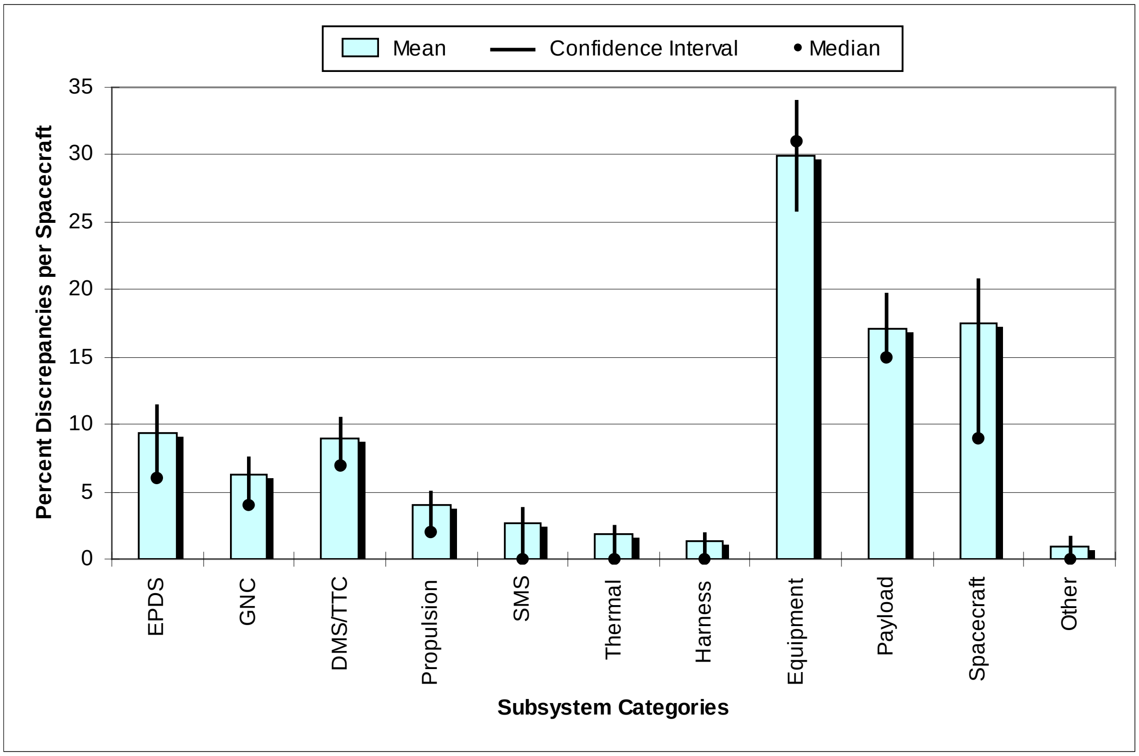


Figure 4.3: Means, confidence intervals, and medians for percent discrepancies per average spacecraft in each subsystem category.

The prevailing philosophy for spacecraft test is to drive the testing to the lowest possible level of integration that is able to find a specific problem. This is based upon the notion that the cost of fixing discrepancies grows by an order of magnitude with each increasing level of integration. This translates to a desire to find unit problems at the unit integration and test level, find subsystem problems at the subsystem integration and test, and find system problems at system integration and test level.

If the goal is to drive testing to the lowest level possible to find a problem, then only system level problems are the type of problems that ideally should be discovered at the system level of integration and test. Currently, subsystem and equipment problems account for nearly two thirds of the discrepancies found during system level I&T. This provides an enterprise metric for measuring progress towards the goal of driving testing to the lowest level possible.

No data were able to be collected for this research on whether or not subsystem problems discovered during system-level test should properly have been caught at subsystem-level testing. It can be argued that finding subsystem problems at the system level of integration may in fact be the most cost-effective method (though no cost-benefit analysis has presented itself). However, it is difficult to argue that finding test equipment problems at system-level integration and test is not waste in the process that should be eliminated. Since a suite of test equipment, particularly for commercial satellite product lines, will be reused again on subsequent spacecraft, there is a potentially large return on investment for addressing and remedying discrepancies associated with test equipment.

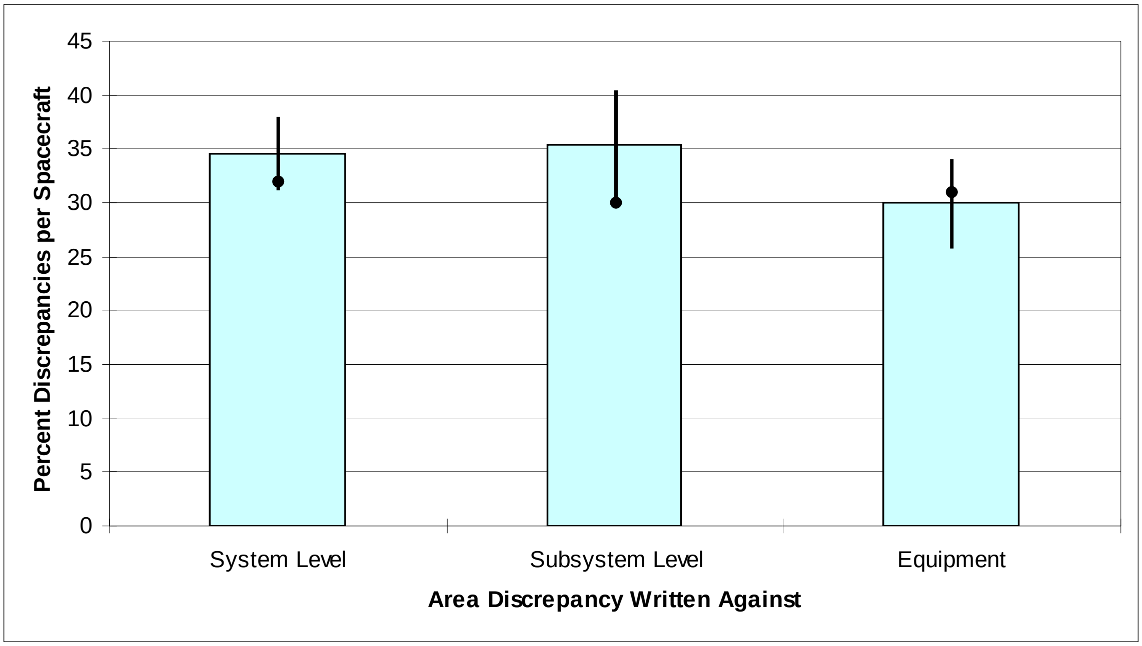


Figure 4.4: Distribution of discrepancies on an average spacecraft at the system level of integration, by aggregated subsystem category area the discrepancy was written against.

4.3.2. Subsystem Means by Mission Area

Figure 4.5 shows the observed sample means of the eleven Subsystem category bins for the subpopulations of communications mission area spacecraft and non-communications mission area spacecraft. The 95% confidence interval upper and lower bounds on those means, as well as the medians, are also shown in the figure.

Statistically significant differences in the means of the two subpopulations show up in six of the eleven Subsystem category bins. A statistically significant difference occurs when the range of the confidence interval surrounding a mean for one population does not overlap with the range of the confidence interval surrounding a mean for the other population.

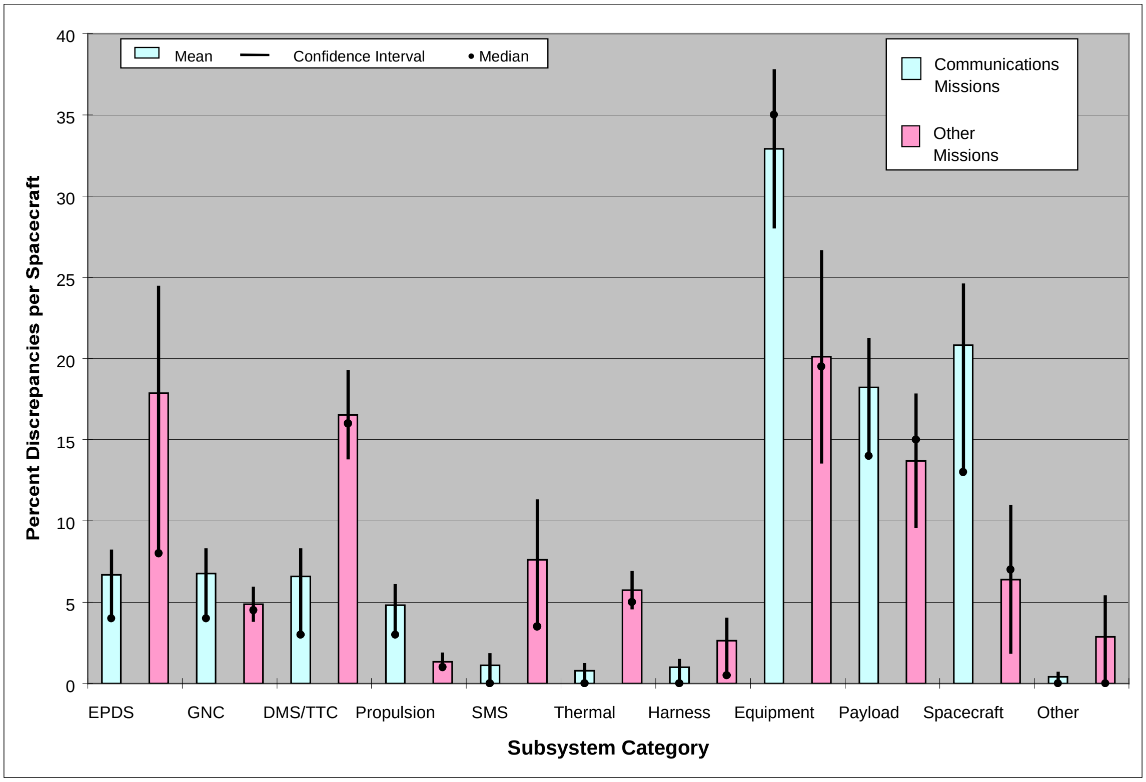


Figure 4.5: Means, confidence intervals, and medians for percent discrepancies per average spacecraft in each subsystem category, broken down by mission area.

Interview data and feedback from industry reviews suggest some differences in the subpopulations may be owed to reuse of the same bus subsystems on communications spacecraft. For example, the percent discrepancies written against the DMS/TTC subsystem is 7% for communications spacecraft versus 17% for non-communications spacecraft. The percent discrepancies written against the Thermal subsystem is 1% for communications spacecraft versus 6% for non-communications spacecraft. It is common for many commercial communications spacecraft to be built using the same bus, whereas most non-communications spacecraft each have a unique bus and do not typically reuse bus subsystems from spacecraft design to spacecraft design. However, this hypothesis might be refuted by a further examination of the discrepancies that were attributed to Equipment, Payload and Spacecraft. If commercial satellite discrepancies were placed in these categories out of convenience due to intense schedule delivery pressures instead of tracing the discrepancy to its subsystem root cause, then these category percentages may be artificially inflated. If this were the case, the hypothesis that reuse of standardized designs and components results in less discrepancies at system test would not be supported.

In addition, the difference in Thermal subsystem discrepancies may be a result of the different experience levels thermal designers have in different orbit geometries. The communications spacecraft used in this research were all designed for geostationary orbits where the thermal subsystem design and implementation is perhaps most well understood. The non-communications spacecraft were designed for a variety of orbits including LEO, MEO, GEO and HEO. Thermal subsystem design and implementation in the non-GEO orbits may not be as well understood, resulting in more discrepancies written against the thermal subsystem for non-communications spacecraft.

The percent of discrepancies written against the SMS subsystem is 1% for communications spacecraft versus 8% for non-communications spacecraft. This may be owed to non-communications spacecraft tending to have many more complex mechanisms and articulating parts than communications spacecraft, and hence a higher percentage of SMS discrepancies. In addition, the structure and mechanisms are typically designed uniquely for each non-communications spacecraft while they are frequently reused from communications spacecraft to communication spacecraft within a company. This reuse and familiarity with the SMS system may also help to explain the lower occurrence of SMS-related discrepancies on communications spacecraft.

The percent of total discrepancies written against the Propulsion subsystem is 5% for communications spacecraft versus 1% for non-communications spacecraft. This may be surprising, as the propulsion subsystem can be considered a part of the bus on communications spacecraft. However, it is not clear that this subsystem designs remains as static between communications spacecraft as other subsystem designs. Currently, propulsion and the ability to station keep is the limiting factor on a commercial communications spacecraft's revenue generating lifetime. It would seem appropriate that the limits of propulsion systems are being pushed on commercial communications spacecraft to maximize their lifetimes. This could help to explain the larger percentage of propulsion subsystem problems on communications spacecraft than on non-communications spacecraft.

Figure 4.6 shows an aggregated version of Figure 4.5, displaying the distribution of discrepancies on an average spacecraft at the system level of integration, by aggregated subsystem category area the discrepancy was written against, and broken down by mission area.

The percent of discrepancies written against the subsystem level of the spacecraft is 28% for communications spacecraft versus 59% for non-communications spacecraft. Non-communications spacecraft are typically one of a kind spacecraft with subsystems developed uniquely for a single spacecraft, whereas commercial communications spacecraft are developed to have a common, reused bus and subsystems. Thus with new subsystems on every spacecraft, it would be expected that non-communications spacecraft might have more subsystem level problems still occurring at system-level integration and test than commercial communications spacecraft that reuse proven and familiar subsystems.

