A Predictive Troubleshooting Model for Early Engagement

by

Glenn Bergevin

B.S. Mechanical Engineering,
University of Massachusetts Amherst, 2008

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A Design for Troubleshoot Tool to Align Engineering Organizations

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Abstract

Raytheon Integrated Defense Systems (IDS) is home to Circuit Card Assembly, the department responsible for the production of circuit card assemblies from across all of Raytheon's businesses. Circuit Card Assembly includes manufacturing, test, quality, finance and other groups, functioning as its own business within Raytheon IDS. Circuit Card Assembly competes with external vendors for contracts from Raytheon businesses outside of IDS, thus the pursuit of competitive advantage in the form of technology, quality and throughput is a continuous activity.

Circuit Card Assembly spends upwards of a million dollars each year on troubleshooting circuit card assemblies that fail first pass testing, in labor alone, with additional costs associated with reprocessing and material replacement. This thesis describes the creation of a design tool that improves electrical design for test, reducing wasteful troubleshooting on hundreds of products each year, saving tens of thousands of dollars on high cost programs, with incremental yearly savings totaling in the hundreds of thousands, and a net present value of over 2.5 million in labor savings. The tool provides designers with real time feedback regarding the impact their design decisions have on expected troubleshooting activity, and provides guidance to improve troubleshootability. The tool reduces spending on non-value added activity buy an average of 50%, while at the same time helping fulfill Circuit Card Assembly's mission to engage design teams at the earliest stages of product development, before potentially costly decisions are finalized and beyond Circuit Card Assembly's ability to influence.

The subject of interaction between groups in different functional silos, between independent Raytheon businesses and with seemingly disparate incentives is investigated as it pertains to the development of the design for test tool. The method of action of the design tool at a personal or organizational level is to raise awareness of total product cost and allow disparate teams to communicate in the same language with a more complete understanding of how to achieve corporate level goals. Communicating effectively across business and functional barriers is the greatest achievement of the new tool, but also the greatest roll out and developmental challenge. The tool is part of a suite of similar activities driving towards operational excellence within CCA.

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Acknowledgments

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I'd like to thank the LGO class of 2013, especially the Davis crew and the MPC. Even if I could have done it without you, I wouldn't have wanted to.

I'd like to thank my family. My mom and dad, for being utterly unsurprised when I told them I got into MIT, and filling my childhood with the love, LEGOs, Transformers and books I needed to get there. My cats, Mounds and Mukwa, for greeting me at the door every night, helping me relax and occasionally, literally, eating my homework.

Finally, I'd like to thank my wife, Melissa Bergevin. I'm glad I could share this time with you. Thanks for helping me do this. I love you.

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Biographical note

Glenn Bergevin was born in Cambridge, Massachusetts. His engineering career began shortly thereafter. Building LEGO space ships longer than he was tall, transforming his Transformers and taking apart his bike occupied his free time. As many little boys do, he 'helped' his father with household chores; the notable difference being that Glenn's help usually meant the difference between getting the job done and calling a professional. Even before he had the strength to turn the screwdriver or wrench, he could see how to solve problems and get his dad to do the grunt work.

Glenn got older and considerably larger, and turned his passion for bicycles and newfound ability to turn wrenches into a career as a bicycle mechanic. Assembling and fixing bicycles at the Cycle Loft gave Glenn a firsthand look at how hundreds of products are made and fit together, forever influencing his thinking about design for assembly and quality. He graduated from sweeping floors to selling bikes, parts and service almost immediately, practicing every day the public speaking skills he would go onto leverage later in life as a consultant and engineer.

Glenn enrolled at UMass Amherst in pursuit of a mechanical engineering degree, which surprised no one. As he progressed academically, the bike shop eventually gave way to professional internships. Glenn designed experiments to minimize production tool downtime at Entegris. Later, he designed tools and fixtures for jet engine assembly and maintenance. Both jobs leveraged the practical skills he had picked through a lifetime of being hands on and the scientific, systematic problem solving skills taught at UMass.

After graduating with honors, Glenn began designing consumer products at Bose. Spending most of his time there with the VideoWave team, Glenn designed over a dozen parts and assemblies, in injection molded plastic, cast zinc and aluminum, and sheet metal, fusing his passion for design with Bose's uniquely integrated approach to product design, which put him in close collaboration with manufacturing and plastics engineers, purchasing and suppliers, in addition to other engineering functions. Glenn's time at Bose was fruitful, but after careful consideration he left for Veryst Engineering.

Veryst Engineering, only four engineers when he signed on, offered Glenn the opportunity to work on incredibly challenging engineering problems as a world class engineering consultant. Being part of a small team afforded Glenn opportunities for increased responsibility, and a vastly broader range of duties. He managed Veryst's lab and shop spaces, including onsite testing facilities, a prototyping and office space at Veryst's second location, and a third warehouse facility housing Veryst's semi-truck scale energy harvesting system – the deliverable of a project he lead. Veryst represented an opportunity to work beyond an engineering role, shaping not just a part or a product, but a business.

Glenn's experiences in the working world brought him to a few conclusions. Product development was important to him – he had been in the thick of it at Bose, and wanted to find his way back. At the same time, so was leadership. He had been inspired by great mentors and managers in his career, and wanted to be able to help others grow as he had been helped. Glenn also saw the power of a technical background combined with managerial acumen – he wanted the chance to shape a business the way he had shaped products. He decided he wanted to get an MBA, to learn the business side of product development and grow as a leader, but he wanted to pursue a master's in mechanical engineering at the same time, to stay true to his roots and ensure he would be technically relevant in the future.

So it was with great joy that Glenn returned to Cambridge, to become a Leaders for Global Operations Fellow at the Massachusetts of Technology, where he has studied Marketing through the Sloan School of Management, Leadership as an LGO, and Product Development and Energy and Sustainability through the Department of Mechanical Engineering.

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1 Introduction

"The goal of a manufacturing organization is to make money."[1]

Perhaps this is obvious, but the finer points of how a business may proceed to do so are not always so cut and dried. At Raytheon, the enormous Massachusetts based defense and aerospace contractor, thousands of engineers and managers make decisions that influence how money is made. In the context of each individual's training, function, organization and project, they do the best they can. This thesis drills down into one particular branch of Raytheon's complicated, many-layered organizational structure to examine how different groups interact and how data driven tools can raise the collective bandwidth of a group of individuals to enable smarter decision making and, ultimately, make more money.

The technical subject of this thesis is a design for troubleshoot tool that Raytheon desires to provide early, data-rooted feedback to design teams to enhance the testability/troubleshootability of their designs. Raytheon troubleshoots thousands of circuit cards each year in the course of business, a fundamentally non-value added activity that improved communication and design practices could drastically reduce. This is a problem because troubleshooting so many products, and spending often multiple hours on particularly challenging products, contributes operational difficulties in the form of reduced throughput, increased overtime processing, and challenges the supply chain and manufacturing organization to keep up with fluctuating demand for specialty components. Troubleshooting labor costs alone totals over a million dollars per year. Current design practice places little emphasis on design for test and troubleshoot, leading to difficult to troubleshoot products and waste in manufacturing, which drives up product cost and inhibits Circuit Card Assembly's ability to acquire new business. As the tool is adopted by Raytheon and the product pool shifts to reflect the information it provides, the projected cost savings due to improved new products is in tens of thousands of dollars per product. Products designed with greater testability through the application of this tool have the possibility of cumulative saving hundreds of thousands of dollars per year, giving the project a present value of over $2.5 million.

The design for troubleshoot tool combines design factors selected for their statistical strength and ability to predict troubleshootability as well as factors intended to further promote whole life cost awareness early in the design process. The tool outputs both yearly and per unit troubleshoot scores, normalized against historical data, with an accompanying color grade to calibrate users to the relative quality of their design. Graphical outputs position the design relative to the database of products used to develop the tool, while the graphic user interface allows users to select input factors to use as filters to generate a 'similar to' list of products, with their associated troubleshoot scores, providing a path to investigate successful products and incorporate the relevant pro-troubleshoot characteristics into the new design.

The core of the tool is data, which is used to synthesize a driving equation for troubleshoot based on CCA's recent production history. Combining statistics with a heavy dose of the decades of tribal knowledge embodied in CCA's test engineering staff, the design for test tool offers new and unique insight into a persistent, expensive problem, and promises to build stronger relationships between design and manufacturing while helping Raytheon produce better products.

1.1 Raytheon and Circuit Card Assembly

Figure 1 Raytheon's corporate headquarters in Waltham, MA.

Raytheon, headquartered in Waltham, Massachusetts, Figure1 builds defense products primarily for the Unites States government, but sells its products globally. Raytheon was born in 1922 building machinery, over the decades acquiring companies like Hughes Aircraft's and Texas Instrument's defense divisions to bolster their homeland security and defense portfolio. A large company by any measure, Raytheon employs over 71,000 employees across the globe and enjoyed over $25 billion dollars in net sales in 2011. Raytheon is a proud company, proud of its work and its products, as well as its role as a supporter of homeland security and strengthening the defenses of the United States and its allies. Raytheon's products are decidedly high-tech, from missile systems deployed from combat aircraft down to sophisticated weapon sights used by individual soldiers, or 'warfighters' in Raytheon parlance. Raytheon's corporate vision is straightforward, captured in Figure 2.[2]

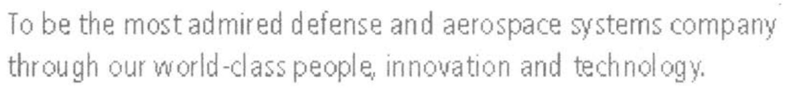
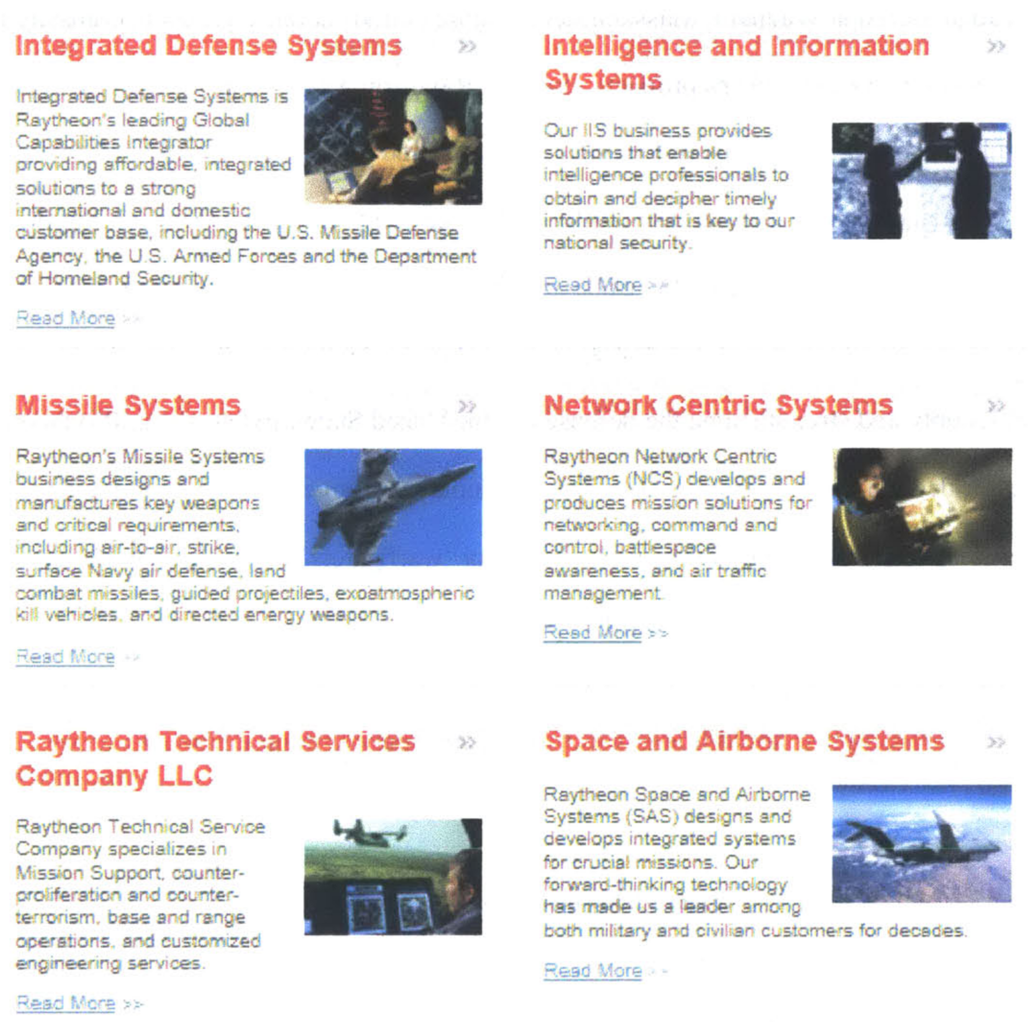

To be the most admired defense and aerospace systems company through our world-class people, innovation and technology.

Figure 2. Raytheon's corporate vision

To make that vision a reality, Raytheon organizes itself into six businesses, reflecting the pattern of growth through acquisition Raytheon has followed, each with its own technical, operations and general administrative staff. Each business operates as an independent unit, with its own president reporting to the CEO at Raytheon Corporate. The six businesses described in Figure 3.



Integrated Defense Systems »

Integrated Defense Systems is Raytheon's leading Global Capabilities Integrator providing affordable, integrated solutions to a strong international and domestic customer base, including the U.S. Missile Defense Agency, the U.S. Armed Forces and the Department of Homeland Security.

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Figure 3. Raytheon's businesses

The largest Raytheon IDS site is Raytheon Integrated Air Defense Center, or IADC, located in Andover, MA – the home of the author's internship, upon which much of this thesis is based. IADC is noteworthy for being the home of the Patriot missile defense system, Figure 4, and for being the seat of Circuit Card Assembly (CCA), Raytheon's circuit card manufacturing group. Beyond the fundamental manufacturing activities associated with actually assembling circuit cards, CCA includes sophisticated production support groups that handle quality, testing and engineering activities, as well its own as finance, business development, human resources and IT staff to support the business as a whole. CCA managers and engineers strive for customer satisfaction in the form of on-time, on-budget delivery of defect free, high quality products.

Figure 4 A Patriot Missile System

CCA handles over 50 active programs, introducing nearly 300 new products on an average year, producing hundreds of thousands of individual cards annually. CCA is the default vendor for its parent business, IDS, but within IDS it operates as its own entity and competes on the open market with other circuit card assembly producers for contracts from other Raytheon businesses. Out of necessity, CCA embraces and internalizes Raytheon's push to embody technological leadership and maximize customer satisfaction [2].

As 'a self-directed business within the Raytheon business,'[2] earning its contracts competitively, CCA has an imperative to reduce costs. One way it does so is through early engagement with its customers, partnering with design teams to help them see the bigger picture of product development that includes manufacturing, quality, test, etc.; the 'back end' of product development so often neglected in the design room.

CCA values data, and uses manufacturing data to produce tools it shares with designers to enable them to make smarter design decisions. Historically, these tools have focused on manufacturing, choosing components and operations that minimize defects. CCA is committed to maximizing first pass yield though controlled, reliable manufacturing techniques, but given the complexity of the product and the tremendous number of opportunities for defects to occur, a certain number of escapes are inevitable. Coupled with frequent line changeovers and some degree of manual processing associated with most assemblies, first pass yield at functional test is almost always less than 100%[3]. The units that fail in testing enter troubleshoot, and then are reworked and retested. Troubleshoot and rework consumes tens of thousands of man hours per year. It's expensive, and in extreme cases can impact delivery.

