Quality Control and Improvement in a Low-Cost, High-Clockspeed Manufacturing Environment

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Submitted to the Department of Electrical Engineering and Computer Science and the Sloan School of Management in Partial Fulfillment of the Requirements for the Degrees of

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ABSTRACT

By making the customer experience essential to its business and vision, Dell Computers is widely recognized as a high-quality computer manufacturer. Internally, however, Dell is undergoing a quality evolution. Given Dell's accelerated product life cycles and low margin business model, their internal quality strategy must satisfy several business concerns as well as corporate values. At a tactical level, the factory requires a means of evaluating defect and defect containment in terms of dollars, factory metrics and customer metrics. At a strategic level, the factory plays a critical role in the customer experience by containing issues within the factory and by preventing future issues by working with vendors and design. The current strategic dilemma is how to move quality further away from detection and containment and more towards prevention and appraisal while conforming to Dell's low-cost, high-clockspeed environment.

The thesis describes a novel approach to identify the cost of defects internal to the factory which overcomes this dilemma and allows simultaneous improvement in cost and quality. The defect cost model employs yield analysis, regression, and a variety of process control tools to evaluate costs via labor, inventory, and cycle time.

The results address the factory's requirement for a per incident cost for defects which lead to recommendations on how to best allocate resources, improve processes, and evaluate the system level impact defects have on the factory. It furthermore shows how current metrics do not adequately address quality related costs and other strategic implications related to quality.

These implications align with classic quality strategies that address cost, variation, waste, and management roles. The thesis demonstrates that quality is not necessarily a trade-off to cost and speed, and emphasizes the strategic role quality plays in a low-cost, high-clockspeed environment.

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1 INTRODUCTION AND OVERVIEW

This introduction and overview describes a classic operational dilemma that is addressed in a unique manufacturing environment. The dilemma concerns the simultaneous optimization of several operational characteristics such as quality, cost, and speed. Dell Computers, a pioneer of many manufacturing and supply chain innovations, provides a novel environment within which this dilemma is analyzed. The thesis, in return, provides a framework to demonstrate how Dell specifically can address this dilemma at both a strategic and tactical level.

1.1 Introduction

Quality strategy is a decades-old management topic. Nonetheless, it remains elusive to many organizations that pursue it. Manufacturing operations have many dimensions along which to mold a strategy: cost, speed, flexibility, quality, capacity, inventory, human resources, and capital equipment to name a few. Optimization may occur simultaneously along all dimensions until an efficient frontier is reached. Once the frontier is met, further optimization of a particular dimension generally requires a trade-off with another [13]. Quality strategy fundamentally challenges companies to realize that they are likely not at this frontier and that they can simultaneously improve quality while improving other dimensions such as cost, speed, and flexibility.

Dell Computers has arguably moved the operations frontier further out than most high technology companies with innovative business practices and with particular attention to its supply chain and its customer. Furthermore, quality is essential to Dell's mission to the customer. Dell is widely recognized as a high quality manufacturer and is recognized as an industry leader in certain product categories. As Dell introduces new products and increases product variety by way of product proliferation and product configurations, quality improvement more explicitly becomes a factor in reducing Dell's costs and improving its brand image. In response, Dell has begun to embrace the many frameworks that describe quality strategies. In doing so, quality is evolving beyond those goals that already ensure customer recognized quality to also include objectives both at the tactical and strategic levels within the factory and across the entire enterprise. This evolution seeks to address how internal quality drives cost and how to integrate each discipline's requirements to create a corporate level quality strategy.

Having already pushed out the frontier along many dimensions, Dell faces an even more daunting challenge than most. As Dell approaches internal quality issues more systematically, Dell finds the classic tension between balancing the need for quality investments and processes with maintaining low-costs and high-clockspeed. Quality investments are rarely justified by the documentable return it provides. The factory has approached this battle by instilling a culture of continuous improvement. Within the framework of continuous improvement, careful problem solving coupled with documented savings associated with proposed solutions has satisfied this tension. The factory then uses its relationship with suppliers and with design to positively impact internal quality in addition to its rigorous insurance of providing quality product to its customers. This approach has saved Dell millions of dollars, and has prompted top management to charge the factory with the task of championing further quality investments and process improvements. Despite the continuous improvement that the factory accomplishes, many realize that a cohesive framework addressing how the factory can best leverage its vast knowledge across the enterprise is still bridled by Dell's business characteristics of low-cost and high-clockspeed. In essence, can Dell simultaneously improve its internal quality without compromising factors such as cost and speed?

The following sections give an overview of Dell's business model and culture and an overview of this thesis, which will provide a framework to answer the question posed above.

1.2 Dell Computers

Dell Computers is a tremendous success story. The start-up turned industry revolutionary has a strong culture that helps promote its success and innovation. Section 1.2 provides an overview of Dell's history, corporate strategy, and mission.

1.2.1 Dell Overview

Dell Computers started as a dorm-room venture by a young entrepreneur named Michael Dell. While attending University of Texas at Austin, Michael Dell built to order IBM "clone" computers and sold directly to his customers. Back in 1984, Dell Computers had $1000 and a good idea. Now, Dell Computers is a multinational company with over $30 billion in revenues [29]. Its impact goes beyond being a Fortune 50 company – Dell has fundamentally changed much of the dynamics of the computer industry as well as the fulfillment dynamics of companies around the world. Although Dell Computers has grown as a company, from a dorm-room outfit to the number one computer maker in the world, its business fundamentals have not changed. Dell's build-to-order system and direct-to-consumers sales channel have remained a cornerstone of Dell's business.

Dell's direct model removes the middleman from the customer experience. By removing this intermediary, both Dell and the end consumer benefit. First, Dell removes a huge risk and source of variability by removing the outbound retail channel. Dell thus is less susceptible to the bullwhip effect as it is closer to the customer and does not have inventory on the market that both rapidly depreciates and is often made obsolete by the rapid change of technology. Second, with direct selling, Dell can pass on the reduced costs to the consumer. Third, working directly with the customer, Dell can truly keep a pulse on the market: understanding market trends, buyer behavior, and desired configurations. Above all, selling direct also is a fundamental enabler of Dell's build to order fulfillment model.

Build to order provides Dell with another competitive advantage. Once a customer places an order, Dell begins production of these systems by pulling inventory into its factory from supplier hubs or logistic centers (SLC). Dell works with the suppliers to keep a certain number of days sales inventory (DSI) in these hubs. Managed by third party logistics companies, the hubs are owned by Dell but the suppliers own the inventory. With this pull system, Dell has virtually eliminated raw goods inventory on its books. Raw goods inventory residing in the production facilities has been reduced to less than five hours of sales and suppliers have consequently reduced the inventory they must keep in the pipe to Dell. In exchange for this system, suppliers charge a piece-part premium to cover inventory-holding costs and they also benefit from reduced overall inventories.

Dell's cash conversion cycle (CCC) is also a huge competitive advantage. CCC involves the relationship of a company's inventory, receivables and payables and is measured in days. A CCC of 100 days, for example, means that a company receives payment for goods 100 days after it paid for the raw materials used to manufacture the goods. The financial metric speaks to how a company manages its money and operations in the following ways:

- How quickly a company can convert raw materials into finished goods
- How quickly this inventory can be sold to customers
- How quickly the company can get its customers to pay for these goods

- How much of a delay the company can secure to pay its suppliers for the goods that it purchases

In particular, Dell receives payment for its product many days prior to when it pays its vendors for the material it consumed to make that product. The resulting negative CCC allows Dell to essentially make use of others money and has helped Dell achieve over 800% return on invested capital.

1.2.2 Dell Products and Competitive Strategy

Dell's product line began with clones of the IBM personal computer. While still Dell's bread-and-butter, desktops have been largely commoditized. As such, Dell relies on system integration, branding, and services as points of differentiation and on its business model to provide competitive advantage. Figure 1 shows how gross margins and commoditization relate.