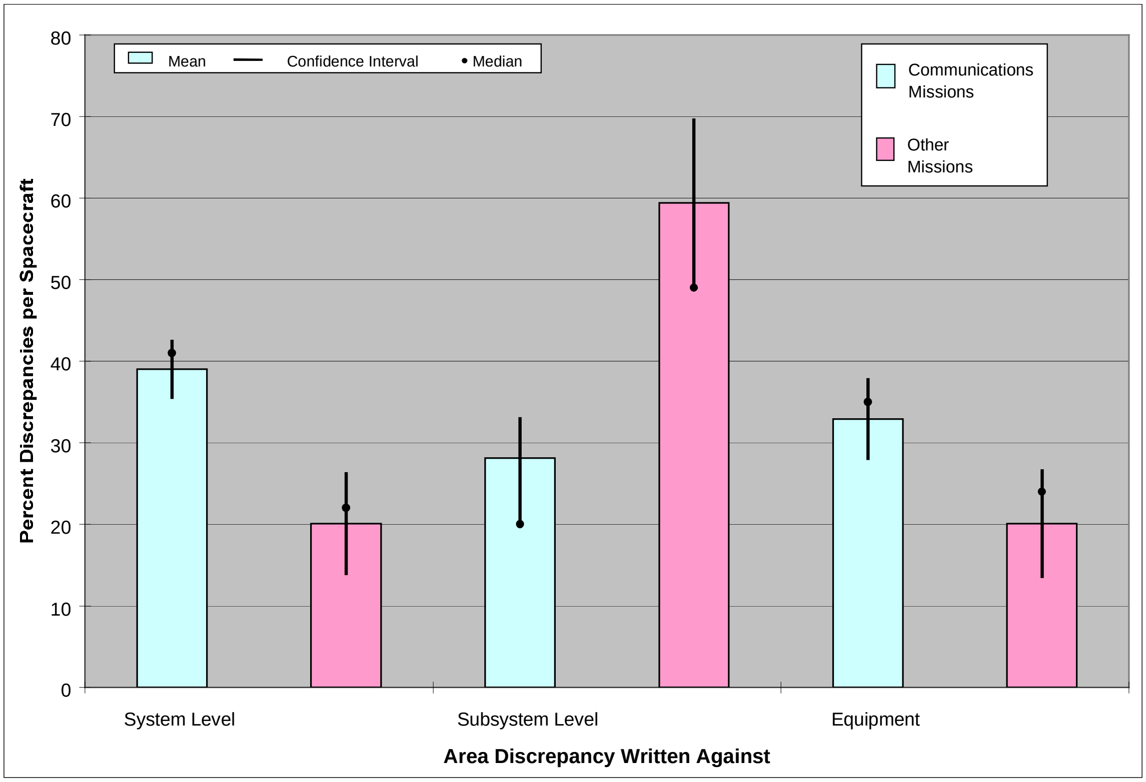


Figure 4.6: Distribution of discrepancies on an average spacecraft at the system level of integration, by aggregated subsystem category area the discrepancy was written against, broken down by mission area.

The percent of discrepancies written against the Test Equipment is 33% for communications spacecraft versus 20% for non-communications spacecraft. Most of the non-communications spacecraft are government contracts where the test equipment is funded as part of the contract, whereas most communications spacecraft in this research are commercial developments where test equipment is likely company-funded. A possible explanatory hypothesis may be that not enough investment is being made in quality test equipment for commercial communications spacecraft, hence their higher proportion of test equipment problems. This is very interesting to note, since test equipment for commercial spacecraft product lines are typically reused on subsequent spacecraft. Thus there is a potentially large return on investment for addressing and remedying discrepancies associated with test equipment on the commercial communications spacecraft side.

4.4. Root Cause

The data contained in the Root Cause category describe the underlying reason for occurrence of a discrepancy. The Root Cause category has eight bins. For a detailed description of each of these bins, please see Chapter 3. The eight bins are:

- Employee/Operator
- Design
- Material
- Equipment
- Software
- No Anomaly
- Unknown
- Other

4.4.1. All Spacecraft Root Cause Means

Figure 4.7 shows the observed sample means of the eight Root Cause category bins for the set of all spacecraft. The 95% confidence interval upper and lower bounds on those means, as well as the medians, are also shown in the figure.. The Operator/Employee (human error) and Design category bins account for the largest percentages of causes of discrepancies on an average spacecraft, with means of 27% and 25%, respectively. An example of human error would be a procedure that was not carried out as written, or a component that was installed not according to specifications. Design problems include the design of both hardware and processes. Equipment is also a significant contributor to the cause of discrepancies, with a mean of 17%.

An analysis of the root cause of problems can be quite insightful for an organization. It can indicate where to spend resources to increase quality or performance. As human error and design-related problems are reported as the leading causes of discrepancies, effective corrective action aligned to address these two areas would potentially yield the largest reduction in discrepancy occurrences. The same workforce, as well as the same test support equipment in the case of most commercial satellite product lines, is reused in the production of subsequent spacecraft. Fixing discrepancies that are caused by these things will thus yield benefits that scale with the production rate. It is interesting to note that the percentage of human error-caused discrepancies per spacecraft has remained more stable over the past thirty years than percentages of the other root cause categories, based on observations of the data used in this research. It is also perhaps interesting to observe that less than half of the discrepancies were related to things typically associated with the challenges of building sophisticated spacecraft, such as design and software problems.

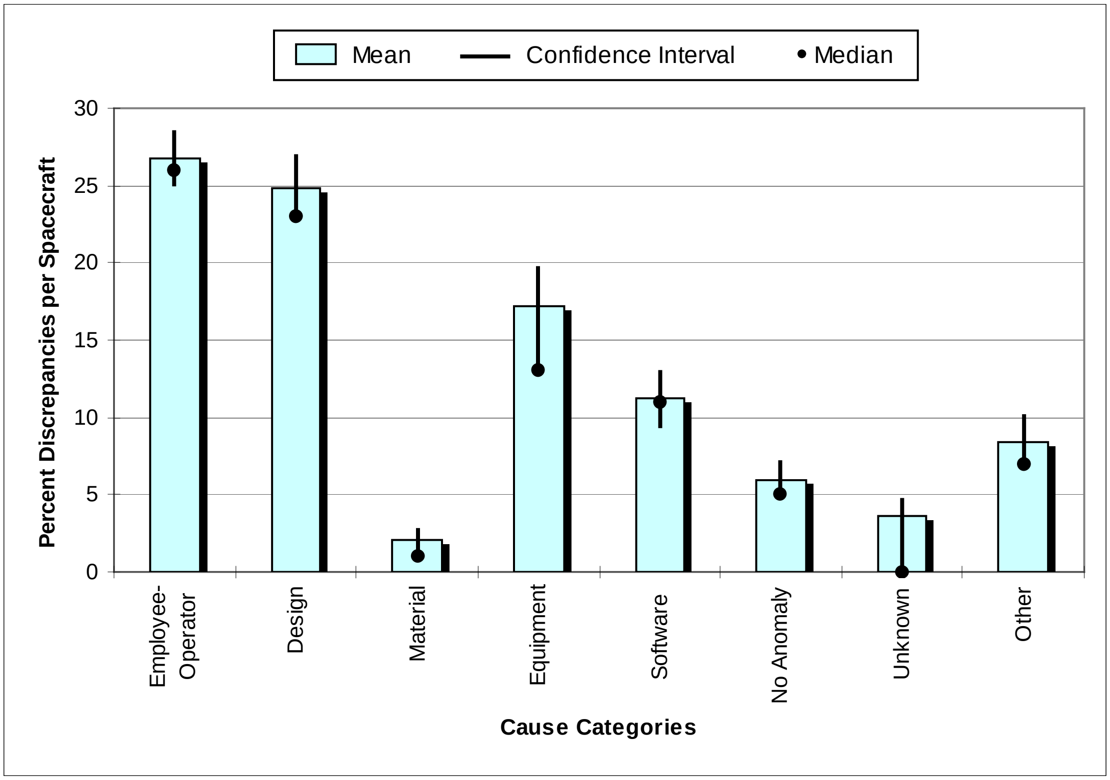


Figure 4.7: Summary chart of means, confidence intervals, and medians for percent discrepancies per average spacecraft in each cause category.

4.4.2. Root Cause Means by Mission Area

Figure 4.8 shows the observed sample means of the eight Root Cause category bins for the subpopulations of communications mission area spacecraft and non-communications mission area spacecraft. The 95% confidence interval upper and lower bounds on those means, as well as the medians, are also shown in the figure.

Statistically significant differences in the means of the two subpopulations show up in the Test Equipment and Other Cause category bins. A statistically significant difference occurs when the range of the confidence interval surrounding a mean for one population does not overlap with the range of the confidence interval surrounding a mean for the other population.

The percentage of Test Equipment root cause is 20% for communications spacecraft versus 9% for non-communications spacecraft. Reasons for this difference are likely similar to the reasons for the higher percentage of discrepancies written against test equipment for communications spacecraft than for non-communications spacecraft. Most of the non-communications spacecraft are government contracts where the test equipment is funded as part of the contract, whereas most communications spacecraft in this research are commercial developments where test equipment is likely company-funded.

It may be that not enough investment is being made in quality test equipment for commercial communications spacecraft, hence their higher proportion of test equipment root causes than for non-communication spacecraft. This is very interesting to note, since test equipment for commercial spacecraft product lines is typically reused on subsequent spacecraft. Thus there is a potentially large return on investment for addressing and remedying discrepancies associated with test equipment on the commercial communications spacecraft side.

The Root Cause category bin of Other is defined as a root cause that is known but doesn't fit into any of the remaining seven Root Cause bins. Examples might include, but are not limited to, unplanned events such as roof leaks or facility environmental control malfunction. The percentage of discrepancies attributed to Other root cause is 5% for communications spacecraft versus 18% for non-communications spacecraft. This implies that the Root Cause bins as defined in this research may not be as well suited to describing non-communications spacecraft discrepancies, as evidenced by the 18% non-communications spacecraft discrepancies falling into the Other root cause bin. The causes that fall into the Other category bin for non-communications spacecraft should be examined closely and perhaps additional category bins created that would more precisely define the causes of discrepancies for non-communications spacecraft. These new, more precise root cause bins would help the enterprise quickly identify appropriate corrective actions in a more effective and focused manner.

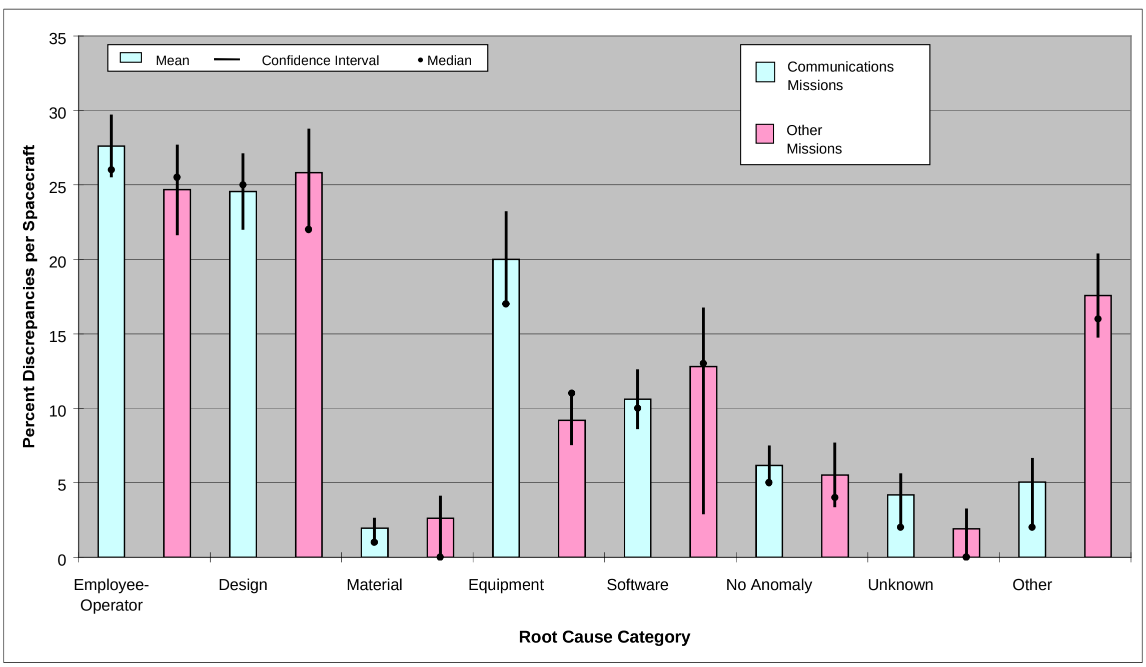


Figure 4.8: Means, confidence intervals, and medians for percent discrepancies per average spacecraft in each cause category, broken down by mission area.

But perhaps more interesting than the differences in the Root Cause category are the similarities across the two different mission areas. Both communications and non-communications spacecraft are experiencing statistically the same percentages at system-level I&T of Operator/Employee cause, Design cause, Material cause, Software cause, Unknown cause, and No Anomaly cause (where a discrepancy was ultimately determined after investigation to not be a discrepancy). Since the Operator/Employee cause and Design cause are the largest single causes and together account for nearly 50% of the discrepancies in both communications and non-communications spacecraft, these are the most obvious places to focus improvement efforts. Lessons learned in this area can perhaps be shared across mission area programs, since both communications and non-communications spacecraft are affected equally by these causes, to the benefit of the entire enterprise.

4.5. Disposition

The data contained in the disposition category describe the immediate fix action that was performed on a spacecraft due to a discrepancy to make only that given spacecraft functional again. Note the difference between disposition, which is for the near term, and corrective action, which is for the long term to prevent a problem from happening again on a future spacecraft. The disposition category has six bins. For a detailed description of each of these bins, please see Chapter 3. The six bins are:

- Use as is
- Rework
- Repair
- Return to Supplier
- Scrap
- Other

4.5.1. All Spacecraft Disposition Means

Figure 4.9 shows the observed sample means of the six Disposition category bins for the set of all spacecraft. The 95% confidence interval upper and lower bounds on those means, as well as the medians, are also shown in the figure. On average over the entire population of spacecraft, Use As Is accounts for the largest percentage of dispositions of discrepancies with a mean of 39%. Use as Is means that no immediate fix action is being taken on the spacecraft as a result of that discrepancy. This can sometimes be due to sufficient design margin or overly stringent specifications. The Repair and Rework dispositions are the next largest percentages of discrepancy dispositions, at 26% and 23%, respectively. It is important to note the main difference between Rework and Repair. Rework indicates a change to the spacecraft that will make it resemble the original blueprint. Repair indicates a change to the spacecraft that will make it different from the original blueprint. For the entire population of spacecraft, it seems that roughly even amounts of rework and repair are taking place. The Scrap disposition accounts for less than 1% of the discrepancy dispositions, as is expected for a product such as a spacecraft with expensive components with long procurement lead times.

