Developing a Methodology to Link Printed Circuit Board Assembly Yield Targets to Commodity Group Quality Goals

By

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Bachelor of Science, Mechanical Engineering, University of California at Berkeley, 2000
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ABSTRACT

The increasing complexity of high-end routing products, a highly diverse product mix, and continually demanding quality requirements have intensified the challenges faced by Cisco. Primary among these is managing the broad array of suppliers to ensure that the parts they are delivering meet the quality needs of the end product while balancing this with the need to remain cost competitive. Because components are often used across many product lines, it is can be difficult to determine exactly how an improvement to the quality of an individual component will impact Cisco's overall yield metrics.

This thesis establishes a methodology for linking component quality to assembly-level yields. The component level quality is measured in Defective Parts Per Million (DPPM) at the Commodity Group level, and PCBA Yield is measured as the percentage of boards which meet Cisco's Six Sigma yield targets. The proof of concept for such an analytical link shows that these two metrics can be analytically related, and furthermore can be used to ensure that the effort expended to improve DPPM is optimally targeted to have an impact on assembly-level yields.

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1 Cisco's Model for Yield Targets

1.1 Development of Unified "Six Sigma" Targets

With an increasingly large product portfolio, Cisco needed to develop a unified way to evaluate yields across all product lines. To achieve this Cisco created a methodology to assign yield targets to every PCBA it manufactures. These targets are based on several factors related to the complexity of the boards, and are designed to enable comparisons of yield performance between boards of similar complexity. Throughout this thesis, these targets will be referred to as the "Six Sigma" targets.

1.1.1 Motivation for developing Six Sigma targets

Prior to developing the Six Sigma targets, Cisco set yield targets for each product line independently. These targets were usually comprised of a combination of historical improvements and often heavily influenced by what the director responsible for a particular product believed was possible based on his experience. This resulted in yield targets – and performance – that was often inconsistent across the company. Similar products that would theoretically exhibit similar yield performance demonstrated wildly differing yields in practice. Because there was no systematic way to aggregate this data to determine what drove these differences, it was not always clear whether discrepancies were caused by product design, process instability, component quality, or any of a host of other possible issues. When problems did arise, it was difficult to determine who was responsible for the problem: ambiguity regarding the cause could lead to finger-pointing and acrimony between different groups. It was clear that a better way was needed to track manufacturing yield performance.

1.1.2 Six Sigma target model

The Six Sigma yield methodology was developed to provide an analytical means to set yield targets that could be applied throughout the company. These targets were intended to be used for current and new products to provide consistent targets across all business units. A statistical analysis revealed the four biggest drivers to PCBA yield and resulted in a formula that could provide a predicted yield target for any type of board. One of these drivers had to do with the components on a board. Boards falling well below this target were selected for improvement or remediation, and boards above the target were deemed to be good quality.

All newly introduced products, as well as production products falling below the designated target, were required to be put on a "Yield Achievement Plan." Each plan outlined the steps for improving board yield, which could include focusing on a particular problematic component, improving a key process step, or even in some cases "re-spinning[1]" an ASIC in order to insure it delivered the required performance to enable achievement of the targets.

In this way, all PCBAs made by Cisco were given clear goals, and teams were aligned to meet these goals by improving the boards.

1.2 Commodity-level goal setting

At the component/commodity level, things worked somewhat differently. Target yields for components are not set on a component-by-component basis, but rather at the commodity group level and include all the components within the commodity group. For example, the ASIC commodity group may have a goal of 5000 DPPM (not the real number) that includes all ASICs. These cover a wide range from very simple ASICs with few pins to very complex ones with dozens of pins. Commodity groups typically have Component Engineers and Supplier Quality Engineers who are responsible for improving the yield of the components in that group, but the number of dedicated engineers varies somewhat from one commodity group to another. However, there is not a consistent method for choosing which commodity groups need to be targeted for improvement within a commodity group and it is often the case that the components being targeted are those that have most recently caused a problem. Though this is an effective means of reactively addressing known problems, it does not meet Cisco's aspiration to pro-actively manage component quality issues.

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[1] Re-spinning is a major redesign of a component, typically an ASIC. Though this can sometimes result in substantial yield improvements, it comes at a substantial cost, so a cost-benefit analysis is required to determine if the improvements predicted in a re-spin will result in sufficient savings to cover the investment.

A lack of actionable data makes determining how many engineers are needed to address issues in a particular commodity group a practice that is more art than science. Ideally, component engineers and supplier quality engineers would be staffed in such a way as to improve component quality such that it had the biggest impact on PCBA yields. Unfortunately, there is not clear data that relates the reduction of DPPM for a particular commodity group to an increase in the number of PCBAs that meet their Six Sigma targets. Building this critical link is a recognized need at Cisco, and is what this thesis endeavors to do.

1.3 Relationship between the two sets of goals

As mentioned above, currently the commodity level DPPM goals and the PCBA-level Six Sigma targets are established completely independently from one another, via independent means. Furthermore, each group tasked with achieving those metrics operates mostly independently. For example, component and supplier quality engineers are not formally incentivized to increase the number of PCBAs that meet their Six Sigma target. A single improvement in component quality will often impact multiple boards (1). In the case of Cisco, this means that the effect of a single improvement can ripple across different business units throughout the organization, but be diffuse enough that it is difficult to measure quantitatively. Component engineers and supplier quality engineers are incentivized to reduce average DPPM for their commodity group with insufficient focus on the impact to the yield of the final products. This disconnect needs to be bridged in order to maximize the effectiveness of the efforts to improve component quality.

2 Project Orientation

At Cisco, the alignment of commodity level goals and the PCBA-level Six Sigma targets has been identified as a critical link in insuring that Cisco will be able to consistently meet its price, quality, and delivery commitments to customers. Perfect alignment would mean that CEs and SQEs would spend 100% of their effort focused on the components whose improvement would have the greatest impact on meeting the PCBA–level targets. There are two key factors that are needed to determine where this effort should be focused to have the greatest impact.

- Impact of Improvements: Choosing commodity groups where improving the DPPM by a given amount would enable the greatest number of PCBAs to meet their Six Sigma targets.
- Effort Required for Improvement: Choosing commodity groups where a given DPPM improvement can be achieved with the least effort as measured in engineering man-hours.

2.1 Project Objectives

This thesis aspires to develop a methodology linking these two sets of metrics, and provide a framework for making decisions about where component engineering effort can be focused to make the biggest impact on PCBA-level yields.

The Mixed Integer Program developed in the course of this work uses the bill of materials data (as broken out by commodity group) for each PCBA to model what impact an improvement in DPPM for a commodity group will have on the number of boards that meet their yield targets. Using this model, it seeks to minimize the amount of effort required to reduce DPPM for each commodity group sufficiently achieve such an improvement.

3 Company Background

3.1 *Cisco History*

Cisco was founded in 1984 by Len Bosack and Sandy Lerner to connect networks in different buildings at Stanford University. In the past twenty-five years, it has grown to be company of more than sixty-seven thousand employees that earned $39.5B in revenue in fiscal year 2008. This growth has been driven both by organic growth and by acquisition. By leveraging both home-grown and acquired technologies, Cisco has maintained an impressive track record of releasing new and innovative products to market each quarter. These products span all types of networking equipment from a simple IP phone to an incredibly complex core router. Recently, Cisco launched Telepresence, a technology that enables individuals to conduct extremely high quality video conferences with one another – these Telepresence meetings use ultra high definition technology for extremely high quality visuals, use stereo speaker for locational audio, and eliminate the slight delay common to most long distance communication. The incredible variety of this product mix is one of Cisco's great strengths but also presents some significant challenges(2).

3.2 *Outsourcing Model*

Headquartered in San Jose, California, Cisco recognized that it needed a more flexible manufacturing base in order to support its level of innovation and growth. Cisco follows an outsourced strategy and outsources its manufacturing to 37 factories worldwide(3), partnering with four primary contract manufacturers (CMs). In addition, Cisco has developed relationships with thousands of component suppliers. These relationships cover the entire spectrum of supplier engagement and integration: arms-length purchasing of commodity products requires minimal information; for high-end or more specialized products, close coordination is needed between Cisco and its suppliers to make sure that needs are aligned with product features and that supplier and customer technology roadmaps are aligned.

Figure 1: Simplified Diagram of Cisco's Supply Chain

The challenge for Cisco is to manage these various relationships in order to be able to offer products that meet or exceed customer expectations for price, quality, and delivery. This is difficult enough for companies like Toyota who produce incredibly complex machines with thousands of parts. For Cisco, this challenge is an order of magnitude more difficult due to the incredible range of the product mix. Cisco's low-end products are typically 1/50,000 the price of its high-end products, and the expectations regarding the quality of the two products are vastly different. If a latent defect causes one 0.1% of IP phones to stop working after three years, it is a substantial - yet manageable - inconvenience. However, if every core router has a 0.1% chance of failing, it represents represent an incredibly large problem that would impact millions of end users. As the impact of a potential defective increases, so to does the quality standard that the unit requires. A related challenge caused by this complexity is the enormous range of volumes of items produced. Whereas yearly shipments for a core router may measure in the dozens, tens or hundreds of thousands of IP phones may ship in a given year. These different manufacturing volumes cause additional challenges when collecting yield information.

3.3 Innovation

Cisco's commitment to innovation introduces still more challenges. Because Cisco positions itself on the cutting edge, it does not have the luxury of using off the shelf products with long field histories. In many cases, key components for important new products are custom designed for Cisco. Though Cisco then puts all products through a rigorous testing and qualification system, there is always some uncertainty about the product performance until there is time to gather sufficient field data.

3.4 *PCBA Manufacture and Component-Related Failures*

PCBA manufacture is a critical and highly complicated endeavor and requires design and process expertise, advanced equipment, and highly-skilled employees. A complicated PCBA can be easily consist of tens of thousands of discrete parts all placed and soldered to the underlying PCB. A schematic representation of PCBA manufacture is shown in Figure 2.

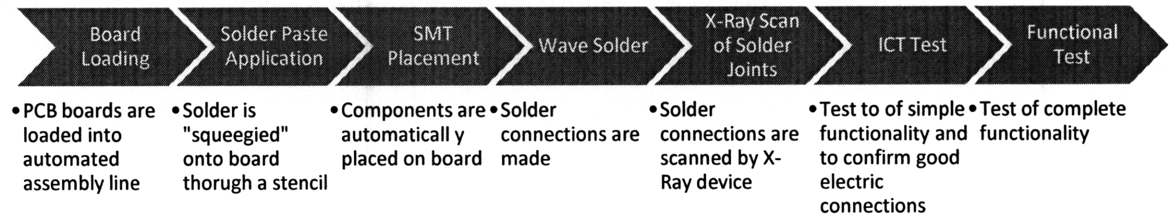

Figure 2: PCBA Process Flow and Assembly Steps

PCBA boards can fail for several reasons which can be broken into three overarching categories: connection failures, component defects, and device interaction.

3.4.1 Connection Failures

Physical failures are caused when an improper physical and electronic connection – either a short or an open circuit occurs - between the device and the board or on the board and is often due incorrect placement or a poor solder weld. These problems are detected either at the Automatic X-ray Inspection (AXI) or at In-Circuit Test (ICT) and are usually not caused by any defect inherent in a particular device.

3.4.2 Component Defects

When a component defect is the cause of a failure, it can be caught in either the ICT test or in the Functional test. The ICT test measures the electronic connectivity and some basic functionality of the components on a PCBA. If a component has a gross functional defect, then it may be caught in an ICT test. However, most defects that are a result of component quality are caught one step later, in the functional test. The functional test pushes the assembly to its limits and uncovers latent defects that may have escaped earlier tests.

3.4.3 Device Interactions

The third type of failure occurs when a problem arises from interactions between devices. This is the most difficult type of failure to isolate and diagnose. Even if every device on a PCBA is operating within its specified parameters, there is still a chance that two devices - both operating too near the edge of their specs - will interact in a way that causes the PCBA to fail the functional test. The chances of this type of failure increase dramatically with the number of components on a board.

4 Challenges to Change – Three Lens Analysis[2]

Aligning the goals for various commodity groups with those for PCBAs faces not only substantial technical obstacles, but also significant organizational challenges. Coordinating these metrics is a truly cross-functional challenge that spans multiple organizations and working groups and touches many stakeholders, each with his or her own incentives, motivations, cultural norms, expertise, and thought structure. The following section discusses some of these challenges as viewed through a Three-Lens Analysis.