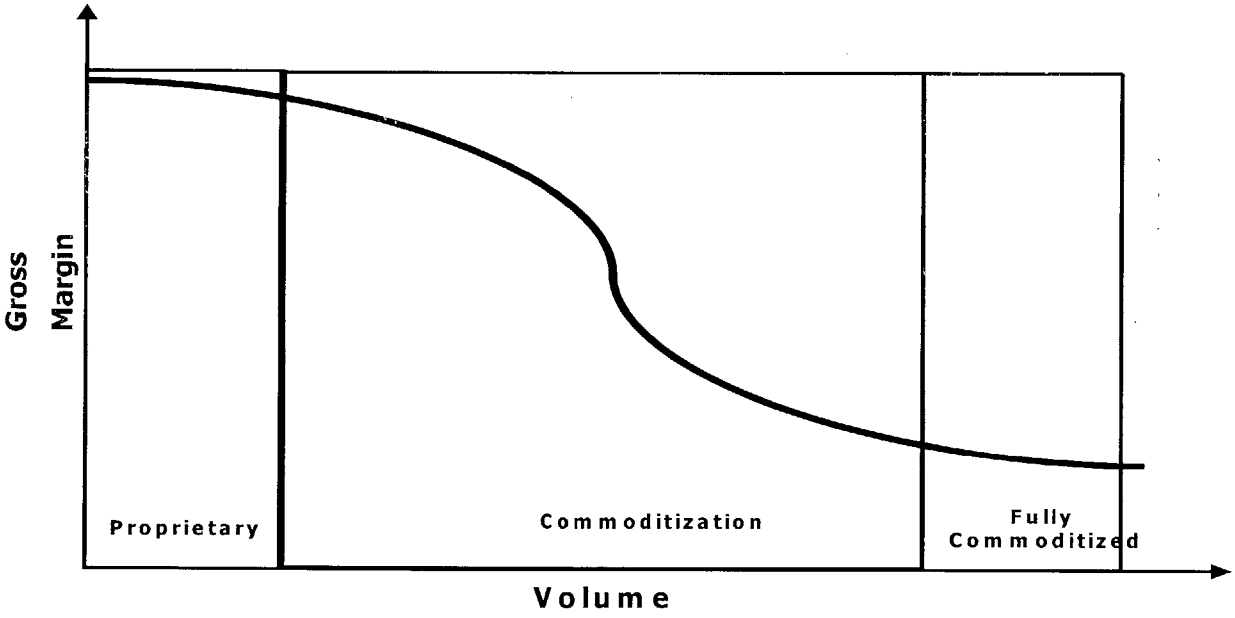

Figure 1. Commoditization curve and impact to gross margin

Dell has also broadened its product portfolio to include laptop computers, servers and storage, and more recently, network switches. In each product group, Dell competes at price-performance points that do not rely on extensive research and development, that provide appreciable volumes, and that generally use industry standard components.

Once in a market, Dell leverages its strengths in a low-margin business to drive down costs and gain market share. Competitors in this industry compete with Dell in three basic ways. First, they can compete at the high-end performance point that usually contains proprietary technologies that Dell does not have. Second, they can subsidize this low margin business with other segments of their business that do have significant margin. Finally, they can compete head-to-head with Dell along price and service. To illustrate, Figure 2 shows that no company in the year starting Q4 '00 to Q3'01 has been able to achieve both market growth and profit competing against Dell.

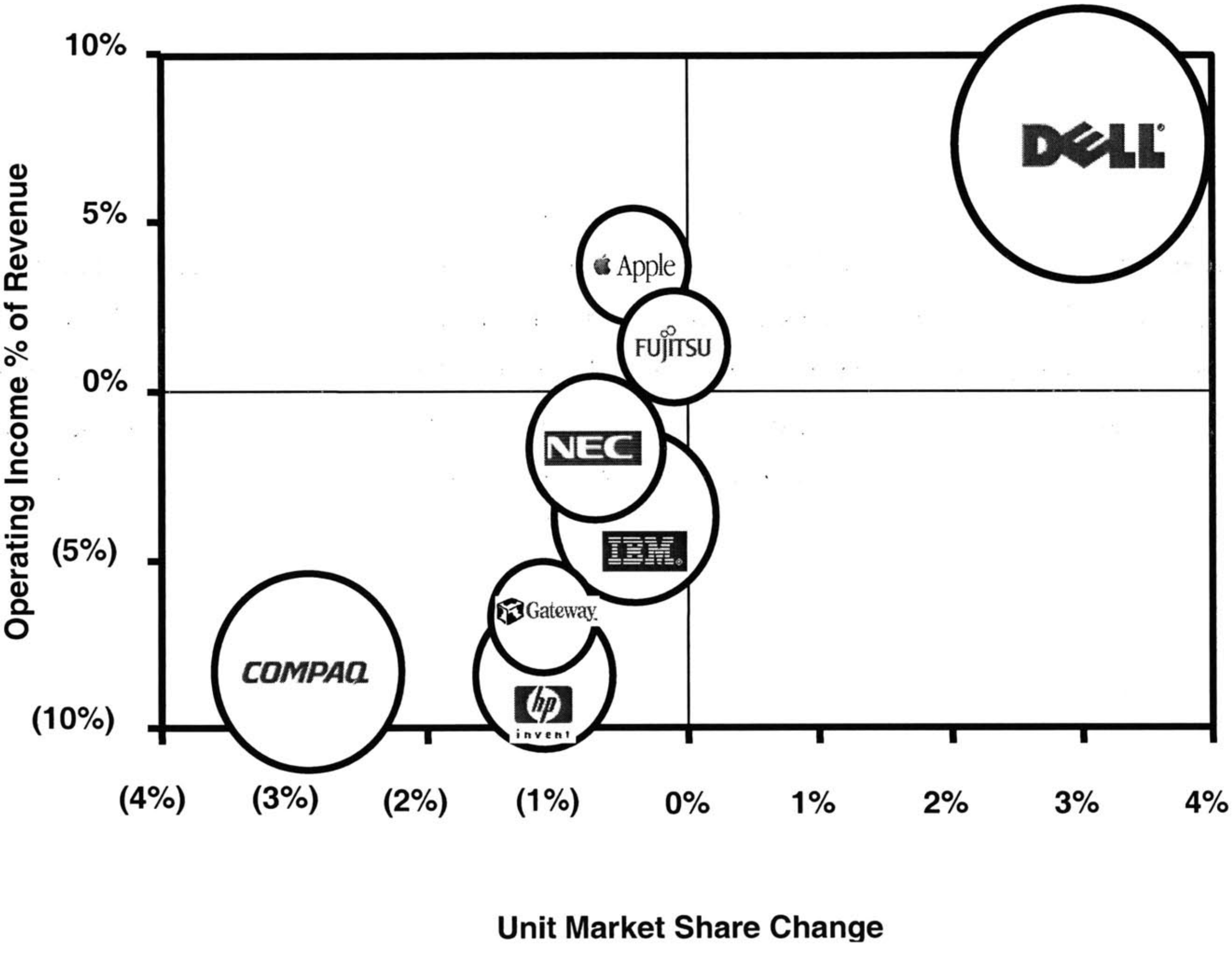

Figure 2. Profit – Market share matrix of PC industry competitors from Q4 '00 to Q3 '01

1.2.3 Dell Culture

"Dell is the biggest startup you'll ever work for," claims CEO and founder Michael Dell. With over 34,000 employees, disbelief is easy to come by. Nonetheless, much of Dell's business relies on the speed, the problem solving, the strong networking, and the innovation that is vital to new ventures.

When five days separate order entry from delivery and five hours separate production from having no parts available to build, speed becomes essential. Speed gives Dell the agility to respond to new technologies, design changes, price changes, unexpected events, quality issues and, most importantly, the customer. Dell's organizational dynamics reflect this need for agility by using command and control management. Alignment to radically new directions can be achieved in a matter of hours or days. Tops down management is complemented by creative solutions and continuous improvement initiated by employees.

Like start-ups, Dell also relies heavily on an employee based knowledge transfer. Networking effectively is thus a critical skill. Within each functional area, one must ascertain the "go-to" individuals who can share best practices, historical facts, and additional relevant contacts. Consequently, Dell employees support open communication, help wherever they can, and always refer to other resources when they themselves cannot help.

Dell's employees also have rapid problem solving techniques and a "whatever it takes" attitude similar to many startups. While until recently this approach succeeded in keeping bureaucracy at bay, Dell has embraced business process documentation and improvement throughout all levels of the organization to increase efficiency, share best practices, and reduce costs. Most improvement projects are developed by production employees and first-line engineers and receive management backing to build momentum. Traditional continuous improvement techniques provide the framework for this business process improvement (BPI).

At this dizzying pace of business, metrics play a significant role in both monitoring performance as well as in decision-making. Metrics help create an operational "dash-board" that quickly informs management of process health and helps direct resources to manage the business.

1.2.4 Dell Mission

Dell's current mission statement is: "To be the most successful computer company in the world at delivering the best customer experience in the markets we serve." The company has three current strategic initiatives:

- Globalization – by increasing market share in regions outside of the US, Europe, and Canada where market share is already well established
- Product Leadership – by providing the best product in the marketplace and never being caught at a disadvantage in terms of features, availability, reliability and value
- Customer Experience – by leveraging the direct model to deliver the best possible experience at all points of contact with the customer

Dell's mission reflects elements of each section of the company overview. It leverages the Dell business model, prescribes the products and price-performance, and relies heavily on the strong corporate culture to deliver products to the world.

1.3 Thesis Overview

This thesis provides a novel analysis of Dell's internal quality control and improvement goals and strategy as related to its corporate culture and business dynamics. By addressing basic operational elements such as cycle time, labor, inventory, cost, and quality, a new defect cost model is developed. The results of the model provide a framework and lessons with which to discuss tactical implications that quality control and improvement has on the factory, the strategic role the factory plays in championing quality, as well as the strategic role quality itself plays in Dell's future success.