Failure, or non-conformance, in test occurs for a variety reasons, including software issues, test machine deficiencies, operator and environmental factors, etc., in addition to manufacturing defects. CCA's data collection systems begin to breakdown at the level where root cause is assigned for failure. Distinguishing between bad components versus manufacturing errors, test software or machine issues, etc falls into a gray area where the available data becomes questionable, and potentially valuable information is missing. The details of what is done to a particular circuit card assembly in the rework phase are often lost to process holes that allow operators to avoid data collection or collect bad data in the name of getting the job done.

CCA's spending on the troubleshooting operation is significant. The reasons a board finds itself in troubleshoot are numerous, but many are related to basic design for test, and others are issues known to CCA but not necessarily to designers, which if identified early enough in the design cycle, can be corrected before they become a problem. The project CCA set out for this internship was to create a tool, not unlike those already in place to evaluate manufacturability, that ties together the circuit card assembly design factors that lead to time spent in troubleshooting and evaluates new designs based on CCA's history with each factor.

1.2 Thesis Overview

This thesis will describe Raytheon and the broad environmental factors that drive CCA and shape its interaction with the wider world of Raytheon, followed by a detailed discussion of the design for troubleshoot tool that is the ultimate deliverable of this internship. Understanding Raytheon's complex structure is necessary to understand much of the challenge facing CCA and the new tool. Beyond the technical tasks associated with collecting, analyzing and synthesizing data into a useful form, creating a tool that can positively impact behaviors across Raytheon means communicating in a way that respects and appeals to individuals spanning disciplines, businesses and geography. Reduced troubleshoot time is simply a metric, one facet of a broader goal driven by CCA outward to align Raytheon's engineering teams on a efficient, profit maximizing way of thinking about design and product life.

2 Motivation

CCA's vision, Figure 5, is not entirely dissimilar from Raytheon's corporate vision. At the corporate level, Raytheon strives for global admiration, while CCA more practically aims to be the circuit card assembly supplier of choice for Raytheon Defense. Many people, including longtime Raytheon employees, are surprised to learn that CCA is not Raytheon's de facto circuit card supplier. CCA supplies circuit cards for all Raytheon IDS programs, with few exceptions, while it bids for contracts with other Raytheon businesses, principally SAS and RMS. CCA can and does occasionally looses contracts to third party producers, on the basis of cost, capacity, technology, etc, any reason a manufacturer may lose business in a competitive market. CCA's motivation to create a design for troubleshoot tool and bring Raytheon's circuit card engineering groups into alignment is rooted in its competitive nature.

Core Delivery and Solutions

Circuit Card Assembly & Delivery

Vision

- Be the Circuit Card Supplier of Choice throughout Raytheon Defense, providing Value-Added, Cost Effective solutions seamlessly for our customers
- Meet the customers' total needs by providing value-added services, operational excellence and continuous improvement
- Delighting customers is the key to CCA success and growth!!

Figure 5. CCA's 2012 vision

This competitiveness is core to CCA's practical operation as a business within a business. While a simple manufacturing arm of another defense company may be content to simply focus on its operations, CCA actively engages in business development activities. This drives CCA to a higher standard of work across all facets of the business, including test engineering. When CCA bids on a project, cost is critical. Too low, and CCA may win a contract they can't fulfill the terms of, too high and they may not win the contract at all. Understanding and controlling cost drives detailed accounting and shop floor management efforts, as well a practical commitment to concurrent engineering; working with customers instead of just for them.

CCA ultimately wins contracts because their customers feel they're the best for the job. CCA is a world class manufacturer because they can assemble sophisticated circuit cards cost effectively, on time; this is what their customers value, this is what any customer of any manufacturing organization values. Anything else that CCA does is not 'value-added,' a term which is evidently of great import to CCA, given that it appears twice in its vision statement.

2.1 What is Value-Added?

For the purposes of this thesis value-added is anything that CCA does that increases the value of the final product they produce for their customer; anything the customer would pay for. Assembling electrical components to a printed wire board is value added, as is testing the completed assembly for function, because the customer can sell these products for greater value than if CCA had not taken these steps. Building product that does not meet specification is not value added. Simple manufacturing errors, bad components, etc, lead to unacceptable product which is of no value to the customer.[13][21] In the face of the inevitability of defective product, CCA follows two strategies. One is simple over production, more commonly used on cheaper and simpler products, so that the required number of finished goods is always ready. This has well understood costs associated with inventory, complicated by the frequently extremely sensitive nature of Raytheon's products and frequent instances of custom components in limited supply. Extra cards, defective or not, often cannot simply be thrown away because of the proprietary nature of the designs and their implications for homeland security.

Because CCA cannot easily dispose of excess product, good or bad, and because holding excess product can be exceptionally expensive, rework becomes a viable option for meeting production goals, much more so than in higher volume and reduced sensitivity environments such as consumer electronics production, where rework is rare.[13] Rework enables lower production volumes because many units initially found defective can be repaired and sold to the customer, but incurs its own substantial cost in technician and engineer time.

At Raytheon and within CCA, rework is not value-added. Customers don't pay CCA to rework bad boards; they pay for the delivery of good boards. Rework is counter to CCA's vision, a necessary evil in the face of limited runs with high expectations of long term performance. Reducing rework is a continuous activity in CCA; the design for troubleshoot tool described in this thesis is just one example of how CCA combats it.

2.2 Defining Rework

Rework is the process by which a board that fails an inspection or test due to a non-conformance is individually troubleshot and repaired in an attempt to make it meet specification.

Inspections take place continuously throughout the manufacturing process. Automatic optical inspection (AOI) machines use cameras to visually inspect each board for solder paste and component placement, component alignment, and even the presence of a wrong component if sufficient identifying marks are present[4]. Optical machines can quickly and accurately inspect high volumes of features, but cannot detect issues such as shorts or missing solder hidden underneath certain component packages, so AOI is almost always supplemented with Automated X-Ray Inspection, or AXI[4]. AXI's ability to find manufacturing errors overlaps with AOIs, with the added capability to see through or under components and identify issues hidden to AOI, at the cost of longer inspection cycle times[4]. Manual inspection of macro scale features occurs at each handling step. Testing includes in circuit test, or ICT, which usually involves mounting the circuit card to a powered fixture and verifying the presence, connectivity and values of components through a predetermined test algorithm. These tests and inspections reveal manufacturing defects. The last testing that occurs at the circuit card assembly level is functional testing, where the completed card is assembled into a fixture that includes power and simulated inputs to stimulate the various design functions of the board [4]. This test reveals functional failure, which may be caused by manufacturing defects not yet identified in previous tests, design deficiencies, component defects, or a myriad of test related factors.

Failure at any of these stages sends a board to rework. Boards taken off the line to be reworked are colloquially known as 'in the bone pile;' time spent in the bone pile is accounted for as idle, with the units held as rework work in progress (WIP). Boards are then troubleshot if necessary, where the reason for failure is diagnosed, then reworked, where the board is physically repaired. Confusingly, 'rework' can refer to the entire spectrum of rework activities that include troubleshooting, etc, as well as the specific act of physically reworking a particular product. Not all products that enter rework are troubleshot – AOI, AXI and frequently ICT can precisely locate a fault, making troubleshooting unnecessary.

The process may be more easily understood by studying a map, Figure 6. Raw material in form of printed wire board, electrical components, etc is received by CCA at left. CCA then assembles and inspects products, passing the majority on to functional test and ultimately out as finished goods. The rework area, in grey, is where products with non-conformances are sent. Issues caught in inspection typically proceed directly to physical rework, while problems found in functional test often, but not always go to troubleshoot for identification prior to physical rework. All products are functionally tested after physical rework, where they may find additional or new non-conformances, resulting in one or more trips through rework cycle.

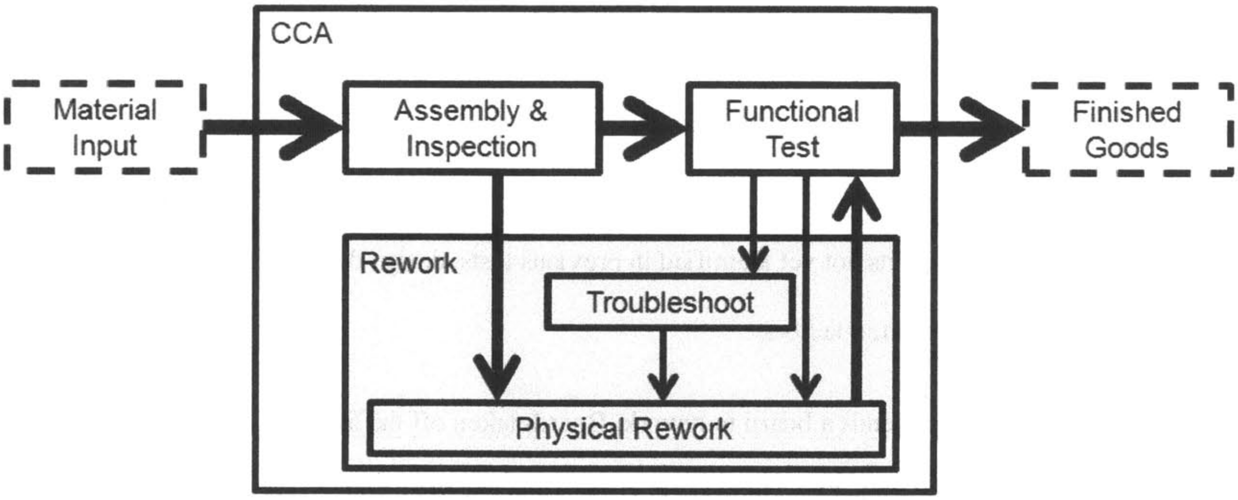


Figure 6 Simplified material flow map

Though only a relatively small number of boards find themselves in rework, CCA spends tens of thousands of man hours on rework every year[3] , at significant cost to the business. The troubleshooting operation, the specific act of identifying why a board failed, accounts for roughly 20% of total rework hours[3]. Troubleshooting is made especially difficult on new products, who's 'personalities' are as of yet unknown to CCA engineers. The 20% figure is representative of mature products, troubleshooting may take substantially longer for new products. Furthermore, because of the sophisticated nature of Raytheon's products, troubleshooting is expensive. Troubleshooting requires both technician and engineering man hours, meaning that troubleshoot is more costly per hour than most other rework operations, as illustrated in Figure 7.

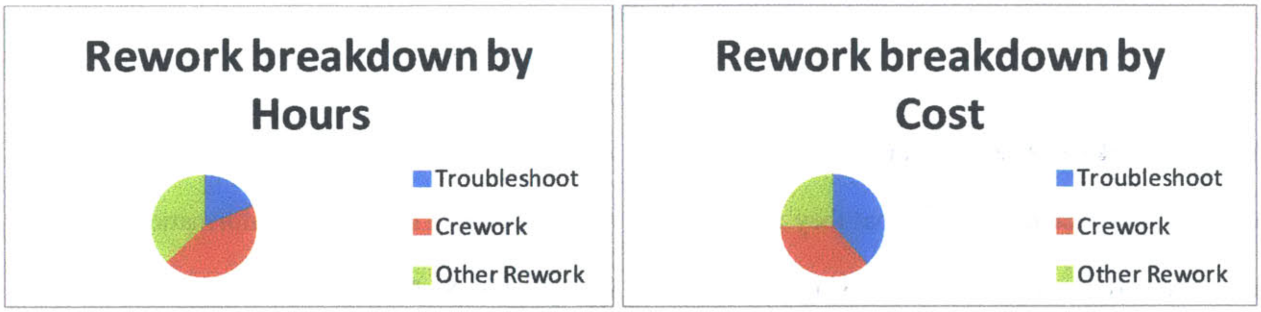


Figure 7 Troubleshoot as a percentage of Rework, but hours and cost

Troubleshoot time is driven in part by design complexity and the degree to which design for test principles are incorporated into the design. Complexity, in the form of board density, pin count, and increasing levels of programmable components with sophisticated functions, etc, means technicians and engineers face a larger number of potential failure causes. Design for test, or DFT, refers to designed in features that allow the product to be tested and troubleshot. Good design for test can make complex boards manageable, by allowing effective fault diagnosis and isolation.[5][13][15]

Design for test is the principal lever available to CCA to reduce troubleshoot time. DFT is not an add-on to a mature design, it must be built in early to achieve maximum effectiveness. DFT is itself a cost and complexity driver[4], thus when design teams, focused on the functionality of their products, make tradeoffs in the name of cost savings, DFT is often first to go. CCA, through the use of the DFT tool, aims to expose the power of DFT as a cost savings tool by giving designers a window into the whole life cost of the product. The DFT tool is based in data CCA has generated through years of production, rather than on general principals, allowing it to function as a strong predictor and provide targeted advice to designers.

Troubleshoot time is the metric chosen for the design for troubleshoot tool, because it is more directly linked to the testability of a design than other operations broken out from the rework umbrella. By analyzing new designs and comparing them against CCA's experience troubleshooting designs with similar features, a practical, data driven assessment of the relative difficulty of troubleshooting a product can be derived. In conjunction with CCA's existing manufacturability tools, an estimate of product failure rate and troubleshoot time per product can be reached, and translated into a troubleshoot cost. This gives designers an understanding of what they're trading off when they slight DFT. If this information is presented early enough, real cost savings are possible.[5][13]**Error! Reference source not found.**

2.3 CCA's Relationship with Design Groups

CCA is constantly interacting with electrical, mechanical and test engineering groups. Circuit cards are designed by teams of engineers under the control of a program office, electrical engineers designing the circuits themselves, mechanical engineers helping with board layout and other mechanical concerns. CCA test engineers have traditionally not been a part of the process until designs are fairly mature; with their components chosen, electrical design largely finalized, final product test strategies developed, etc.

Being left out of the loop until late in the design phase creates challenges for CCA, and for the program as a whole. The concept of the majority of project cost being designed into a product early[6], as illustrated in Figure 8, is proven out in the data CCA has collected on a number of design variables. Prior studies have shown that component package type alone has a dramatic impact on the manufacturability, measured in expected defects per unit of a circuit card design [7]. CCA's expertise in testability is largely absent from the design table; with designers largely focused on functional issues over the whole life cost of the product, products end up containing design elements not conducive to manufacturing. This obviously makes CCA's job as a manufacturing organization more challenging, but also ripples up and out to affect the program as a whole.