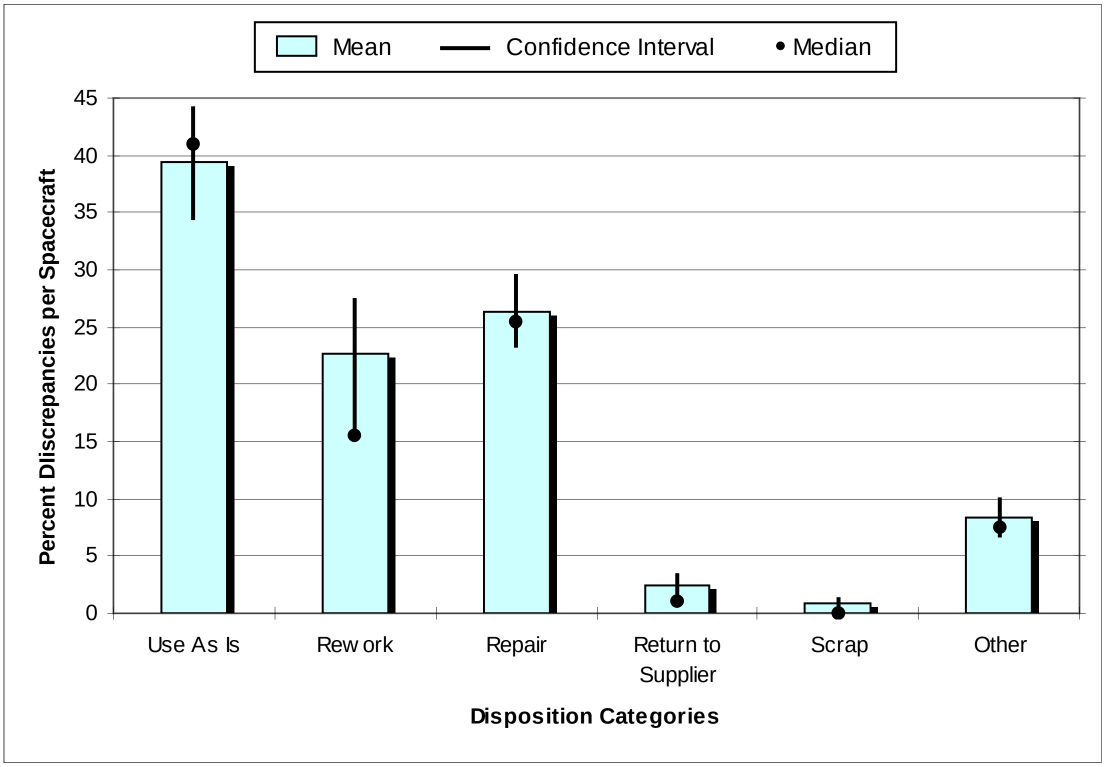


Figure 4.9: Summary chart of means, confidence intervals, and medians for percent discrepancies per average spacecraft in each disposition category.

4.5.2. Disposition Means by Mission Area

Figure 4.10 shows the observed sample means of the six Disposition category bins for the subpopulations of communications mission area spacecraft and non-communications mission area spacecraft. The 95% confidence interval upper and lower bounds on those means, as well as the medians, are also shown in the figure.

Statistically significant differences in the means of the two subpopulations show up in the Use As Is and Rework category bins. A statistically significant difference occurs when the range of the confidence interval surrounding a mean for one population does not overlap with the range of the confidence interval surrounding a mean for the other population.

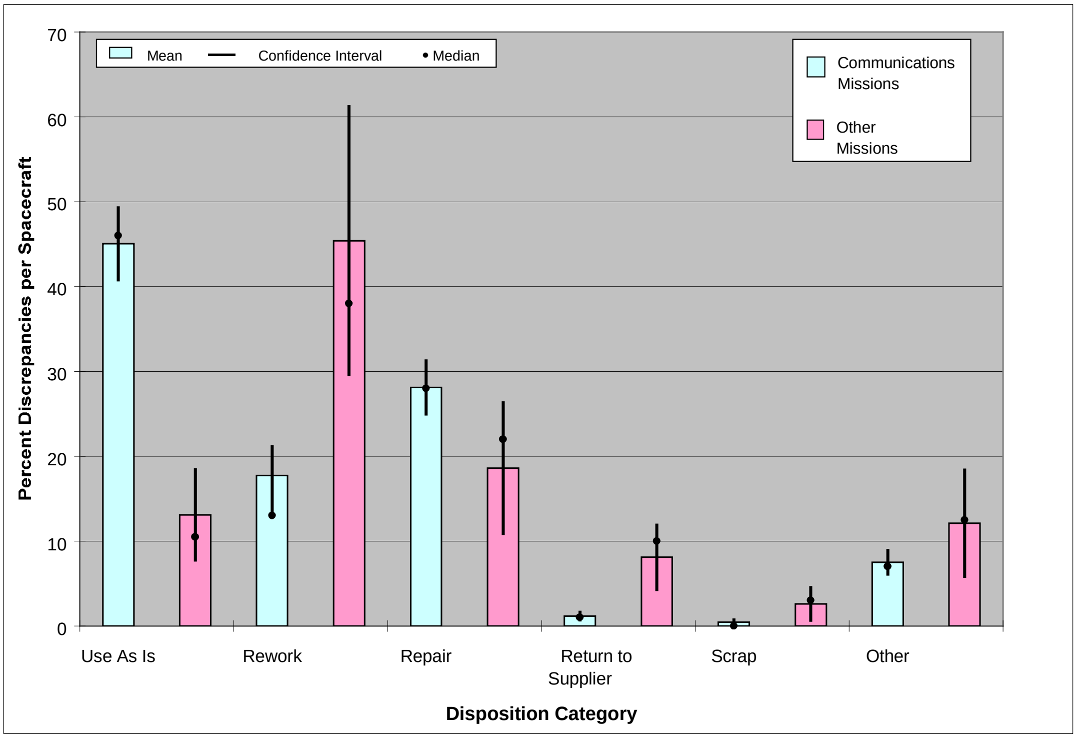


Figure 4.10: Means, confidence intervals, and medians for percent discrepancies per average spacecraft in each disposition category, broken down by mission area.

The percent of Use As Is dispositioned discrepancies is 45% for communications spacecraft versus 13% for non-communications spacecraft. In addition, the percent of Rework dispositioned discrepancies is 18% for communications spacecraft and 45% for non-communications spacecraft. With the exception of Return to Supplier, the other Disposition category bin means are statistically the same, meaning that communications and non-communications spacecraft are experiencing approximately equal percentage occurrences of Repair, Scrap and Other dispositions. Thus it would seem that communications spacecraft are choosing to use their discrepancies as is the same percentage of time that non-communications spacecraft are choosing to rework their discrepancies to make the spacecraft comply with the original blueprint.

The percent of Return to Supplier dispositioned discrepancies is 1% for communications spacecraft versus 8% for non-communications spacecraft. This is an interesting difference to note, and may be a result of the larger team efforts with many subcontractors and suppliers required to execute a non-communications (typically government) spacecraft contract.

4.6. Corrective Action

The data contained in the Corrective Action category describe the long-term corrective action that was prescribed to prevent the discrepancy from occurring on future spacecraft.

The Corrective Action category has eight bins. For a detailed description of each of these bins, please see Chapter 3. The eight bins are:

- Operator/Employee
- Drawing/Spec
- Process/Procedure
- Software Change
- Equipment
- Supplier-related
- No Action Required
- Other Corrective Action

4.6.1. All Spacecraft Corrective Action Means

Figure 4.11 shows the observed sample means of the eight Corrective Action category bins for the set of all spacecraft. The 95% confidence interval upper and lower bounds on those means, as well as the medians, are also shown in the figure. The No Action Required subcategory, with a mean of 23%, accounts for the largest percentage of corrective action for discrepancies on an average spacecraft. This is troublesome because it appears to point out missed opportunities for improvement. Toyota production philosophies say that mistakes are more valuable than gold, because they are opportunities for learning and improvement. Without mistakes, it is hard to improve. Thus, each discrepancy, or problem, points out opportunities for improvement. A measure of how well an organization is capitalizing on these opportunities is a measure of how an organization is learning and improving itself.

Employee/Operator, Drawing/Spec, Process/Procedure, Software and Equipment each account for between 11% and 17% of corrective action for discrepancies on an average spacecraft. Supplier-Related and Other corrective action each account for only a few percent of corrective actions for discrepancies on an average spacecraft. In addition, it was found that the supplier was involved in long-term corrective action only 1 out of 3 times per discrepancy whose root cause was traced to a supplied component. This disconnect will need to be addressed in the future. As spacecraft companies increase their reliance on suppliers and out-sourced parts, a close relationship with suppliers will become even more necessary and mutually beneficial.

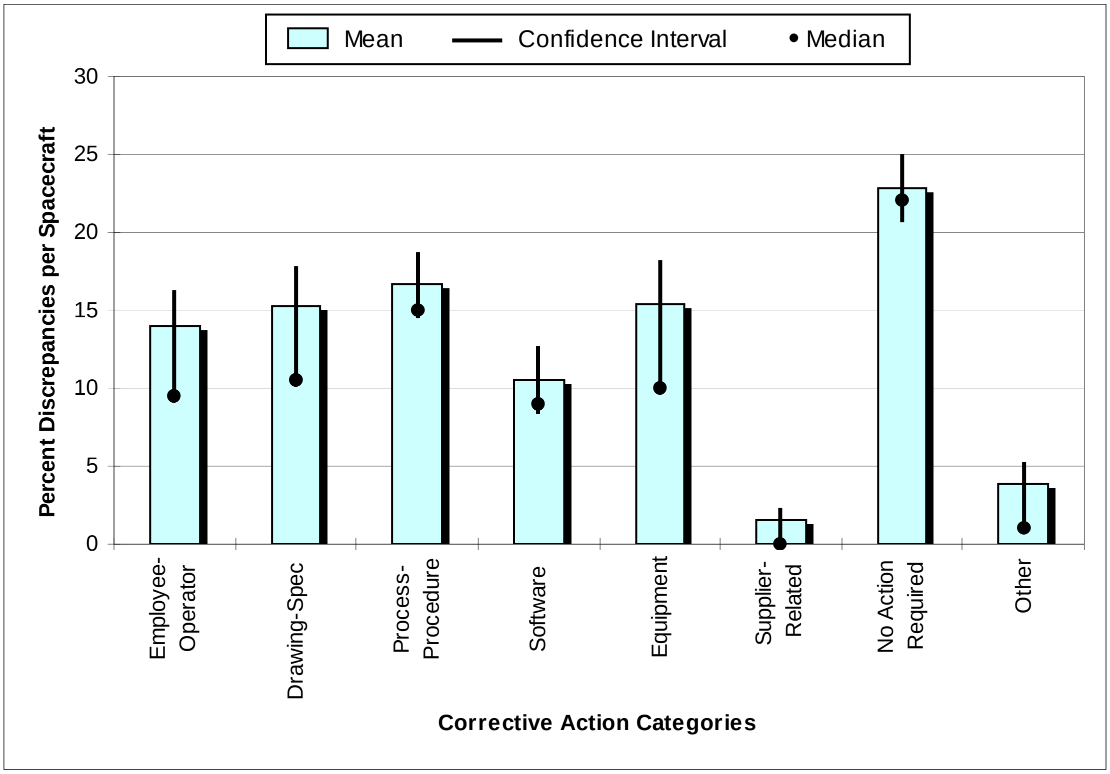


Figure 4.11: Summary chart of means, confidence intervals, and medians for percent discrepancies per average spacecraft in each corrective action category.

4.6.2. Corrective Action Means by Mission Area

Figure 4.12 shows the observed sample means of the eight Root Cause category bins for the subpopulations of communications mission area spacecraft and non-communications mission area spacecraft. The 95% confidence interval upper and lower bounds on those means, as well as the medians, are also shown in the figure.

Statistically significant differences in the means of the two subpopulations show up in the Process/Procedure corrective actions and Test Equipment corrective actions. A statistically significant difference occurs when the range of the confidence interval surrounding a mean for one population does not overlap with the range of the confidence interval surrounding a mean for the other population.

The percent of discrepancies prescribed Process/Procedure corrective actions is 14% for communications spacecraft versus 24% for non-communications spacecraft. The reason for this difference is not immediately apparent.

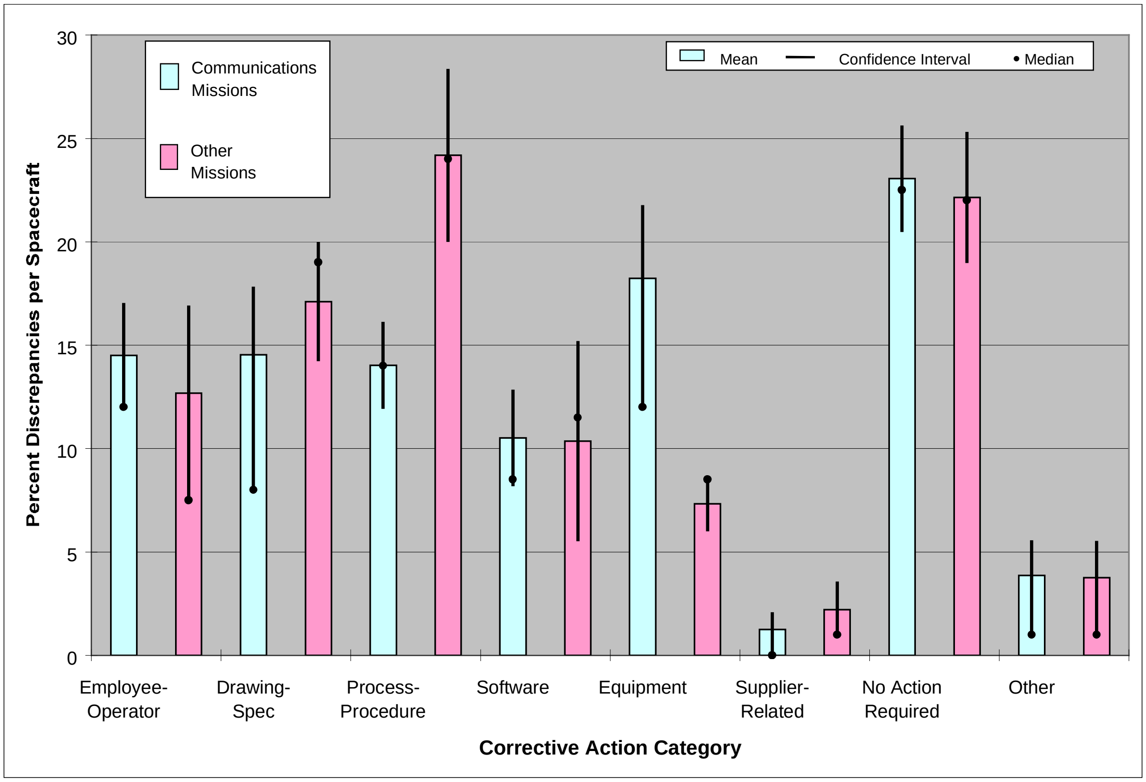


Figure 4.12: Means, confidence intervals, and medians for percent discrepancies per average spacecraft in each corrective action category, broken down by mission area.