1.3.1 Tactical and Strategic Objectives

Primarily, internal quality improvements focus on factory incurred defects. While historically, these defects have been managed by a Dell defined yield metric, the thesis attempts to translate factory defects into costs via labor, inventory, and cycle time. This approach not only mimics how defects and reliability issues that Dell's customers face are costed, but it also allows internal quality to be discussed in terms of operational elements that are simultaneously optimized in a cohesive operational strategy.

A cohesive strategy provides the factory with information for best directing resources to simultaneously reduce cost and improve quality. At an enterprise level, this strategy best leverages the factories extensive knowledge base and relationship with vendors, design, and customers to again simultaneously reduce costs and improve quality.

1.3.2 Project Considerations

This analysis borrows not only from classic quality literature relevant to the project objectives, but also recognizes the organizational dynamics and other management considerations that impact any strategic framework. Leadership, culture, corporate strategy, organizational inertia, cost systems, and knowledge transfer add context and depth to the discussion and resulting framework.

1.3.3 Thesis Organization

The discussion first expands on the thesis problem statement and objectives followed by relevant influences within Dell, particularly in the factory. The section detailing the method and approach relate how the new cost model leverages the literature and benchmark data, the factory manufacturing flow and data obtained from it, and other organizational factors. Once the proposed defect cost model and its components have been presented, the section on tactical results discusses how the model translates defects to cost and its implications to factory related quality. These tactical results are then followed by strategic implications and recommendations that address whether quality control and improvement can simultaneously occur with low-costs and high-clockspeed. The conclusion draws out key findings and lessons learned from the context of Dell's continued pursuit of quality. While acronyms are used throughout the thesis, each is accompanied initially by a full reference and a consolidated list is documented in Appendix A.

2 PROJECT OBJECTIVES AND BACKGROUND

An LFM project must satisfy several needs, most importantly a need that is of strategic relevance to the sponsoring company. The project framework and objectives recognize the factory's need to reduce quality and costs and have been influenced by many factors including the economic environment, several new influences in the factory, and the current state of quality control and improvement.

2.1 Quality Control and Improvement in a Low-Cost, High-Clockspeed Manufacturing Environment

Cost pressures within the factory arise from the price-performance strategy that Dell embraces and the role of the factory as a cost center. The current business environment then compounds the cost pressure. Since materials costs make up most of the total cost of producing a Dell product, procurement aggressively drives costs downs at the suppliers while balancing other requirements such as quality, service and continuity of supply, and technology.

Given the absolute importance of velocity and cost, how should quality improvement best be attacked? Strategically, Dell places quality as one of its three key goals in its corporate wide mission statement. Quality not only ensures customer satisfaction but is also part of Dell's brand value. Dell also places continuous improvement and BPI training as a business-critical objective. Suggested quality improvements arise generally from the manufacturing environment. Executive management has thus charged the factory with driving the quality culture in both directions: upstream to design and to vendors and downstream towards the customer. Upstream helps prevent defects before they occur. Downstream helps isolate the customer from quality issues to contain defects internally. While the few defects that impact the customer are immediately addressed, internal defects and their related quality improvements must show a viable return on investment (ROI) via cost savings to justify the changes. The low-cost business requirement compounded with rapid change creates a higher hurdle rate for internal quality improvements; Dell is in a dilemma that relegates most internal quality improvement to incremental change rather than radical improvement.

2.1.1 Thesis Problem Statement

The thesis thus addresses quality improvement in a low-cost, high-clockspeed environment. Quality improvement has generally developed in industries with much slower product development cycles, less rapid process innovation, and bigger, slower organizations. In relation to the operational frontier, it has been demonstrated in many of these companies that they were within the frontier and could simultaneously improve quality and reduce costs. In addition, these organizations had already in place many of the business processes and tools required to promote a quality improvement strategy.

Dell, on the other hand, has cost pressures that apparently do not justify radical or substantial investment in internal quality improvement and has time pressures that prevent a viable ROI. Furthermore, the server and storage manufacturing environment has many other business and technology issues that further confound internal quality improvement.

While many potential projects arose from the initial conversations with factory and engineering management and the thesis advisors alike, it became quickly evident that a more fundamental problem exists. Dell's current approach to internal quality improvement is many levels of abstraction higher than the defects themselves and even further abstracted from the related costs. Rather than to try and impact the metric, a deeper understanding of quality costing is required. By understanding the cost drivers, the varying degrees to which each defect mechanism or component incurs cost, and the Pareto of issues that most effectively reduce costs, resources can then be best deployed to create a quality improvement strategy. Using the framework of low-cost and high-clockspeed, the following tactical and strategic project objectives are identified.

2.1.2 Tactical Objectives

The cost of external defects at Dell has long been understood and is readily tracked by a metric called FIR (field incident rate) and IFIR (initial field incident rate) for issues that occur in the first 30 days. The per incident cost of (I)FIR has three components:

- The cost of initial servicing – call center costs
- The cost of dispatching a service representative – the associated labor costs
- The cost of dispatching a replacement part – the component cost plus shipping costs

In prior practice at Dell, an internal defect only had labor costs associated with it. This labor comes primarily from the associates who service failed systems in the electro-mechanical repair (EMR) area. Section 3.2.1 has further details of the manufacturing flow and areas. The cost of quality, as Juran and others have illustrated [11], go well beyond the cost of retesting and servicing. Although a very complex cost model was initially pursued, a cost model that mimics that used for external defects is proposed in this thesis. While a very complex cost model would be more thorough and would be able to address the many components of cost that Juran professes (summarized in Section 3.4.1), it was larger in scope than what the project time-line allowed, the data would quickly become obsolete, and it invited more skepticism than agreement.

Tactically, the project creates an average per incident defect cost that mirrors per incident (I)FIR costs. The three components of internal defect costs are identified as labor, inventory, and cycle time.

- Labor –analyzed throughout the entire defective system flow including lost build time, service time, system disposition time, retest time, and component disposition.
- Inventory –analyzed for scrap, inventory related to quality repair and servicing, and inventory in disposition.
- Cycle time – analyzed for system failures, as they not only increase the cycle time of the failing system but also for the order with which it is associated. The delayed shipment of systems due to quality issues cause delayed revenue that can be assigned a cost via Dell's cost of capital.

In addition to the average per incident cost, Paretos of the costs associated with various products, components, and defect mechanisms are also identified as a quality management tool. A ranked order helps guide resource allocation for quality improvement activities. Together the average per incident cost and a prioritized list of quality improvement initiatives can help the factory move forward in attacking quality and cost within its walls and help further formulate its strategic role as champion of quality at Dell.

2.1.3 Strategic Objectives

Although the factory had been tasked to be the quality champion within Dell and the driver of change, the breadth of the role is not clear. Many feel the factory is the catchall for any quality issues since it is the step prior to product reaching the customer. As such, detected defects are "good" as they protect the customer from potential problems. Others recognize that defects are more costly the further along the value stream they occur and should be moved upstream into design and to the component vendors. However, without a compelling business case (the labor associated with EMR often did not justify a design or vendor change), the factory finds its role as champion difficult at best. Furthermore, accelerated product lifecycles mean that design resources are often reallocated and unavailable to support changes after product release.

Once the tactical objectives have been completed, the larger task of aiding in quality improvement addresses the following questions:

- How can the quality and cost data be used effectively to further the factory's efficacy in championing quality improvements within the factory itself and upstream with design and vendors?
- How should Dell approach the total cost of ownership and quality?
- How can quality strategies be economically deployed given Dell's business model challenges of low-cost and high-clockspeed?

The following sections detail the other environmental factors that influence the thesis objectives and formulation including the current business environment, cost considerations, technology considerations, organizational dynamics, and current approach to internal defect management.

2.2 Business Environment

The end of the last decade provided unprecedented growth for the computer industry. Specifically, the year 2000 brought about much of the recent flurry of information technology investment due to the Y2K bug. 2000 was also the zenith before a worldwide downturn in the industry and overall economy.

During late 2000, as the bottom fell out of the computer industry, Dell initiated an industry wide price war [17]. While many criticized Dell for draining profits from the industry and for being short-sighted to think prices would bounce back, Dell had a very specific objective in mind: market share. Referring again to Figure 2, Dell not only gained market share but also remained profitable. Dell achieved about $300M in profit while the rest of the industry racked up over $1B in losses. Both achievements are testaments to Dell's competitive strengths in the low margin industries. Dell's strategy coupled with the economic environment spurred an industry shakeout. The price war is very likely the major reason Hewlett-Packard recently moved to acquire Compaq and why Compaq is moving towards services and away from competing directly with Dell in the personal computer market.

2.3 Manufacturing Cost Center

Each of these elements of the business environment only emphasizes manufacturing's role as a cost center. A long-standing approach to assigning decision rights within the firm, responsibility accounting recognizes business units and departments within the firm as a cost center, a profit center, or an investment center.