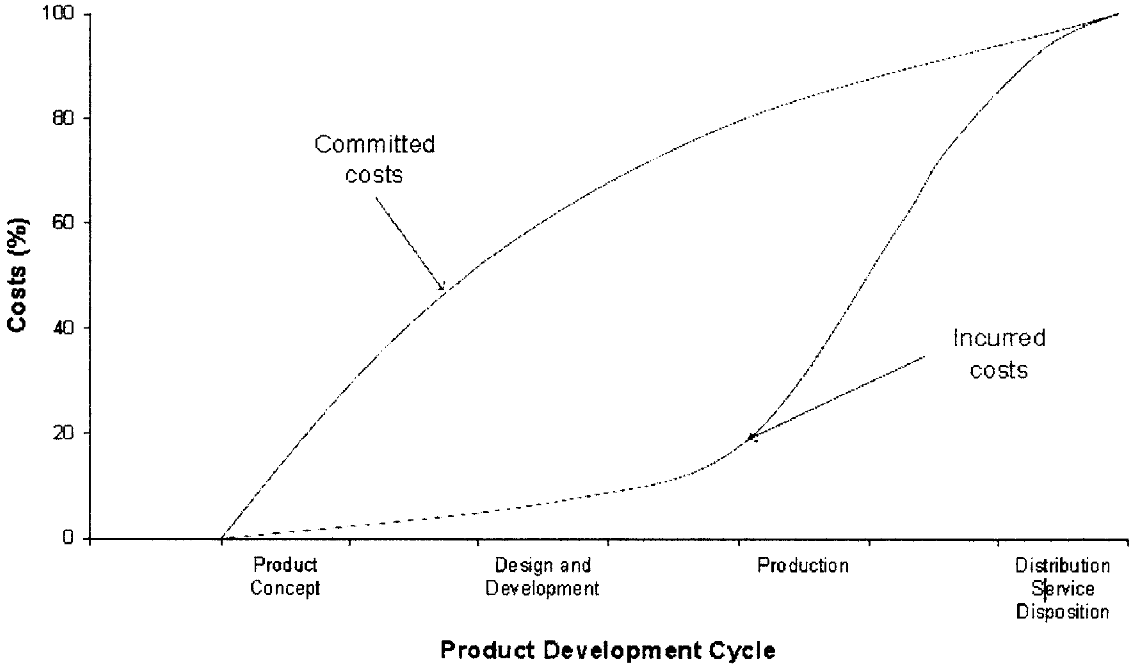


Figure 8. Product cost is largely fixed in the design stage.

Engaging other engineering groups early and helping them understand what drives cost in circuit card assembly enables smarter design decisions to be made when there is still time to make them cost effectively. A consequence of the complexity of Raytheon's products is the inability to easily implement changes as the design matures. In this light Figure 9 echoes Figure 8; a change easily made early in the design stage becomes prohibitively expensive to enact later, saddling the organization with greater product cost than otherwise would be necessary. CCA understands this well, and has been working to build a culture of upfront collaboration in the design teams they interface with.

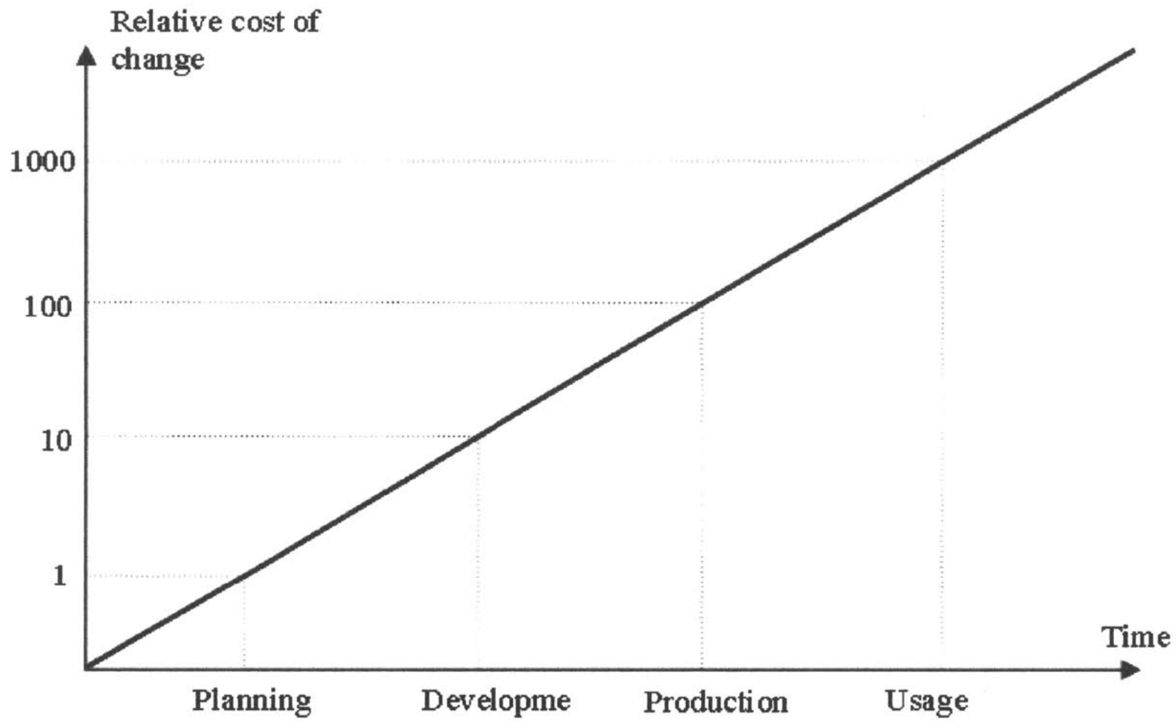


Figure 9. The relative cost of design changes.

CCA test design activities are not engaged in the design process until relatively late; after components have been chosen, boards laid out, etc. Earlier engagement between CCA and design will facilitate better design for troubleshoot; engagement itself is facilitated through the knowledge sharing possible with a design for test tool. By sharing knowledge in the form of guidelines, tools and the types of 'tribal knowledge' that can only be transferred when CCA personal actually work with designers, CCA has been able to raise awareness of Design for Manufacturing. The effort is ongoing, but has been successful enough to warrant expansion into additional areas, including Design for Test, or DFT.

3 Literature Review and Prior Art

The broader field of test engineering, in which much of the work of creating a troubleshoot tool could be said to belong to, is rich in academic activity, with papers published through professional societies such as the American Society of Test Engineers, and as whitepapers through Agilent, Teradyne and other businesses associated with the field. Much has been written that pertains to test coverage, fault isolation and general product design issues as they relate to testability, and will be briefly discussed here. At the same time, Raytheon is already using several tools similar in some way to the troubleshoot tool described here; these prior art have all served in some combination of template, guide or pathfinder for the development of the new tool.

3.1 Circuit Test

The relationship between test engineering and design, as well as test design, the intermediate discipline that deals specifically with designing test strategies and test functionality into new products, is constantly evolving. At Raytheon, decades of tightening schedules and increasing emphasis on lowering cost have pushed test designers largely out of the product development process.

This is dangerous, as highlighted in Peter Wilson's *The Circuit Designers Companion*, engineers should know the nature of the testing that will be required in production, so that the design can be optimized for, or at least accommodating of, the desired test strategy. "This is a more effective way of incorporating testability than merely bolting it on at the end."[13] Wilson goes on to discuss the practical integration of a variety of test strategies into design, but tempers these discussions with consideration of cost, the principal enemy of good design for test.

Many test strategies require significant upfront investment to implement, including the popular JTAG IEEE 1149.1. JTAG components include four additional pins to enable automated testing, which is itself a cost driver, but harvesting any benefit from a JTAG component requires a second investment in writing test code, as well as designing the board to maximize the test coverage.[5][13] This challenges Raytheon both because the production volume of many products is low enough that cost savings from automated testing may not always offset the additional cost of implementation and because board space is frequently extremely limited on high performance missile circuit cards, making the inclusion of additional pins, pull up resistors, etcetera, a challenge.

Per Raytheon's own test development documentation, complete net, or circuit, access is optimum either through JTAG or physical methods, like a bed of nails testing fixture, but this goal is often not met.[13] Without the ability to probe each net, manufacturing or 'structural' defects can escape to downstream processes. Structural defects include missing, wrong or misplaced components and many types of missing or poor solder joints, but cannot capture the functional issues that may arise from defects associated with complex microchips and other integrated circuits.[4] [14]

More subtle issues beyond the simple presence or value of a component are accomplished through functional testing.[4][13][14] Functional testing is particularly important to Raytheon as a facet of their Mission Assurance initiative, to guarantee only functional product ships to the next highest level assembly. However, much like structural, in circuit tests, the strength of that guarantee is only as strong as the fault coverage that exists at functional test. Functional testing requirements may include substantial redundancy with structural tests, and may even cover components missed in lower level tests, but because functional test by definition requires significant programming, and thus engineering expenditure, to stimulate and stress complicated components, functional tests are intentionally sparse, create additional opportunities for gaps in fault coverage.[4][14]

The net effect of a multilayered testing strategy, when not carefully designed in step with the circuit card itself, is a test plan that is at once redundant and incomplete. Figure 10 illustrates how this situation arises.[14] Across the top row of blocks is SMT, referring to the manufacturing process, MVI or Manual Visual Inspection, ICT or In Circuit Test and FT or Functional Test. Below each is a corresponding grid representing the coverage provided by each method. At the bottom right the summation of the coverages offered by each inspection or test. Areas of overlapping coverage illustrate where tests are redundant, while the surrounding, white box shows the full spectrum of failures possible. Uncovered areas of white represent opportunities for escapes.[14]

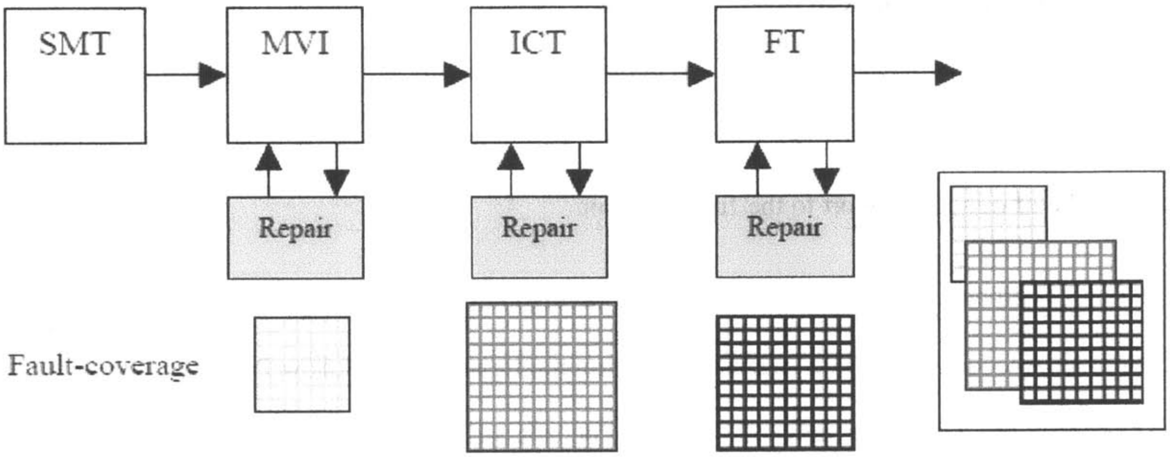


Figure 10 Fault coverage diagram[14]

3.2 Existing Tools

CCA already makes use of several design tools to enhance manufacturability and troubleshootability. These tools, along with the DFT tool and other tools currently under development are slowly being integrated into Mentor DMS, the design software used by Raytheon electrical designers. [11] The principal tools in use today are discussed below.

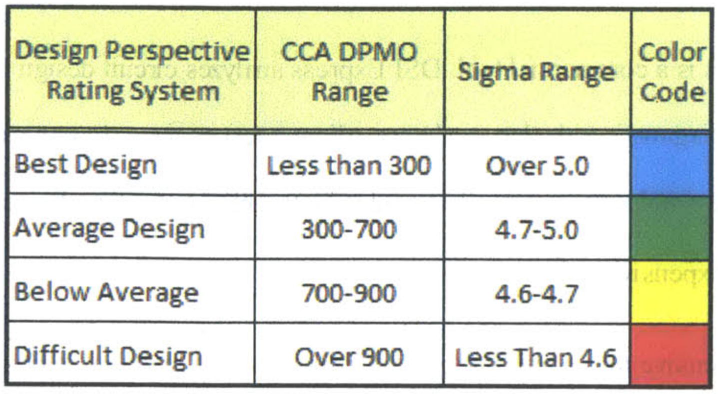
3.2.1 PCAT and PCAT Express

PCAT and PCAT Express allow CCA and design engineering to evaluate the quality of a new design, in terms of defects per million opportunities (DPMO). PCAT was developed approximately twenty years ago, and has been in wide use for the last decade. The tool takes detailed design data as input, asking the user for a great deal of data about the features of the product and the associated manufacturing steps involved. The tool compares the inputs to an extensive database of defect rates based on data collected on the shop floor and outputs a quality score in DPMO, as well as derived quality metrics and cost estimates. This basic model inspired the original concept behind the DFT tool.

PCAT was developed in a bygone era of circuit card technology. Many of the design details and manufacturing processes included in the analysis have passed into obsolescence and constitute unnecessary weight on the on the interface to the user. PCAT Express is a modernization of PCAT that streamlines the input process by eliminating not only the old inputs, but also a smattering of factors believed to be of minimal import to the final solution.

PCAT Express produces a DPMO while only considering component package sizes, lead pitches, and lead material. Anecdotal evidence suggested that manufacturing defects follow Pareto's Law, and that these few factors accounted for upwards of 80% of defects. [12]

The accuracy of PCAT and PCAT express was believed to be excellent, with regular updates of the PCAT databases ensuring PCAT predicted defect rates to within 10% of actuals each year. PCAT is important to this project not only because it served as a catalyst driving its development, but also because PCAT scores, were anticipated to be an important tool input, assuming that the defect rate of a given product would strongly correlate to troubleshoot time. PCAT scores practically break down into four buckets, as shown in Figure 11, this basic approach was ultimately used in the design for test tool to leverage the established method of understanding board quality PCAT has created.



Design Perspective Rating System	CCA DPMO Range	Sigma Range	Color Code
Best Design	Less than 300	Over 5.0	🟦
Average Design	300-700	4.7-5.0	🟩
Below Average	700-900	4.6-4.7	🟨
Difficult Design	Over 900	Less Than 4.6	🟥

Figure 11 PCAT score breakdown

3.2.2 **Valor**

Valor is a commercial circuit card design checker. It allows CCA to rigorously verify that design engineering has complied with Raytheon's established standards for component placement and pad size. Valor automates what was once an arduous manual process, saving time and reducing errors. In the past, teams of engineers poured over board schematics, checking individual pad sizes, component spacing, orientations, etc. Escapes from this process would sometimes make it to the shop floor, leading to difficulty getting production of the ground, delays, and expense.

Valor follows rules developed by CCA over years of production experience. Part of the tool's value lies in the fact that it brings these rules out into the design environment through the interface with Mentor DMS, Raytheon's electrical design tool. By making the rules more than just words in a document, to be pushed, creatively interpreted or outright ignored, Valor gives CCA practical power in the design world. Designs cannot advance without a 'clean' Valor screening, meaning both layout errors and intentional rules violations are minimized.

This is representative of the end state CCA envisions for most of its tools – integration into Mentor DMS to streamline use, while getting CCA's desires into the design room early and giving them some teeth. The long term goal of the DFT tool is to integrate into Mentor DMS so that as engineers iterate on a design, they can see their troubleshootability evolve with the design.

3.2.3 DSI Express

Like Valor, DSI Express is a commercial tool. DSI Express analyzes circuit design and test requirements to build fault trees and diagnostic aids that, in theory, allow a test engineer to trace a fault to its most likely cause. DSI Express holds great promise to enhance troubleshootability, however, realizing this promise is deceptively expensive.

DSI Express is labor intensive to run, requiring significant expertise and time to program in the required design and process information. Output quality is directly related to the completeness of the input, meaning that to obtain the full value of DSI Express's capability, there are no shortcuts. DSI Express produces a detailed report of the interdependencies in the design, illustrating what components are potential defect drivers, and provides a detailed map a test engineer can follow from failure to problem component. Issues of LRU, lowest replaceable unit, the smallest number of components that a problem can be isolated to, still exist, but DSI Express has the capability to largely eliminate the 'logical shotgun' approach currently favored on the shop floor for replacing components.