4.1 Strategic Design

When considering the impact of component quality on manufacturing yields, there are a large number of working groups, organizations, and business units who must be counted as stakeholders. The most central among these are Manufacturing Ops, Component Engineers, Contract Manufacturers, Commodity Managers, Suppliers, and Product Ops. A brief description of each of these groups follows.

4.1.1 Manufacturing Operations (MfgOps)

Manufacturing Ops is responsible for the manufacture and sustaining improvement for all of Cisco's product lines. It is the group primarily responsible for managing the contract manufacturers and for the final quality of the products. Its goals include improved yields, reduced manufacturing defects, and improved quality on products that are already well into their product lifetime. Sub-groups within MfgOps are generally focused on and aligned with one of the four contract manufacturers.

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[2] A Three Lens Analysis is a technique developed by the faculty at MIT Sloan in order to shed light on some of the less obvious organizational challenges incurred when introducing or change. The first lens "Strategic Design" looks at the formal structures within an organization (hierarchies and incentives, for example) that shape motivations and actions. The second "Political" focuses on the various informal influences, stakeholders, allegiences, and potential for significant changes in the power or prestige of individuals or groups. The third "Cultural" considers the working patterns, attitude, and other factors that determine the "feel" of a particular group or organization.

4.1.2 Component Engineers (CEs)

Component Engineers are responsible for improving the quality of components purchased from suppliers as is measured by the DPPM of that component when used in production. Component Engineers also qualify and sign off on new suppliers and new components needed for New Product Introduction. CEs are grouped by commodity groups that align with their own personal expertise (such as ASICs, Power Supplies, etc.) A single CE will typically be responsible for components within one commodity group that end up in various Cisco products at all Contract Manufacturing sites.

4.1.3 Contract Manufacturers (CMs)

Contract manufacturers are responsible for all production and assembly as well as data collection and test for every one of Cisco's products. They are currently compensated by an activity-based costing model and managed by MfgOps to improve yields and reduce lead-times. When there is a problem with a PCBA, one of the common rework practices is to replace one suspected component at the time until the board passes the test, meaning that several components can be replaced before the problem is resolved. Incentives for CMs are designed to encourage high quality and low cost manufacturing, but there is only a secondary emphasis on accurate recording and monitoring of infrequent failure modes. Due to this and other factors, the DPPM data collected for defective components is believed to be pessimistic and may not always reflect the true quality of the underlying components.

4.1.4 Commodity Managers (ComMgrs)

Commodity managers are responsible for the business side of relationships with suppliers. Though in a separate organization (reporting to a separate VP) than the Component Engineers, they are co-located with them in the same physical space, and have similar alignment with particular commodity groups. Like CEs, commodity managers typically work with suppliers from the sourcing decisions associated with new products through the lifespan of a particular component. However rather than dealing directly with technical and defect issues, ComMgrs are focused on price reductions and cost. Though it is widely acknowledged that the Cost of Poor Quality (COPQ) may have a significant impact on the total cost that may offset the gains of a slightly lower piece price, this Cost of Poor Quality is difficult to quantify and equally difficult to factor into purchasing allocations.

4.1.5 Suppliers

Parts purchased (either by Cisco or one of the CMs) from the suppliers are assembled into Cisco's PCBAs at the CM sites. Though all products purchased from suppliers are referred to as components, the term covers a wide range of complexity. A so-called component can be as simple as an individual resistor, as challenging as a cutting edge ASIC or Microprocessor, even a sub-assembly (which can contain optical devices, ASICs, resistors, capacitors, optical components and dozens of other components as well). Suppliers are motivated to maintain long term relationships with Cisco, and no supplier wants their quality defects to be the cause of a major problem. However, when a problem occurs with a supplier's component on the manufacturing floor – even if the CMs collect the defective products for return to the supplier – the problem may remain unresolved if the supplier is unable to replicate it on the test bench.

4.1.6 Product Operations (Product Ops)

The Product Ops group is responsible for the product throughout its entire lifetime, from cradle to grave. The most intensive period for the Product Ops group is during the New Product Introduction process, when the Business Unit design organization hands off the product to Manufacturing Ops. Whereas the Manufacturing Ops group is organized by CM, and the CEs and Commodity Managers are organized by Commodity Group, the Product Ops sub-groups are organized by product line. As a result, they become the primary experts on a particular product or product line with secondary expertise for the components that go in it or the manufacturing facility in which it is produced.

4.1.7 Strategic Design – Summary

These different organizations and working groups, with their different alignments, incentives, and expertise present considerable challenges for any change to normal procedures at Cisco. The Six Sigma Yield initiative shifted governance of yields from the Product Ops teams to the Quality Engineers within Manufacturing Ops and overcame substantial organizational resistance through tireless communication, VP-level support and buy-in, and – eventually – signed contracts from each one of the Directors of Product Ops. Introducing a methodology for extending these yield targets to the commodity level will also require buy-in, executive support, and organizational alignment. The next section will discuss some of the political ramifications of such a change.

4.2 *Political*

Currently, DPPM values are measured by the CMs, collected by Cisco's internal Quality Data group, and used by Component Engineers to measure performance against goals. These goals are currently established within the Component Engineering group based on historical improvements and perceived industry benchmarks but without a thorough understanding of how much - or if - achieving these goals will have a significant impact on PCBA yields. A methodology that links the Commodity Group goals to the PCBA goals should have the benefit of aligning more closely the work of the group with the best interest of Cisco, but may take away some of the Component Engineers' ability to leverage their expertise to provide input on what goals are reasonable. Furthermore, since much of CE's current work is in "fire-fighting" the latest problem, this methodology would focus their efforts in a more systematic way. This should have benefits for achieving more consistent gains, but will also reduce the opportunities for the "hero effort" or "diving catch" which is still appreciated (even if officially discouraged) at Cisco.

4.3 *Cultural*

Cisco has a very product-focused culture. Traditionally, Cisco has used its major product releases once per quarter to generate buzz and build brand recognition among corporate clients; however, it has also recently increased its marketing effort to improve brand recognition among consumers. Also, moving to a 100% outsourced model has enabled the culture become even more Product focused (and away from the process focus of a manufacturing company). This product focus permeates most parts of the organization.

However, Component Engineers are significantly less product facing, and with notable specific exceptions, do not have a clear view of exactly how and what impact incremental component

DPPM improvements have on manufacturing yields throughout the organization. Introducing a methodology to connect these two yields introduces an opportunity to help connect these dots, but also faces challenge of requiring a slightly different mindset among CEs. Furthermore, there is the risk that a CE's laser-like focus on one commodity group enables him or her to use his or her expertise to drive down DPPM, and that any shift towards a product focus would serve as a distraction and undermine this goal.

4.4 Three Lens Summary

The introduction of any new system at a company as large and diverse as Cisco represents a substantial challenge. Even the partial list of major stakeholders above reveals how different the incentives, organizations, and motivations of the various groups are. Furthermore, the political impact of such a change could be substantial, but in this case it is not clear exactly how the change would impact the various formal and informal sources of power. Finally, though it could enable alignment between currently unaligned groups, there is the risk that altering the focus of the CEs would reduce their effectiveness.

5 Literature Review: Linking PCBA Yields to Component DPPM

Various attempts have been made to develop methods to predict the expected yields of PCBAs based on various complexity parameters. One such study, conducted by Li, Mahahan, and Tong, was able to predict the yields of 30 part numbers with a sample size of at least 1000 units per part number. The methods used were a linear regression model and an artificial neural network. The three factors identified as significant by the linear regression were the number of terminations of chip components on the top side of the board, the number of gull-wing leads, and the number of Plastic Leaded Chip Carriers. The results of the ANN method were the same as those found with the linear regression.(4)

Helo, Ellis, and Kobza describe another method to link assembly-level yield and the components defects. The method described divides components into several categories based on component size, number of pins, and mounting type, the three of which are proxy measures of the mounting difficulty and the complexity of the components. Using the Poisson approximation for the binomial distribution, they assume that each component type has an (unknown) fault probability. The optimization algorithm then optimizes the various fault rates such that the absolute value of difference of the measured yields and the predicted yields is minimized. Through this method, for a sample of 30 different boards, the yields were able to be predicted with an average difference of less than 3%.

Modeling the behavior of different components with the binomial method implies that failures of different component groups are independent. In order to check this assumption, the researchers also used the negative binomial yield model based on Stapper's analysis of clusters of faults on ICs. Because the results of this method were did predict the actual yield as well as the Poisson method, the research confirmed that the component failures were, in fact, independent. The authors also were able to reformulate the exponential Poisson estimate into a linear form (by taking the log of each side of the equation) to enable significant improvements in calculation time. (5)

6 Methodology

6.1 *Description and Development of Model*

The Mixed Integer Program is designed provide a tool to determine how to achieve a designated level of performance while optimally applying engineering effort to do so. Performance is measured by the percentage of boards which will meet or exceed their Six Sigma targets, and this target percentage is one of the inputs to the algorithm. The predicted yield for a board is calculated by modeling the board's fallout rate based on the average DPPM of the commodities used to build the PCBA. This modeled yield is then compared with the Six Sigma target to determine if the board will pass or fail the target. The amount of effort required to improve the DPPM for a particular commodity group is estimated by the historical rates of improvement. Running the optimization is intended to provide guidance for targeting future efforts to yield the greatest improvements in Six Sigma compliance. In other words, which commodity groups should be improved to have the biggest impact on PCBA yields.

6.2 *Approach*

The first step in developing alignment between Six Sigma targets and Commodity Group goals is to collect data about the current performance of PCBAs and Commodity groups, and the relationship between the two. These data are then used as inputs into the MIP. After running through the optimization algorithm to minimize the objective function while meeting all of the constraints, the MIP outputs values corresponding to the effort required for each commodity group to achieve the desired percentage of passing PCBAs.

6.2.1 Rolled Throughput Yield Model

In order use a MIP as an efficient optimization method, it was necessary to develop a linear approximation to the classic rolled throughput yield equation.[3] In the rolled-yield equation the

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[3] PCBA yield can be modeled as by the rolled throughput yield, where each component is treated as one stage in the series because in this case, the failure of any component is independent of the failure of any other, and the failure of one component will cause the entire PCBA to be defective.

total probability of fallout is equal to the product of one minus the probability of failure for each component I (*p_i*), raised to a power equal to the number of those components (*n_i*) (6).

Equation 1

$$PCBA\,Yield = \prod_i (1 - p_i)^{n_i}$$

In order to calculate the probability of catching x defects, the binomial equation can be used (7).

Equation 2

$$b[x; n, p] = \frac{n!}{x!\,(n-x)!}\left(\frac{\lambda}{n}\right)^x \left(1 - \frac{\lambda}{n}\right)^{n-x}$$

Where

Equation 3

$$\lambda = np$$

Though this provides an accurate way for modeling yields, it has the undesirable consequence of forcing the optimization equation to be non-linear, substantially complicating the solution process. Given that this methodology needs be able to account for boards numbering in the thousands in order to be applicable to Cisco's product portfolio, a linear formulation is needed in order to enable the calculation to be manageable for a large data set. The following section describes this linearization and draws heavily from the work of Helo et al (5) (8).

6.2.2 Linearization of the Yield Model

The Poisson equation is a valid approximation of the Binomial equation when the true fault probability p is small relative to the number of occurrences (5), (7). The difference in absolute predicted yield between the Binomial distribution and the Poisson approximation is less than 0.0005 (0.05%) for 10 components with 10000 DPPM; the error in the approximation gets smaller as the DPPM decreases. Actual approximation errors are likely to be much smaller because the likelihood of any component having such a high DPPM is exceedingly small. Using the Poisson approximation, the yield for a particular PCBA *j* can be expressed by the following equation, where n_{ij} is the number of components of type i on board j.

Equation 4

$$PCBA\,Yield_j = e^{\sum_i p_i n_{ij}}$$

Though this is a step in the right direction it still does not result in an appropriate linear formulation. In order to complete the linearization the logarithm is taken of both sides of the equation, giving:

Equation 5

$$\log(PCBA\,Yield_j) = \sum_i p_i n_{ij}$$

In order to test if the modeled yield of each board meets the Six Sigma target or not, the log of the target is taken as well for each PCBA. The modeled log of the yield is compared to the log of the Six Sigma target to determine whether or not a PCBA meets its target.