Dell's sales and market organization performs all pricing decisions and relies on manufacturing reported cost figures to establish sales goals, price points, product mixes, and to manage profit. Consequently, manufacturing's main goal is to minimize total costs given the required product mixes and volumes. Three major metrics are used to monitor how well manufacturing is achieving this objective: cost per box, defects per hundred units, and ship to target all of which will be described in the metrics section below.

2.4 Server & Storage Manufacturing

Servers and storage devices were added to Dell's product portfolio within the last five years. They represent a higher margin opportunity than desktops currently allow [14]. Like desktops, servers and storage use some of the same basic technology. In contrast to desktops, they are relatively low volume, high complexity, and high variation products. As such, servers and storage present a significantly more difficult manufacturing problem than desktops. The variation has driven the number of storekeeping units (SKUs) to increase sharply in comparison to desktops. Lower volumes make the learning curve for each system longer as both assemblers and engineers gain knowledge of the systems and root out issues. High complexity provides many opportunities for failure both at the component level and at the system level.

2.5 New Factory Leadership

During the time of the internship, the server and storage manufacturing facility came under new leadership. Many of the key positions were filled with individuals who have had industry experience at Motorola and IBM, both companies renowned for their mature approach to business process and manufacturing quality. Quality has been further instilled into the daily tasks of every level of the organization. It became the focus of both containment and prevention with particular regard to cost, continuous improvement, and zero defects.

2.6 New Product Engineering Group

The renewed emphasis on quality and a workforce reduction prompted the merger of formerly separate product introduction and product quality groups. The combination of these roles, renamed product engineering, has several positive impacts. First, it removes the hand-off between introduction and sustaining that often prevents quality improvements from being integrated into subsequent product introductions. Second, it gives quality engineers insight into the development process. Third it promotes a "life-time" approach to decision making since there is no longer a hand-off of products to the product quality or sustaining group.

2.7 Metrics

Manufacturing facilities at Dell are held to three major metrics. These metrics monitor both the timeliness of manufacturing as well as the health of manufacturing. Many of these metrics translate to metrics outside of manufacturing. In each of these three cases, the metrics contribute ultimately to the customer experience. The first, cost per box, has an immediate impact on pricing. The second, ship to target, affects on-time delivery. The last, defects per hundred units, is a measure of defect captures within the factory and correlates to a certain degree to external defects and reliability issues.

2.7.1 Cost Per Box

Cost per box (CPB) is the budgeted transformation cost of a unit of production. Using activity based costing, CPB is assigned both a manufacturing component and a general overhead component, as shown in Figure 3. Manufacturing allocation is made up of both direct and indirect costs. Additional charge-ins are other indirect costs that arise from centralized support groups, information technologies, inbound and outbound logistics, and excess and obsolete (E&O) inventory.

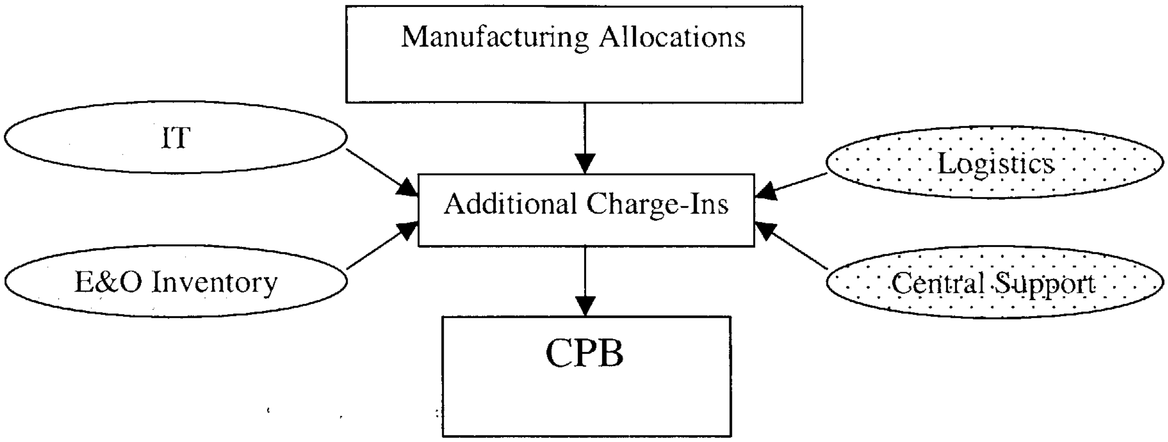

Figure 3. Cost per box allocation

The main manufacturing cost drivers include build times, test times, number of components, labor, support, and quality. Again, compared to the other products that Dell produces, servers and storage have dramatically higher production costs. Although a majority of the cost stems from the activity based costing (ABC) allocation of overhead, servers and storage also represents a tremendous opportunity to reduce costs at Dell and to obtain margins that no longer exist in Dell's other lines of business.

Manufacturing is held accountable for the differences between actual and budgeted CPB. Furthermore, CPB is the internal transfer price Sales and Marketing uses to set pricing, product mixes, and profit goals. CPB has also become a benchmark to compare manufacturing facilities to one another and has been used to make sourcing decisions. As always, the danger in making production decisions based on average costs is that often the associated opportunity costs are not recognized. Many of the costs associated with CPB are unavoidable and CPB cannot be a strict point upon which sourcing decisions are made.

2.7.2 Ship to Target

Ship to target (STT) is a measure of units that ship within the predescribed lead-time that Dell sets for its products. A standard lead-time for most of Dell's products is currently five days. Order fulfillment can be broken down into three major processes, each of which are allowed a certain portion of the lead-time. Although the metric measures how many units meet the overall lead time, each process must account for issues that drive cycle times longer than what it has been allotted.

Manufacturing ultimately controls the last portion of order fulfillment. The last segment spans order introduction to the factory floor (termed traveler pull) to order shipment. The factory execution is allotted one of the five days comprising STT. Any outliers undergo Pareto analysis and are addressed once ranked. Factory STT violations include quality issues on the factory floor, lines down issues, lack of available components for build, and engineering holds, among many others. The factory seldom impacts the overall STT metric, often surpassing 90% order completion within the one day.

2.7.3 Defects Per Hundred Units

Defects per hundred units (DPHU) is the ratio, expressed as a percentage, of units that fall into the fail flow during production to the number of units that ship. Failure can occur due to assembly errors, system tolerance stack-ups, connectivity issues, and component failures. The shipments in the denominator can be independent of the failing units and are also subject to delays. The idiosyncratic nature of both components of the ratio makes DPHU a highly volatile metric, especially when viewed at the individual product level versus the aggregate factory level.

Another difficulty related to DPHU is the attribute nature of quality data within the production flow. Most statistical process control (SPC) deals with variable data. In contrast, Dell testing provides only pass/fail information known in SPC terms as attribute data. This type of attribute defect data is generally charted as a count, as a percentage, or as parts per million. If a constant sample size is used, SPC generally dictates the use of a C-chart; otherwise, SPC suggests the use of a P-chart where the control limits reflect the changing sample size [26]. As shown in Figure 4, the P-chart gives the goal, the weighted average, the actual data, and the upper and lower control limits (UCL and LCL, respectively).

By reviewing historical products that may be predecessors for the current product, product engineers set the goal lines for DPHU. This baseline may arise from shared components, follow-on designs, similar electromechanical characteristics, or heuristics. General improvement requirements also guide goal line setting. For example, management may require a 5 or 10% improvement over the prior product.

The other chart elements, shown in Figure 4, come from actual data. The weighted average, denoted $\bar{p}$, is calculated by weighting the DPHU values by their respective sample size, n. Once $\bar{p}$ is found, the UCL and LCL lines are calculated from this center line as follows,

$$UCL = \bar{p} + 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}} \qquad LCL = \bar{p} - 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}}$$

Equation 1. Upper and lower control limit formulation

The P-charts have several significant drawbacks. First, there is no distinction between the various defect modes nor is there any note of the defects' relative importance. Secondly, as the control limits allow greater variability with smaller sample sizes, the low volumes inherent to servers and storage often push the control limits further from the mean value. Finally, performing variation reduction on attribute data is often trying at best, as the underlying mechanisms are not explicitly understood.