The reason DSI Express is not more commonly used and isn't seen as the answer to CCA's troubleshooting problem is that it still relies on the testability of the board and presence of sufficient diagnostic tools. Even with the detailed fault dictionary DSI Express generates, test engineers hands are tied by a lack of information. Many times complicated tests involving hundreds of components output a simple 'Pass/Fail,' without indicating the nature of the failure. DSI Express assumes electrical access where it is often mechanically prohibited, by a fixture design or safety requirements, meaning that where a critical bit or voltage measurement is unobtainable, preventing effective fault diagnosis and forcing test engineering to best guess or 'logical shotgun' the affected circuit. Troubleshooting is still an afterthought. Without providing troubleshoot friendly fixtures, board designs and software, DSI Express is effectively neutered.

The DFT tool takes a very different approach to troubleshootability from DSI Express. Rather than dig deep into the electrical design of the circuit, the DFT surveys the characteristics of the design and its related testing process to get a sense of how it stacks up against CCA's history, and grading it accordingly. That grade, presented as early as possible in the design process, becomes a behavioral driver that promotes the development of a more complete troubleshooting strategy.

4 Driving Behavior across Engineering Groups

CCA works across Raytheon's businesses and with a variety of functions. Achieving alignment on production goals and maintaining the relationships essential to mutually profitable business relationships are challenges rooted in understanding Raytheon's people and structure.

4.1 Understanding Raytheon: A3 Lens Analysis

MIT Sloan's Three Lens system of organization analysis provides a useful framework for understanding as complex and rich an organization as Raytheon. Even within the subdivisions of IDS and CCA, many groups interact with different goals, competing for shared resources while nominally all working under the same roof. The Three Lenses are the Strategic, which looks at an organization as a machine, the Cultural, which looks at an organization as an institution and the Political, which looks at an organization as a contest. When taken together, the three lenses offer holistic insight into the practical functioning of an organization. [9]

4.1.1 Strategic

Raytheon's strategy, as shown in Figure 12, revolves around taking advantage of their strengths in each business's domains, while delivering and making good on their technological promises. How that strategy is functionally and structurally manifest is the subject under scrutiny in the strategic lens.

It is worth noting here that Raytheon is an exceptionally large and diverse organization. The observations related here stem from the authors experience working at the IADC facility. Different facilities, in different business units and even other countries may 'feel' very different.

- Focus on key strategic pursuits, Technology, and Mission Assurance, to sustain and grow our position in our four core markets:
  - **Sensing:** Provide the breadth of sensing solutions required to meet our customers' mission needs.
  - **Effects:** Leverage kinetic energy-based expertise into EW, directed energy and cybersolutions.
  - **C3I:** Broaden market presence in communications, C2, networking and knowledge management.
  - **Mission Support:** Expand product support, engineering services and training.
- Leverage our domain knowledge in air, land, sea, space and cyber for all markets.
- Expand international business by building on our relationships and deep market expertise.
- Continue to be a Customer Focused company based on performance, relationships and solutions.
- Deliver innovative supply chain solutions to accelerate growth, create competitive advantage and bring valued, global solutions to our customers.

Figure 12. Raytheon's corporate strategy.

4.1.1.1 Independent Businesses

As discussed in the introduction, Raytheon is composed of six independent businesses. These are not 'business units' as one might find in other companies, but large, very independent organizations that integrate nearly all their business functions under one roof. CCA's home business in IDS, but CCA itself retains substantial independence.

The separation between businesses complicates daily work in CCA. Raytheon's systems are not uniformly standardized, for example, each business uses its own product data management (PDM) tool, which is contraindicative of easy access to data. CCA regularly interacts with the businesses it builds circuit cards for, but obtaining data is still challenging. For example, finding the right person to reach out to grant access to a PDM in another business unit is difficult on its own, but following initial contact substantial justification for access rights must be provided, given the frequently sensitive nature of Raytheon's product data. This is a manifestation of weak linking between organizations. Despite relying on one another for success, the ability to interact is hampered systematically.

With separate systems, locations, organization and management come practical differences how work is done. Files from one business may not match the format of others, circuit cards themselves often favor different design elements based solely on the culture and history of that group. Different businesses release specifications and documentation in different styles, with different information included, complicated processes for CCA, the receiving party of the variation in practice. Veteran engineers with extensive experience in one business's environment have demonstrated difficulty in translating their skills across business, largely based on these differences in style.

CCA is particularly sensitive to the Raytheon's multi-business nature in the context of the DFT tool. Delivering the testability CCA desires can be costly for the responsible design team, which is often part of another business which will balk at the impact to its bottom line. Raytheon's structure can serve to weaken the drive to succeed as Raytheon, in favor of motivation by more local metrics.

4.1.1.2 A Matrix Organization

Within an individual business, relationships between groups and individuals can be just as complicated as across businesses. Understanding how an organization is grouped is a critical part of the Structural lens.

Raytheon organizes along a matrix structure, with functional groups like operations and engineering crossed against project teams that pull members into mixed groups that develop products under the guidance of a main product office, or into groups responsible for the operations and manufacturing associated with a given product. In Raytheon parlance, these latter groups are responsible for the Value Stream, illustrated in Figure 13, "all activities required to bring a product from your vendors' raw material into the hand of the customer."[8]

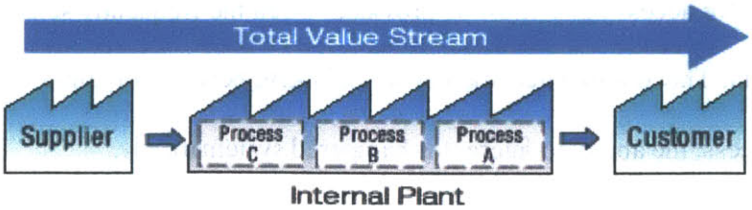


Figure 13. Value Stream illustration [8]

CCA fits as a 'Process' within the Internal Plant shown in Figure 7. But Raytheon's organizational depth does not stop there.

CCA is lead by a director reporting up through the Operations functional branch of IDS. In addition to operations personnel, 'Cross Business Team' leads representing CCA engineering, test engineering, quality, etc report to that director. Test engineering is a group with the Electrical Engineering Directorate, CCA Engineering a group with the Mechanical Engineering Directorate, which are both in turn part of the Engineering functional group, a peer organization of Operations. CCA is composed of individuals reporting up through their functional chain, their leadership within CCA, and stakeholders in their Value Stream, along a complicated network of direct and 'dotted line' reporting paths.

The complexity of the organizational grouping means that most personnel resources are completely committed, if not over committed, and the relationships that develop between different groups can be complicated. As an entity, CCA is behind the concept of a design for test tool, but getting individual level commitment from people outside of the core project team was often difficult, simply due to the demands placed on their time by their myriad allegiances.

4.1.2 **Cultural**

The Cultural Lens studies, among other things, the identity, traditions and habits of an organization, and how they are reflected in symbols. Raytheon culture is distinct, with some elements highly visible and broadly published and others more subtle but possibly even more deeply ingrained. It is these cultural artifacts that define the context of the day to day for Raytheon employees, and provide framing for the impact of any larger undertakings, such as the creation of new design tools.

4.1.2.1 Mission Assurance and the Warfighter

Raytheon's facilities, internal and external website, and official communications all present a consistent message of patriotism and national pride, as well as a pride in Raytheon's contribution to national security. Images of flags, eagles and military hardware head pages of Raytheon's intranet homepage, along with action shots depicting soldiers on the ground, missiles firing and aircraft maneuvering. These images, including Figure 14, are symbols, presented as plainly as possible for maximum effect.

Figure 14 A Raytheon missile in action.

Raytheon takes pains communicate this aspect of its culture. The term Warfighter is unique to Raytheon, referring to those in the armed services, and appears in press releases, product descriptions, vision statements, etc. Raytheon establishes Warfighter and other unique terms in their Style Guide, which acts as a written record for the culture Raytheon cultivates.[9] Mission Assurance is Raytheon's corporate quality organization, working with virtually all facets of Raytheon's business to ensure work is being done well and on time. Both terms serve to connect Raytheon's business to military service, which in addition to being the end use of most Raytheon products, is also where many Raytheon employees have a background.

Certain hallways in the IADC are decorated end to end with patriotic imagery, but many Raytheon employees personally embrace similar symbols. Desktop backgrounds and cubicle walls depict war memorials or tributes to 9/11, desks are adorned with plaques proudly declaring the veteran status of their owner or their owner's children. On the shop floor, private work spaces sport Semper Fi bumper stickers and American flags. The culture of patriotism runs deep.

The connection to the military and national pride is obvious at all levels within Raytheon, extending far deeper than a simple corporate message. The phrase 'it's gotta work, it's for the military' or something similar is often heard around the office – people believe what they're doing is important.

4.1.2.2 Hierarchy

The complicated structure Raytheon enjoys, coupled with strong military connection, leads to a culture rooted in hierarchy. Everyone has multiple bosses, drawing funding from multiple budgets trying to achieve a range of often conflicting goals.

This project would not have been possible without the assistance of group of over a dozen test engineers, whose intimate knowledge of certain products could not be equaled by any database Raytheon has developed. Getting their participation in the project became an exercise in understanding the culture. Asking them for help outright was often ineffective, but sharing that their boss was on my team and wanted them to help garnered a much stronger response. Similarly, approaching an test engineer without a charge number, a code tied to a the budget funding this project, would result in resistance – each engineer is under significant pressure to reduce time charged to any single account – even if one 'boss' wants work done, Raytheon employees are constrained by budget structures.

Raytheon is proud of their hierarchy. Org charts are freely available, but too simple to capture all the detail and nuance of who works for whom, so Raytheon uses RSpace, an internal social networking site that allows users to follow a chain of command all the way up to the corporate level. RSpace makes finding the critical name to use in a conversation to get the help you need easy, when it may have otherwise been impossible. Some engineers work geographically far from their direct supervisors, interacting with project leadership that may not have the kind of influence over their careers needed to push an already overworked individual to do more. People often ask 'who's this for?' in the same breath used when asking for a charge number.

Extended hierarchy is only possible with substantial size, which Raytheon has. With nearly 14000 employees, IDS alone is a substantial organization, and this size coupled with the convoluted layers of organization and multi-branched reporting trees lend an air of slowness to every action at Raytheon. Information has to be requested, and approved by multiple managers. Meetings called to discuss that information must include a wide range of stakeholders; even meeting resources like conference rooms go through an approval process that can only be successfully navigated by know who has a stake in what room.

4.1.2.3 A Willingness to Work

All pride in and fascination with hierarchy aside, Raytheon employees tend to work very hard.

Most employees at Raytheon IADC nominally follow a 9/80 schedule, working 80 hours in 9 days over the course of two weeks, taking every other Friday (the tenth day) off. In practice, most work far longer hours to get their jobs done. Working every Friday is common, Saturday hours are not unheard of, and long days any time are the norm.

Some of this stems from the rigid structure and hierarchy previously mentioned. Any one person can be tasked with several projects with rapidly approaching deadlines. The Raytheon response is to stay late and get all your work done by the deadline. At the same time, the fundamental sense of pride plays a role as well, because each employee feels like their work is contributing to something they believe is important.

Early on, the author found a particularly surprising tendency to work through the end of a meeting, even if that meant missing your next meeting. Essential personnel usually receive a phone call if they're attendance at a meeting is truly critical; otherwise a good meeting may not end until the value of gathering the team has been exhausted. This has worked both for and against the author – my team members have worked with me through their next meetings on several occasions, placing value on the work being done over making an appearance at what might be a less valuable use of their time. Conversely, team members occasionally miss my meetings, which they had previously agreed to attend. Punctuality and attendance are valued far less than doing 'real' work.

4.1.2.4 An appreciation for Security

Hand in hand with the high tech, military nature of many of Raytheon's products is the need for security. Raytheon ingrains this seamlessly with their nationalistic messages – breaching corporate security becomes not just a fire-able offense, but also a matter of homeland security. Raytheon's mandatory employee training gives great weight to matters of security and information control, and guards are posted at all building entrances, as well as entrances to IADC grounds. Badges at Raytheon tell a detailed story of whom that person is, what they can know and where they can be, meaning that everyone wears their relative sensitivity to security issues on their chests.

This is another value that Raytheon employees embrace from the bottom up, which shapes how work is done on a day to day basis. At each meeting, I was introduced as a contractor, a US Citizen, and a person lacking Secret clearance, particularly for the benefit of virtual attendees who could not see my badge, which would have provided the same information at a glance. The workers on the floor, engineers and administrators I relied on for information were always careful to ask if I understood the information security issues surrounding anything I requested. Though security issues frequently slow the pace of business, Raytheon is by necessity committed to ensuring it remains a secure workplace; the level of commitment observed at the individual employee level is a reflection of Raytheon's strength as a cultural generation engine.

4.1.3 **Political**

The Political Lens breaks down an organization in terms of power and influence, stakeholders and the paths taken to resolve conflict. Raytheon's political landscape is a reflection of its complicated structure, and is heavily flavored with the consequences of its culture.

4.1.3.1 Implications of a Matrix Organization

The multiple reporting relationships maintained by each employee, to their functional, project and group leadership, lead to employees being pulled in multiple directions. Getting priority in someone's queue happens in one of several ways.

Budget is of paramount concern. Without funding, practically, a charge number to report time against, CCA employees are generally unlikely to give one much time. Everyone has enough funded work to fill their working hours, so the author quickly learned to have a charge number at the ready during any discussion. Funding is synonymous with the power to get things done.

Power also comes with respect, which is in turn largely a function of demonstrated capability and official position. The author battled basic credibility early on, particularly as someone from a mechanical engineering background working with predominately electrical engineers, but after generally not making a fool of himself found most engineers willing to work with him. Carrying the MIT name was a strong credibility bolster, as was the company kept; many in test engineering report to members of the core project team supporting the DFT tool project. These formal, org chart reinforced relationships have the power to shift behaviors.

4.1.3.2 Philosophies across Functions/Disciplines

CCA suffers with the burdens that so many manufacturers carry; being at the end of the design process, they bear the consequences of decisions made early on in the process, often without CCA input and without a complete understanding of the long term consequences those decisions have on the shop floor. There is a recurring struggle between design and manufacturing, test development and project teams, supplier engineering and CCA engineering, over the myriad compromises that arise in design. A fundamental goal of the design for test tool, along with the wider suite of similar tools being co-developed within CCA, is to export the knowledge earned on the factory floor up and out to the design teams that can use it to design more producible products.

The politics of program development put CCA low on the totem pole. CCA's desires are often squeezed out by scheduling pressures and contract demands. A thorough evaluation of the costs of accepting, for example, increased defects rates in the name of lower standard cost, is generally not a part of the decision making process. CCA lacks both formal power to bring to such negotiations; their representation in any project is generally at a low level, and does not begin until many important details have been 'set in stone' by the design team. At the same time CCA's 'back end' role means their ability to impact costs upfront is perceived as limited.

The relationship with different businesses as customers is also important – CCA must carefully balance any discussion of cost or manufacturing difficulty with the real risk of losing the business to a third party perceived as more capable. CCA's requests for design changes are often met with the response, 'X can deliver it as designed, why can't you?' Regardless of 'X's actual capabilities, this attitude concerns CCA and is illustrative of the relative distance between design and CCA level appreciation for manufacturing concerns.

4.2 Current State

Circuit Card Assembly builds tens of thousands of circuit cards every year, across hundreds of different products, for four Raytheon businesses. Product diversity is tremendous, and the frequent line changes required to accommodate the high product mix pose constant manufacturing, operations and quality challenges. Production is frequently sporadic, with orders coming in at irregular intervals. Production and rework cycles are similarly sporadic, with some products overbuilding to account for less than 100% yield rates and limited ability to rework on the fly, and others troubleshooting and reworking as they go along to meet production goals.