6.3 Data Collection

In order to determine where effort would best be applied, the following data is needed.

1. Yield targets for PCBAs. These targets are taken as a given and based on board complexity and Cisco's Six Sigma yield targeting methodology
2. DPPM data for each commodity group. Based on manufacturing fallout rates, historical DPPM data for each commodity group are needed to determine DPPM Slope and the DPPM Current parameters in the MIP.
3. DPPM Benchmarks. Using a combination of industry benchmarks and Cisco expertise, best-in-class DPPM values are needed to establish the minimum conceivable DPPM levels for each commodity group.
4. Usage Data. The bill of materials (BOM) of each PCBA contains components from several different commodity groups. This information is critical for modeling how an improvement in the DPPM of a particular commodity group will impact board-level yields.

The collection of the critical data outlined above is discussed in more detail in the following sections.

6.3.1 PCBA Yield Targets

PCBA Yield targets are established based on Cisco's Six Sigma method. Using factors that represent the complexity of a given board, this method assigns a particular yield target for each PCBA made by Cisco's contract manufacturers. Because board fallout can be caused by several factors, one of which is component defects, the entire fallout target is allocated between each of these factors, with only a portion given to components. In other words, the yield target for only component-related failures is higher than the yield target for the overall boards (which includes both component-related and other failure modes). As shown in Figure 3, component-related fallout is only one of the factors used to calculate the Six Sigma fallout targets.

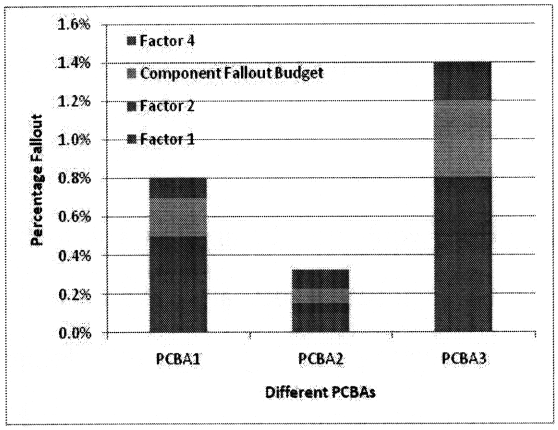


Figure 3: Example of the Contributions of Different Factors to Six Sigma Targets

For the purposes of this analysis, only the component portion of the overall Six Sigma target is relevant.

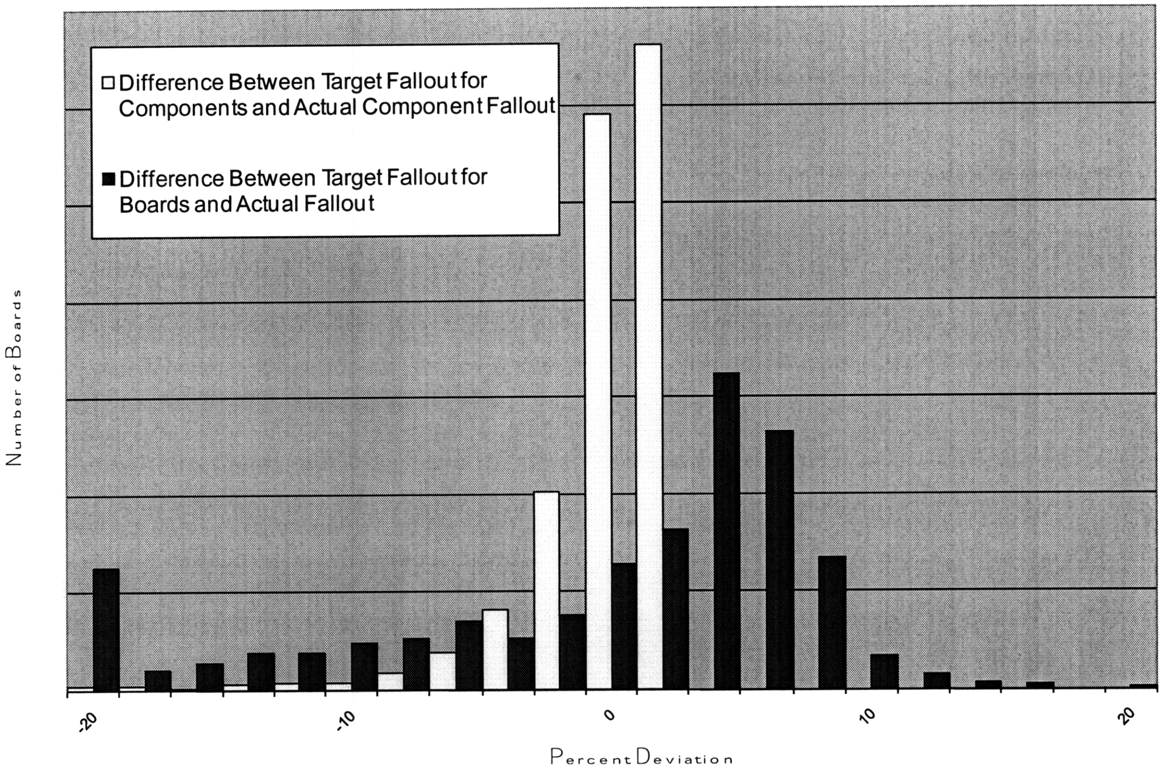


Figure 4 a histogram of PCBA shows the performance vs. Six Sigma targets. The darker colored columns represent the distribution of PCBA yield with respect to their overall Six Sigma targets. The lighter columns represent the distribution PCBA yield due to component-caused fallout with respect to the component portion of the Six Sigma targets. The boards represented by the columns to the right of the graph are passing their the Six Sigma targets, while those to the left are not meeting them.

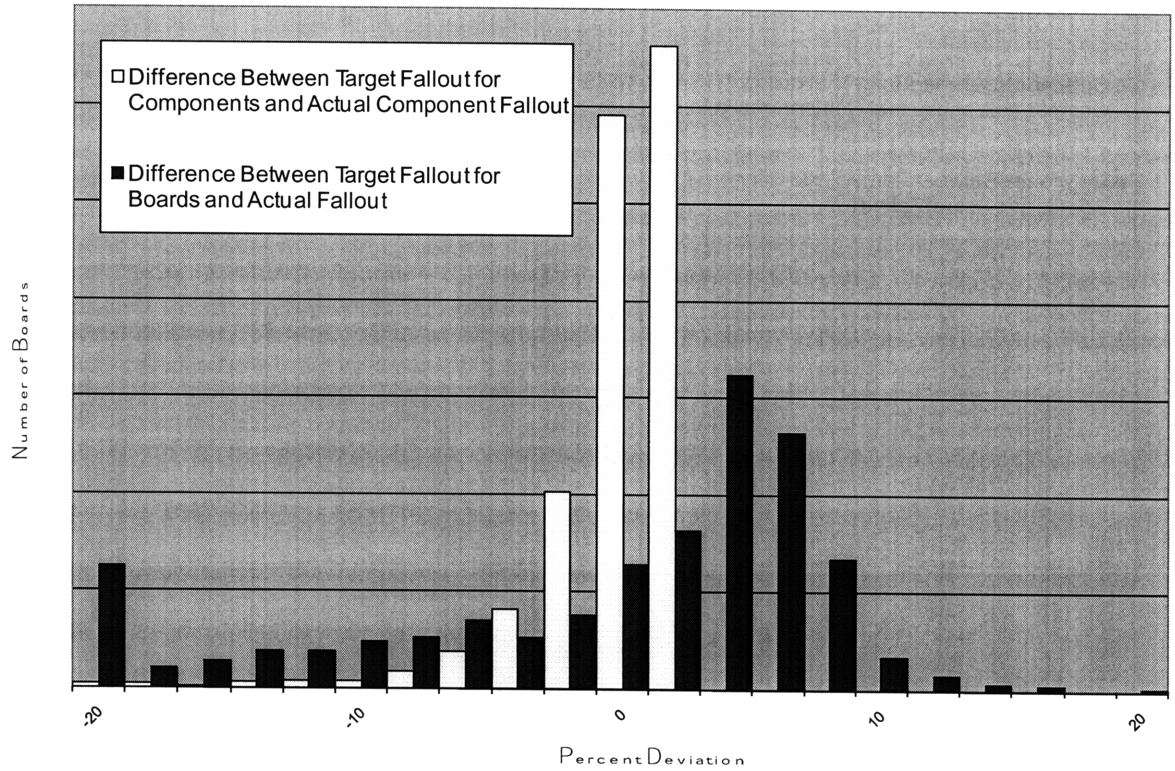


Figure 4: Performance vs. Six Sigma Target

As is clear from Figure 4, there are many boards which still do not meet their overall Six Sigma targets, and even more that miss their component budget for those targets. Component quality issues still cause a large fraction of boards to not meet their Six Sigma targets. However, it is not clear which commodity groups are responsible for pushing more of the boards below the targets.

6.3.2 DPPM Historical Data

Currently, DPPM goal setting occurs by looking at historical improvements of each commodity group and setting future targets accordingly. This process has led to progressively better DPPM performance for commodity groups. This progress that has not always been matched by PCBA yield improvements.

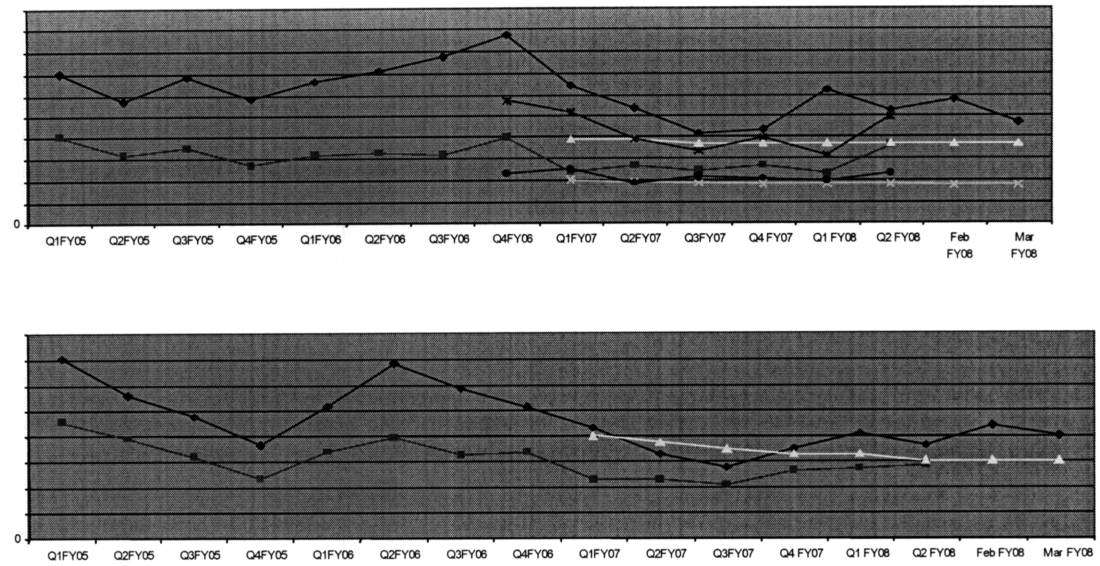


Figure 5: Historical DPPM for Representative Commodity Groups

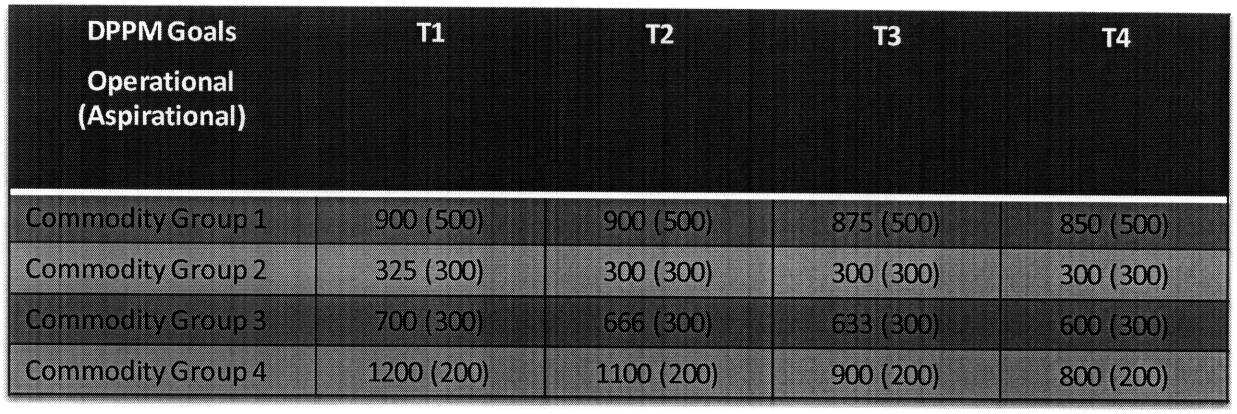
In addition to the DPPM Slope information derived from this historical data, it was also necessary to assess the current DPPM rates for each commodity group, this information is read off as the most recent data point for each commodity group.