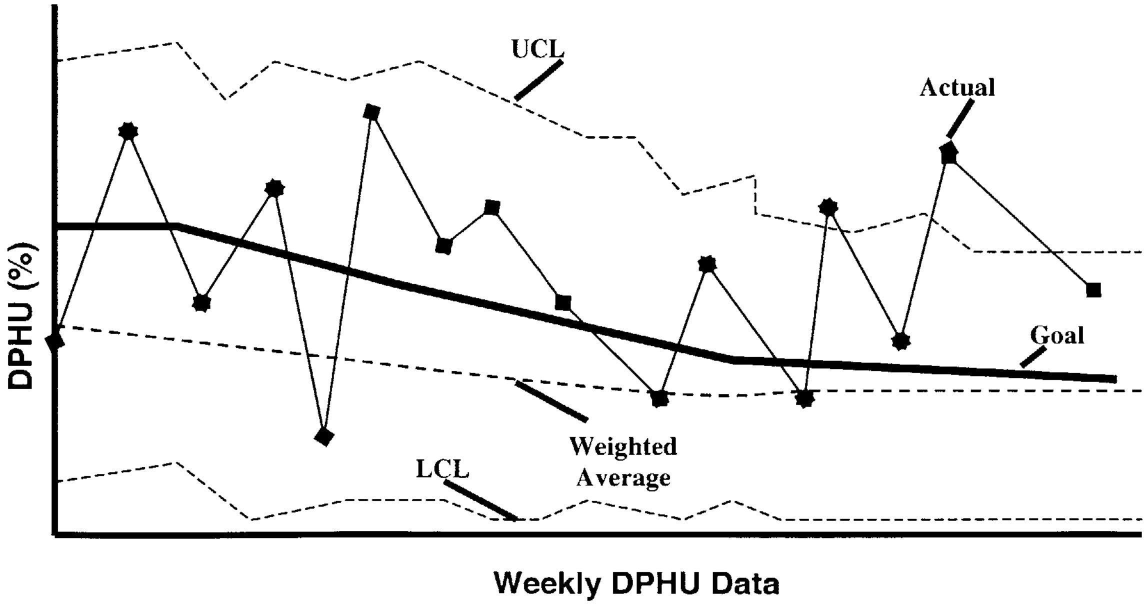

Figure 4. P-chart showing goal, actual and control lines

Pareto analysis can further classify the DPHU once additional attributes are associated with the defects. Information regarding the source of the defect (Dell, vendors, or intermittent), the nature of the defect (workmanship, connectivity, system repair), and if a repair is required, by the commodity involved help rank DPHU issues.

The strategic quality groups within Dell's server manufacturing facility openly recognize the many shortcomings of DPHU. While it remains a fixture in management control (i.e. a dash board metric that can be easily understood), many improvements are required to help make appropriate management decisions. Improvements have come from many directions. As Dell embraces quality more rigorously, six-sigma and business process improvement (BPI) put forth frameworks in which to evaluate quality. Quality managers have invited analysts and engineers to think in terms of defects per million units so that they may eventually record defects per million opportunities – the language of six-sigma improvement. Furthermore, BPI has a rigorous problem solving approach that has helped dissect attribute data into issues that can be more readily addressed and controlled. This approach has spurred several improvement projects during the course of the internship that explicitly break DPHU down by categories such as connectivity, workmanship, and commodities. DPHU has been traditionally attacked by volume. The intuition is that DPHU relates directly to cost as well as potential customer issues. Each product's DPHU is calculated and is then weighted by volume. Thus mostly high volume products have been the focus of quality improvement. The high volumes also help justify any investment required for quality improvement.

3 METHODOLOGY AND APPROACH

Four major phases are used to address the tactical and strategic goals. Phase I is a discovery process: understanding the characteristics of Dell as a whole and of Dell manufacturing. Phase II involves a literature search and analyzes the current quality strategy at a factory and corporate level as well as against benchmarks. Phase III populates the new cost model and performs data mining and analysis. The final phase involves communicating the findings and relating the tactical results to the strategic questions put forth by the project goals. The following section details the project's methodology and approach.

3.1 Overview of the Proposed Defect Cost Model

A previous study into quality had been conducted by Dell's personal computer organization. The hypothesis at the time was that quality was a significant contributor to cost per box. The analysis calculated an expected value for defects and then determined what portion of CPB defects comprised. The number was deemed insignificant, and many felt as though significant quality investments could not be justified due to the limited impact defects had on CPB [5]. The prior study does, however, provide one key insight for the approach of the new proposed quality framework: to emphasize the marginal cost of defects, not the average cost subsidized by total volume.

The proposed cost model traces systems and components through the manufacturing flow and associates costs to defects via labor, inventory, and cycle time. As a system is manufactured, it incurs labor costs if it fails during build or test and requires service. At the time of service, a commodity can potentially be replaced. If scrapped, these commodities incur inventory costs. Finally, as systems return from service back to the manufacturing flow, if they are shipped late, they incur a cycle time cost. Furthermore, other systems awaiting the serviced system(s) are virtually impacted by the failure and also incur a cycle time cost since they are shipped as a group. The following sections detail the first three phases of the initial model construction. Section 4 describes the final model and its results.

3.2 Discovery Process

To create change as the proposed model is intended to do, discovery is required to understand the issues at hand, identify stakeholders, create a knowledge base, and to begin to build momentum for this change. Without it, change, regardless of its validity is often met with resistance [1]. In the context of Dell, this requires an evaluation of the manufacturing flow, the product technology, the key stakeholders, and more generally the organization dynamics and culture in relation to quality improvement.

3.2.1 Manufacturing Flow

Dell's order fulfillment flow is depicted in Figure 5. Once sales representatives or the website receives an order, the order enters Dell's order management software. This software downloads the order to Dell's enterprise resource planning (ERP) software that schedules parts delivery to the factory. Once the parts are delivered, the ERP software releases the order to the factory floor. All of the systems per the order are produced in a batch and are shipped together when completed. More fulfillment details can be found in Appendix B.

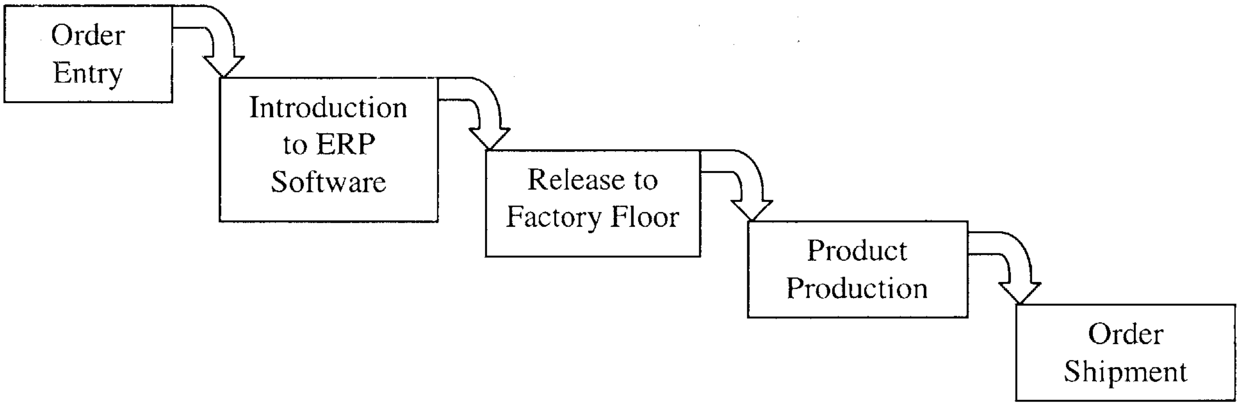

Figure 5. Dell's product fulfillment flow

Within the factory, the various manufacturing areas pull raw material, assemble, test, and disposition failing systems and components. Figure 6 shows the material flow and follows the brief explanation of these areas.

- **Traveler Pull**: factory associates check material availability and pull orders for which all systems in the order have parts available to build. A traveler is a hardcopy of the BOM (bill of materials) and includes other order and system identifiers/specifications that travel with the system until boxing.
- **RAM cage** – here, associates pick all high-dollar inventory items such as microprocessors, memory, and redundant array of independent disks (RAID) keys
- **Motherboard (MB) prep** – associates install RAM cage material to the MB and additional hardware (heat sinks, processor cards, etc.). Once a MB is complete, it runs along a conveyer and is scanned which simultaneously initiates a chassis pull and the kitting process.
- **Chassis pull** – the metal chassis per system is pulled and placed on a tray which travels by conveyer to the merge point.
- **Kitting** – all components that are not already mounted in MB prep are pulled excluding basic hardware that resides in the individual build cells. Kitting components include various drives, cables, various printed circuit boards, and labels. All kitting components are placed within a tote.
- **Merge** – the MB, chassis, and kitting tote all merge together and begin down the assembly conveyer. The system number associated with the kitting tote should match the MB and chassis system numbers.
- **Distribution** – process engineering-optimized distribution software routes the merged system into the build cells. A first in first out (FIFO) routing of systems is employed and the only conditions that may determine specific routing include: lines or builders that might be dedicated to a product type or product line, and only one system can be in queue for a builder while a builder is assembling a system.
- **Build** – each cell builds a system and conducts a quick test within the station. If the quick test is occupied and another system has been built, the built system is pushed out and tested within the quick test spur located at the end of the build cells.
- **Quick Test** – quick test (QT) is the initial test for conductivity, parts check, and basic functionality.
- **Burn** – systems are routed to racks of power supplies and network connections to perform extended tests for both Windows and DOS and to perform software downloads

for any pre-loaded software. Systems accumulate in burn for the other systems in the same order before proceeding to boxing.