First pass yield at functional test averages across all products is usually less than 100%, this is the type of yield most commonly discussed in CCA, but is deceptive. An individual circuit card may have entered rework and incurred troubleshoot time several times before reaching functional test. Actual first pass yield, from production order to functional test, is generally 30% lower. Manufacturing defects drive low yield, but a minority of issues are caused by component and board failures unrelated to CCA manufacturing.

The detection of a defect, wherever it occurs, sends boards into Rework, where it is troubleshot and ultimately repaired. So much troubleshoot time is spent working with software, tools and products that are not capable of efficiently supporting the troubleshoot process. By understanding where the deficiencies lie, the troubleshoot tool will help identify problems before they reach production and begin costing money.

5 Creating a Design For Troubleshoot Tool

Raytheon's manufacturing environment, product mix and relationship with its customers means that troubleshoot will likely always be a part of CCA's production activities. A core belief of the CCA's New Product Introduction team, which is typically the first line of contact between CCA and a new program team, is that troubleshoot times can be reduced and better understood, to the benefit of Raytheon as a whole. This concept was the genesis of the troubleshoot tool creation project, leading to the author's internship at Raytheon and this thesis.[2][13][19]

The troubleshoot tool was developed through a process of exploratory research, combining investigations into design, test, and fundamental CCA processes.

5.1 Goals

The principal goal of the tool is to enable more profitable production of circuit cards for Raytheon by predicting and facilitating the reduction of troubleshoot time of new circuit card products. This cuts across Raytheon's structure of multiple businesses, and informs the nature of the tool's use. Money saved within CCA through reduced troubleshooting must outweigh any additional cost to the business purchasing the board. At a deeper level, this primary goal is achieved through three basic mechanisms, as follows:

1. Improved electrical design
2. Earlier, deeper design side engagement
3. A mechanism for continuous improvement.

Improved electrical design relates primarily to the core issue of troubleshoot spending, specifically that many products are extremely difficult to troubleshoot. Improved fault isolation either through physical access or digital means like JTAG to eliminate the 'logical shotgun' approach to troubleshooting boards that exists today. At the same time, better registers for fault reporting, free pins to enable more control over integrated circuits and better built in diagnostics to help isolate faults in more complicated, expensive components. Improvements in electrical performance relating to design margin are also important, though these are being pursued primarily on the design side of Raytheon's program structure.

Earlier and deeper design side engagement is essential to making the desired product changes a reality. Today, CCA's involvement in the design process is limited; with little insight into critical decisions impacting troubleshoot until later in design. Even when CCA is able to make its preferences known, they are frequently overruled in the name of scheduling or cost issues. A troubleshoot tool that is integrated into the design process gives CCA the ability to share the impact of design changes on the manufacturability of a design early on, when changes are cost effective, and do so in such a way that makes program teams aware of the total cost of their product.[6]

Finally, continuous improvement of designs and the tool is strongly desired. The tool will track design iterations, so a design's progress with respect to troubleshootability through time will be documented. The tool will also collect basic data on the board, including component count, primary technology, etc, and store that information in a database so that the tool's accuracy can be assessed as new products enter production. The tool will also be tied to manufacturing databases, to facilitate continuous updating of the libraries which define its functionality, so that as CCA collects more data and learns more about troubleshooting, so will the tool.

5.2 Metrics and Sample Set

A measure of troubleshoot time is the principal desired output, though careful definition of how the troubleshoot cost of a product is defined is needed.

Total troubleshoot time in hours over the course of one year serves as the primary guiding metric for the tool. Total troubleshoot time is the 'bottom line' number, an analog for the total spending associated with a given product over the course of a year. This number is intuitively related to yearly production volume; data analysis bears this theory out. Looking at troubleshoot time naturally tends to place emphasis on high production rate cards, which is dangerous because production is often highly variable. For example, in one year only 200 examples of one product may be ordered, but a new contract in the following year could see production increase 10 fold. At the same time, some products are inevitably produced only in very small volumes, as low as 10 units over the life of the product. The total troubleshoot times of such products is low compared to many higher rate items, but the cost per unit can be staggering, and represent a substantial opportunity for savings on a per program basis.

Troubleshoot per unit, or per SFC, Raytheon's Shop Floor Control number which is used to track individual units, naturally became a secondary metric. The count of units used to derive Troubleshoot per Unit is not total units produced, it is the total units that enter troubleshoot in the same year that total troubleshoot time is measured. Thus troubleshoot time is normalized over the total number of units requiring troubleshooting, which is generally much lower than the number of units produced. Though the per unit cost of troubleshoot time is less immediately financially relevant to CCA, it can be used in conjunction with rate to predict the total troubleshoot time and can be extremely important on a per program basis, as described above.

As illustrated in Figure 15, a spectrum of both board types exists, those that are expensive on yearly and per unit bases. The top ten worst products in respect to total troubleshoot time represent more than half the total spending on troubleshoot per year. The top ten with respect to troubleshoot/board represent roughly 30% of the total spend. Comparing the two lists, 6 products appear in both – meaning that they are notably poor performers on a per unit basis, and produced and failing in enough numbers to be similarly bad when looked at over the course of a year. These are the products that gravitate towards the upper right hand quadrant of the plot in Figure 15. In contrast, products that cluster in the lower left quadrant are in general 'good' products that take little time unit to unit, and overall, to troubleshoot.

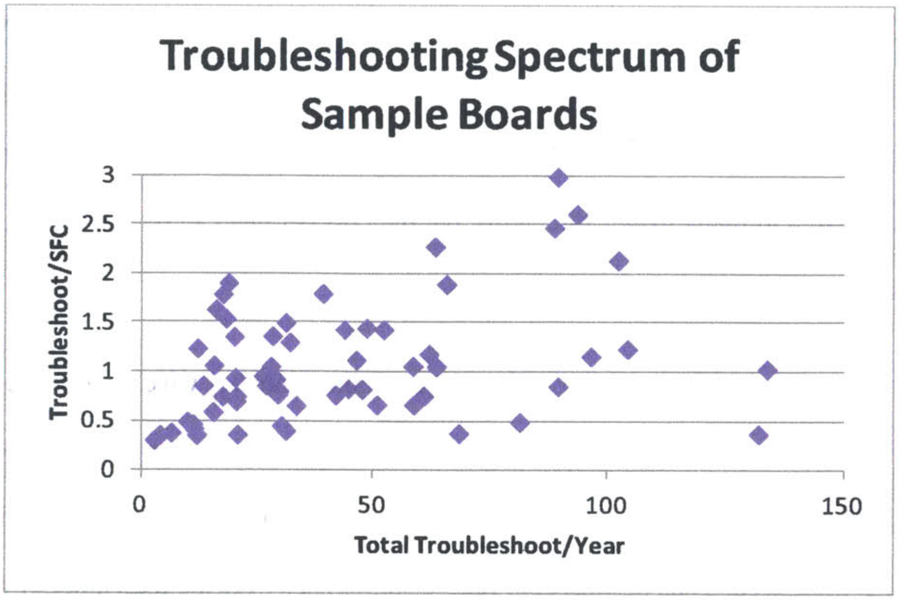


Figure 15 Troubleshoot/year vs. Troubleshoot/SFC

Several other potential metrics were explored, including measures of troubleshoot against number of defects, total production rate, defects per unit, and others. Each was dismissed, either due to being too indirectly related to the core goal of understanding troubleshoot time as it relates to product cost, or due to a lack of supporting data.

The tool is designed around the principal outputs of Troubleshoot and Troubleshoot/SFC. These variables are related through the production volume of the product, and were judged to adequately 'cover the bases' of maximizing potential savings at the CCA level bottom line, and for individual programs.

The 80 products used to generate Figure 15 are the same used to build a sample data set for the model. They represent approximately a quarter of the total number of unique products currently in production within CCA, and encompass a spectrum of product varieties. Designs from different business units, with different levels of complexity, types of technology, age, etc are included to create a representative sample set. Due to the variable nature of CCA production, the entire product family isn't entirely suitable for analysis; some products have been out of production for months, others are new products still subject to a learning curve, etc. At the same time, CCA's data systems struggle with only 80 cards, so a larger sample size quickly becomes unfeasible at this scale of research.

5.3 Inputs

Inputs to the tool were generated with consideration for several factors. There is no preexisting model for troubleshoot, only a collection of loosely related hypotheticals describing the roles of many potential drivers in the process. A broad approach was taken to incorporate anything that might be important, taking care to break down the many complicated variables as far as possible to avoid convolution and achieve concrete measurements or at least a quantitative understanding of each. The goal was initially to explore the design space alone, but analysis soon revealed that looking at as wide a spectrum of potential drivers as is feasible is necessary. [20]

To facilitate brainstorming, inputs were broken down categorically, in a number of ways. Beginning with design related variables, we grouped testing characteristics, board type and technology, component information, mechanical feature information, basic physical characteristics and manufacturing characteristics. Through brainstorming efforts, we were able to fill in these categories and generate upwards of 100 variables believed to have a role in defining a products relative troubleshootability. Over time, data collection challenges and preliminary analysis helped eliminate many of these starting variables, and several new categories of variable that included factors beyond simply design were added.

New categories included Test Machine Factors, Test Software Factors, Process Complexity, Process Quality, etc. This broader mode of thought brought not only dozens of additional variables into the project, but also many more 'soft,' challenging to rigorously express variables.

5.3.1 Practical Considerations

Brainstorming produced a large number of variables; too many to use in the final tool, but without a priori knowledge of which variables will be the most powerful explanatory tools, it is difficult to thin the herd based on feeling alone with risking the loss of an important piece of information. Guidance as to what variables are not useful can come from careful examination of the design process, with consideration for how the tool is intended to ultimately be used.

Figure 16 depicts the high level flow of the product development process, with 'gates' spaced along the timeline, and CCA's current suite of tools engaging in the process along the way. [2] Via PCAT and PCAT express, CCA can start to impact the manufacturability of a product revision almost as soon as design begins. Between gates 5 and 6, the 'Requirements Definition-Preliminary Design' is where manufacturability and troubleshoot should begin to enter into a program's thinking; CCA has made great strides on the manufacturability front, but troubleshooting is still an afterthought. Not considering troubleshoot up front is a recipe for disaster, something CCA understands, but needs this tool to help educate the design world.[13]

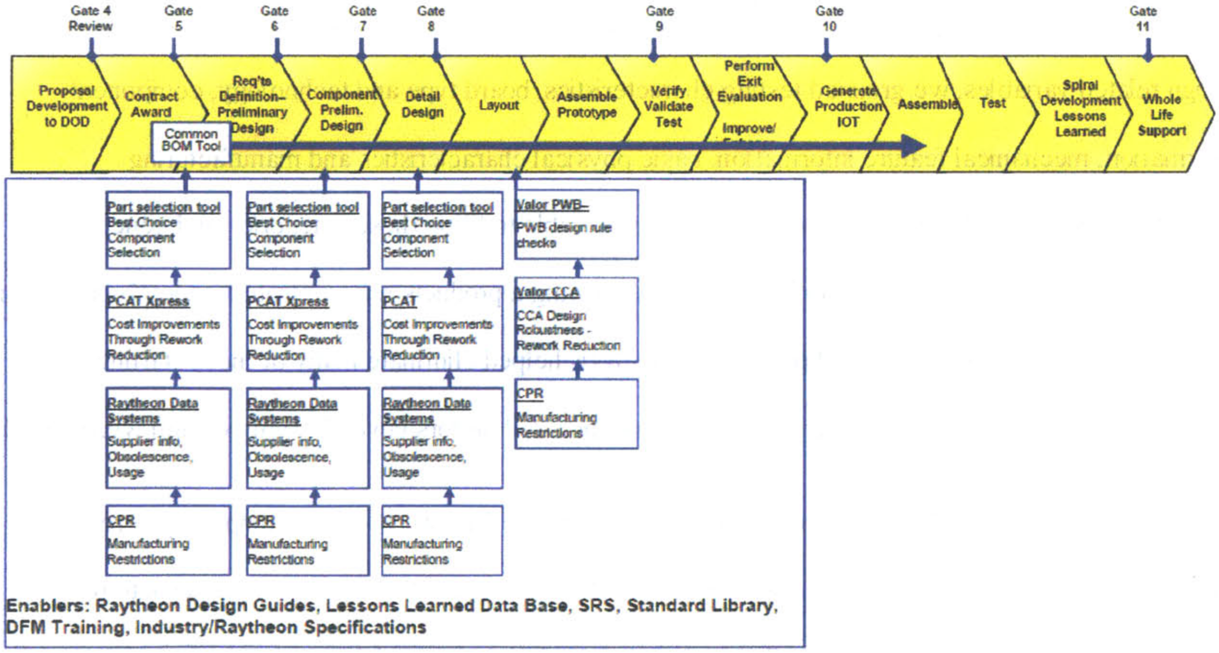


Figure 16 Product Development Gates[2]

Asking the right questions is fundamental to the success of the tool. By studying the flow of information along the process diagram, variables can be thrown out or reevaluated if they don't represent information that is available in the preproduction stage, before Gate 9 in Figure 16.[16] Designers typically won't be able to evaluate many parameters specific to test, like the age of test machines, or the complexity of test fixturing. Similarly, asking questions about the quality of a handoff between CCA and design are difficult or impossible to accurately evaluate at the design stage; the handoff has not occurred yet, and it's unwise to use data based on a projection or hope regarding the quality of that handoff, particularly given that there is incentive to score well on that parameter.

Each variable must serve a specific purpose within the tool, must make sense within the context the tool will be used in, and must be in some way important.[20] From a purely practical standpoint, loading the tool down with 'extra' inputs will discourage adoption and accurate reporting. If these variables can be cut early on, then the tool creation process becomes that much easier.

5.3.2 Statistical Considerations

Because of the variety of the products and the factors that describe them, as well as the large volume of data available to work with, regression analysis was chosen as the fundamental tool used to transform input data into a useful tool. Regression is an adaptable technique for modeling the relationships between variables, well suited to building a data driven tool, even in the face of wide variation. With this in mind, variables where carefully screened for a number of characteristics beyond simply the hope of describing the problem, in order to build a strong, statistically valid model. [20]

Regression variables can take many forms. The can be categorical, as in the case of primary board technology; digital, RF, etc, or continuous, such as the number of components on a board. Continuous variables are largely easy to work with, but scrutiny must be applied to ensure there is sufficient variation within the spectrum of values in the sample, and that the variable really is 'continuous.' Some variables are binary, or exhibit significant bimodality, for example appearing strongly one way or the other rather than displaying a more even distribution between two extremes. Such variables are excellent candidates to be transformed into categorical variables, to better evaluate the real effect of a factor. Categorical variables generally require more careful manipulation. Binary variables, which are either on or off, yes or no, are usually straight forward, but categorical variables that can take many values are more challenging. Often not every variable is required, and the variables can be grouped to simplify and strengthen analysis. [18][20]

Other variables defy categorization, or seem continuous but are difficult to measure. The ability to break a variable down into a measureable phenomenon or discrete states is essential to the regression process; when this proved impossible to do without losing the original intent of the variable, that factor was eliminated from further data collection and analysis. These variables are excluded from this study, but are excellent candidates for future evaluation. [17][18]

Sufficient data supporting each variable is essential as well. Many of the factors examined are not databased, and in some cases the information required was lost to time or holes in the CCA process. Minitab, the chosen statistical tool for analysis, can compensate for a few missing data points, but only up to a point. Variables with insufficient data support were eliminated. [18]

5.4 Analysis

Data analysis was conducted principally with Minitab, a statistical analysis software package. Single and multiple linear regression, ANOVA and related analyses were used to understand the role each potential input has in the troubleshoot process.