6.3.3 DPPM Benchmarks

The DPPM benchmarks are derived from a combination of industry knowledge and benchmarks provided by external consultants during a recent study. The values are typically well below the average values for DPPM currently measured by Cisco, and are taken to represent "best in class" performance, and classified as "aspirational" targets within Cisco. The Operational targets are updated on either a quarterly or monthly schedule as DPPM performance improves.

DPPM Goals Operational (Aspirational)	T1	T2	T3	T4
Commodity Group 1	900 (500)	900 (500)	875 (500)	850 (500)
Commodity Group 2	325 (300)	300 (300)	300 (300)	300 (300)
Commodity Group 3	700 (300)	666 (300)	633 (300)	600 (300)
Commodity Group 4	1200 (200)	1100 (200)	900 (200)	800 (200)

Figure 6 shows historic and current operational targets, as well as the "aspirational" industry benchmarks.



DPPM Goals Operational (Aspirational)	T1	T2	T3	T4
Commodity Group 1	900 (500)	900 (500)	875 (500)	850 (500)
Commodity Group 2	325 (300)	300 (300)	300 (300)	300 (300)
Commodity Group 3	700 (300)	666 (300)	633 (300)	600 (300)
Commodity Group 4	1200 (200)	1100 (200)	900 (200)	800 (200)

Figure 6: Operational and Aspirational Targets for DPPM in Commodity Groups

6.3.4 Usage Data

Each PCBA is assigned an assembly part number and each contains a printed circuit board (PCB) with anywhere to a few dozen to tens of thousands of components on the board, which fall into different commodity groups. Commodity groups are used for component engineering, but when pulling BOM information, the components are classified differently, by "Commodity Codes." Because the components are classified differently for BOM data than they are for commodity management, it is necessary to create a mapping between the two taxonomies. Such a mapping is shown in Figure 7.

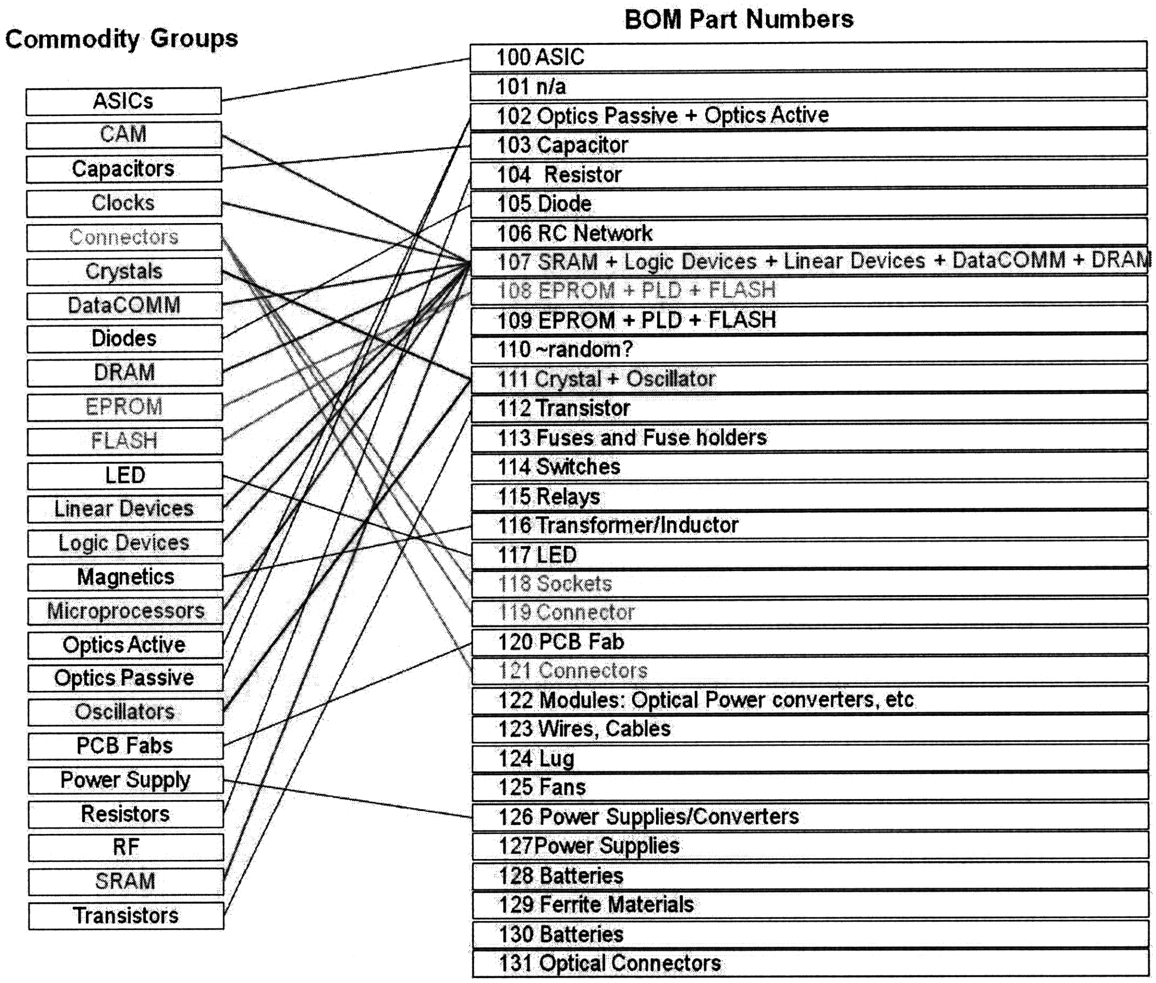


Figure 7: Decoder Ring between BOM-designated Component Groupings and Commodity Group Classifications

With these two sets of data reconciled it is possible to create a Commodity Group-based BOM for each board, showing how many components from each commodity group are used in each PCBA. A partial list of this information is shown in Figure 8.

	Commodity Group 1	Comodity Group 2	Commodity Group 3	Commodity Group 4	Commodity Group 5
PCBA1	8	0	0	26	4
PCBA2	4	0	2	12	4
PCBA3	8	0	0	26	4
PCBA4	8	0	0	26	4
PCBA5	4	0	6	10	2
PCBA6	0	0	0	27	18
PCBA7	7	0	12	16	2
PCBA8	4	0	14	0	8
PCBA9	4	0	0	6	12
PCBA10	4	2	6	8	2
PCBA11	8	0	7	16	2
PCBA12	8	0	7	16	2
PCBA13	8	0	7	16	2
PCBA14	8	0	7	16	2
PCBA15	14	2	0	14	0

Figure 8: Usage Information

6.4 Key Assumptions

Several simplifying assumptions have been made in order to make the optimization algorithm feasible.

6.4.1 Key Assumption 1 - Components within commodity groups perform similarly

The first and most significant assumption is that the mean is a good approximation for the performance of an entire commodity group. This assumption works reasonably well for some groups, but is a significant limitation for groups with a large and skewed distribution of DPPM, most notably in ASICs. As shown in Figure 9, ASICS are heterogeneous enough that none cluster into a normal distribution, and the mean is not a good representation of the performance of the group.

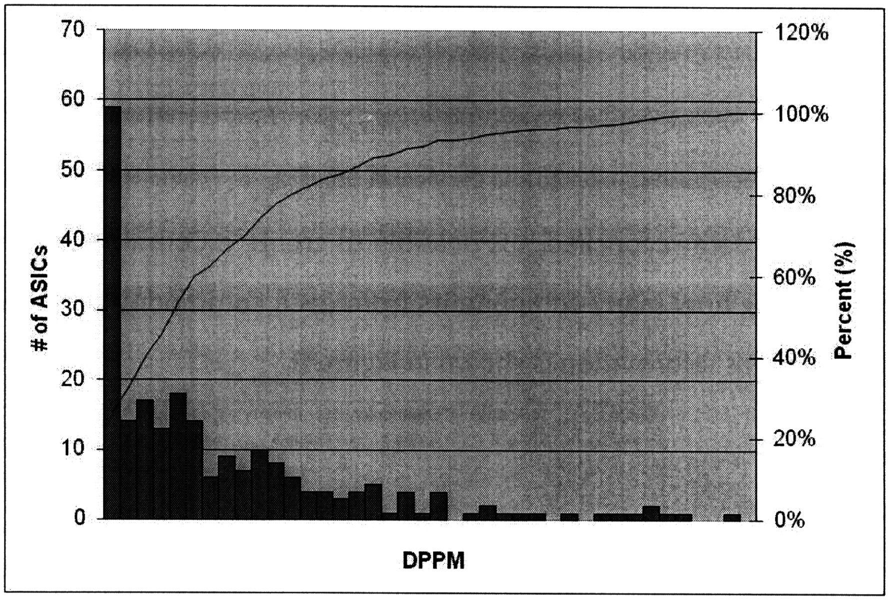


Figure 9: Distribution of DPPM over different ASIC Part Numbers

This limitations imposed by this assumption also highlight the inadequacy of the current method of setting commodity level goals, which are set by comparing the weighted average DPPM of the commodity group to a target.

6.4.2 Key Assumption 2 – Improvement is proportional to effort

The second key assumption is that past improvement of DPPM is a good means of characterizing likely future improvement. Furthermore, it is assumed that if historic improvement can be achieved with the current amount of effort (in terms of engineering hours, etc.) then proportionally more improvement can be achieved by increasing the intensity of the effort.

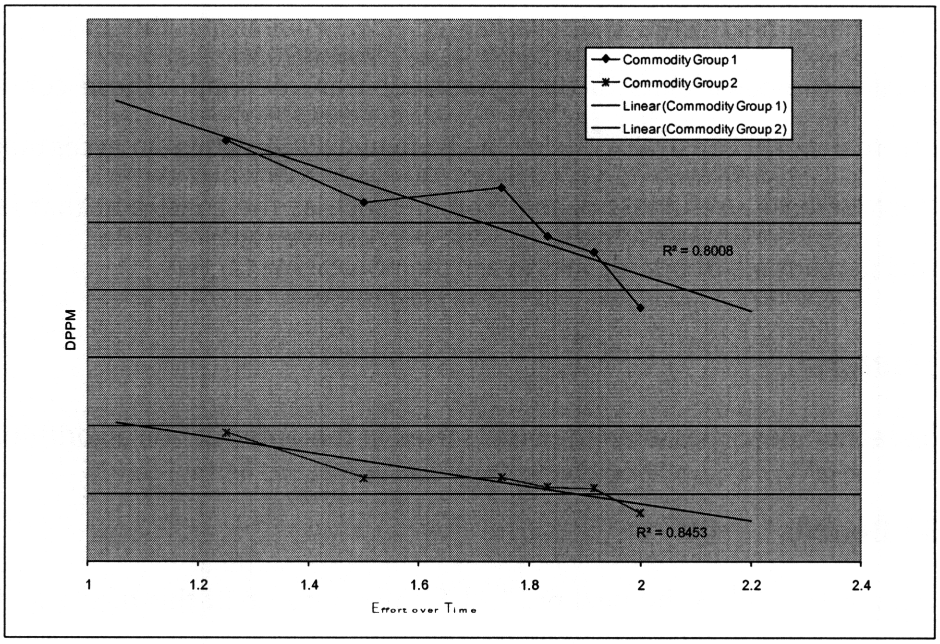


Figure 10: Graph of DPPM Improvement vs. Normalized Engineering Effort

Though proportionality may not prove true for every case, it also captures the current way commodity-level goals are set, namely by using historic trends in DPPM data to extrapolate goals for each successive quarter.

6.4.3 Key Assumption 3 – Faults occur Independently

Though it expected that defects occur within a particular commodity group as predicted by the Poisson approximation to the binomial equation, it assumed that the defects that occur within one group happen independently from defects which may occur in another group. There are faults caused by the interaction between two different components that are not independent. These types of defects are assumed to occur relatively infrequently and are outside of the scope of this thesis.