- **Boxing** – the final area performs "wipedown" where systems are checked for cosmetic issues, associates pick required documents and box the systems to be shipped.
- **EMR** – Electromechanical repair does system level debug and usually receive systems routed from quick test and from burn. Generally, repairs entail reconnecting loose cables, reseating parts, or replacing parts. Debug is limited to failure codes generated from diagnostic tests run in quick test and/or burn and to engineering judgment on what part(s) are faulty. EMR can also deem a system CND, cannot duplicate, if the documented failure from QT or burn does not recur. Any replaced components are routed to the materials requisition board (MRB) that can scrap a part, return a part to the vendor, or send the component to the failure analysis lab.
- **FA** – Failure analysis conducts root cause investigation of components deemed potentially bad from EMR. While conducted at Dell, much of it is vendor-supported capability and resources. FA places components into three general categories: process or Dell induced defects, vendor induced defects, or CND if no fault can be found. CND components and repaired components can be readmitted to the floor as long as they meet strict quality guidelines while the others are returned to MRB for further disposition.

To understand the flow and issues that workers face during production, participation in or observation of each of the factory areas described above reveals the tension between process control and quality with respect to throughput and velocity. While metrics exist to promote all of these characteristics, many times one metric receives much more focus than others. The flow itself stresses velocity versus cycle time. In other words, the bottleneck of the process is designed to be in build. Failures occur after build and therefore preserve velocity of individual systems and do not affect the bottleneck. Nonetheless, the overall order cycle time is impacted by systems that fail since orders do not ship until the entire order is complete.

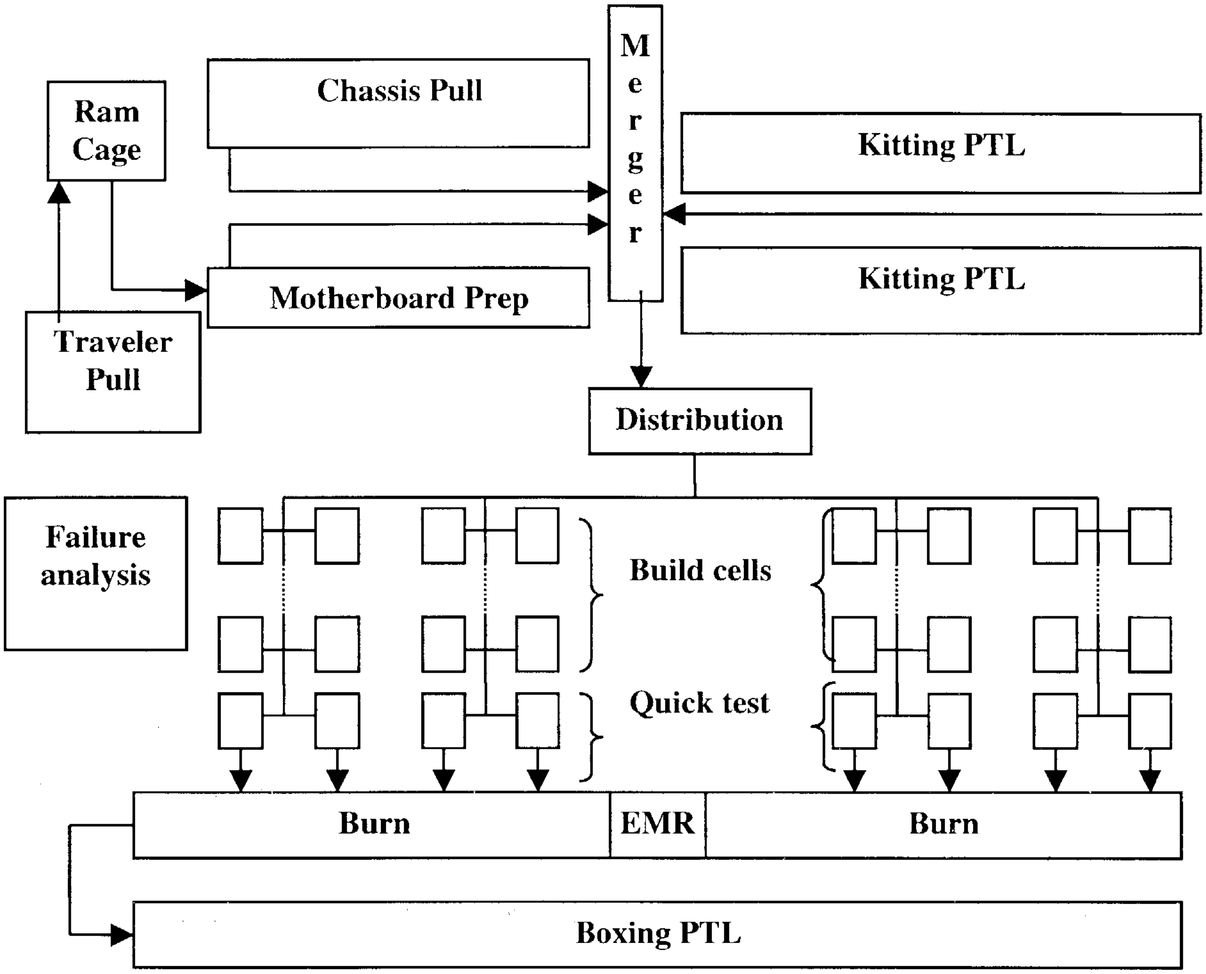

Figure 6. Server & Storage manufacturing flow

3.2.2 Server & Storage Technology

Although the underlying components that comprise servers and storage products do not differ drastically from personal computers, the product requirements and the integration varies greatly from personal computers (PCs). Servers, the primary focus of the project, differ from PCs through requirements on performance, on scalability, and on availability. Each characteristic must be understood to appreciate the manufacturing challenge that servers and storage face.

Performance is measured not only in raw power (processing speed and memory size) but efficient use of this power (bandwidth and instructions per second). Performance has driven several characteristics that make server manufacturing difficult as described in Section 3.3.

These difficulties arise from multiple processors, larger memories, and the inclusion of chipsets to aid performance. The sheer number of components and the connections between these components introduce many opportunities for failure or for tolerance stack-up problems.

Scalability is the ability to increase performance during the lifetime of the product. Both servers and storage allow the addition of several processors or disk drives. These open connections often introduce the need for more printed circuit boards and additional connections that again introduce the opportunity for failure.

Availability requires a great deal of redundancy to either protect data integrity in case of system failure or to provide alternative operating paths in the case of component failure. While in a real system application, redundant systems and components may fail and still allow proper operation. In contrast, Dell's test process must ensure that all redundant components and data are functioning. Again, availability introduces failure opportunities through redundancy.

3.2.3 Multi-disciplinary Network

Dell's knowledge base is highly distributed among key individuals throughout the company. Networking thus becomes essential to battle the learning curve that any new employee or intern faces. To accomplish this project, a useful practice is for each conversation and meeting request to include a request for additional contacts. These contacts help bridge functional groups within Dell as the project relies on data from many different disciplines. Finance controls cost information, Procurement controls much of the vendor interaction, Design and Reliability control many of the component specifications, and Sales and Marketing determine pricing from manufacturing cost information. Interviews with members of each of the disciplines reveal, at an enterprise level, the various trade-offs and decisions that are made that affect final quality, as summarized below.

Finance organizations within the factory and within procurement maintain Dell's CPB and inventory financials. Quality arises in many factors used to calculate CPB including DPHU (often used as a multiplier in overhead allocation), scrap, quality support, test time, and EMR labor. During development of the proposed cost model began to develop, consultation with finance to ensures a proper treatment of the financial numbers, ensures the viability of the information for future use, and establishes proponents of the results once the project is complete and knowledge transfer is begun.

Procurement activities reside within two organizations within Dell. One group generally works with design to specify and obtain new components while the other works more closely with production, geared more towards hub inventory and factory replenishment. Both groups aided in understanding:

- How vendors are placed on aggressive cost reduction plans
- How integrated components such as motherboards are priced
- How quality and price varies as vendors source from different geographic regions
- How vendors themselves struggle with the learning curve required to meet Dell's cost reduction plans or expected quality levels
- How Dell has helped create engineering positions at their vendors that are dedicated to Dell products that serve as a more direct liaison to resolve quality issues rapidly
- How Dell uses a balanced scorecard approach to rating vendors and moves total available market based on performance to this rating

Design and Reliability work closely together to determine the system requirements for a product. Reliability has become an even more critical part of server and storage design due to system critical roles that servers and storage play in networked systems. Electrical components have a different reliability profile than mechanical and electromechanical components. The bathtub curves, as described in Figure 7, for each component type thus differ and are reflected in the types of field issues that Dell must face. IFIR's timeframe of 30 days represents the fall-off of typical electrical quality issues. Electromechanical quality issues have a much longer settling time that can reach one year in some instances.