5.4.1 Variable Coding

As discussed in previous sections, many variables required manipulation, or coding, in order to enhance their value as statistical tools. For example, the total number of components on a product is one of the stronger predictors of troubleshootability. This makes intuitive sense, as products with more components are potentially more complex to manufacture, more prone to failure, and may take longer to diagnose as a direct result of their higher component count. In this case, intuition stands up to statistics, and the component count is found to be statistically significant. [17][18][20]

Studying component count versus troubleshoot, as shown on the left of Figure 17, reveals a general trend – low and moderate parts counts are acceptable, while the highest parts counts are notably worse, but also more variable. The data is noisy, characterized by irregular jumps in either direction between data points. This is unsurprising given the highly variable nature of troubleshoot as an output, and the high number of drivers that work alongside component count to influence total troubleshoot time. The right plot in Figure 17 depicts a smoother, more readily interpretable curve that follows the general trend established in the raw data at the left. The right curve plots component count quartiled – breaking the sample into four equally sized groups based their magnitude. All values below a certain threshold determined by the sample as a whole are grouped under the first quartile, and values between the first and second thresholds grouped as the second quartile, and so on. The mean troubleshoot time of the quartiles is plotted against each quartile, smoothing the response greatly and allowing more direct observation of any trends that may exist in the data. [17]

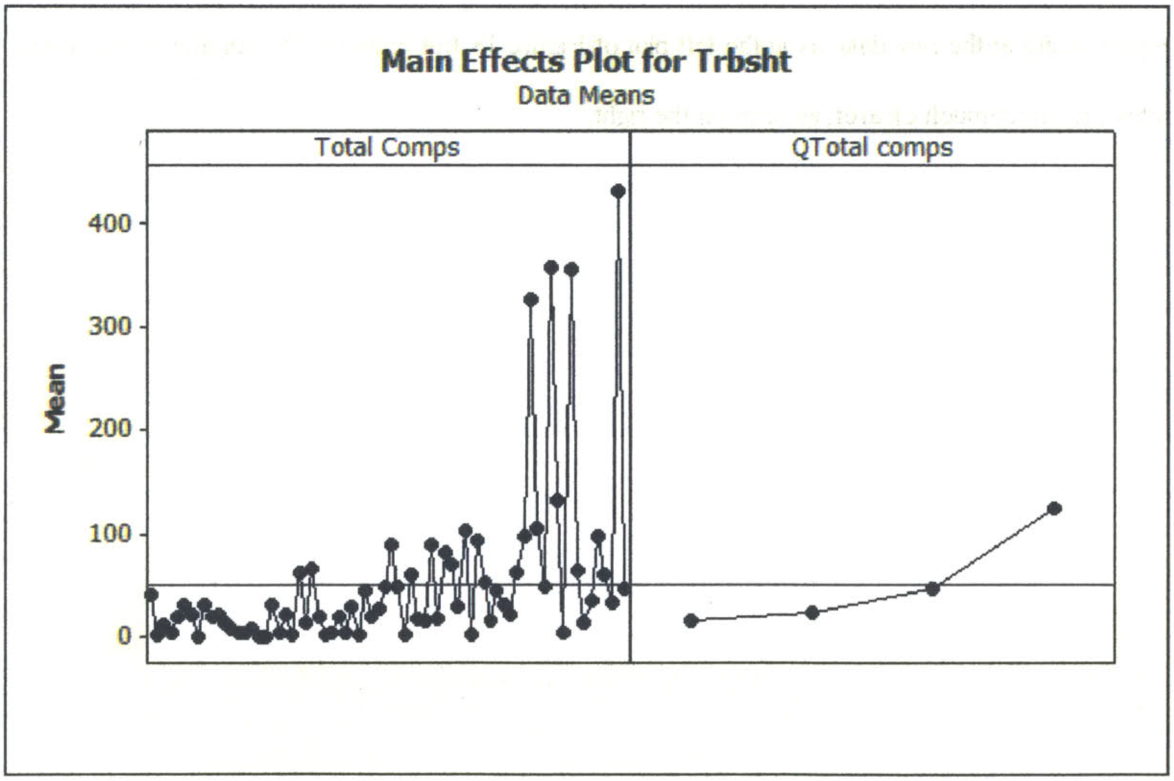


Figure 17 Main Effects Plots of Component Count against Total Troubleshoot Time

Categorical variables often needed to be sorted to make them more useful. For example, when looking at the In Circuit Test (ICT) machine associated with a given product, the majority used either a Takaya flying probe type machine, or a bed of nails G410. Several products used custom, unique approaches to ICT, while others used alternative machines not part of the 'common platform' promoted at Raytheon and thus practical outliers. Rather than regress 80 samples with ten unique categories, the ICT machine variable was grouped into three categories – Takaya, G410, and 'other,' drastically simplifying the analysis and facilitating a deeper understanding of the importance of being on a common platform test machine.

Similarly, the variable addressing the security classification of a product was simplified down from a number of very product specific and diverse categories down to a simple 'No Classification' or 'Classified or Above.' It is hard to understand the roll of classification as a source of troubleshoot challenge looking at the raw data, as in the left plot of Figure 18, but reducing the number of variables illustrates the effect much clearer, as seen on the right.

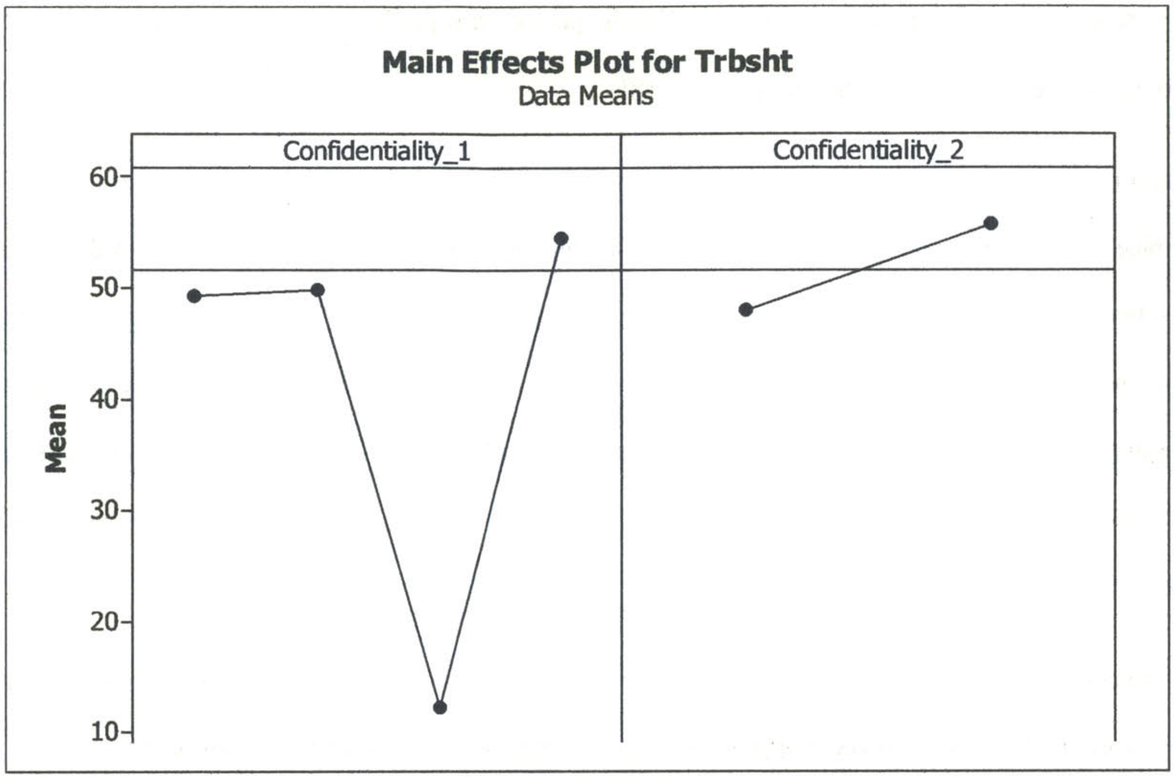


Figure 18 Main effects plot of model data

5.4.2 Regression

Data collection and preliminary analysis were completed to support a multiple linear regression approach to creating a model for troubleshoot time. Regression allows a greater level of discrimination to take place, removing variables that might otherwise appear interesting or important, but don't really contribute to the phenomenon at hand. Because no preexisting model for troubleshoot exists, and the process itself is so variable and hard to intuit, this is tremendously powerful. The ultimate output of regression analysis is a regression equation, which forms the backbone from which a tool grounded in statistics and data can be constructed.[20]

Regression is a powerful tool for statistical analysis. Beyond the regression equation, software packages such as Minitab; used extensively over the course of this project, output additional information about the relative statistical strength of each variable analyzed, how it may interact with other variables, etc, along with several indicators of the strength of the regression equation, both in explaining the existing data, and it's theoretical power as a predictive equation. For the project, this predictive strength is perhaps the most important descriptor of the regression equation.[18]

Before a regression equation can be evaluated, the variables that should be included in it must be determined. Having previously screened factors based on suitability of analysis, availability of data, etc, as described in previous sections, the last great discriminator becomes the 'P' value. P values are used to discern statically significant variables from those that are not statistically significant. Variables meeting the required P value are known, with some degree of confidence, to play a role in the process in question. P values do not indicate causality; they only serve to say the variable in question is related to the output variable.[18] [20]

The common rule of thumb when using P values is that a variable with $P<0.05$ is statistically significant, with 95% confidence. More relaxed approaches, for example with $P<0.10$ and 90% confidence are less common. Using higher P thresholds effectively weakens the statement one is trying to make, or in this case the foundation the tool will rest on, but also has broader impacts when modeling complex processes. Using $P<0.10$ drastically increases the number of significant factors available for use in the model, without a corresponding increase in accuracy. [18]

The first truly statistical evaluations of the suitability of the data gathered revolved around the P values calculated in linear regression. Looking at the variables individually and eliminating those with high P values drastically thins the herd, facilitating multiple linear regression greatly.

With the pool of variables thusly reduced, the next step becomes investigating which variables are the most relevant; those that explain the most variation. The coefficient of determination, more commonly called R-squared or R-sq, is a measure of how well an input variable explains the input variable, based on the current data. With only one variable, this number is a good indicator of the strength of a variable, but it doesn't tell the whole story. In multiple regression, better diagnostic tools are needed to understand how strong a regression really is.[18][20]

When combining the strongest variables into a multiple linear regression, either via intuition or according to a model building algorithm, the R-squared term can be misleading, as adding more and more variables will never reduce the quality of the fit of the equation. 'Bad' variables, can't take away from the fit obtained by stronger variables, and any passing relationship they may have with the output will artificially inflate R-squared. A better measure is R-sq (adj), a Minitab output that controls for the effects of additional variables. R-sq (adj) is always lower than R-sq, and will often drop further when extraneous variables are added, a problem known as over fitting, even as R-sq continues to rise.[18] R-sq (adj) is thus a powerful tool for deciding when 'enough is enough' and an optimum balance between statistical relevancy and model completeness has been reached.[18][20]

Both these terms look at the strength of the model with respect to the current data set. The goal of the model is in this case to build a predictive tool, thus a measure of that tools expected accuracy when applied to theoretical future datasets is desired. This is available in another R-sq derivative, R-sq(pred), as well as S, the standard error of the regression. R-sq(pred) is similar to R-sq(adj) in that it helps the user prevent over fitting, but is calculated to reflect the models predictive capability, and thus is both a lower value, and more useful. S is useful as a surrogate for a tolerance on the model; one can think of the predictions the model makes being within +/-S of the predicted value. Therefore, a lower S is preferred. [18]

5.5 The Three Roles of Inputs

Not all inputs serve the same purpose. As analysis continued, a gap opened up between intuition and CCA's intent for the tool and the available data. To preserve the integrity of the tool, statistical analysis was not compromised, but the tool was built to accept additional inputs as needed to obtain results deemed favorable by CCA. Three basic types of variables emerged: statistical, political and database.

5.5.1 Statistical

The regression equation ultimately obtained relates a selection of the input factors to the two outputs, annual troubleshoot time and troubleshoot time per unit. This equation forms the basis of the tool. It is a statistically sound estimator of troubleshoot parameters from real data obtained in production by CCA.

The factors employed by the tool, based on their statistical strength and applicability to the design process are the anticipated rate in units per year, the total component count, the area of the circuit board, the presence of heat sinks or mechanical covers, the number of custom components, and whether or not the board is double sided. The complete list of variables treated is in the Appendix [22].

5.5.2 Political

This small selection of factors doesn't tell the whole story behind troubleshoot. A critical component of the tool is its capacity to integrate variables that aren't statistically backed. These are the rules of thumb and the 'fudges' CCA uses and intends to use to drive behavior in the design space. These variables evolved to become 'political' variables, because they're more about politics that statistics.

An example would be PCAT score. As discussed in Section 3.2.1, PCAT is a tool CCA developed to predict the manufacturability of a product, analogous to the way this tool predicts troubleshootability. It seems rational that a more producible product, i.e. one with fewer defects, will require less time in troubleshoot than one with more defects. PCAT gives no insight into the nature of a potential defect or the time it might take to troubleshoot it, and indeed a relatively manufacturable product may be prone to significant troubleshooting difficulty for any number of reasons. [7]

PCAT score as an input to the troubleshoot tool was one of the first thoughts driving the initial tool design effort, but in practice the data does not support its use. PCAT score does not strongly correlate to either annual or per part troubleshoot times. This is likely in part to the myriad factors influencing the troubleshoot process, but also a result of PCAT's own accuracy issues, but the result is clear – the statistics don't support using PCAT score as a variable. PCAT accuracy is discussed further in Section 6.2.

As a political variable, we override statistics. Poor PCAT scores are unacceptable – CCA knows that a bad PCAT score indicates a product that will be expensive and difficult to manage in production. To emphasize the importance of reaching at least an average PCAT score, when PCAT is below average, the troubleshoot scores at best follows PCAT score. The means that when PCAT is poor, troubleshoot is poor.

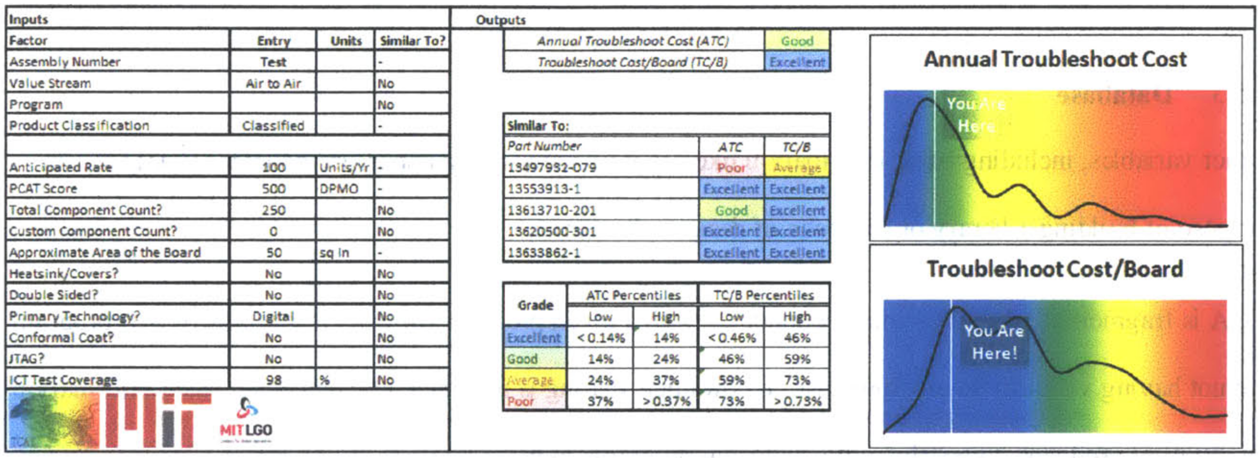
5.5.3 Database

Other variables, including basic information like program name and number, are collected solely for the purpose of building a library or database of design information.