6.5 Mixed Integer Programming Optimization

The mixed integer optimization will converge to a solution by selecting decision variables that minimize the optimizing function subject to the pre-defined constraints. In the following sections, the various parameters which characterize the nature of the optimization are defined and explained. This is followed by a description of the decision variables, and the decision expressions – expressions that are based on the values of the decision variables. The objective function is described next with a discussion of how minimizing the engineering effort is achieved. Finally, the constraints to the optimization are defined. These constraints model both practical, real-world constraints - such as keeping DPPM within an acceptable range- and constraints that increase usefulness of the model – such as the constraint that more than the predetermined percentage of boards must pass their Six Sigma targets.

6.6 Parameters

The following section describes all of the inputs used in the optimization algorithm.

6.6.1 PCBA Boards

The PCBA board is treated as the final product for the purpose of this thesis, and final yield is measured at the board or assembly level. Each board consists of a unique bill of materials (BOM) that consists of anywhere from zero to hundreds of components from each commodity group.

In production, boards are measured in functional tests to determine if they will pass or fail. The functional yield rate (passing boards/tested boards) is required to meet a target specified by the Six Sigma analysis described above. In the model, each board is indexed by

Equation 6

$$b = 1 \ldots m \text{ to represent each PCB Assembly}$$

6.6.2 Commodity Groups

Each PCBA is made up of a PCB and components from each of several commodity groups. The commodity groups shown in Figure 7 are indexed in the model by

Equation 7

c = 1…n to represent each Commodity Group {ASIC, Capacitors, …}

6.6.3 Usage Data

The usage data is a representation of the number of components from each commodity group that appear on each board. It is a 2x2 matrix with a number of rows equal to the number of boards, and a number of columns equal to the number of commodity groups. It is represented in the model as

Equation 8

$$U_{bc} = number\ of\ components\ of\ commodity\ group\ c, used\ on\ PCBA\ b$$

6.6.4 Six Sigma Yield Target

The Six Sigma Yield Target is defined as the target yield for each board when only taking into account fallout that can occur due to defective components. This input for each board *b* based on the Six Sigma yield methodology defined in the internal Cisco process. This methodology first specifies a target component-based DPU for each board based on its components, and the Six Sigma Yield Target (S_b) is calculated from that as below.

Equation 9

$$\mathrm{S_b} = e^{-DPU_b}$$

6.6.5 DPPM Current

DPPM Current is inputted for each commodity group c and represents the most recent average DPPM performance for that commodity group. This is represented in the model by the variable DC.

Equation 10

$$DC_c = the\ average\ current\ DPPM\ for\ a\ particular\ commodity\ group\ c$$

6.6.6 DPPM Slope

DPPM Slope is a parameter inputted for each commodity group and is used to represent the baseline rate of improvement of DPPM for that particular group. Typically this number is based on a straight-line linear regression of the historical rate of improvement over the past several quarters (see Figure 5: Historical DPPM for Representative Commodity Groups), but for some very low DPPM parts that do not yet have the infrastructure in place to measure and report DPPM these numbers had to be estimated. It is represented in the model as DS.

Equation 11

$$DS_c = the\ rate\ of\ improvement\ of\ DPPM\ for\ commodity\ group\ c$$

6.6.7 DPPM Min

There are practical limits to how much DPPM improvement can be estimated with a linear regression. For example, no matter how much effort is expended, DPPM cannot be negative. In order to prevent such impossibilities, as well as to incorporate some of the expertise that Cisco component engineers hold regarding DPPM, a Minimum DPPM is inputted for each commodity group that corresponds with the industry benchmarking for the best in class. It is represented in the model as DM.

Equation 12

$$DM_c = the\ minimum\ threshold\ value\ for\ a\ commodity\ group\ c$$

6.6.8 Percent Pass Threshold

The Percent Pass Threshold is a user-defined percentage that corresponds with the number of boards that must pass the Six Sigma Yield targets. As PCBA yield performance improves, this value can be ratcheted up to find new opportunities for efficiently improving yields. However, too high a threshold can force a solution to be infeasible. The percent pass threshold is equal to the percentage of boards that must comply with the Six Sigma targets, therefore it is alternatively referred to as the Six Sigma Compliance rate.

Equation 13

$$PPT = the\ required\ rate\ of\ compliance\ to\ Six\ Sigma\ Targets$$

6.6.9 Summary of Parameters

	Variable	Equation/Source	Comment
Equation 6	b	1...n to represent each PCBA	Index
Equation 7	c	1...m to represent each Commodity Group	Index

Equation 8	U_{bc}	Number of components of Commodity group *c* used on PCBA *b*	Derived from BOM data
n/a	DPU_b	Target for Defects per Unit for each PCBA board b.	Based on the component makeup of a board, as defined by Cisco Six Sigma methodology
Equation 9	S_b	e^{-DPU_b}	Based on Cisco Six Sigma methodology
Equation 10	DS_c	The most recent average DPPM data for a commodity group	Data based on recent manufacturing data
Equation 11	DS_c	The rate of improvement of DPPM for a commodity group	Derived from linear regression of historical DPPM improvement
Equation 12	DM_c	The minimum threshold value for the commodity group	Defined by industry benchmarks and opinions of available SMEs
Equation 13	PPT	The required rate of compliance to the Six Sigma Target	A user inputted value that can be ratcheted up as component quality improves

Table 1: Summary of Parameters

6.7 *Decision Variables*

6.7.1 DPPM Effort

The model is formulated such that the decision variables correspond to the amount of effort spent to improve DPPM for a particular Commodity Group. When the model is run, this value minimized to enable the prescribed fraction of PCBAs to reach their Six Sigma targets with a minimal investment of engineering effort. This is represented by the decision variable X_c

Equation 14

$$X_c = the\ effort\ expended\ to\ improve\ DPPM\ in\ commodity\ group\ c$$

Inherent in this parameter is the assumption that engineering effort currently applied in one commodity group (e.g. ASICs) can be transferred to another commodity group (e.g. Microprocessors) if that would result in better overall PCBA yields. Because each commodity group requires a specialized set skills and experience, major shifts in effort or focus are only appropriate for longer-term planning and staffing.

6.7.2 Binary Variable -Pass Six Sigma Target

The second key decision variable is the binary variable associated with each of the PCBAs that indicates whether the board must pass its Six Sigma target or not. This variable is set equal to 1 if it is required to pass and 0 if it is not. It is represented for each board by the variable PS_b

Equation 15

$$PS_b = \left\{ \frac{1\ if\ Board\ b\ is\ required\ to\ pass\ Six\ Sigma\ Target}{0\ if\ board\ is\ not\ required\ to\ pass} \right\}$$

The constraints section contains a more complete discussion of how this binary variable must be equal to 1 for enough boards so that the percentage that are modeled to pass their Six Sigma targets is greater than or equal to the target percentage.

6.7.3 Summary of Decision Variables

	Variable	Equation/Source	Comment
Equation 14	X_b	The amount of effort chosen to improve DPPM for a commodity group	
Equation 7	PS_b	1 if board is required to pass 0 if board is not required to pass	Binary DV to ensure that there are enough boards that meet the Six Sigma targets

Table 2: Summary of Decision Variables

6.8 Decision Expressions

In order to simplify equations and improve model readability, several intermediate Decision Expressions have been created that are based on the values of the Decision variables.

6.8.1 Total DPPM Effort

The total DPPM effort is equal to the sum of the effort expended to improve DPPM on each commodity group c. It is this effort that the objective function seeks to minimize while satisfying the constraints of the optimization. This expression is represented as TE

Equation 16

$$TE = \sum_{c} X_c$$

6.8.2 Percent Pass

Percent pass (PP) is the percentage of boards that are modeled to pass their Six Sigma Targets, it is derived by dividing the number of passing boards (PB) by the total number of boards analyzed (TB).

Equation 17

$$PP = \frac{PB}{TB}$$

6.8.2.1 Count Passing Boards

The number of passing boards is calculated by summing the binary variable Pass Six Sigma Target (PS) over the all boards (b).

Equation 18

$$PB = \sum_{b} PS_b$$

6.8.2.2 Count Total Boards

This is total number of boards analyzed (m).

Equation 19

$$TB = m$$

6.8.3 DPPM Improvement and Used DPPM

Used DPPM is a key decision expression used to represent what DPPM value is achievable for each commodity group given an expenditure of effort to improve DPPM. If the DPPM Effort is equal to zero, then the Used DPPM will remain equal to the DPPM Current. If the DPPM effort is equal to one, then the DPPM will be modeled to continue to improve at the historic pace. A doubling of the DPPM Effort (i.e. DPPM Effort = 2) corresponds to a doubling of the pace of improvement. DPPM improvement is defined as the product of DPPM Effort (X) and DPPM Slope (DS). It is represented as DI.

Equation 20

$$DI_c = X_c * DS_c$$

The Used DPPM is represented as DU, and is the value of DPPM that is used in the model to predict the modeled fallout rate for the PCBAs.

Equation 21

$$DU_c = DC_c + DI_c$$

6.8.4 Modeled DPU

The Modeled DPU is based on the Used DPPM and the Usage for each board. It is represented as the summation of the product of the number of defects expected for each Commodity Group, and the number of Devices from Each group on each board. It is represented as MDPU.

Equation 22

$$MDPU_b = \sum_c \frac{DU_c}{10^6} * U_{bc}$$

6.8.5 Six Sigma Target Minus Modeled DPU

The decision expression Six Sigma Target Minus Modeled DPU represents the difference between the Six Sigma target for DPU and the Modeled DPU described above. Recall from the above discussion that the Six Sigma DPU is an inputted parameter and a fixed value, and the Modeled DPU for each board constantly changes as the optimization seeks the optimal solution. Six Sigma Target Minus Modeled DPU is positive for a given board when that board is "good" and passes the Six Sigma Target, and is negative when a given board is "bad" and fails the Six Sigma Target. It is represented in the model as TMM (target minus model)

Equation 23

$$TMM_b = DPU_b - MDPU_b$$

6.8.6 Summary of Decision Expressions

	Variable	Equation/Source	Comment

Equation 16	TE	$\sum_{c} X_c$	The total amount of effort expended to improve DPPM for all commodity groups
Equation 17	PP	$\frac{PB}{TB}$	The percentage of boards modeled to pass their Six Sigma Targets
Equation 18	PB	$\sum_{b} PS_b$	The number of boards that are modeled to pass
Equation 19	TB	m	Total number of boards being analyzed
Equation 20	DI_c	$X_c * DS_c$	Improvement in DPPM based on the historic rate of improvement and the effort chosen
Equation 21	DU_c	$DC_c + DI_c$	New DPPM value based on improvement and recent value
Equation 22	$MDPU_b$	$\sum_{c} \frac{DU_c}{10^6} * U_{bc}$	Modeled PCBA fallout rate based on usage and used DPPM
Equation 23	TMM_b	$DPU_b - MDPU_b$	Gap between modeled PCBA fallout and target fallout

Table 3: Summary of Decision Expressions

6.9 *Objective Function*

The objective of this optimization algorithm is to enable a defined percentage of PCBAs to meet their Six Sigma Targets by allocating engineering effort in an efficient and targeted way to be focused on the particular commodity groups where it is likely to have the greatest impact. In order to make sure that effort is not wasted and employed to either (1) improve yields to the point where they no longer help to meet the established targets or (2) work on commodity groups that are not having a major negative impact on yields, the objective function seeks to minimize the decision expression representing the Total DPPM effort (as defined above).

Equation 24

$$Minimize\ (TE)$$

6.10 Constraints

While adjusting the decision variables to minimize the DPPM effort, the algorithm is subject to the following constraints

6.10.1 DPPM May not Fall below Min DPPM

Though a linear approximation is assumed to be a reasonable estimate of the improvement of DPPM within the current regime, there are also practical or other limits where this assumption no longer holds. Used DPPM is constrained to be greater than or equal to the Minimum DPPM – defined above - for all commodity groups c.

Equation 25

$$\forall c\colon DU_c \geq DM_c$$

6.10.2 Passing Boards

This critical constraint assures that enough boards are passing the Six Sigma target. There are two possibilities, when the binary variable PS is equal to 1, and the board **must** pass; when the binary variable is equal to 0, and the board may or may not pass the target. Each case will be taken separately, but either case is represented by the equation below. The large multiplier guarantees that any board that is even slightly passing can be accounted for by the binary decision variable 1, whereas any board that is failing will be represented by the binary decision variable 0.