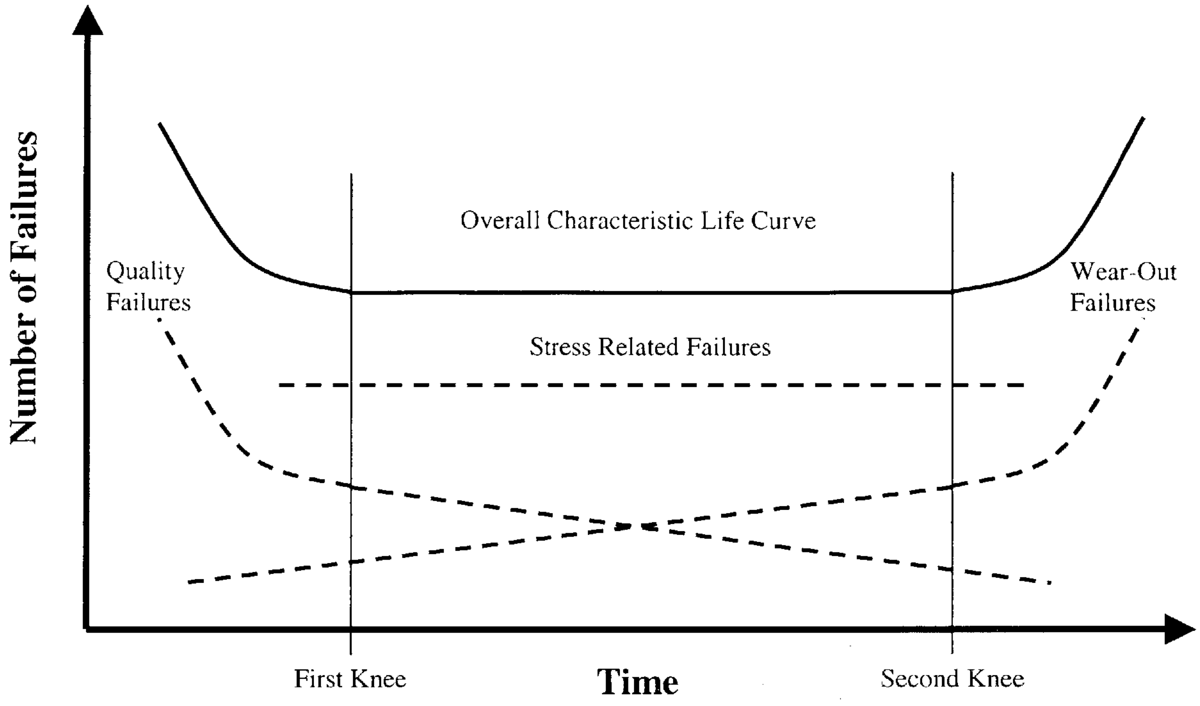

Figure 7. Characteristic life curve or "bathtub curve"

Since electromechanical and mechanical issues actually do not reach the first knee in the bathtub curve often until 90-120 days, reliability for these parts is more expensive in terms of design, customer satisfaction, and Dell warranty costs. Another issue, tolerance stack up, is a worst-case scenario where all integrated components are at their negative tolerance or all are at their positive tolerance and is a known issue that is difficult to ascertain in the factory's go/no-go testing process. Tolerance stack-up is most evident with component alignments, connections, switches and monitors. Reliability engineers also rely on an industry standard approach to cost of quality called the rule of 10's. The rule of 10 relates how average costs of quality and reliability issues vary as a product moves through the value stream as depicted in Figure 8. Design issues are relatively low in cost since they are at best still on paper. Quality and reliability cost increases by an order of magnitude the further along the value stream defects are identified. Intuitively from this relationship, defects are less costly to catch upstream. The challenge Dell faces is to determine what level of investment is needed to catch or prevent defects upstream and whether that cost can be justified.

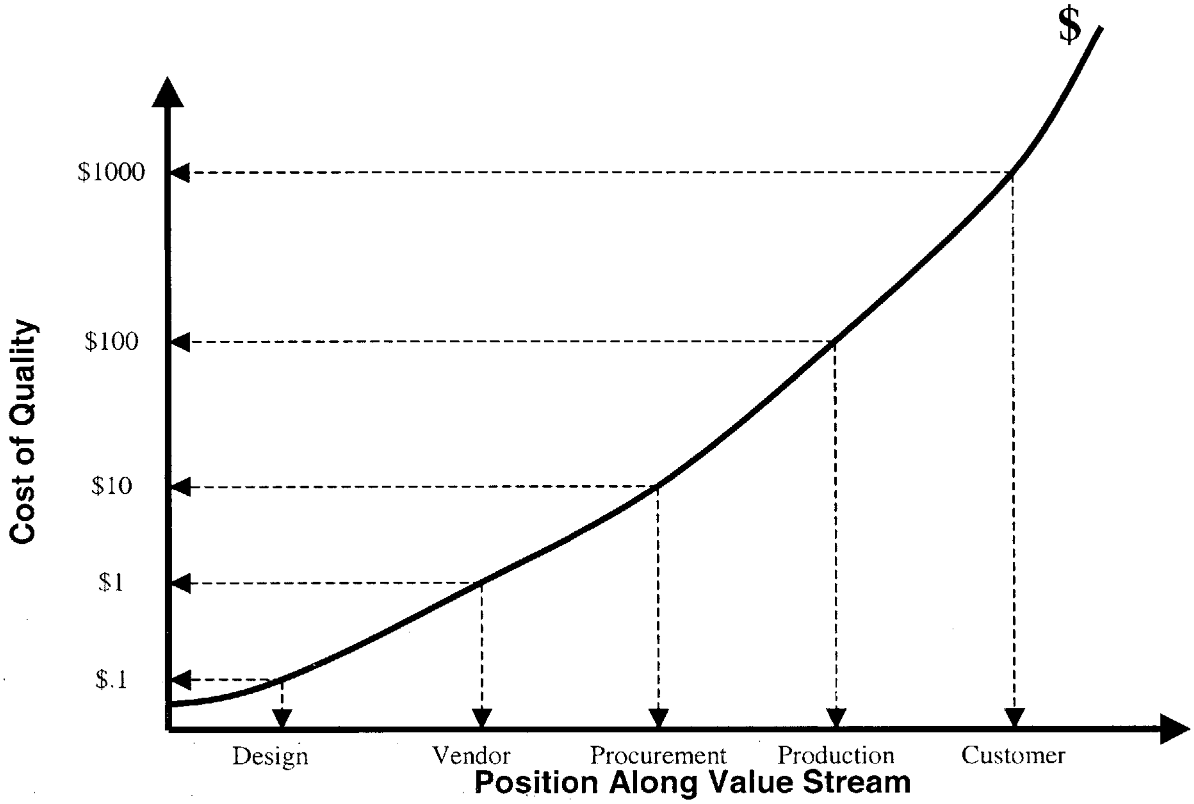

Figure 8. Rule of 10s: cost per quality/reliability incident versus position along value stream

Sales and Marketing provides insight into how these organizations rely on manufacturing cost information. Furthermore, Sales actively sets price to assure that Dell continues to deliver the best value to the customer per its mission statement and is always wary of competitors' price moves. The Sales group was instrumental in launching the price war that Dell began in September of 2000 that has resulted in a significant industry shakeout and increased market share for Dell.

Within the factory, associates on the production floor provide invaluable insight into assembly or process issues that unavoidably contribute to internal quality issues. Associates are instrumental in identifying systematic DFX (design for assembly, repair, service, test, etc.) issues that impact their performance as well as contribute to DPHU. The factory management, support organizations, and associates also engage in continuous improvement to address issues including: reducing time delays that occur in closed-loop corrective action, managing the requirements of many diverse metrics, promoting processes which reduce DPHU, and communicating factory issues effectively to the various support organizations such as process engineering, test, product engineering, electromechanical repair, and failure analysis.

Networking across these various groups is important for reasons beyond discovery and learning. It also helps address the needs and expectations of all stakeholders for the project. Integrating stakeholders early in the process helps build momentum, helps give a system-level approach to the problem, and helps communicate results once the project is complete including recruiting proponents for strategic initiatives that arise.

3.2.4 Organizational Dynamics and Quality Culture

Section 1.2.3 introduced the Dell culture. Inertia is strong and necessarily so at a company like Dell where velocity reigns. Inertia originally swept the project towards an objective to reduce DPHU by some percentage and therefore reduce cost as measured by CPB. Although this approach was aligned with the current organizational objective, it lacked the framework to cohesively relate defects with cost. Instead, this thesis project seeks to provide value to the group, but more importantly to also address strategic and tactical implications. This approach has gained momentum by validating itself as a legitimate concern to the group and by building credibility. Credibility stems from the discovery process, by understanding manufacturing at Dell, attaining familiarity with the underlying technology, being well networked, and understanding the language with which each group communicates.