CCA is fragmented, with individuals connected with a given program knowing the details of that program but not having visibility to anything else. Knowledge sharing is inhibited, and obtaining basic information on different products, comparing notes between programs to try to leverage the learnings associated with one product on another is very difficult. By building up a common database of unclassified information on each product reaching CCA, the DFT aims to combat this effect while serving its greater purpose related to troubleshoot.

6 Outcomes

The author's internship at Raytheon culminated with the release of a prototype design for troubleshoot tool, named 'TCAT,' or Troubleshoot Capability Analysis Toolset, both in tribute to the PCAT tool which it shares much in concept with, but also as a means of capitalizing on the existing familiarity and political capital PCAT enjoys, as a means of gaining more immediate and broader acceptance of the new tool. TCAT's graphic user interface, or GUI, is shown in Figure 19.



Inputs

Factor	Entry	Units	Similar To?
Assembly Number	Test		-
Value Stream	Air to Air		No
Program			No
Product Classification	Classified		-
Anticipated Rate	100	Units/Yr	-
PCAT Score	500	DPMO	-
Total Component Count?	250		No
Custom Component Count?	0		No
Approximate Area of the Board	50	sq In	-
Heatsink/Covers?	No		No
Double Sided?	No		No
Primary Technology?	Digital		No
Conformal Coat?	No		No
JTAG?	No		No
ICT Test Coverage	98	%	No

Outputs

Annual Troubleshoot Cost (ATC)	Good
Troubleshoot Cost/Board (TC/B)	Excellent

Similar To:

Part Number	*ATC*	*TC/B*
13497932-079	Poor	Average
13553913-1	Excellent	Excellent
13613710-201	Good	Excellent
13620500-301	Excellent	Excellent
13633862-1	Excellent	Excellent

Grade	ATC Percentiles		TC/B Percentiles	
	Low	High	Low	High
Excellent	< 0.14%	14%	< 0.46%	46%
Good	14%	24%	46%	59%
Average	24%	37%	59%	73%
Poor	37%	> 0.37%	73%	> 0.73%

Figure 19. 'TCAT' Graphic user interface

6.1 DFT Tool Current State

TCAT was coded as a standalone Microsoft Excel workbook, with a single file containing the GUI, underlying math, databases, and utilities for graphic generation and data management spread over several pages.

Excel was chosen principally because it is not only the author's preferred coding tool for most basic engineering calculations, but also because it is a lingua franca among engineers, ensuring that the tool prototype will not only endure, but be understandable and dissectible in the future to facilitate the next stages in the development of the tool.

Given the scale of CCA's operations, the intent behind the project was never to launch a complete tool in the span of a single project, but to break that process down into more manageable portions. The first of which is represented in this thesis; the process of research and development leading to the creation of the prototype tool depicted in Figure 19. This tool works; it accepts real inputs and outputs real troubleshoot time predications, but its Excel based implementation is intended as a stop gap between projects. It provides a testable, exercisable and self-contained closing to the author's internship, while serving as a picking up point for further development, as described in the next chapter.

6.2 Accuracy

The accuracy of any tool intended to be used for planning or as the basis for decision making is obviously of paramount concern. In order to makes sure that decisions are made to push development in the right direction, the tool must be sophisticated enough to accommodate a range of variation in product type and potential configuration while still producing a useful output.

The statistical analysis that forms the foundation of the tool is useful for informing one's intuition regarding the level of accuracy that may be expected. With R-Sq (pred) values between 20 and 25%, and S values between 30 and 38 for annual troubleshoot and troubleshoot per board, the initial feeling was that accuracy is marginal at best. Recall that R-sq and derivative quantities measure the degree to which the explanatory variables in questions account for the output effect in question. Given the complexity of processes at hand, relatively low R-Sq values should be neither surprising nor particularly discouraging.

Having a relatively wide tolerance on the tool output does create challenges around how to best express that output. Raw numbers, the annual hours and hours per board, are attractive because they are straight forward, but also dangerous, because they can present communication or interpretation challenges. Issuing a simple answer with a caveat regarding tool accuracy undermines the perceived strength of the tool, while failing to make any allowance for thc tool's capability opens another door for criticism. For example, if the tool predicts a given board will require 40 minutes of troubleshoot time per board, and the actual product requires only 20 in reality, the tool may be perceived as drastically overestimating the troubleshoot time. Normalizing the outputs against a variety of sample characteristics can mitigate this problem to some degree, but in practice makes the parameter less easily understood by the casual user of the tool, creating new problems. After some experimentation with CCA staff by exposing them to different transformations of the outputs, a compromise solution of presenting a grade or rating as opposed to a hard number was reached.

The tool scores each board, estimating the troubleshoot times as normal, but the actual numbers are not revealed to the user. The tool then compares them to the quartiled troubleshoot quantities in the data, breaking them down such that the lowest quartile is Excellent, while the highest, longest times are Poor, with Good and Average in between. This creates a very easy to understand score, because rather than a number that is potentially subject to misinterpretation, designs are simply labeled 'good' or 'poor,' etc, as is appropriate. This also inherently helps address the issue of tool accuracy. Across the spectrum of a quartile, the tool has leeway to miss the actual troubleshoot mark while still outputting the right quartile. Referring back to the previous example, both 20 and 40 minutes fall into the 'Excellent' band; the tool would output the correct grade despite predicting a troubleshoot per board twice that of the actual. To better understand the accuracy of the tool as a whole, the tool output versus the sample set can be mapped as shown in Figure 20.

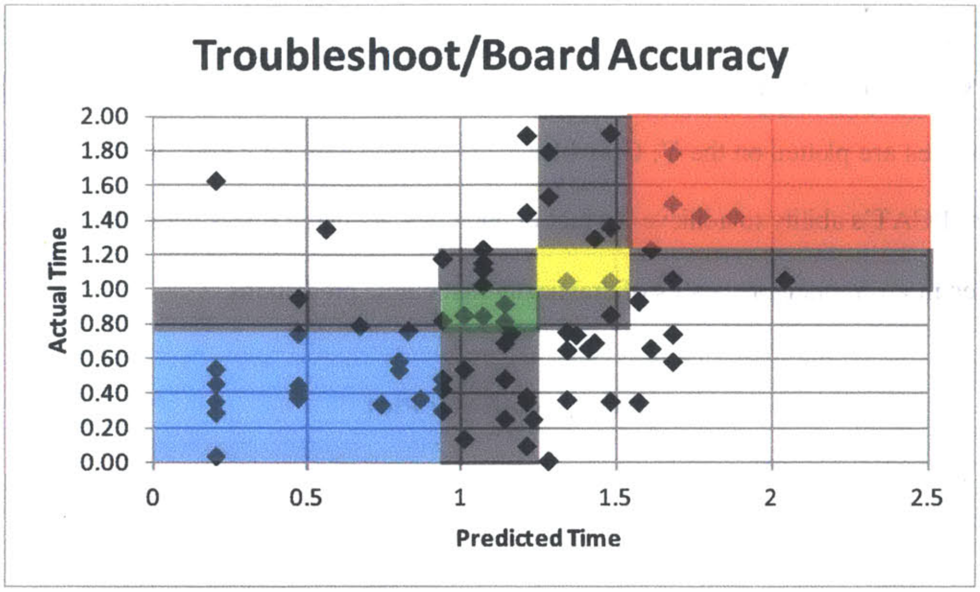


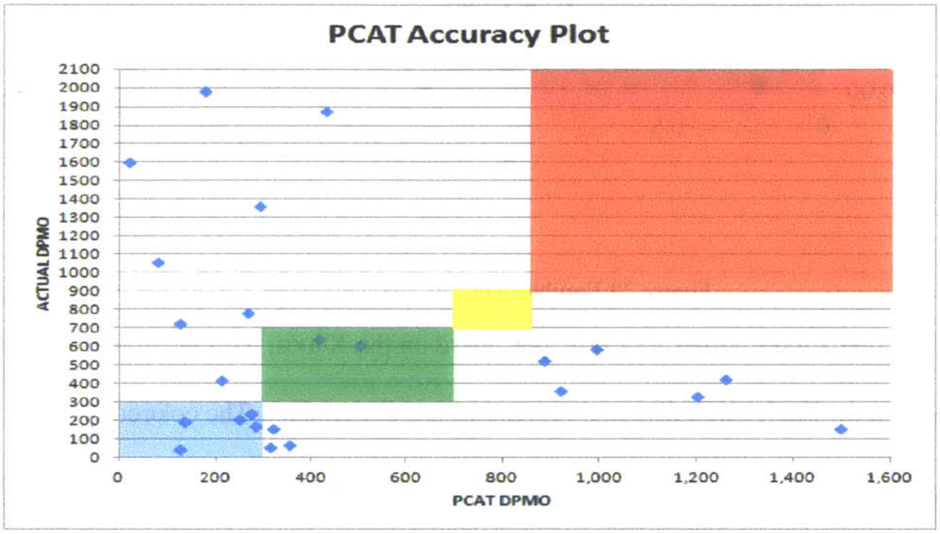
Figure 20 Troubleshoot per board mapping.

Figure 20 plots the predicted troubleshoot time per board on the X axis, with the actual troubleshoot time per board on the Y axis. Each black diamond represents a CCA product. The colored; blocks, blue, green, yellow and red, correspond to the performance quartiles; excellent, good, average and poor, respectively. Any time a black diamond is inside a colored block, the tool has achieved 'perfect' accuracy in that instance, meaning that the grade the tool predicted is the same as the grade the board would receive based on its actual performance in assembly.

The grey blocks bracketing the colored blocks represent 'within one color' accuracy, in other words, the tool predicts a grade that is within one grade of that which the product would receive based on its actual performance. For example, if the tool predicts that a board will be Excellent, and the board is in reality only 'Good,' this data point would fall in the gray block directly above the blue block in Figure 20.

40% of cases achieve 'perfect' accuracy, while 80% achieve at least 'within one color' accuracy. This level of accuracy is more than sufficient for CCA, surpassing other tools such as PCAT, and providing a simple, easy to explain output for the tool.

CCA is pleased with this level of performance. Contrast Figure 20 with Figure 21, the analogous accuracy mapping of PCAT scores for several of the same products. PCAT's predictions are plotted on the X axis, while actual values are plotted on the Y. Gray blocks are omitted here for clarity; it is obvious by inspection that PCAT's ability to achieve perfect or one color accuracy is less than TCAT's, and that PCAT includes more frequent instances of drastically inaccurate predictions.



6.3 Value

Evaluating the value of the tool to CCA is a matter of carefully addressing assumptions. The value of the tool comes from the money that can be saved through improving the troubleshoot times of boards in CCA's product mix. The two most important questions are what are the potential savings, and when those savings will be realized, allowing the net present value (NPV) of the tool to be calculated.[21]

As illustrated in Figure 15, the annual troubleshoot costs of CCA products falls along a broad spectrum. This is largely consistent year to year; without an emphasis on the importance of troubleshoot new products entering CCA's product pool are often as challenging as any leaving. Products typically experience several revisions over their lifetimes, some as frequently as every year, others at a slower pace, but over time opportunities present themselves to improve upon existing products. Each of these opportunities is a chance to apply the tool.

The actual ability of the tool to impact design decisions is still an open question, and will remain so until sufficient time to evaluate its performance has elapsed. For the purposes of this value calculation, it is assumed that production rates would remain constant and the troubleshoot times could be pushed down to the 30 minute mark, a 'gut feel' assessment of what a reasonable troubleshoot time is for a good product in CCA. Savings is calculated by taking the difference between the current troubleshoot time of the board and the 'good' troubleshoot time, and multiplying that number by a labor standard to reach a dollar value.

Calculations are conducted at today's labor rates, though projected rates are available for the next several years and can be calculated as needed for additional years. Inflation is similarly ignored, though Raytheon's labor rates rise greater than inflation, making the net effect one of conservatism, underestimating the potential value of the tool.

The issue of timing is similarly fraught with assumptions. Based on CCA's track record and roadmap for TCAT and related production technologies, the tool is anticipated to be in wide circulation in approximately two years. Assuming that CCA can target application of the tool to the most expensive products, applying the tool to revisions of the 5 most expensive to troubleshoot products per year, it will take approximately 10 years to apply the tool to the entirety of CCA's product mix. This allows for the fact that the tool will not necessarily be employed by all design teams as soon as it is available; this assumed pacing is conservative in that it doesn't account for entirely new product introduction, where the tool can potentially have the most impact.

Taking these two points together and plotting them over time, the impact of the tool can be visualized as in Figure 21. Actual dollar values are normalized out to protect Raytheon operations spending information. The blue line shoes the cash value of the savings realized through the tool each year. Troubleshoot costs are distributed across products such that hitting a few products will quickly create large value; subsequent products add less and less over time, leading to diminishing returns and the concave down character of the blue curve. The NPV, or value in today's dollars, of each year of savings is plotted in red.

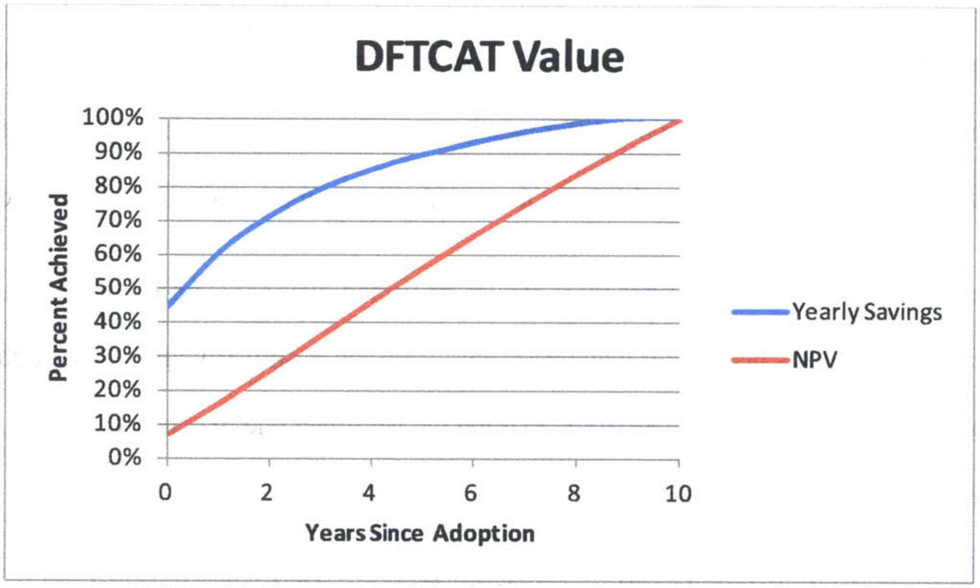


Figure 21 Financial Impact of TCAT

The net effect is a lifetime value of 2.5 million dollars. This is, as discussed, a somewhat elusive number to calculate precisely, but where it was possible to do so, the calculation was kept conservative. In this light, and in comparison to the cost of a Leaders for Global Operations internship, funding such a project and following through to emphasize the cost of troubleshoot to designers obviously makes financial sense for CCA.