The percent of discrepancies prescribed Test Equipment corrective actions is 18% for communications spacecraft versus 7% for non-communications spacecraft. This likely follows from the same type of difference between the two populations in the percent of Test Equipment causes. Since test equipment cause and test equipment corrective action are highly correlated, it would be expected that there would be similar proportions of test equipment corrective actions as test equipment causes.

But perhaps more interesting than the differences in the Corrective Action category are the similarities across the two different mission areas. Both communications and non-communications spacecraft are experiencing statistically the same percentages at system-level I&T of Operator/Employee corrective action, Drawing/Spec corrective action, Software corrective action, Supplier-related corrective action, Other corrective action, and No Corrective Action Required.

4.7. Open Duration

The data contained in the Open Duration category describe the time in days a discrepancy report remained open. Typically a discrepancy report is opened upon discovery of the discrepancy and closed upon resolution of the discrepancy and prescription of a corrective action. This open duration is not, however, an indication of the total labor hours that are spent on discrepancies. The Open Duration category has seven bins. The seven bins roughly correspond to months:

- 0-30 Days
- 31-60 Days
- 61-90 Days
- 91-120 Days
- 121-150 Days
- 151-180 Days
- Greater than 180 Days

4.7.1. All Spacecraft Open Duration Means

Figure 4.13 shows the observed sample means of the seven Open Duration category bins for the set of all spacecraft. The 95% confidence interval upper and lower bounds on those means, as well as the medians, are also shown in the figure. The 0-30 days subcategory, with a mean of 43%, accounts for the largest percentage of open durations for discrepancies on an average spacecraft. As the category bins get longer in duration, the percentages of discrepancies in the bins drop exponentially. Discrepancies open for greater than 180 days account for 12% of discrepancies at the system level of integration on an average spacecraft.

4.7.2. Open Duration Means by Mission Area

Figure 4.14 shows the observed sample means of the seven Open Duration category bins for the subpopulations of communications mission area spacecraft and non-communications mission area spacecraft. The 95% confidence interval upper and lower bounds on those means, as well as the medians, are also shown in the figure.

Statistically significant differences in the means of the two subpopulations show up in the 0-30 Days bin and the Greater than 180 Days bin. A statistically significant difference occurs when the range of the confidence interval surrounding a mean for one population does not overlap with the range of the confidence interval surrounding a mean for the other population.

The percent of discrepancies open 0-30 Days is 47% for communications spacecraft versus 29% for non-communication spacecraft. In addition, the percent of discrepancies open greater that 180 days is 10% for communications spacecraft versus 20% for non-communications spacecraft. The remaining Open Duration bins have statistically the same means for both subpopulations. Though the open duration is not a direct indication of how much time is spent on a discrepancy, an open discrepancy indicates that the spacecraft is not ready to be launched yet. Thus, long open durations do indicate potential delays in the delivery process and are important to monitor. The difference seen

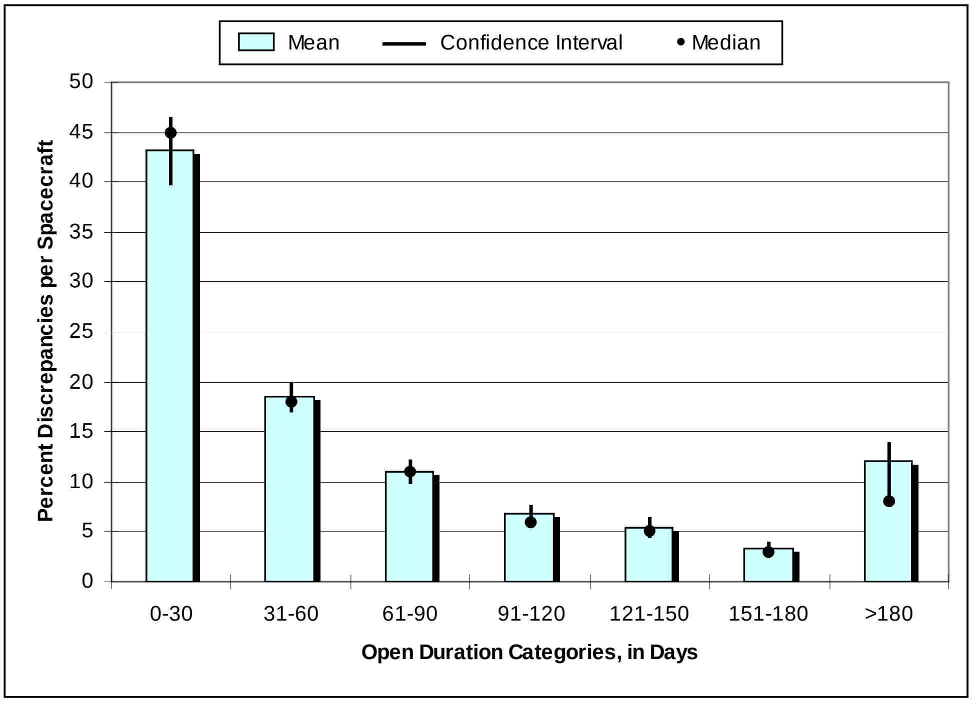


Figure 4.13: Summary chart of means, confidence intervals, and medians for percent discrepancies per average spacecraft in each open duration category.

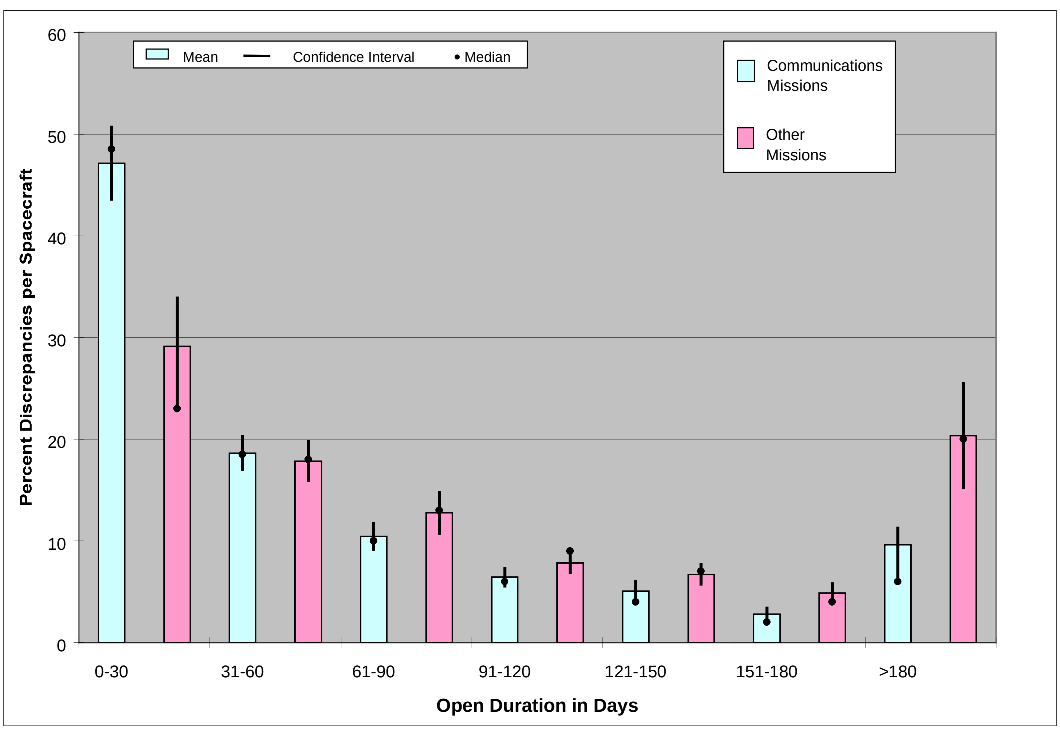


Figure 4.14: Means, confidence intervals, and medians for percent discrepancies per average spacecraft in each open duration category, broken down by mission area.

here between the two subpopulations may be proportional to the system-level I&T cycle times in each subpopulation. Since communication spacecraft system-level I&T cycle times are typically shorter than non-communications spacecraft, it may be expected that open durations would be somewhat proportional. Hence, the open durations for communications spacecraft should be shorter on average and are observed as such.

4.8. Conclusions

Analyzing the behavior of various aspects of discrepancies such as root cause, disposition, corrective action, and others used in this research can provide valuable insight for an enterprise. System test provides a learning opportunity for the organization and a chance to receive feedback on many aspects of the product development process, such as design and manufacturing. When enterprises learn and improve for the long term from the test activities, they increase value they derive from test activities.

The analyses of central tendency for spacecraft system-level I&T discrepancies demonstrate several key points.

- Problems with test equipment, defined as any non-flight equipment used in integration and test (I&T), comprise a large percentage of discrepancies reported during system-level I&T. Test equipment problems are clearly waste in the system-level I&T process.
- Test Equipment and Employee/Operator error together cause nearly half of the discrepancies. Particularly on commercial spacecraft product lines, these are the two resources that may be reused on subsequent spacecraft to come through the factory. Thus there is potential for large returns on investment in these two areas.
- The corrective action prescribed most often is “No corrective action,” reported in 24% of the discrepancies. This indicates missed opportunities for improvement in the enterprise.
- A significant percentage of subsystem discrepancies were discovered during system-level testing. If the goal is to drive testing to the lowest level possible, then opportunity exists for improvement. However, finding these problems at system-level test may be the most cost-effective method available, though no evidence has presented itself either way.

In summary, it appears that various aspects of the spacecraft industry are not yet aligned with addressing and solving problems using long term, cross-program, enterprise-wide solutions. Solutions optimized for the enterprise, not the program or spacecraft, are needed for long-term growth and prosperity of the enterprise.

Chapter 5.

Discrepancy Distribution Research: Results of Correlation Analysis

5.1. Chapter Introduction

The correlation, or degree of association of two variables, tells how independent the behavior is of those two variables. Thus, correlation is defined as the degree of relative correspondence between two sets of data. The correlation between variables X and Y, for example, can be interpreted as the ability to predict or explain the behavior of variable X based upon variable Y's behavior. It is important to note that correlation indicates a relationship between variables, but does not indicate a direction of causality of that relationship. It is also important to note that this chapter examines the correlation of aggregated data, and not the correlation of individual data points. Such individual data point correlation analysis is very time-intensive, and due to schedule constraints, was not performed in this research. However, such analysis would be a valuable follow-on activity to provide validation and additional insights into the aggregated data analysis present here.

This chapter explores the relationships observed between various affected subsystems, root causes, dispositions and corrective actions, and hypotheses are made about these relationships. Correlation analysis, performed using Spearman's Rho at the 0.01 or less level of two-tailed significance, and regression analysis form the basis for this chapter. Discussion of the relationships between various aspects of discrepancies are organized into three areas:

- Organizational learning
- Test Equipment relationships
- Spacecraft relationships

These correlation relationships are presented for the whole population of spacecraft used in this research, and are also contrasted with the relationships seen in two subpopulations:

- Communications Spacecraft – a spacecraft whose primary mission is to provide communications. This includes fixed and mobile broadcast, relay spacecraft, telephony, paging, and other transmission of communication services.

- Non-Communications Spacecraft – a spacecraft whose primary mission is not communications, though the spacecraft may have some communications capability. These spacecraft might have weather, remote sensing in the broadest sense, early warning, planetary or space science, etc. as their primary mission.

Statistically significant differences in the relationships between these two subpopulations and the whole population are noted, and hypotheses about those differences are presented. The chapter concludes by highlighting important analysis findings that underpin the themes of this monograph and form the basis for the recommendations presented in the final chapter.

5.2. Organizational Learning

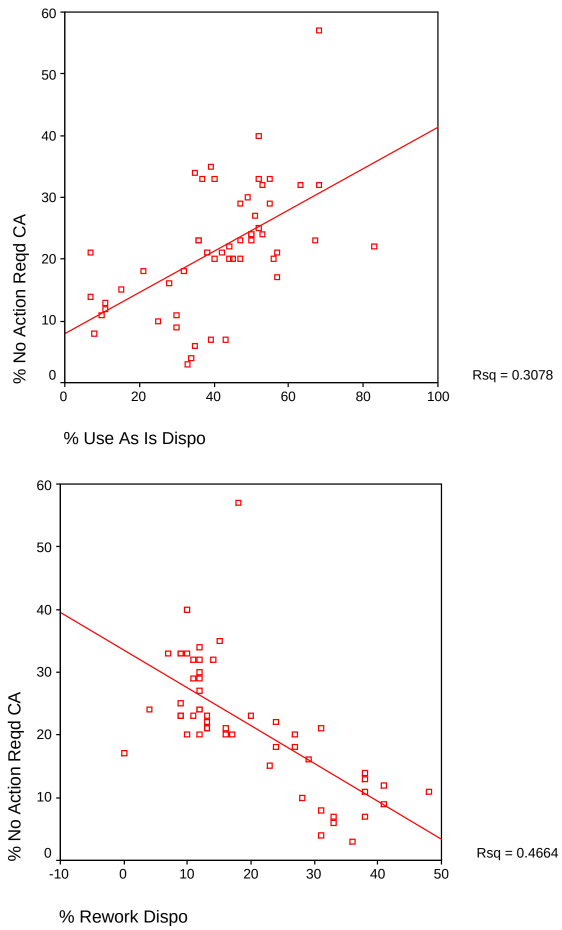
The ability of an organization to learn from its mistakes and grow over time is a necessary skill for organizational survival and competitiveness in the long term. Taiichi Ohno, a Toyota executive, was fond of his “Five Whys” tactic that helped to get at the real root of a problem and see ways to fix it from happening again. For example, he might ask someone “Why did that component break?” And they would answer, “The test equipment gave it the wrong command.” Ohno would then reply with “Why did the test equipment give the wrong command?” This line of questioning would then continue at least five iterations, after which time the real root cause of most problems was able to identified in such a way that the corrective action necessary to prevent the problem from reoccurring was easily recognizable.