Equation 26

$$\forall b\colon TMM_b \geq [PS_b - 1] * 10^9$$

6.10.2.1 Binary Variable = 1

When the binary variable is equal to 1, the right hand side of the equation above is equal to 0, meaning that Six Sigma target Minus Modeled DPU must be greater than or equal to 0. Recall from the discussion of this decision expression above that when PS is greater than 0, it represents a passing board.

6.10.2.2 Binary Variable = 0

When the binary variable is equal to 0, the right hand side of the above equation is equal to a number that is large and negative. This enables the left hand side of the equation to be nearly anything, and the board can be either passing or failing.

6.10.3 Percent Passing Six Sigma Targets

The value Percent Pass is the number of boards that currently have modeled yields that are greater or equal to their Six Sigma targets. This constraint forces the optimization algorithm to continue to run until every PCBA with a binary variable of 1 is passing, either by continuing to increase the DPPM effort or by reallocating the number 1's to map to the boards that are already passing. It is required that the percentage of boards that are passing the constraint target (i.e. the percentage of boards where the binary variable is set to 1) must be greater than or equal to the Percent Pass Threshold (PPT) defined by the user. The higher the Percent Pass Threshold, the more boards will pass the Six Sigma targets (and the more component improvement effort will be required).

Equation 27

$$PP \geq PPT$$

6.10.4 Summary of Constraints

	Constraint	Comment
Equation 25	$\forall c: DU_c \geq DM_c$	No commodity group may exhibit DPPM levels below what has been determined to be the lower bound.
Equation 26	$\forall b: TMM_b \geq [PS_b - 1] * 10^9$	The binary constraint forces any PCBA modeled to not meet the Six Sigma target to have a PS value of zero
Equation 27	$PP \geq PPT$	This constraint enables the user to define the rate of compliance with the Six Sigma targets

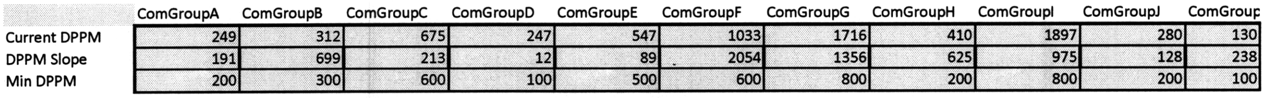
Table 4: Summary of constraints

7 Optimization Proof of Concept

In order to test the functionality of the optimization algorithm, a representative set of data was gathered and run. This representative set included one-hundred commonly made PCBAs and eleven different commodity groups for which historical DPPM information was available. All of the data has been intentionally disguised or obscured to protect Cisco's proprietary information.

7.1 Data Inputs

In order to run the simulation, current and historic DPPM information was input for eleven Commodity groupings for which there was available data. As described in the above section, the Current DPPM values were taken from the most recent average DPPM values for a particular group, the slope value was based on how that DPPM had changed over time, and the Min DPPM numbers were derived from a combination of industry benchmarks and conversations with subject matter experts.



	ComGroupA	ComGroupB	ComGroupC	ComGroupD	ComGroupE	ComGroupF	ComGroupG	ComGroupH	ComGroupI	ComGroupJ	ComGroup
Current DPPM	249	312	675	247	547	1033	1716	410	1897	280	130
DPPM Slope	191	699	213	12	89	2054	1356	625	975	128	238
Min DPPM	200	300	600	100	500	600	800	200	800	200	100

Figure 11: Input for DPPM Data for Test Run

Usage data was taken from one hundred representative boards. Minor components that did not have DPPM data available were classified as other and assumed to have negligible DPPM when compared with some of the higher DPPM parts included in the analysis. For brevity, only the first twenty-five boards are shown in the figure, the complete list is shown in the appendix.

	ComGroupA	ComGroupB	ComGroupC	ComGroupD	ComGroupE	ComGroupF	ComGroupG	ComGroupH	ComGroupI	ComGroupJ	ComGroupK
PCBA1	0	2	4	0	0	0	0	0	0	8	0
PCBA2	1	0	2	0	1	0	0	0	0	1	0
PCBA3	1	1	7	7	1	0	4	0	1	7	0
PCBA4	1	0	0	2	0	0	2	1	0	6	2
PCBA5	0	2	10	4	2	0	4	0	0	12	0
PCBA6	0	1	4	2	1	0	1	0	0	6	0
PCBA7	0	0	0	0	0	0	0	0	0	0	0
PCBA8	0	0	4	3	0	0	0	0	0	14	4
PCBA9	0	0	0	0	2	0	0	0	0	8	0
PCBA10	0	10	0	4	6	0	0	0	8	10	0
PCBA11	0	2	2	2	0	0	0	0	0	0	2
PCBA12	0	0	6	1	1	0	0	0	0	0	4
PCBA13	0	0	0	1	1	0	0	0	0	0	0
PCBA14	0	0	4	2	2	0	0	0	0	4	0
PCBA15	0	0	0	0	0	0	0	0	0	3	0
PCBA16	22	0	0	2	6	0	4	14	0	0	8
PCBA17	12	2	4	10	18	0	10	0	4	12	16
PCBA18	0	0	8	1	2	0	2	0	0	4	0
PCBA19	0	0	4	2	0	0	0	0	0	1	5
PCBA20	0	0	0	0	0	0	0	0	0	0	0
PCBA21	0	1	1	1	0	0	0	0	0	1	1
PCBA22	0	0	1	0	0	0	0	0	0	0	0
PCBA23	1	3	1	2	0	0	8	7	0	16	2
PCBA24	0	4	0	2	0	0	0	0	0	0	0
PCBA25	0	0	4	3	0	0	0	0	0	14	4

Figure 12: First 25 PCBAs used in Analysis

The final input needed to run the optimization is the percent pass threshold. For the first run, 30% was chosen because it is lower than the current level of compliance and therefore would be able to reliably produce feasible solutions. This means that the optimization will increase the amount of effort it allows to improve the DPPM of each commodity group until 30% of the PCBAs pass their Six Sigma Targets.

7.2 Outputs

In less than ten seconds of run-time, the optimization converged on a solution that met the constraints, with 30% of the boards meeting their six sigma targets. The results for the first twenty five boards are shown below in Figure 13: Results for First 25 Boards (Complete Results in Appendix).

	Modeled Yield	Six Sigma Yield	Modeled - Six Sigma	Passing Six Sigma
PCBA1	99.8682%	99.5654%	0.3036%	1
PCBA2	99.9746%	99.7908%	0.1841%	1
PCBA3	99.9991%	99.9874%	0.0117%	1
PCBA4	99.4045%	99.4886%	-0.0846%	0
PCBA5	99.8587%	99.8434%	0.0153%	1
PCBA6	99.9362%	99.9473%	-0.0112%	1
PCBA7	98.4504%	99.1465%	-0.7046%	0
PCBA8	99.9978%	99.9701%	0.0277%	1
PCBA9	99.2203%	99.1411%	0.0799%	1
PCBA10	99.4199%	99.4287%	-0.0089%	1
PCBA11	99.9990%	99.9867%	0.0123%	1
PCBA12	99.9944%	99.9239%	0.0706%	1
PCBA13	99.7180%	99.9636%	-0.2460%	0
PCBA14	99.7955%	99.9334%	-0.1381%	0
PCBA15	98.4465%	99.0933%	-0.6549%	0
PCBA16	98.4464%	99.0929%	-0.6546%	0
PCBA17	99.9749%	99.7945%	0.1806%	1
PCBA18	99.8587%	99.8434%	0.0153%	1
PCBA19	99.7377%	99.9612%	-0.2238%	0
PCBA20	99.9066%	99.6802%	0.2268%	1
PCBA21	99.1529%	99.0303%	0.1237%	1
PCBA22	99.3439%	99.4747%	-0.1316%	0
PCBA23	99.4909%	99.3115%	0.1804%	1
PCBA24	99.7042%	99.6416%	0.0628%	1
PCBA25	99.6093%	99.5681%	0.0413%	1

Figure 13: Results for First 25 Boards (Complete Results in Appendix)

In order to achieve these results, effort was allocated to a few different commodity groups, particularly G, I, and K. Interestingly, achieving 30% compliance may be possible without doing any work to improve several commodity groups currently being monitored.

	ComGroupA	ComGroupB	ComGroupC	ComGroupD	ComGroupE	ComGroupF	ComGroupG	ComGroupH	ComGroupI	ComGroupJ	ComGroupK
DPPM Effort	0	0	0	0	0	0	0.53	0	0	0.62	0.1
New DPPM	249	312	675	247	547	1033	997.375304	410	1897	200.760765	106.166957

Figure 14: DPPM -Related Output

7.3 Ratcheting up the Percent Pass Threshold

Though the initial outputs gave an indication where effort could be better applied to reach the desired percent pass threshold, they are the results of only single threshold, and do not indicate what the best path for continuous improvement is. In order to understand these dynamics better, a range of PPTs is needed to determine the effect of "ratcheting up" the quality standards. This is achieved by varying the required PPT over multiple runs of the optimization algorithm. For each run, the total effort was minimized in order to achieve the prescribed level of Six Sigma compliance.

7.4 Results

Intuition would suggest that additional efforts in DPPM reduction are required to achieve higher levels of six sigma compliance, and the first result confirms this intuition. As is shown in Figure 15, the total amount of effort required increases as the Percent Pass Threshold increases. Also interestingly, around the threshold of 37% compliance, the amount of effort required to improve compliance still further increases dramatically. Furthermore, at about 45% compliance, the optimization becomes non-feasible as the values for DPPM hit their lower limits.

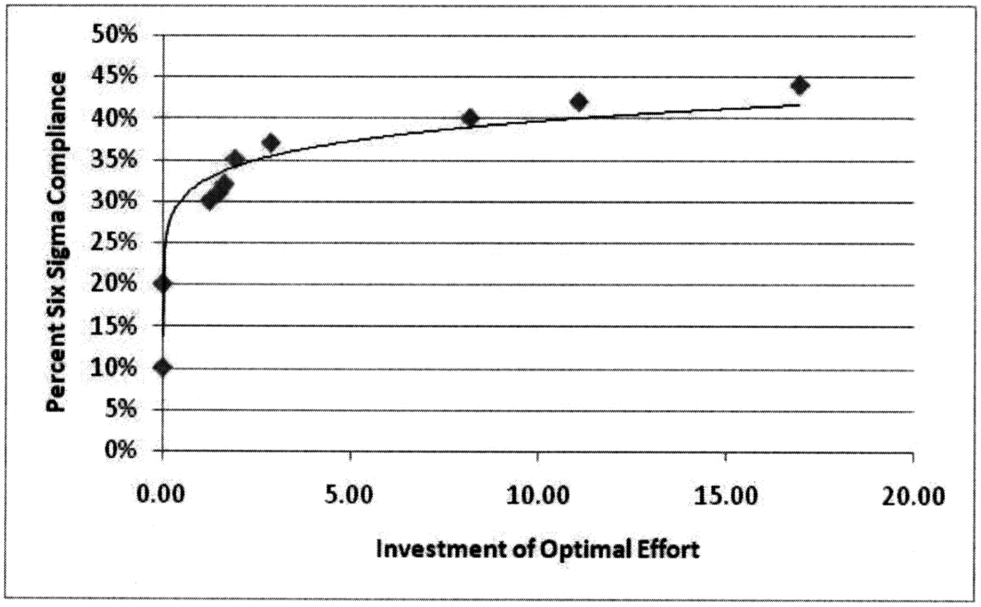


Figure 15: Six Sigma Compliance as a Result of Invested Effort

It is important to emphasize that these results do not indicate that higher levels of Six Sigma compliance are themselves infeasible, but rather that these lower bounds were set at a point in time to bound the model the regime in which DPPM improvement is assumed to be linear. As, as DPPM improves across all commodity groups, it is expected that these bounds will also change.

Though the first result is unsurprising – that an increase in effort will lead to a monotonic improvement in results with diminishing returns – the second result is much less intuitive. As is shown in Figure 16, small changes in the desired compliance level may require large differences in the amount of effort invested in improving DPPM for a particular commodity group. The most notable example is for ComGroup A, which requires absolutely no investment if the desired compliance level is 35%, but requires an investment of more than four times the current effort if the desired compliance level is 40%. Furthermore, investing in ComGroup I seems to be the optimal way to take the compliance rate from 35% to 37%, but as compliance goes to 40%, the effect of ComGroup A dominates, and motivation for investing in I subsides. Results such as these indicate that there may be different strategic decisions required depending if the goal is to achieve immediate gains in quality or if it is to improve six sigma compliance in the long run.