6.4 Impact

DFTCAT has the potential to radically reduce the amount of troubleshoot time spent on problem products. In accordance with the assumptions laid out in the previous section, the practical, real time impact of DFTCAT is significant.

CCA builds products that score across a spectrum of troubleshoot performance. The 'worst' include numerous driving features that are known problems, including problem component selections, DFM/DFA rules violations, etc. Barring these special cases, DFTCAT can evaluate the average CCA board and realize up to a 50% reduction in total troubleshooting time, with up to 86% reductions possible for certain 'high fliers,' on a per board basis.

Because troubleshooting is largely manual and slow, this reduction in processing time represents the majority of the touch time a given board experiences, drastically reducing the contribution of labor to production cost. Production lots are frequently organized around the anticipated troubleshoot time, and are thus oversized to account for fallout, and scheduled with a time buffer to allow rework to be completed prior to delivery. A result of this practice is substantial inventory and accompanying holding costs. Complete but defective boards may spend a month or more in the 'bone pile' before being troubleshot and reworked; this problem is less visually obvious than a truck sized Patriot radar in inventory, but with over 10% of hundreds of thousands of circuit cards requiring rework at any one time, the 'bone pile' becomes s subtle but significant drain on resources. Eliminating troubleshoot hours can shrink the bone pile and enable more efficient production planning.

Troubleshoot time is an analogue for value in this discussion; the value of the tool calculated here is based solely on the labor associated with troubleshooting. The impact of the tool goes beyond simple labor savings. Standardizing test machine platforms, enforcing PCAT rules, and creating positive feedback loops across designs all contribute to better design, which in turn lower labor requirements that enable CCA to further develop as a data driven organization. As part of the tool suite CCA is developing to help guide their partners along their manufacturing technology roadmap, a fully integrated DFTCAT will enable increased test machine up time, reduced training and improve sourcing of common parts to reap substantial operational gains.

7 Future State and Recommendations

The tool the author left with CCA is a prototype. It is a robust and transparent Excel model, with the technical integrity for widespread application within Raytheon, but not necessarily the ease of use or practicality a more sophisticated software implementation would enjoy.

The greater work yet to be done is in the realm of integration. As part of translating the tool into an executable format or higher level programming language, much of the underlying work done to build the tool in the first place can be automated through links to CCA operating systems. Incorporating or at least addressing *all* of CCA's data may be possible, leading to a more accurate and robust tool. At the same time, better data integration on the design side, the 'front end,' will facilitate accurate and thorough data input, largely without user intervention required. Raytheon's vision for a data centric, information rich design environment is shown in Figure 22.

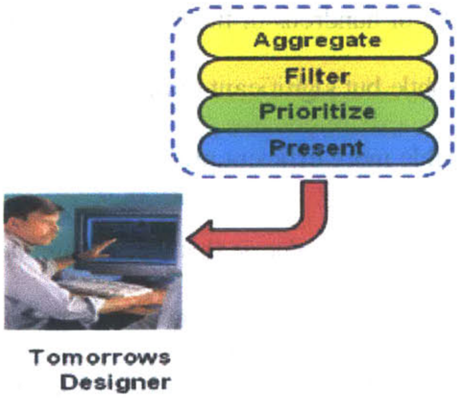


Figure 22 Raytheon's goal of 'Tomorrow's Designer'

The ideal future state is one where TCAT is rarely seen as an independent entity. TCAT will be a part of a production readiness assessment dashboard visible to designs, mining information from design files and operations history, reporting out both to designers and CCA manufacturing engineers, while storing and tracking data through time, self assessing and self updating along the way. TCAT's core logic serves as a transformation engine, not just for data, but for how teams see troubleshoot across CCA. This concept is illustrated in Figure 23. Visiprise and FOS are described in section 7.2.

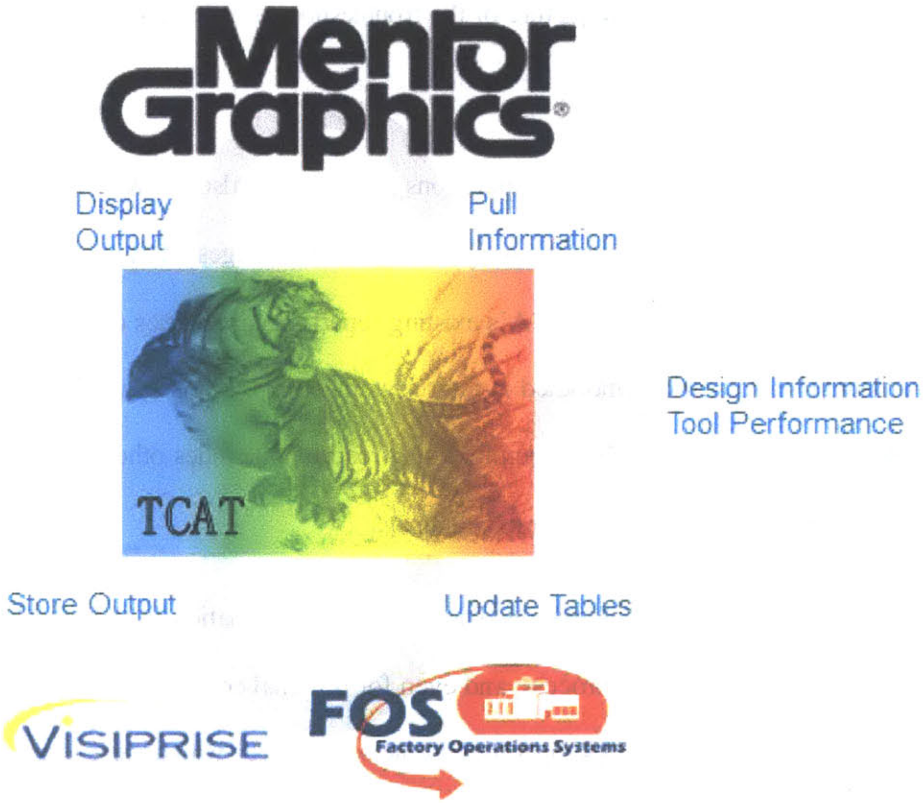


Figure 23 TCAT integration end state

7.1 Linking to Mentor

Mentor Data Management System is a commercial software tool Raytheon design teams use to design products and share information across functions, teams and businesses. Mentor as a dashboard for a broad array of tools is a core concept in Raytheon's vision.[11]

Mentor integrates electrical schematics, mechanical product information, component data, etc, aggregating enough data to populate most fields with TCAT automatically. By integrating TACT into Mentor such that minimal user input is required, accuracy can be increased through the reduction of human error, and tool acceptance will become more natural because it becomes vastly easier and less labor intensive to use. The tool will be able to work better, because more detailed information can be drawn from design information. The practical consideration of not overly burdening the user is mitigated, giving TCAT and CCA a more complete picture of the troubleshoot profile of a new product.

7.2 Linking to VM

A strong connection to the 'back end,' CCA's operations databases, is also desired. Visiprise Manufacturing (VM) and the Factory Operations Systems (FOS) packages CCA employ aggregate tremendous amounts of data, so much that CCA's existing reporting capabilities can't begin to scratch the surface of the amount of information embodied in their systems. Simply by having this data, CCA is on a path to better management practice. CCA's manufacturing roadmap includes other tools like TCAT that take advantage of the huge resource this data represents.

Fully capitalizing on VM data means integration. The volume of information is sufficiently large to be impractical both for individual users to process, and even for personal computers to retrieve and manipulate efficiently. With TCAT's logic operating at the server level, with access to the entirety of Raytheon's operations data, greater accuracy is possible, as is greater sensitivity to changing trends in product and manufacturing technology.

To preserve the practicality of the tool, future builds will need to carefully filter this data. Old data becomes less relevant with time, and data on brand new products may be colored by a learning curve in manufacturing, for example. Human intervention to grow and maintain the tool can be minimized with appropriate algorithms, but making sure TCAT is intelligent enough to spot issues in data and raise the appropriate flags is critical.

Integration into VM also facilitates better record keeping. Other existing tools, PCAT especially, generate reports that are easily lost in the shuffle of transitioning a product to manufacturing, impacting accountability and discouraging CCA maintaining a real time sense for how the tools are performing.

Much of this stems from the fact that PCAT is run on a user's local machine, where all output data is stored. It becomes the responsibility of the individuals involved to appropriately transfer the information and subsequently store it in an easily accessible way. In practice, this is very difficult and rarely done. By making TCAT part of the database system at Raytheon, reporting will be centralized, and further tool utilities can be generated to track metadata concerning the tool. This includes usage information, such as how often users access the tool, how design scores change over time relative to tool usage, etc, and output tracking, making sure data is easily referenced in the future, and tracking the TCAT's predictions against reality.

7.3 Recommendations

Recommendations fundamentally follow the prior discussion concerning linking TCAT to Mentor and VM. Wide deployment of TCAT as it exists today follows the path PCAT took over ten years ago. While effective, this is a slow path, and recent analysis has brought to light the fact that PCAT's performance has dangerously degraded, while exposing several process holes related to PCAT's application.

By embedding TCAT in Raytheon's systems, not only does the tool itself become stronger, but engagement and exposure across Raytheon will come faster, while ensuring the long term sustainability of the accuracy of the tool and facilitate data driven decision making, not just about new designs, but about the tool itself and how to best evolve it to meet Raytheon's needs.

An ideal future state is one where TCAT is itself seldom seen, but it's outputs are seamlessly integrated into Mentor, informing designers of the costs associated with their decisions, while at the same time feeding engineers and managers in CCA information on how designs are evolving and what CCA's troubleshoot performance is. While TCAT continues to update itself and remain relevant, troubleshoot times continue to drop on new products, and perhaps most importantly, CCA gains a new foothold in a design world that is more well rounded and appreciative of the role they play in manufacturing.

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9 Appendix

The troubleshooting tool as originally conceived during the planning phase of the internship was to based entirely on empirical data obtained through a study of CCA's current product portfolio. This appendix details the variables selected, how they were analyzed, and what the outcomes were for each variable.

Not included is a comprehensive list of the variables that were proposed and rejected prior to rigorous analysis. Over the course of many hours of discussion with upwards of 35 technicians, engineers and managers, countless variables were introduced and subsequently removed from the pool, due to issues of redundancy or co-linearity, difficulty or impossibility of data collection and/or no reasonable method statistical quantification.

This list, broken down into practical data categories, includes all the variables for which sufficient data was collected for analysis, along with a brief description of the variable and how it is measured.

9.1 Basic Information

Information describing the products of interest.

- Assembly Number - The number used to identify different products. Each Assembly Number represents a unique circuit card assembly.
- Value stream - The Value Stream the product belongs to.
- Program - The Program the product belongs to.
- Test Engineer - The test engineer responsible for product test. Test engineers served as invaluable resources for data collection.
- Actual Rate – The actual production rate of the product, in units/year.
- Business - The Raytheon business of origin of the product.
- Operator - The test technician or technicians responsible for actually testing each product.

9.2 Output Statistics

Performance data of existing products for use as responses in regression, and to evaluate the strength of potential explanatory variables.

- Trbsht Hrs - Hours spent in the troubleshoot phase over the period of performance. Primary metric for tool.
- Trbsht SFC Count - Total number of SFCs, Shop Floor Control numbers, troubleshot. Each SFC represents a unique circuit card assembly unit in the system.
- Trbsht/SFC - Trbsht Hrs/Trbsht/SFC. Used as an alternate tool metric.
- Defects, Total - Total number of defects found per Assembly Number
- Defects, PCAT- Total number of PCAT relevant defects found per Assembly Number. For more information on Defects, consult Appendix 9.2.
- DPMO, PCAT - PCAT relevant defects per million opportunities. Each soldered connection in an assembly is counted as an opportunity.

9.3 Design Data

General design related data describing the card.

- PWB Area - The surface area of the printed wire board, in square inches.
- Total Opportunities – The total number of defect oppurtunities – solder joints – on the board
- Opportunities/sq in- Total oppurtunities divided by PWB Area
- Total Components - The total number of electrical components on the board
- comps/ sq in- Total components divided by PWB Area
- Percent SMT- Percentage of total components that are surface mount
- PWB Layers- Number of layers in the printed wire board
- Double Sided- Binary variable indicating the presence of electrical components on both sides of the PWB
- High Voltage- Binary variable indicating voltage above 30V applied during testing

- High Current - Binary variable indicating current above .1A applied during testing
- Flex Cable - Binary variable indicating the presence of at least one flex cable on the board
- Heatsinks- Binary variable indicating the presence of at least one heatsink, heatplate, cover or similar mechanical component on the board
- LEDs- Binary variable indicating the presence of at least one LED on the board
- Conformal Coat- Binary variable indicating the product receives a conformal coating
- Bonded Comps- Binary variable indicating some components are bonded to the board
- Jumper Wire- Binary variable indicating the presence of at least one jumper wire on the board
- Custom Percent- Percentage of custom components on the board

9.4 Functional Data

- Analog - Binary variable indicating significant portion of board uses analog technology
- Digital- Binary variable indicating significant portion of board uses digital technology
- Power- Binary variable indicating power conditioning functionality
- RF- Binary variable indicating significant portion of board uses radio frequency technology
- Programmable - Binary variable indicating presence of programmable components

9.5 Test Related Data

- Total Nodes- Total number of nodes in the circuit design
- ICT Test Coverage- Percentage of nodes accessed during in circuit test
- ICT Test Station- In circuit test station used
- Boundary scan / JTAG- Binary variable indicating use of 1149.1 JTAG boundary scanning technique at test
- Functional Test Station- Type of machine used at functional test
- Test Machine Age- Age of functional test machines used

- Active Connectors- Number of connectors used in functional test
- Active Pins- Number of pins used in functional test
- 'Special' Connectors/Cables – Binary variable indicating the presence of troublesome or otherwise noteworthy connectors or cables. For example, connectors requiring a specific torque or having a finite lifespan, cables with poor shielding.
- PCODE Count- The number of PCODEs evaluated at functional test, each PCODE corresponding to a single test.
- Mhz/Ghz measurement Count- The number of high frequency measurements made at functional test
- dBm/dB measurement count- The number of RF signal strength measurements made at functional test
- Thermal Test – Binary variable indicating functional test performed with thermal cycling
- Vibration Test - Binary variable indicating mechanical vibration performed before functional test
- Complexity of Fixture- Variable indexing fixture complexity according the presence of mechanical complexity, such as mechanical slides for environmental isolation, and electrical complexity, such as the presence of external logic components between the test station and unit under test
- Test Strategy Reviewed by CCA – Binary variable indicating the test strategy accompanying the product was reviewed by CCA prior to the start of production
- Formal Handoff to Test?- Binary variable indicating the presence of a formal handoff between test and design engineering. What constitutes a formal handoff varies across time and between businesses
- Diagnostic Software Support/BIT? – Variable indexing the presence of diagnostic software and the presence of built in test capability for troubleshooting.
- Fault Dictionary - static, manual, closed loop/Agilent? – Variable indexing the degree to which a fault dictionary, if it exists, is updated to reflect lessons learned in troubleshoot

9.6 Process Data

- MSA Performed- Was a measurement system analysis performed on the test station
- Length of Main- What is the length of the main in the test software?

- Number of Cards Validated-How many cards were validated on production test machines at prior to start of production