As seen in Chapter 4, 24% of discrepancies were assigned no corrective action. From Ohno’s perspective, this would indicate that organizations are passing up opportunities to capitalize on their mistakes. Several correlations are present in the data set that give further insight into the issue and current state of organizational learning in the space industry.

5.2.1. No Corrective Action Required

There is a positive correlation between the No Action Required corrective action and the Use As Is disposition. As the number of Use As Is disposition discrepancies goes up, the number of No Action Required corrective actions goes up. A scatter plot of the correlation data is show in Figure 5.1. No Action Required corrective actions are those prescribed when it is determined that no corrective action is needed. Use As Is dispositions are those that use the anomalous item in its present state, not requiring any changes to the spacecraft.

This relationship indicates that a Use As Is discrepancy is likely to be prescribed no long-term corrective action. While it is understandable why a problem where no immediate fix action is taken would also be assigned no long-term corrective action, this does not indicate that organizations are emphasizing long-term learning. What is often missed on Use As Is discrepancies is that they can require significant analysis and investigation to reach the ultimate conclusion of “Use As Is.” Thus, they are not always inexpensive discrepancies, and their reoccurrence could cost an organization time and money.



(a) **(b)**

Figure 5.1: Scatter plots and linear regression lines for No Action Required corrective action and (a) Use As Is disposition and (b) Rework disposition.

There is a negative correlation between No Corrective Action required and the Rework disposition. As the number of Rework disposition discrepancies goes up, the number of No Action Required corrective actions goes down. A scatter plot of the correlation data is shown in Figure 5.1. No Action Required corrective actions are those prescribed when it is determined that no corrective action is needed. Rework dispositions are those that require the spacecraft to be altered to resemble the original blueprint.

This relationship indicates that a Rework discrepancy is unlikely to be prescribed No Corrective Action. This means that organizations seem to recognize that the kind of discrepancy that results in rework requires a corrective action for the long term. Rework indicates that the original blueprint or design for the spacecraft was correct, but the spacecraft is currently not in compliance with the blueprint and needs to be made compliant. In other words, deviations from the design in the manufactured item are recognized as requiring corrective actions. This demonstrates an area where organizations are learning for the long term.

5.2.2. Employees and Unknown Causes

There is a positive correlation between Employee/Operator corrective actions and unknown root causes. As the number of Unknown caused discrepancies goes up, the number of Employee/Operator corrective actions also goes up. A scatter plot of the correlation data is shown in Figure 5.2. Employee/Operator corrective actions include training, warnings, notifying supervisors, etc. Unknown root causes are causes that are unknown or unable to be determined.

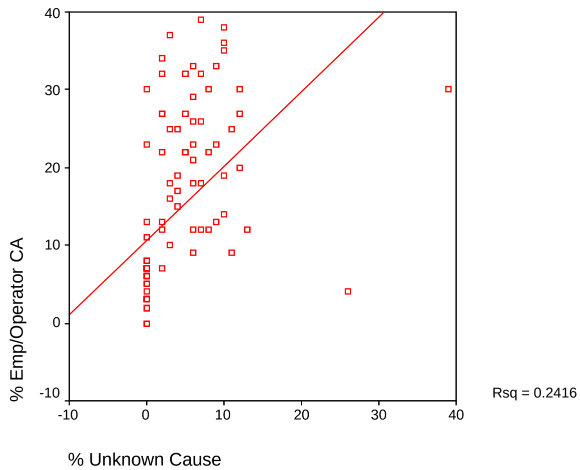


Figure 5.2: Scatter plot and linear regression line for Employee/Operator corrective action and Unknown cause.

It seems very typical that when a cause is not known, an employee would be the target of corrective action. However, an investigation of other circumstances surrounding unknown cause discrepancies might yield insights on more effective and focused corrective action.

5.3. Test Equipment Relationships

Test equipment is called out separately in this chapter for discussion, because there are many interesting correlations involving the equipment. In many ways, the relationships seen with the test equipment are part of the theme of organizational learning discussed above. Especially for commercial spacecraft product lines, test equipment is often reused on subsequent spacecraft, and hence learning and improvement for the long term in the area of test equipment has tremendous potential for large returns on investment. As seen in Chapter 4, test equipment accounts for nearly 30% of the discrepancies discovered in system-level integration and test.

5.3.1. Design Problems

Correlations between test equipment and the dispositions of rework and repair indicate that there are design issues with test equipment. Rework is defined as an immediate fix action that restores the discrepant part to its original blueprint or design. Repair is defined as an immediate fix action that leaves the discrepant part different from its original blueprint or design. Thus an increased amount of rework on the test equipment would indicate that the design of the test equipment is sound, but the equipment has perhaps not been manufactured to its intended design, while an increased amount of repair would indicate that the original design of the equipment cannot be used.

There is a positive correlation between Repair and the Test Equipment subsystem, as well as between Repair and Test Equipment cause. This means that as the number of discrepancies written against the Test Equipment subsystem go up, the number of Repair dispositions also goes up. Also, as the number of discrepancies attributed Test Equipment causes goes up, the number of Repair dispositions also goes up. A scatter plot of the correlation data is shown in Figure 5.3.

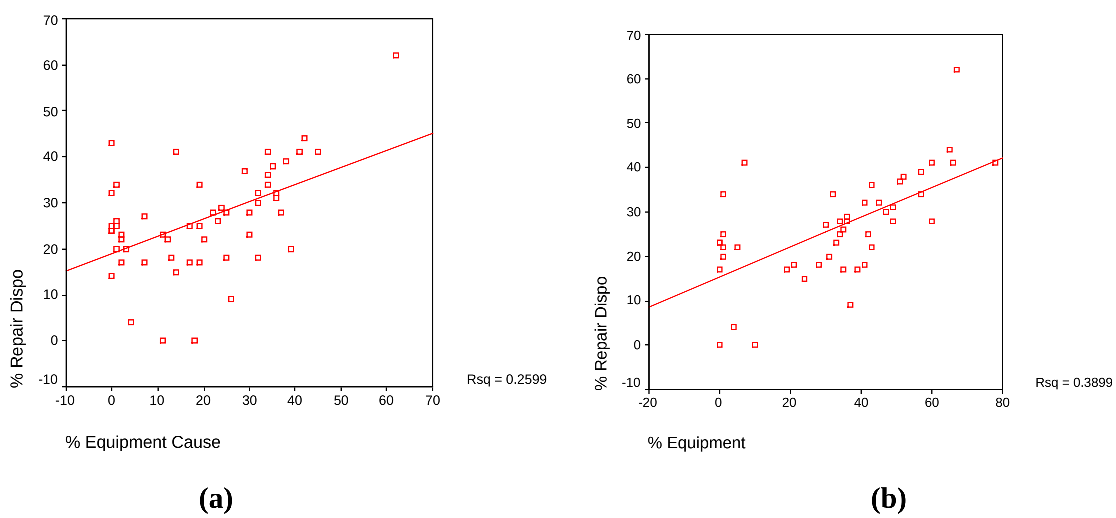


Figure 5.3: Scatter plots and linear regression lines for Repair disposition and (a) Equipment cause and (b) Equipment subsystem.

There is a negative correlation between Rework and the Test Equipment subsystem, as well as between Repair and Test Equipment cause. This means that as the number of discrepancies written against the Test Equipment subsystem go up, the number of Rework dispositions goes down. Also, as the number of discrepancies attributed Test Equipment causes goes up, the number of Rework dispositions goes down. A scatter plot of the correlation data is shown in Figure 5.4.

The positive relationship with Repair and the negative relationship with Rework presented here indicate that the Test Equipment may suffer from systemic design problems. Thus, investment in proper initial design of test equipment may help to reduce the number of discrepancies at system-level I&T.

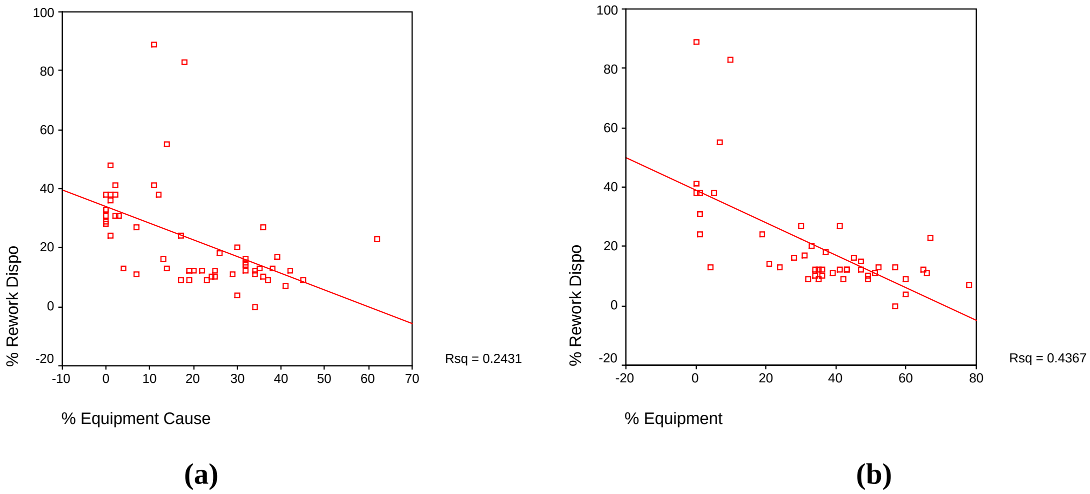


Figure 5.4: Scatter plots and linear regression lines for Rework disposition and (a) Equipment cause and (b) Equipment subsystem.

5.3.2. False Alarms

Correlations in the data with the No Anomaly cause indicate relationships that are responsible for "false alarms" in discrepancies. No Anomaly discrepancies are discrepancies that were written up in error or determined later to not be anomalies. False alarms cause time and resources to be spent on things that really aren't problems.

There is a positive correlation between the Test Equipment subsystem and No Anomaly causes. This means that as the number of discrepancies written against the Test Equipment subsystem goes up, the number of discrepancies attributed No Anomaly cause also goes up. A scatter plot of the correlation data is shown in Figure 5.5.

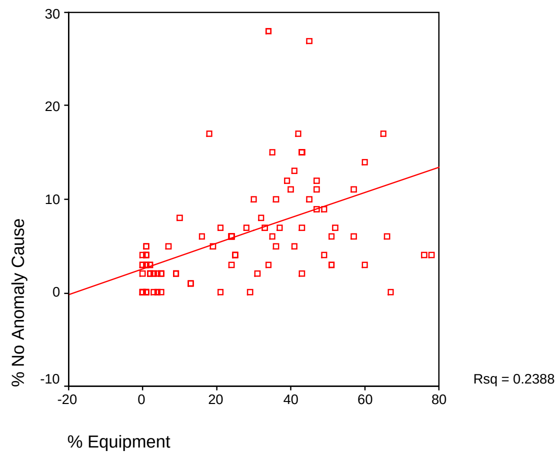


Figure 5.5: Scatter plot and linear regression line for Equipment subsystem and No Anomaly cause.

5.3.3. Differences for Communications Spacecraft

Certain stronger correlations with Test Equipment are seen in the subpopulation of communications mission area spacecraft.

There is a positive correlation between the Test Equipment subsystem and Test Equipment cause that is slightly stronger in the communications subpopulation than in the spacecraft population as a whole. This suggests that there is slightly better traceability from the Test Equipment subsystem directly to Test Equipment cause on communications spacecraft than on all spacecraft taken together.

There is a positive correlation between the Test Equipment subsystem and Unknown cause that is much stronger in the communications subpopulation that in the spacecraft population as a whole. This suggests that a discrepancy written against the Test Equipment subsystem is likely to result in an Unknown cause more for communications spacecraft than for all spacecraft taken together.

5.4. Spacecraft Relationships

A large number of significant correlations in the discrepancy data appears between subsystems, causes and corrective actions for spacecraft. The links between these areas for spacecraft systems are discussed here. By understanding the links of subsystems and causes with corrective actions, current practices for long-term corrective action in the spacecraft industry can be assessed.