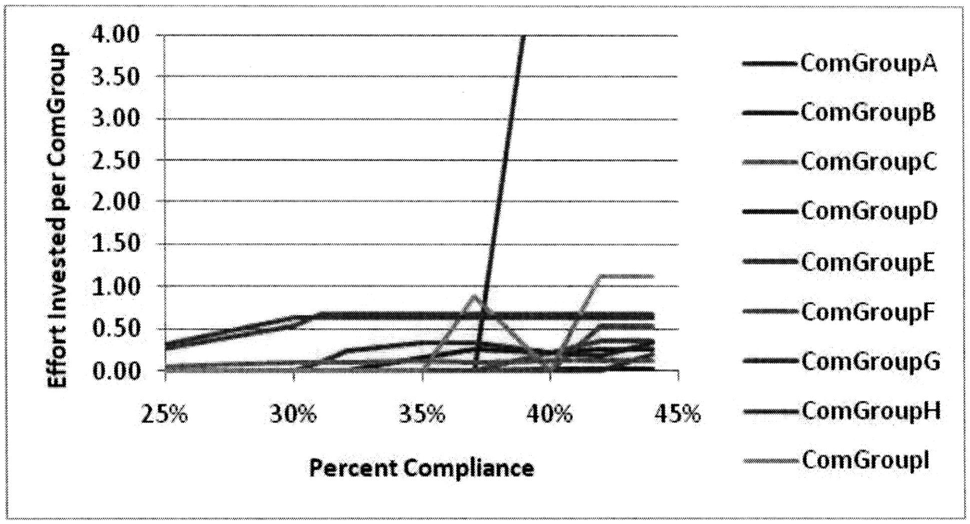


Figure 16: Effort per DPPM Group as a Function of Desired Compliance Level

7.5 Summary

Through the above analysis, it has been demonstrated that a MIP optimization approach can be used to indicate where effort can be directed to improve Commodity Group DPPM in order to have the biggest impact on PCBA compliance with Six Sigma targets. An increase in total effort leads to better compliance, but with diminishing returns. Yet, this is only true for total effort, and does not hold for effort expended on individual commodity groups. An improvement in compliance may require zero, a moderate amount, or a great deal of effort to improve the DPPM individual commodity group depending on where this improvement falls relative to the overall compliance level.

8 Recommendations for Future Study

8.1 Refining Input Data

The collection of the necessary data for input is particularly challenging for two reasons. The first is that the Usage data for each PCBA cannot be read directly from the BOM. That is, the BOM data provides information on what components are on each PCBA, but only in some cases can this data be used to determine what commodity groupings these components fall into, without manual checking of each component. For the purposes of this analysis, general principles were applied to group each component into an appropriate commodity group, but a more transparent way is needed to understand this data in order to scale the solution.

The second challenge is that Cisco employs several different metrics for the DPPM of a component on the manufacturing line. Though it is outside the scope of this analysis, it is worth noting that both "Raw" DPPM and "Validated" DPPM are used to measure component quality. These metrics generally correlate to one another, and are believed to give a good indication of component quality, yet neither (even the "validated" DPPM) represents components that have been definitively measured to be defective. An improvement to the reliability and of these metrics would bring large benefits to any efforts to improve component DPPM.

8.2 Improving Commodity Groupings

The biggest limitation to this methodology comes from using the weighted average DPPM to represent the DPPM of the entire commodity group. This issue can be significantly alleviated if some of the commodity groups with wider distributions of DPPM data were broken into multiple groups, clustered by similar DPPM. For example, by using clustering algorithms, ASICs could be segmented into three (or more) groups (easy, medium, and hard) so that each cluster would be better represented by its mean.

In theory, this process could be extended to segment the each commodity group as much as was necessary so that every segment was accurately represented by a single DPPM number.

8.3 *Expanding the Size of the Data Set*

As a proof-of-concept, this analysis was completed with one hundred boards and eleven commodity groups. The scope was limited in part by the optimization software used and additionally by the availability of some of the data. The most direct extension of this work would be to increase the number of PCBAs and the number of Commodity Groupings used for the analysis. The results from such an analysis could provide better understanding of where strategic investments in DPPM could yield the greatest impact across all business units at Cisco.

8.4 *Improving the Model of DPPM Improvement*

For the purposes of this thesis, the DPPM improvement is modeled as a linear function which is a reasonably good approximation over a fairly small range. However, the improvement trajectory would likely be more accurately modeled as a logistic curve. In order to capture this performance while maintaining a linear model, a piecewise linear function could be used.

8.5 *Optimizing for Total Cost*

The model above attempts to minimize the effort needed in order to meet a give Six Sigma compliance rate. In order to get a better understanding of the bigger picture, it would be necessary to convert the amount of effort to a dollar value (possibly in terms of absolute engineering hours). Furthermore, it is necessary to calculate the rework cost of a particular component failure. With comprehensive data of this kind, it would be possible to expand the optimization equation to account for achieving any six sigma compliance level at a minimum of total cost.

9 Conclusions

As Printed Circuit Board assemblies become increasingly complex, and components are shared across a wider array of boards, efforts to track and improve PCBA-level quality become increasingly complicated. In addition, as the number of components, suppliers, and commodity types that are used on these boards continue to increase, determining which commodities need the most attention is an increasingly difficult task. The need to bridge this gap and develop a more comprehensive understanding of exactly how improvements to component quality impact board-level yields is widely understood to be the key to fewer defects and to knowing the true cost of poor quality. This thesis addresses two of the key challenges for ensuring that continual improvements to component quality result in improvements in PCBA yields. This thesis proposes a method of constructing an analytical link between PCBA yields and component quality; in addition, it addresses some of the organizational challenges might surface when such a link is implemented.

The mixed integer program described herein represents one promising method that could be employed to create this analytical bridge on a macro level. It has always been possible to understand how a single component impacts the quality of a single board. However, when that component is used on dozens (or hundreds) of boards, then the true impact is much harder to track. Furthermore, if improvement of a particular component has spillover effects on other components in the same commodity group – as in the case where improving a component results in process improvements that impact all products from a single supplier – it is very difficult to track and quantify the impact of this effect.

By drawing the linkage between the commodity group goals and the six sigma targets, this method opens the door to better alignment of and incentives for diverse teams within Cisco, but aligning incentives is helpful yet insufficient for creating change. In addition, the organization must be prepared for such a change. As evidenced by similar previous evolutions – most notably, the move to Six Sigma targets at the PCBA level – such a change often requires executive level support and advocacy and even so can face significant resistance from corners of the organization.

Nevertheless, the need to align the work of the entire organization is clear. All stakeholders, in all areas of Cisco, its customers, and its contract manufacturers, benefit from achieving improvements in product quality with minimal investment. Any methodology that enables such improvement will create value throughout the company.

10 Appendix

10.1 Appendix A: Definition of Terms

PCBA – Printed Circuit Board Assembly, also referred to as "boards," or "assemblies." The primary unit that is manufactured by Cisco's contract manufacturers, consisting of a PCB (Printed Circuit Board) and anywhere between ten and tens of thousands of components. Once the PCBA is assembled, the functionality is measured and tracked to provide a value for the yield.

Components – ASICS, other ICs, LEDs, Resistors, capacitors, and other electronic devices mounted to a PCBA. Components are classified, tracked, grouped, and managed by their "Commodity Group." The key quality metric for a component is its DPPM

Contract Manufacturer (CM) – one of the four companies Cisco has partnered with to do the assembly of the PCBAs

DPU – Defects per unit. The number of defective units (boards, components, etc) divided by the total number of produced units

DPPM or DPMO – The number of Defective Parts Per Million or Defects Per Million Opportunities. Until recently these terms were used interchangeably at Cisco to characterize component yield rates. The move now is to discuss component yields only in terms of DPPM.

Suppliers – Companies who provide the components – which are procured either directly by the contract manufacturers, or through Cisco's procurement system – for assembly

Component Engineers (CEs) – Engineers responsible for reducing the defect rate (DPPM) of components used in Cisco products

Supplier Quality Engineers (SQEs) – Engineers responsible for assessing, auditing, and improving the quality systems of Cisco's suppliers through data analysis and expert coaching.

10.2 Appendix B: Optimization Code

```
/*********************************************
 * OPL 5.5 Model
 * Author: Jason
 * Creation Date: 4/22/2008 at 9:30 AM
 *********************************************/

{string} Boards = ...; /*names of each PCBA*/
{string} Commodity_Groups = ...; /*names of each commodity group*/


/* define information about commodity DPPM*/
float DC[Commodity_Groups] = ...;  /*Current DPPM for a Commodity Group*/
float DM[Commodity_Groups] = ...;  /*Minimum threshold for DPPM*/
float DS[Commodity_Groups] = ...;  /*Rate of DPPM improvement*/

/*Define information about boards*/
int U[Boards][Commodity_Groups] = ...; /*Usage data*/

float DPU[b in Boards] = formula obscured for Cisco Confidentiality /*Six Sigma DPU for Yield Target*/
float PPT = ...;  /* Percent Passing Target*/

/* decision variable is how much will be spent per commodity group*/
dvar float+ X[Commodity_Groups]; /*Amount of effort expended to improve commodity group*/
dvar boolean PS[Boards];  /*Binary variable for passing boards*/

/* intermediate variables improve readability of optimization function and constraints*/
dexpr float TE = sum(c in Commodity_Groups) DS[c]; /*Total DPPM Effort*/
dexpr float DU[c in Commodity_Groups] =
  DC[c]-DE[c]*DS[c];  /*Used DPPM*/
dexpr float MDPU[b in Boards] =
  sum (c in Commodity_Groups) DU[c]/10^6 * U[b][c]; /*Modeled DPU*/
dexpr float TMM[b in Boards] = DPU[b]-MDPU[b]; /* Six Sigma Target Minus Modeled DPU*/

dexpr int PB = sum(b in Boards) PS[b]; /*Passing boards*/
dexpr int TB = sum(b in Boards) 1;  /*Total Boards*/
dexpr float PP = PB/TB; /*Percent Pass*/
dexpr float Six_Sigma_Yield [b in Boards]= exp(-DPU[b]);

/* minimize total cost and spend*/
minimize
  TE

/*constrain DPMOs to be greater than the minimum DPMO*/
subject to {
  forall(c in Commodity_Groups )
  DPPM_Ct:
```

```
  DU[c] >= DM[c];

/*constraint forcing all boards to conform to Six-Sigma*/
  forall (b in Boards)
  Yield_Ct:
  TMM[b] >= (PS[b]-1) * 10^9;

   Per_Pass_Ct:
   PP >= PPT;
```