5.4.1. Drawing/Specification Corrective Actions

The Drawing/Specification corrective action involves drawings or specifications that need to be changed, corrected or modified in any way. There is a positive correlation between the Drawing/Specification corrective action and the following three categories:

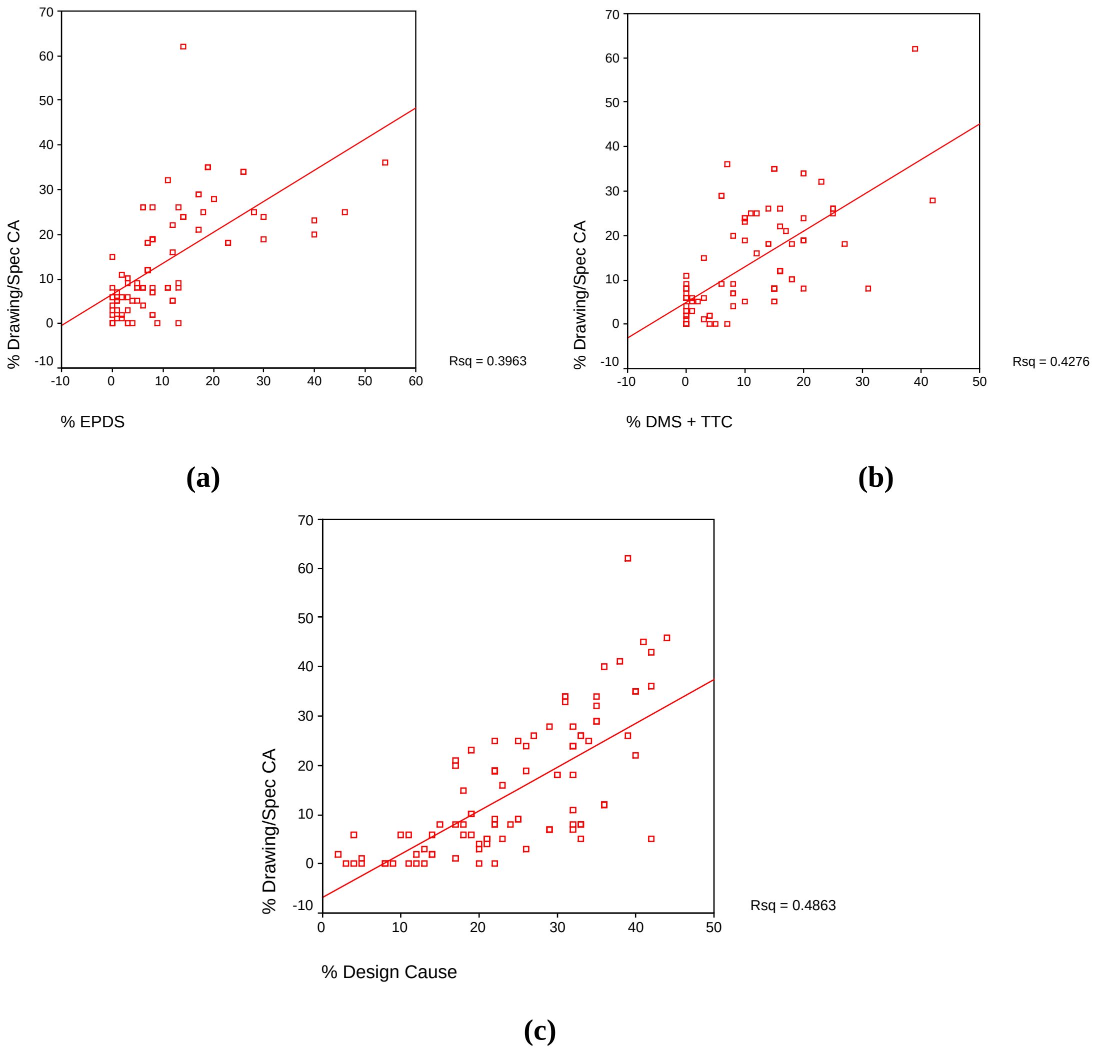


Figure 5.6: Scatter plots and linear regression lines for Drawing/Specification corrective action and (a) EPDS subsystem, (b) DMS/TTC subsystem, and (c) Design cause.

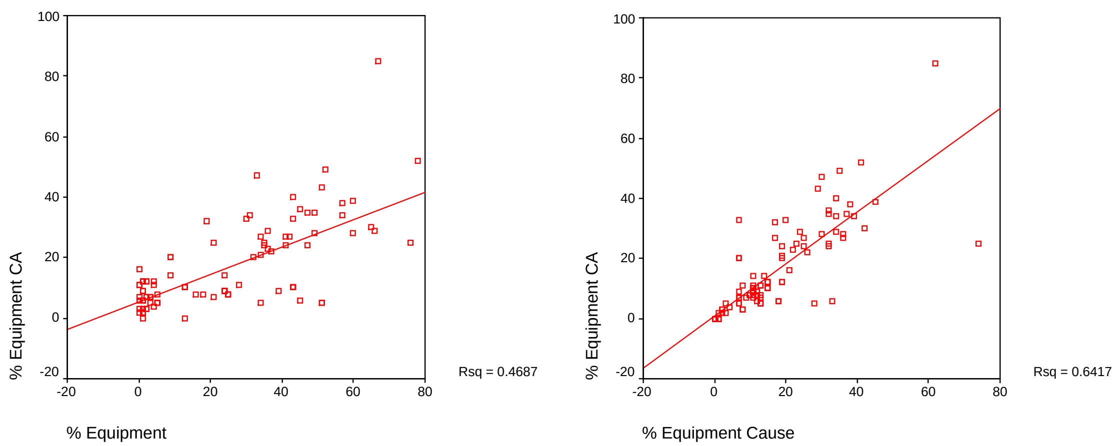
- EPDS – The electrical power distribution subsystem on the spacecraft is responsible for the generation, regulation, storage and distribution of electrical power through the spacecraft. As the number of discrepancies written against the EPDS subsystem goes up, the number of Drawing/Specification corrective actions also goes up.
- DMS/TTC – The combined Data Management subsystem and Telemetry, Tracking and Command subsystem distributes, accumulates, stores, formats and communicates data from the spacecraft, payload and the ground. As the number of discrepancies written against the DMS/TTC subsystem goes up, the number of Drawing/Specification corrective actions also goes up.

- Design Cause – Discrepant behavior caused by incorrect design of the spacecraft or processes/procedures associated with assembly and integration. As the number of discrepancies attributed to Design cause goes up, the number of Drawing/Specification corrective actions also goes up.

These positive correlations indicate that EPDS discrepancies, DMS/TTC discrepancies and Design-caused discrepancies are currently likely to be corrected for the long term with a drawing or specification change. A scatter plot of the correlation data is presented in Figure 5.6.

5.4.2. Test Equipment Corrective Action

The Test Equipment corrective action involves testing, manufacturing and assembly equipment that needs to be repaired, replaced, recalibrated, corrected, etc. Equipment is defined as an item of hardware involved in the I&T process that is not flight equipment on the spacecraft. There is a positive correlation between Test Equipment corrective action and discrepancies written against the Test Equipment subsystem, as well as a positive correlation between Test Equipment corrective actions and Test Equipment root causes. The correlation is somewhat weaker for the Test Equipment subsystem, but gets stronger once the root cause has been traced to Test Equipment. Scatter plots of these correlations are presented in Figure 5.7.



(a) **(b)**

Figure 5.7: Scatter plots and linear regression lines for Test Equipment corrective action and (a) Test Equipment subsystem, and (b) Test Equipment cause.

5.4.3. Software Corrective Action

The Software corrective action involves software changes, corrections or modifications either on the spacecraft or on the test/ground support equipment. There is a positive correlation between Software corrective actions and Software root causes. Software root causes are caused by software either on the spacecraft or on the test/ground support equipment. This demonstrates good traceability between the software causes and corrective actions. A scatter plot of the correlation is presented in Figure 5.8.

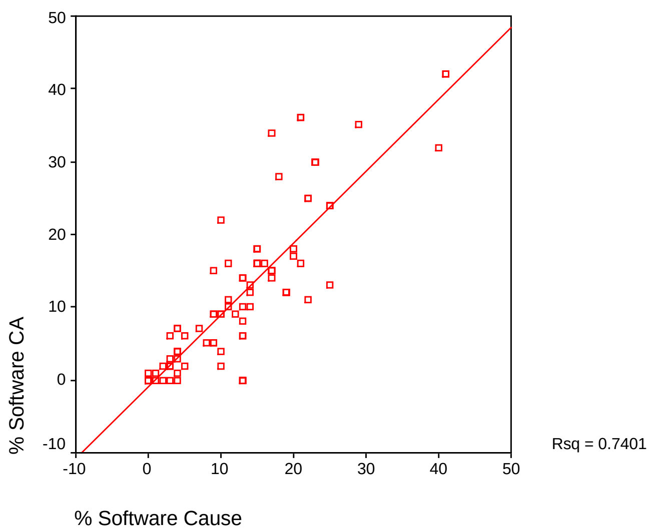
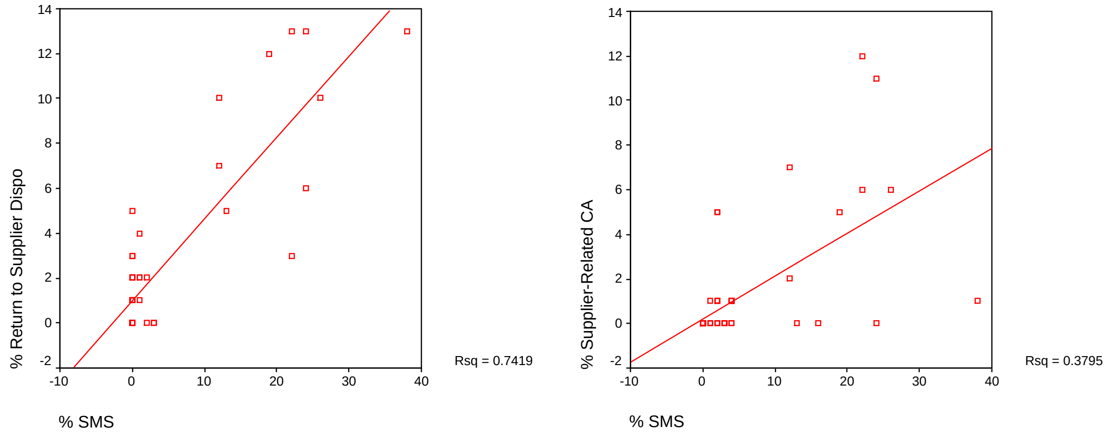


Figure 5.8: Scatter plot and linear regression line for Software corrective action and Software cause.

5.4.4. Supplier-Related Concerns

Correlation analysis reveals a relationship between the SMS subsystem and supplier-related dispositions and corrective actions. The Structures and Mechanisms subsystem (SMS) is responsible for providing support structure, booster adaptation, and moving parts for the spacecraft. A Return to Supplier disposition involves returning the discrepant part to its supplier, and a Supplier-Related corrective action involves a supplier or subcontractor.

There is a strong positive correlation between the SMS subsystem and Return to Supplier dispositions, and a weaker positive correlation between the SMS subsystem and Supplier-Related corrective actions. Scatter plots of the correlation are shown in Figure 5.9. The difference in the correlation strength between these two relationships indicates that not every Return to Supplier disposition received a Supplier-Related corrective action. This may be nothing alarming, but needs further investigation. On the surface, it appears as though suppliers, while helping to fix immediate problems, are being left out of the long-term corrective action loop. Mutually trusting and beneficial relationships all along the supply chain are critical to an enterprise's success, particularly on the issue of fixing problems.



(a) **(b)**

Figure 5.9: Scatter plots and linear regression lines for the SMS subsystem and (a) Return to Supplier disposition, and (b) Supplier-Related corrective action.

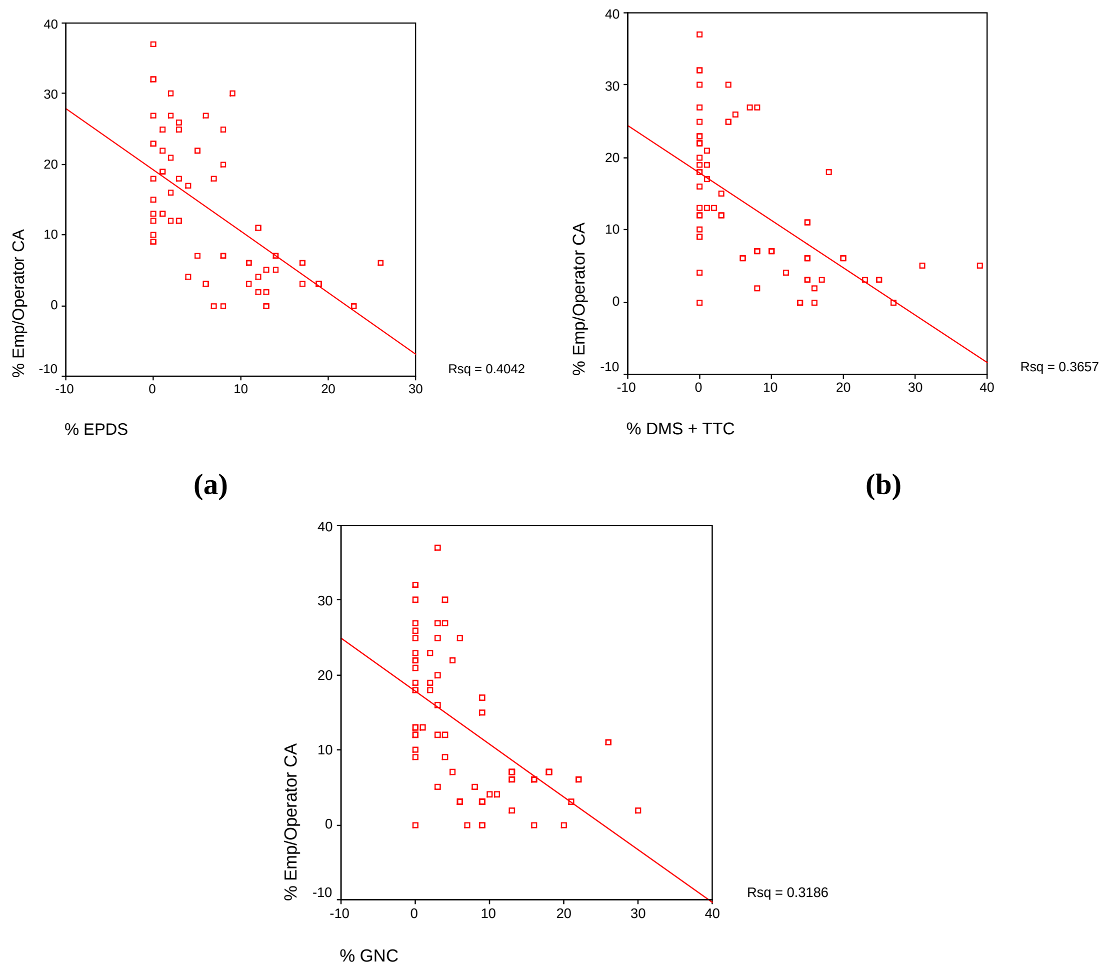
5.4.5. Differences for Communications Spacecraft

Certain stronger correlations with Employee/Operator corrective actions are seen in the subpopulation of communications mission area spacecraft. The EPDS subsystem, the GNC subsystem and the DMS/TTC subsystem all exhibit negative correlations with Employee/Operator corrective action. Employee/Operator corrective actions include training, warnings, notifying supervisors, etc. The three negative correlations seen with the subsystems are:

- EPDS – The electrical power distribution subsystem on the spacecraft is responsible for the generation, regulation, storage and distribution or electrical power through the spacecraft. As the number of discrepancies written against the EPDS subsystem goes up, the number of Employee/Operator corrective actions goes down. This correlation is much stronger in the communications subpopulation than in the spacecraft population as a whole.
- DMS/TTC – The combined Data Management subsystem and Telemetry, Tracking and Command subsystem distributes, accumulates, stores, formats and communicates data from the spacecraft, payload and the ground. As the number of discrepancies written against the DMS/TTC subsystem goes up, the number of Employee/Operator corrective actions goes down. This correlation is slightly stronger in the communications subpopulation than in the spacecraft population as a whole.
- GNC – The Guidance, Navigation and Control subsystem is responsible for providing determination and control of orbit and attitude, plus pointing of spacecraft appendages. As the number of discrepancies written against the GNC subsystem goes up, the number of Employee/Operator corrective actions goes

down. This correlation is slightly stronger in the communications subpopulation than in the spacecraft population as a whole.

Scatter plots of these three correlations are shown in Figure 5.10.



(a) **(b)** **(c)**

Figure 5.10: Scatter plots and linear regression lines for Employee/Operator corrective action and (a) EPDS subsystem, (b) DMS/TTC subsystem, and (c) GNC subsystem.

5.5. Conclusions

Analyzing correlation relationships between various aspects of test discrepancies, such as subsystems, root cause, disposition and corrective action lead to valuable insights for the enterprise. Many significant relationships with a single item, such as those examined for the test equipment, can indicate strong and constant trends over time. System test provides a learning opportunity for the organization and a chance to receive feedback on many aspects of the product development process, such as design, manufacturing and test. When enterprises learn and improve for the long term from the test activities, they increase value they derive from test activities.

The analyses of correlation for spacecraft system-level I&T discrepancies demonstrate several key points.

- Test Equipment, defined as any non-flight equipment used in integration and test (I&T), exhibits many strong relationships with various discrepancy aspects, most notably, indicating design problems and causing discrepancy false alarms. Test equipment problems are clearly waste in the system-level I&T process. Greater investment and attention to test equipment would help to reduce problems.
- No corrective action exhibits links with several immediate fix actions, giving insight into which kind of discrepancies are typically being prescribed corrective action and which are not. This indicates which kinds of discrepancies to focus on to reduce the occurrence of no corrective action being prescribed.

In summary, it appears that various aspects of the spacecraft industry are not yet aligned with addressing and solving problems using long term solutions. Solutions optimized for the enterprise, not the program or spacecraft, are needed for long-term growth and prosperity of the enterprise.

Chapter 6.

Discrepancy Flow Time Research: Methodology and Analysis Results

6.1. Chapter Introduction

Discrepancies in system-level integration and test are considered to be the most costly to fix, in general, with respect to all other levels of integration. Yet little published information exists on more precise costs of discrepancies at this level. Further, companies participating in this research reported they did not maintain very detailed records of the time employees spent on discrepancy discovery and resolution. It is difficult to evaluate the cost-benefit trades of fixing problems for the long term if the cost information is inadequate to perform such analysis. For the purposes of this research, time (labor hours, facility hours, etc.) will be used as a surrogate for cost.

This chapter describes the research design and methodology for investigating the cost of spacecraft system-level integration and test (I&T) discrepancies and presents results of that research. Key questions are presented, the research methodology is introduced, and the interview questions and resulting data products are explained. The results of the research are then summarized. Finally, potential sources of error are listed, as well as barriers encountered in the research and ideas for enabling further research in this area.

6.2. Key Questions

Several key questions that succinctly explain the research were formulated to help guide the research process. These are:

- How much labor time do discrepancies take?
- How much serial flow time do discrepancies take?
- How significant is that time?
- Is further research into discrepancy time warranted?

6.3. Research Methodology

Recorded data from spacecraft manufacturers on the costs of discrepancies were initially sought, but this information was not available in current cost accounting structures. This indicated that an alternative means of obtaining the data had to be used.

A survey instrument and a structured interview instrument for gathering this data were evaluated. A structured interview setting provided the best opportunity for obtaining complete and thorough data. It permitted asking for clarifications, explaining questions to respondents in more detail than possible on paper, and being confident of a high response rate.

Quality of information, not quantity, was stressed in the data gathering. Thus, an expert interview approach was chosen over a large sample size approach because there were few people in any organization who had enough insight on the time spent on discrepancies to provide a reasonable and credible answer to the interview questions.

Initial, unstructured interviews were set up at spacecraft manufacturer sites to see facilities, gather information on which product lines might be available for inclusion in the research and discuss which personnel would be needed for the structured interviews. Two spacecraft manufacturers agreed to make commercial spacecraft product lines available for this research.

On return visits to those two spacecraft manufacturer sites, 1- to 1.5-hour structured interviews were conducted with over 50 experts, including program managers, systems engineers, subsystem engineers, unit engineers, I&T engineers, and quality assurance engineers. The range of expert experience was chosen to include everyone who played in role in the discrepancy lifecycle, with a particular emphasis on non-factory floor personnel and non-program office personnel, such as the typically cross-program matrixed organization functions of system, subsystem and unit engineering. These experts were asked to give their best estimate of the probability distribution of labor hours they and their associated staffs would spend on different types of system-level I&T discrepancies throughout the entire discrepancy lifecycle. They were also asked to give a probability distribution of the serial flow time that gets spent on discrepancies at the system level of integration.

The probability distributions produced from the interview questions were used to generate expected values for the time required for different types of discrepancies. The different types of discrepancies had traceability to a particular feature in the discrepancy reports that were used in investigating the central tendency and correlation discussed in Chapter 4 and Chapter 5. Thus, an expected time value could be matched up to each discrepancy that had actually occurred on a program, and a total discrepancy time was calculated for each system-level I&T discrepancy on each spacecraft.

6.4. Interview Questions and Products

The three types of interviews conducted and the products drawn from them are listed below.

6.4.1. Initial Interviews and Products

These interviews were loosely structured and their main purpose was qualitative data gathering and familiarization. They were designed to elicit descriptions of the spacecraft manufacturer's organizational structure, their I&T structure and philosophy, and how personnel participated in system I&T and the discrepancy lifecycle. A graphic showing the various stages of the discrepancy lifecycle and the personnel involved in each stage is shown in Figure 6.1.

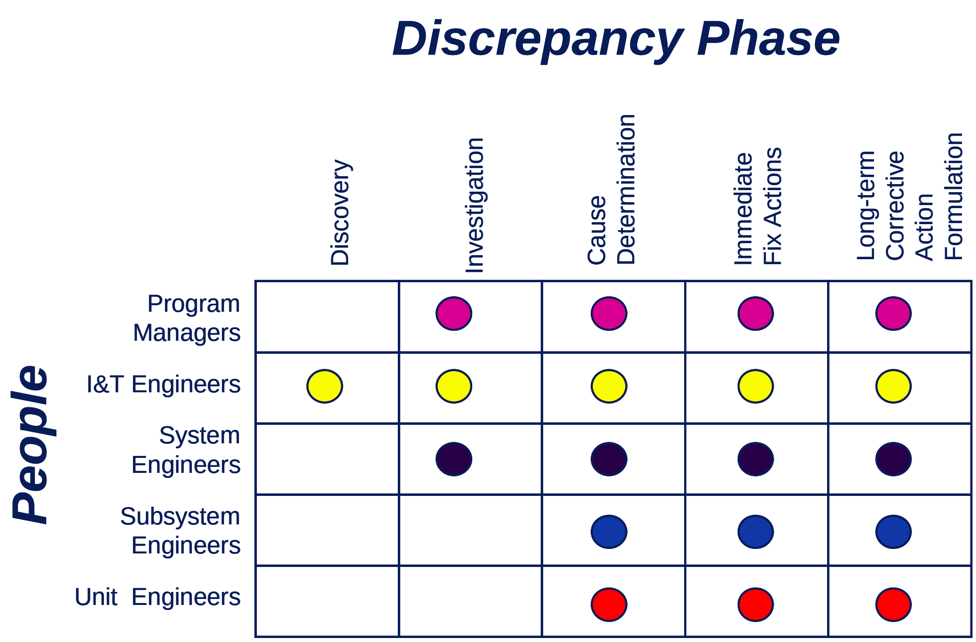


Figure 6.1: Matrix of discrepancy phases and employee involvement.

6.4.2. Structured Interviews on Labor Hours

These interviews were designed to elicit specific responses about the probability distributions of labor hours spent on discrepancies. Interviewees were told to consider all their associated staff, all the meetings, all the paperwork and all the analysis that goes on during the entire lifecycle of a discrepancy. They were then asked to answer a question such as "What is the distribution of labor hours you and your staff spend on mechanical discrepancies over the whole lifecycle of the discrepancy?"

6.4.3. Structured Interviews on Serial Flow Time Hours

These interviews were designed to elicit specific responses about the probability distributions of serial flow time hours spent on discrepancies. Interviewees were asked to think about the total production line downtime that is associated with different kinds of discrepancies, considering only the true downtime of the production line that prohibits the accomplishing of other tasks on the program. They were then asked to answer a question such as "What is the distribution of serial flow time hours for mechanical discrepancies?"

6.4.4. Structured Interview Products

These two types of structured interviews resulted in specific probability mass distributions for each type of discrepancy, reflecting the fact that there is variability in the time each discrepancy takes within a category. In equation form, the function $p_x(x_o)$ is known as the probability mass function (PMF) for discrete random variable *x*, defined by[20]

$$p_x(x_o) = \text{Probability that an experimental value of random variable } x \text{ obtained on a performance of the experiment is equal to } x_o$$

The PMF is often presented graphically. Figure 6.2 shows a sample probability mass function that resulted from the structured interviews.

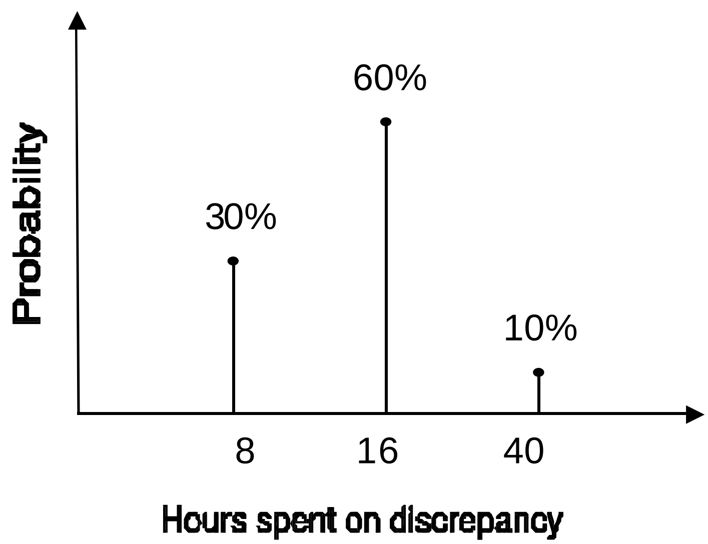


Figure 6.2: Graphical representation of sample probability mass function derived from interview data.

[20] Drake, Alvin W. Fundamentals of Applied Probability Theory. New York: McGraw-Hill, 1988. p. 45.

6.5. Deriving Data from Interviews

Using an expected value calculation, the expected time for a discrepancy type can be derived from its PMF as follows:

Let x be a random variable, and let *g(x)* be a single-valued function of its argument. Then *g(x)* is a function of a random variable and is itself a random variable. *E[g(x)]* is defined as the expectation, or expected value, of this function of random variable *x*, to be[21]

$$E[g(x)] \equiv \sum_{x_o} g(x_o) p_x(x_o) \equiv \overline{g(x)}$$

An example will help illustrate this. Using the PMF displayed in Figure 6.2, for a certain discrepancy type, the calculation for the expected value of that discrepancy type yields

$$\text{Expectation} = (8\text{ hrs}) \times 0.3 + (16\text{ hrs}) \times 0.6 + (40\text{ hrs}) \times 0.1 = 15.7\text{ hours}$$

After calculating the expected time for each discrepancy type as just demonstrated, the expected time for both labor hours and serial flow hours was summed for all discrepancies occurring on each spacecraft used in this cost part of the research. This produced two measures:

- Total labor time spent on system I&T discrepancies per spacecraft
- Total serial flow time spent on system I&T discrepancies per spacecraft

6.6. Results of Flow Time Analysis

Flow time findings are discussed in two categories: Labor time, and Cycle time. Labor time refers strictly to hours that personnel spend on certain tasks. Cycle time refers to the serial calendar time required to deliver the product. Time is important because it is a surrogate for cost. So far, this monograph has examined an enterprise-level picture of discrepancies at the system level of integration, but without an idea of the costs involved with those discrepancies, that picture is of questionable value to a decision-maker.

6.6.1. Labor Time

As discussed above, rough order of magnitude estimates were developed of commercial spacecraft discrepancy cost and schedule losses per spacecraft at the system level of integration. For an average commercial satellite, the total labor time spent on

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[21] Entire paragraph drawn from Drake, Alvin W. *Fundamentals of Applied Probability Theory*. New York: McGraw-Hill, 1988. p. 53.

discrepancies per satellite is about 12 to 13 person-years. This figure includes anyone in the organization who could reasonably be determined to play a part in the discrepancy process – from finding the discrepancy, through investigation, root cause determination, making repairs, and prescribing a long-term corrective action. This included program managers, system, subsystem and unit engineers, I&T personnel, and quality assurance. This estimate does not include the time of other people waiting that might be owed to a discrepancy occurrence. It also does not include facility time such as might be incurred by needing to rerun a test. Feedback from industry stakeholders indicates that these discounted areas might be large contributors to cost in and of themselves.