Appendix C: Supplementary Data

10.2.1 Usage Data for 100 Boards and Eleven Commodity Groups

	ComGroupA	ComGroupB	ComGroupC	ComGroupD	ComGroupE	ComGroupF	ComGroupG	ComGroupH	ComGroupI	ComGroupJ	ComGroupK
PCBA1	0	2	4	0	0	0	0	0	0	8	0
PCBA2	1	0	2	0	1	0	0	0	0	1	0
PCBA3	1	1	7	7	1	0	4	0	1	7	0
PCBA4	1	0	0	2	0	0	2	1	0	6	2
PCBA5	0	2	10	4	2	0	4	0	0	12	0
PCBA6	0	1	4	2	1	0	1	0	0	6	0
PCBA7	0	0	0	0	0	0	0	0	0	0	0
PCBA8	0	0	4	3	0	0	0	0	0	14	4
PCBA9	0	0	0	0	2	0	0	0	0	8	0
PCBA10	0	10	0	4	6	0	0	0	8	10	0
PCBA11	0	2	2	2	0	0	0	0	0	0	2
PCBA12	0	0	6	1	1	0	0	0	0	0	4
PCBA13	0	0	0	1	1	0	0	0	0	0	0
PCBA14	0	0	4	2	2	0	0	0	0	4	0
PCBA15	0	0	0	0	0	0	0	0	0	3	0
PCBA16	22	0	0	2	6	0	4	14	0	0	8
PCBA17	12	2	4	10	18	0	10	0	4	12	16
PCBA18	0	0	8	1	2	0	2	0	0	4	0
PCBA19	0	0	4	2	0	0	0	0	0	1	5
PCBA20	0	0	0	0	0	0	0	0	0	0	0
PCBA21	0	1	1	1	0	0	0	0	0	1	1
PCBA22	0	0	1	0	0	0	0	0	0	0	0
PCBA23	1	3	1	2	0	0	8	7	0	16	2
PCBA24	0	4	0	2	0	0	0	0	0	0	0
PCBA25	0	0	4	3	0	0	0	0	0	14	4
PCBA26	0	0	9	3	3	0	0	0	0	21	0
PCBA27	0	0	0	10	4	0	0	0	0	0	0
PCBA28	1	0	1	2	1	0	0	0	0	4	0
PCBA29	1	3	1	2	0	0	5	4	0	10	2
PCBA30	1	0	1	2	1	0	0	0	0	4	0
PCBA31	0	0	0	0	0	0	0	0	0	0	0
PCBA32	0	0	2	0	0	0	0	0	0	8	4
PCBA33	0	0	0	1	2	0	0	0	0	6	0
PCBA34	144	4	4	12	28	0	48	0	10	20	0
PCBA35	0	0	0	0	1	0	0	0	0	3	0
PCBA36	1	0	3	2	1	0	0	0	0	2	0
PCBA37	0	0	1	2	0	0	4	6	2	8	2
PCBA38	1	3	1	2	0	0	5	4	0	10	2
PCBA39	0	0	0	1	1	0	0	0	0	6	1
PCBA40	0	0	6	1	1	0	0	0	0	0	4
PCBA41	0	0	4	2	0	0	0	0	0	8	5
PCBA42	0	1	0	0	0	0	0	0	0	0	0
PCBA43	0	0	0	0	0	0	0	0	0	0	0
PCBA44	36	2	2	6	10	0	14	0	2	14	0
PCBA45	0	1	0	0	1	0	0	0	0	2	0
PCBA46	15	0	1	4	5	0	2	3	0	9	5
PCBA47	1	3	1	2	0	0	8	7	0	16	2
PCBA48	0	0	2	0	0	0	0	0	0	1	0
PCBA49	0	0	0	0	0	0	0	0	0	0	0
PCBA50	0	0	5	2	2	0	1	0	0	4	4
PCBA51	2	0	0	2	0	0	3	2	0	9	2
PCBA52	0	4	2	6	0	0	8	0	0	26	4
PCBA53	15	0	4	3	0	0	4	0	0	6	12
PCBA54	0	0	1	3	0	0	0	0	0	9	2
PCBA55	1	0	0	2	0	0	2	1	0	6	1
PCBA56	0	2	0	0	0	0	2	0	0	2	4
PCBA57	0	0	0	0	0	0	0	0	0	0	0
PCBA58	0	0	4	3	0	0	0	0	0	14	4
PCBA59	0	1	0	0	0	0	0	0	0	1	0
PCBA60	0	0	1	2	0	0	0	0	0	4	2
PCBA61	108	3	3	9	12	0	36	0	3	39	0
PCBA62	1	3	1	2	0	0	8	7	0	16	2
PCBA63	75	5	0	5	16	0	55	0	10	148	0
PCBA64	0	0	0	2	0	0	4	6	0	10	2
PCBA65	0	0	2	0	0	0	0	0	0	2	4
PCBA66	1	3	1	2	0	0	5	4	0	10	2
PCBA67	0	0	4	3	0	0	0	0	0	14	4
PCBA68	0	0	6	1	1	0	0	0	0	0	4
PCBA69	0	0	0	0	0	0	0	0	0	4	0
PCBA70	0	4	2	6	0	0	8	0	0	26	4
PCBA71	0	0	0	0	2	0	0	0	0	9	0
PCBA72	0	0	0	0	1	0	0	0	0	8	0
PCBA73	0	0	0	0	0	0	0	0	0	2	1
PCBA74	0	0	3	1	1	0	0	0	0	7	0
PCBA75	1	3	1	2	0	0	5	4	0	10	2
PCBA76	0	0	2	4	0	0	0	0	0	10	4
PCBA77	0	0	0	1	0	0	0	0	0	0	0
PCBA78	1	0	1	1	0	0	2	1	0	6	2
PCBA79	0	1	7	1	2	0	2	0	0	4	0
PCBA80	2	0	0	4	0	0	4	2	0	12	4
PCBA81	0	4	4	10	0	0	0	0	0	12	8
PCBA82	0	1	0	2	0	0	1	0	0	0	0
PCBA83	0	0	0	1	0	0	0	0	0	0	0
PCBA84	2	0	1	3	1	0	0	0	0	1	0
PCBA85	0	1	0	2	0	0	1	0	0	0	0
PCBA86	0	0	12	2	2	0	0	0	0	0	8
PCBA87	1	3	1	2	0	0	8	7	0	16	2
PCBA88	2	0	0	2	0	0	3	2	0	9	2
PCBA89	0	2	0	0	0	0	0	0	0	2	0
PCBA90	0	0	0	0	0	0	0	0	0	0	0
PCBA91	0	7	1	0	1	0	0	0	3	0	0
PCBA92	0	0	4	0	1	0	0	0	0	0	0
PCBA93	0	2	10	4	2	0	4	0	0	12	0
PCBA94	0	2	0	1	0	0	0	0	0	0	0
PCBA95	0	0	0	2	0	0	7	12	0	16	2
PCBA96	0	0	2	1	1	0	0	0	0	1	0
PCBA97	0	0	1	3	0	0	0	0	0	3	4
PCBA98	0	0	0	1	2	0	2	0	0	0	0
PCBA99	1	0	3	2	1	0	0	0	0	2	0
PCBA100	0	0	3	6	0	0	0	0	0	27	18

10.2.2 Output of Optimization Run

	Modeled Yield	Six Sigma Yield	Modeled - Six Sigma	Passing Six Sigma
PCBA1	99.8682%	99.5654%	0.3036%	1
PCBA2	99.9746%	99.7908%	0.1841%	1
PCBA3	99.9991%	99.9874%	0.0117%	1
PCBA4	99.4045%	99.4886%	-0.0846%	0
PCBA5	99.8587%	99.8434%	0.0153%	1
PCBA6	99.9362%	99.9473%	-0.0112%	1
PCBA7	98.4504%	99.1465%	-0.7046%	0
PCBA8	99.9978%	99.9701%	0.0277%	1
PCBA9	99.2203%	99.1411%	0.0799%	1
PCBA10	99.4199%	99.4287%	-0.0089%	1
PCBA11	99.9990%	99.9867%	0.0123%	1
PCBA12	99.9944%	99.9239%	0.0706%	1
PCBA13	99.7180%	99.9636%	-0.2460%	0
PCBA14	99.7955%	99.9334%	-0.1381%	0
PCBA15	98.4465%	99.0933%	-0.6549%	0
PCBA16	98.4464%	99.0929%	-0.6546%	0
PCBA17	99.9749%	99.7945%	0.1806%	1
PCBA18	99.8587%	99.8434%	0.0153%	1
PCBA19	99.7377%	99.9612%	-0.2238%	0
PCBA20	99.9066%	99.6802%	0.2268%	1
PCBA21	99.1529%	99.0303%	0.1237%	1
PCBA22	99.3439%	99.4747%	-0.1316%	0
PCBA23	99.4909%	99.3115%	0.1804%	1
PCBA24	99.7042%	99.6416%	0.0628%	1
PCBA25	99.6093%	99.5681%	0.0413%	1
PCBA26	99.5361%	99.9279%	-0.3929%	0
PCBA27	99.2755%	99.3530%	-0.0781%	0
PCBA28	99.7935%	99.9072%	-0.1139%	0
PCBA29	99.9341%	99.7826%	0.1517%	1
PCBA30	99.8581%	99.9711%	-0.1132%	0
PCBA31	98.5495%	98.6230%	-0.0746%	0
PCBA32	99.9648%	99.9293%	0.0355%	1
PCBA33	99.6607%	99.8610%	-0.2009%	0
PCBA34	99.0744%	99.8576%	-0.7874%	0
PCBA35	98.9611%	98.8412%	0.1212%	1
PCBA36	99.4168%	99.3841%	0.0329%	1
PCBA37	99.9389%	99.9847%	-0.0458%	0
PCBA38	98.7699%	98.9351%	-0.1671%	0
PCBA39	98.4661%	98.5527%	-0.0879%	0
PCBA40	99.9381%	99.9728%	-0.0347%	0
PCBA41	99.7831%	99.8998%	-0.1169%	0
PCBA42	99.6844%	99.9144%	-0.2304%	0
PCBA43	99.5361%	99.9279%	-0.3929%	0
PCBA44	99.5361%	99.9279%	-0.3929%	0
PCBA45	99.4168%	99.3841%	0.0329%	1
PCBA46	92.7720%	93.5802%	-0.8674%	0
PCBA47	99.0604%	99.2578%	-0.1991%	0
PCBA48	98.7943%	98.8624%	-0.0689%	0
PCBA49	99.7662%	99.9422%	-0.1762%	0
PCBA50	99.6993%	99.8468%	-0.1478%	0
PCBA51	99.6795%	99.7107%	-0.0314%	0
PCBA52	99.1178%	99.2339%	-0.1170%	0
PCBA53	99.8040%	99.9133%	-0.1095%	0
PCBA54	99.9978%	99.9697%	0.0280%	1
PCBA55	89.4736%	93.8019%	-4.7242%	0
PCBA56	99.7662%	99.9422%	-0.1762%	0
PCBA57	99.5787%	99.4243%	0.1552%	1
PCBA58	99.8128%	99.3561%	0.4587%	1
PCBA59	99.8498%	99.7219%	0.1281%	1
PCBA60	99.0604%	99.2578%	-0.1991%	0
PCBA61	99.9988%	99.9830%	0.0158%	1
PCBA62	99.9988%	99.9830%	0.0158%	1
PCBA63	99.4008%	99.4402%	-0.0396%	0
PCBA64	99.1497%	99.2639%	-0.1151%	0
PCBA65	99.0984%	99.3726%	-0.2763%	0
PCBA66	98.6195%	98.9024%	-0.2865%	0
PCBA67	99.5484%	99.4169%	0.1322%	1
PCBA68	99.3707%	99.4318%	-0.0614%	0
PCBA69	99.7448%	99.2447%	0.5027%	1
PCBA70	99.8856%	99.9381%	-0.0526%	0
PCBA71	99.0565%	99.2055%	-0.1503%	0
PCBA72	99.8771%	99.9582%	-0.0812%	0
PCBA73	99.6844%	99.9144%	-0.2304%	0
PCBA74	98.6156%	98.8503%	-0.2377%	0
PCBA75	98.6195%	98.9024%	-0.2865%	0
PCBA76	99.7203%	99.3179%	0.4043%	1
PCBA77	99.3707%	99.4318%	-0.0614%	0
PCBA78	99.6194%	99.5701%	0.0494%	1
PCBA79	99.7414%	99.4697%	0.2729%	1
PCBA80	99.6870%	99.8118%	-0.1251%	0
PCBA81	98.5495%	98.6230%	-0.0746%	0
PCBA82	98.6156%	98.8503%	-0.2377%	0
PCBA83	98.7297%	98.1227%	0.6167%	1
PCBA84	99.9457%	99.9398%	0.0058%	1
PCBA85	99.4924%	99.4663%	0.0263%	1
PCBA86	96.8427%	97.4445%	-0.6194%	0
PCBA87	99.5424%	99.7426%	-0.2009%	0
PCBA88	99.3707%	99.4318%	-0.0614%	0
PCBA89	99.9138%	99.9137%	0.0001%	1
PCBA90	98.7543%	98.3241%	0.4366%	1
PCBA91	99.6536%	99.6281%	0.0256%	1
PCBA92	99.0565%	99.2055%	-0.1503%	0
PCBA93	98.8136%	98.7220%	0.0927%	1
PCBA94	99.5566%	99.3916%	0.1659%	1
PCBA95	99.7889%	99.7073%	0.0818%	1
PCBA96	99.7825%	99.8926%	-0.1103%	0
PCBA97	99.3707%	99.4318%	-0.0614%	0
PCBA98	90.1919%	93.0482%	-3.1178%	0
PCBA99	98.3935%	98.1077%	0.2909%	1
PCBA100	96.7485%	96.6871%	0.0635%	1

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