To translate the total labor time into a rough idea of cost, the labor time in person-years is multiplied by a full burdened cost estimate of a person-year in the aerospace industry. Using a figure of $160,000 per person year in $FY00[22], that equates to roughly $2M per satellite for discrepancy costs at the system level of integration. This does not include the cost of capital due to the associated cycle time delay (cycle time delay is discussed in the following section), which may be large.

To put the $2M cost of discrepancies figure into perspective, it can be compared it to an estimate of profit made on an average commercial communications satellite. Taking a number from a widely used textbook on spacecraft design, the average communications satellite costs about $130M[23]. If a profit margin per satellite of 15% is assumed, then the profit per satellite is approximately $20M. If discrepancies were eliminated at the system level, and all resulting cost savings were put towards that bottom line and not passed on to the customer, the profit margin per satellite would be increased by 10%.

6.6.2. Cycle Time

This research finds that on average, a commercial spacecraft would experience nearly two months of serial time delays due to discrepancies at the system level of integration. If the industry standard for commercial spacecraft cycles times have been 24-36 months in the 1990's, and the goal is to bring that down to 12-18 months in the coming decade, then this apparent cycle time delay will have to be addressed.

Figure 6.3 presents a summary of flow time findings. The labor time and cycle time impacts appear large, but currently these metrics are not adequately tracked to permit conducting cost-benefit trades on fixing problems for the long term. Further work is warranted in this area, with the potential for large benefits.

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[22] Wertz, James R. and Wiley J. Larson. *Space Mission Analysis and Design, Third Edition*. California: Microcosm Press, 1999. p. 801.
[23] Ibid p. 808.

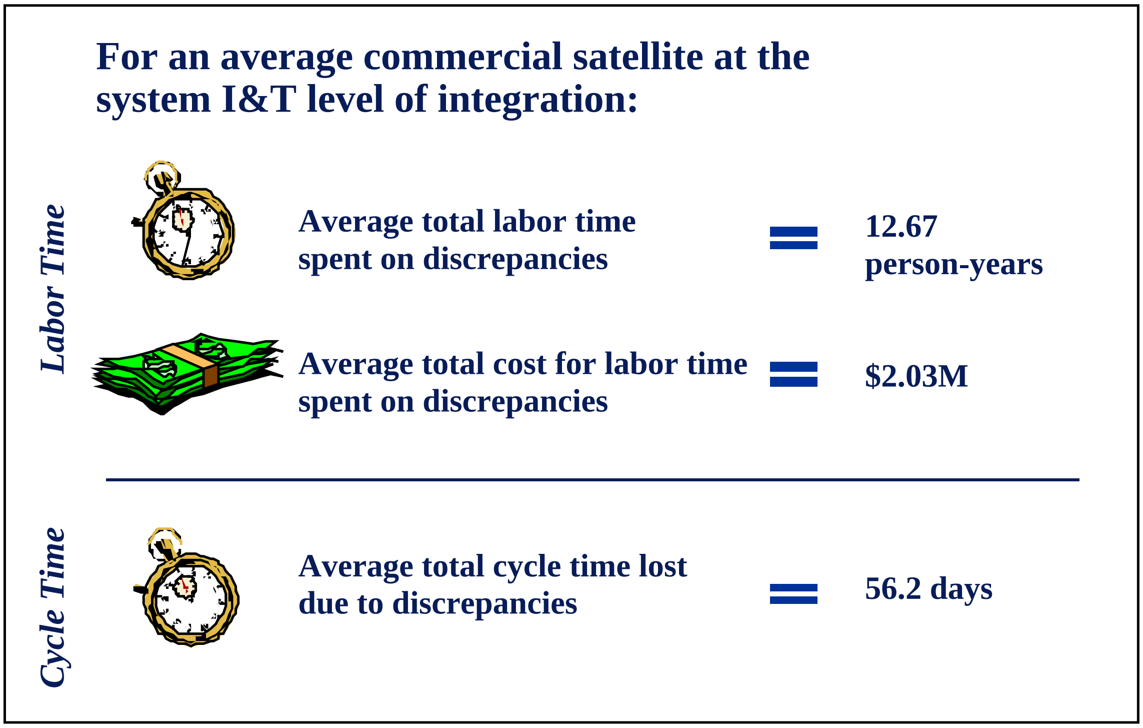

Figure 6.3: Graphic of Labor and Cycle Time Spent on Discrepancies at the System Level of Integration, per Spacecraft.

6.7. Potential Sources of Error

Since the labor and flow time data were obtained through interviews, they are subject to the errors inherent in interview data, namely the ability of interview subjects to accurately answer the questions being posed. Clarity of the questions and the ability of the interviewer to communicate the correct question also come into play.

The underreporting of socially undesirable behavior has been documented in other interview- and survey-based social science research efforts.[24] Fixing a problem is considered a somewhat socially undesirable behavior for the purposes of this research. This is actually beneficial for the cost research on discrepancies, for it means that the results presented here on the labor and flow time can be viewed as a kind of lower bound on the actual numbers. The actual time is likely much larger than the time reported through interviews.

[24] See Maisto, S.A et al. "Self-Report Issues in Substance Abuse – State of the Art and Future Directions" *Behavioral Assessment*, Vol. 12, No. 1. 1990. p. 117-134. And also, Hays, R.D et al. "Impact of Response Options and Feedback About Response: Inconsistencies on Frequency of Alcohol Use Self-Reports by Microcomputer" *Journal of Alcohol and Drug Education*, Vol. 42, No. 2. 1997. p. 1-18.

Lastly, the cost research is based on an expert interview approach instead of a large sample size approach because there were few people in any organization who had enough insight on the time spent on discrepancies to provide a reasonable and credible answer to the interview questions. As such, the results of the research are dependent on the quality of the information provided by those experts.

6.8. Barriers Encountered

Two barriers that were encountered in the course of the cost of discrepancies research were proprietary concerns by research participants and lack of standardization of systems across spacecraft manufacturers.

Proprietary concerns by spacecraft manufacturers were a similar barrier to the cost research as it was to the discrepancy distribution research described in Chapter 3. Proprietary concerns limited the detail level and granularity of information that could be exchanged, and this in turn limited the ability of the interviewer and interviewees to communicate in an efficient manner.

A lack of standardization across spacecraft manufacturer discrepancy reporting systems dictated that the interview questions had to be unique for each company participating in the cost of discrepancies research. This is because the cost interview questions need to be linked back to the discrepancy reporting systems. Because of the uniqueness of the questions to the different spacecraft manufacturers, direct comparisons between the companies at lower levels were very limited, and only a comparison in the aggregate would be possible.

6.9. Enabling Future Research

Research into the cost of discrepancies can be greatly enabled by the use of a higher fidelity cost accounting system. Such a system would track the people, materials, facilities and resources involved in the discrepancy lifecycle and keep a record of activities performed and time spent. In addition, such a cost accounting system should be integrated with the discrepancy reporting and tracking system, to enable real-time analysis of both jointly. The coupling of these two data sources can provide a powerful enabling tool for performing cost-benefit trades on repairs, corrective action, and implementing product development process improvements.

Chapter 7.

System Test as an Enterprise Enabler: Recommendations for Increasing Value

7.1. Summary of Research Findings

This monograph began by introducing some background on the origins of lean practices, the Lean Enterprise Model (LEM), and the spacecraft development process. Motivated by the LEM principles of waste minimization and continuous improvement, this research investigated spacecraft system-level integration and test discrepancies, which are considered waste in the integration and test process. If this waste could be removed, cost and cycle time reductions would follow, as well as quality and reliability improvements in the product. An examination of the distribution and flow time of spacecraft discrepancies at system-level integration and test yields several key findings for the enterprise:

- *Problems with test equipment comprise a large percentage of the discrepancies reported during system-level I&T.* Test Equipment, defined as any non-flight equipment used in integration and test (I&T), exhibits many strong relationships with various discrepancy aspects, most notably, indicating design problems and causing discrepancy false alarms. Test equipment problems are clearly waste in the system-level I&T process. Greater investment and attention to test equipment would help to reduce problems.
- *Half of the system I&T problems are caused by "non-spacecraft" things, such as human error and test support equipment*. Especially for commercial spacecraft product lines, the same workforce, as well as the same test support equipment, is reused in the production of subsequent spacecraft. Fixing discrepancies that are caused by human error and test equipment will thus yield benefits that scale with the production rate.
- *Cycle time and labor time impacts of system I&T discrepancies appear large, but currently these metrics are not tracked in adequate detail*. For spacecraft in this research, about 10% of the product development cycle time and 10% of the profit per product are spent fixing discrepancies at the system level of integration.

- *Organizations are passing up opportunities to capitalize on problems they have spent significant time and money to find*. Testing is an expensive part of any spacecraft development program. The high percentage of discrepancies for which no long-term corrective action is prescribed serves to enhance the point of missed opportunities. In addition, interview data suggests that follow-through on prescribed long-term corrective actions tends to get overcome by more urgent and immediate needs.

In summary, there appears to be inadequate long-term organizational learning and improvement from test discrepancies in the spacecraft industry. Though discrepancies on a spacecraft in system test are rectified and the spacecraft is made fit to fly, less attention appears to be focused on preventing the cause of that discrepancy from occurring again on future spacecraft. It also appears that various aspects of the spacecraft industry are not yet fully aligned with addressing and solving problems using long term, cross-program, enterprise-wide solutions. Solutions optimized for the enterprise, not the program or spacecraft, are needed for the true long-term growth and prosperity of the enterprise.

7.2. Recommendations

Significant opportunities exist to increase the value-added contribution of test across the entire enterprise. Several important recommendations emerge out of this research that will help organizations to make progress towards that end. A list of the Lean Enterprise Model (LEM) Overarching Practices (OAPs) that support each recommendation is also given. Please see Chapter 1 or http://web.mit.edu/lean for more information on the Lean Enterprise Model.

7.2.1. Establish Inter-Organization Discrepancy Working Group

An inter-organization discrepancy working group composed of spacecraft manufacturers and government agencies should be established. This working group would set compatibility guidelines for discrepancy reporting across the spacecraft industry so that discrepancy data from different spacecraft manufacturers can be studied. These guidelines might resemble the discrepancy data categorization system used for this research and presented in Chapter 3. This categorization system does not require changes to individual spacecraft manufacturer reporting systems, but instead would provide a mapping or translation from individual company discrepancy reporting systems into a common industry-wide discrepancy data categorization system.

This inter-organizational discrepancy working group could perform an industry-wide assessment of discrepancies on a periodic basis, bringing to light systemic problems in the industry that might benefit from shared pre-competitive research projects. These pre-competitive research projects could be sponsored by the government, cost-shared between government and industry, or wholly funded by industry. In addition, a pre-competitive R&D organization for the spacecraft industry, similar to SEMATEC for the semi-conductor industry, could be established in the future to execute these research projects.

This recommendation is supported by the following LEM OAPs:

- 1: Identify and optimize enterprise flow
- 2: Assure seamless information flow
- 6: Develop relationships based on mutual trust and commitment
- 7: Continuously focus on the customer
- 9: Maximize challenge of existing processes
- 10: Nurture a learning environment
- 12: Maximize stability in a changing environment

7.2.2. Align Incentives

It is critical to align incentives, in the broadest sense and at all levels, with fixing problems for the long term. Interview data suggest that the current incentive structure in organizations may not be entirely consistent with this, and needs some examination in that regard. In particular, organizations appear to be structuring incentives that result in a sub-optimization of performance and profit at the program level. Incentives should instead be structured to optimize performance and profit at the enterprise level.

This recommendation is supported by the following LEM OAPs:

- 1: Identify and optimize enterprise flow
- 8: Promote lean leadership at all levels

7.2.3. Continuous Improvement

Continuous improvement should be encouraged, valued and maintained as part of the corporate culture. Through an attitude of continuous improvement and desire for long-term organizational learning, the rewards of waste minimization and a lean environment can be achieved. Improvement also involves a commitment to find the true root cause of discrepancies or problems, and implement an enterprise-wide solution to prevent them from reoccurring. While many companies have already made strides along these lines, more support and appropriate recognition needs be given to employees at all levels that are eagerly trying to pursue the goals of continuous improvement. Barriers they frequently encounter need to be identified and broken down. Finally, improvements need to be measured and evaluated for their effectiveness.

This recommendation is supported by the LEM principle of continuous improvement. It is also supported by the following LEM OAPs:

- 1: Identify and optimize enterprise flow
- 3: Optimize capability and utilization of people
- 7: Continuously focus on the customer
- 10: Nurture a learning environment

7.2.4. Collect Data and Perform Trades

While some data is currently being tracked for discrepancies, increased data collection on several aspects of discrepancies would be very beneficial to an organization. In particular, data on costs and cycle time delays associated with discrepancies should be collected in greater detail than is currently practiced. This data then forms the basis for evaluating a host of cost-benefit trades on reducing waste – discrepancies – from the integration and test process by improving the upstream product development processes. Cost-benefit is a key decision criteria for both commercial and government programs, and proper data is required to achieve a meaningful metric. Accounting systems will likely have to adapt to the new data collection requirements, and some investment will be required. It is anticipated that this investment will pay for itself from savings on future spacecraft.

This recommendation is supported by the following LEM OAPs:

- 1: Identify and optimize enterprise flow
- 7: Continuously focus on the customer
- 9: Maximize challenge of existing processes
- 12: Maximize stability in a changing environment

7.3. Concluding Remarks

If discrepancies can be better understood, then perhaps they can be reduced or even eliminated. Reducing discrepancies will result in cycle time and cost savings, as well as increased product quality and reliability. This research has taken a first step towards that goal for the spacecraft industry by characterizing the cost and flow time impacts of system-level integration and test discrepancies. Industry and government must take the next steps by implementing the recommendations presented above. If these recommendations are implemented, it is the authors' belief that long-term rewards can be reaped across the entire spacecraft enterprise, benefiting customer and spacecraft manufacturer alike.