Quality has a business role in supporting Dell's mission statement, the fulfillment dynamics, in brand management, and in cost reduction. Quality is most often personified by metrics at Dell. However, since quality can be an emotional topic, the interpretation of quality varies depending on which discipline it concerns and can be approached with a variety of frameworks. A new framework necessarily has to speak in terms that many disciplines can understand and that managers and employees alike can appreciate. Thus, the proposed quality framework employs labor, inventory, and cycle time to address cost: none of which can be easily disputed. Whenever possible, these costs are related to other terms in the Dell vocabulary to help individuals get a sense of the magnitude of excess cost related to poor quality.

Despite decades of quality programs and process development, quality can still be considered a "black art." Much of the costs are soft, unmeasured, or immeasurable.

Furthermore, many of the principles have to be instilled at a cultural level. Once established, corporate values can take precedent to dollars, and strategic aspects of quality such as brand management, lower total costs (when viewed across the entire organization), and customer experience can be best appreciated. Finally, Dell essentially faces a "not-invented here" syndrome. Given Dell's business model, it is a challenge to see how significant quality investment can ever be justified, although companies on the frontier of quality-cost improvement once faced the same dilemma.

3.3 Benchmarking

Benchmarks of two companies, Teradyne and Intel, reveal how others deal with the same dilemma. Teradyne builds low-volume, high complexity semiconductor tester products that include many of the same components as PCs, servers and storage. Furthermore, Teradyne is recognized as a leader in total quality management and has developed a long lasting relationship with a supplier that Dell has struggled with in the past. Interviews reveal the importance of the supplier relationship and of recognizing the learning curve that suppliers must endure. Teradyne has helped instill a similar quality culture within the vendor's organization that addresses process control, second and third tier supplier management, and collaboration.

Intel, on the other hand, is a supplier to Dell. While processors and SPC control of their production is generally well understood, Intel is relatively new at making populated printed circuit boards that it supplies Dell and faces a new realm of quality issues. In general, interviews with Intel emphasize a quality value system that identify the "right" thing to do that does not always seem the most economic. Quality goals can reach many different stages. Often companies go no further to improve quality than what the market will bear. Others pursue excellence rather than meet marginal quality goals.

Both points are valid and are incorporated into the thesis. However, a deeper understanding of quality at an academic level is necessary to be able to translate these points to practice for Dell.

3.4 Relevant Literature Search

The existing literature touches on three major aspects of relevance to the thesis: quality, cost, and clockspeed. A brief overview Dell's business followed by the associated literature is given for each topic.

3.4.1 Quality Control and Improvement

Dell is highly regarded in terms of quality. Yet, Dell still faces many challenges in both containing quality issues and in preventing quality issues in new products. In general, Dell approaches quality in terms of branding and cost. Branding addresses external quality (the customer experiences) while cost addresses internal quality (the factory experiences.) In the literature, quality control and improvement has many languages with which it can be framed. Many treatments take on a particular aspect of quality as a mantra. These focal points have included waste reduction, variation reduction, and total quality management, to name a few.

Waste reduction is pivotal to lean manufacturing. Lean manufacturing has several driving principles as detailed by Womack and Jones [24] including:

- Value – can only be constructed in terms of the customer and addresses how a product meets the needs of a customer, the customer's willingness to pay, and the time horizon in which the need should be fulfilled.
- Value Stream – is the entire flow of resources required to deliver a product including: product conception; design and launch; information processing from order entry to shipment; and transformation of raw materials to finished goods.
- Flow – is the process of removing departmental separation usually inherent to the value stream and regarding the continuous processes of adding value to better understand interdependencies and to view system level interaction.
- Pull – in the same vein of just-in-time manufacturing, lean manufacturing prescribes letting the customer pull production rather than push either unwanted quantities or unwanted products to the customer.
- Perfection – encourages thinking in terms of approaching zero defects and 100% yield rather than thinking in terms of incremental improvement. Perfection is thought to be achieved by using all of the prior disciplines.

Deming and Taguchi both approach quality mostly through the identification and reduction of variation [2, 11, 22]. Deming's approach to quality management is to use statistical process control (SPC) as the main tool to identify the differences between common causes and special causes. The rigor of SPC, however, is merely a construct to evaluate processes. Quality improvement itself came through management's use of SPC data to execute his "14 points of management." Management, in Deming's view, is the root of poor quality. The 14 points are management-level objectives that call for creating a quality culture, for providing the necessary training, for eliminating metrics and barriers to maximum worker productivity, for sharing quality objectives across departments and organizations, and for no longer trading quality for productivity or cost/price.

Taguchi addresses variation specifically in relation to tolerances in a product or system. Using design of experiments, the various tolerances within a product can be assessed to determine which ones drive failure and consequently need to be tightly specified, as opposed to those that can be relaxed due to lesser order effects or none at all. For Taguchi, process capability and proper tolerance specification and control are targeted in quality improvement.

Total quality management (TQM), as Shiba et.al. elaborates [20], provides several mechanisms for quality control. TQM has four major facets, or "fitnesses" to quality improvement:

- Customer focus
- Continuous improvement
- Total participation
- Societal networking

Each fitness has a related set of tools to promote problem diagnosis, problem solving, learning, teamwork, and continuous and iterative improvement. TQM also makes a distinction between reactive and proactive quality improvement. This distinction becomes important in addressing cost of quality.

3.4.2 Low-cost

With Dell's business model, cost becomes a vital element to success. As such, Dell has driven much of the cost out of its business through its innovative supply chain strategies, direct to consumer sales, and in its payment strategy with vendors. To help enable further cost reductions, Dell procurement places a cost reduction schedule on its vendors as well. To balance the many competing expectations Dell has for its vendors, Dell uses a TQM approach to awarding business. Using a balanced scorecard, Dell awards business across its many suppliers. The scorecard includes measurements of quality, price, support, availability, and technology leadership [9].

However, the cost of quality is often not well understood by organizations that pursue it and even more often, Deming relates how most companies see a tradeoff between the elements of operations strategy. Likewise, Pagell, et.al. [13] refer to an "inherent" trade-off between quality, cost, flexibility and other elements of a manufacturing strategy. Crosby who proclaimed, "Quality is free, it's non conformance that costs!" gives one approach to the cost of quality. He compared quality-associated costs with operating numbers such as sales or revenue to show the true magnitude of quality issues and the related opportunity for cost reduction. Juran [8], on the other hand, uses the TQM distinction between defect prevention and defect containment and also the distinction between internal and external defects to categorize defect costs.

- Internal failure costs – defects that occur prior to shipment to the customer and include costs related to rework, scrap, retest, downtime, and product disposition
- External failure costs – defects found after shipment that include costs related to warranty, returned materials, and servicing
- Appraisal costs – are costs associated with containing defects and determining the fitness of products or materials and includes costs related to testing and inspecting
- Prevention costs – are costs associated with preventing defects before they occur and include costs related to training, planning, process control, reporting, and concurrent engineering with design

These cost contributions are then compared in relative terms in the worst case, best case, and typical scenarios. At best, most of the cost is attributed to defect prevention and the least external defects. At worst, the opposite is true. More typically, companies incur cost via appraisal and internal defects, as illustrated by Figure 9.

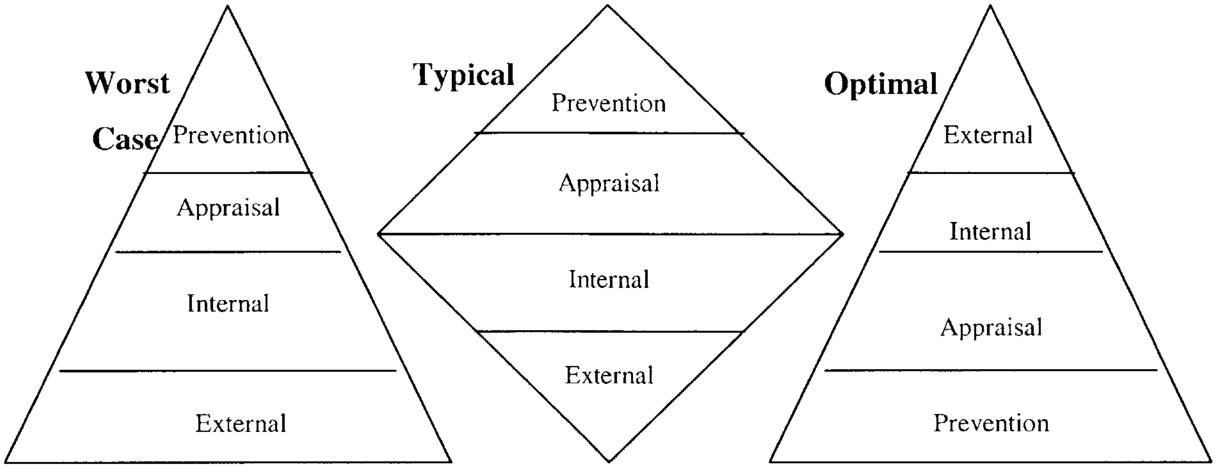

Figure 9. Distribution of quality costs for worst case, typical, and optimal distributions

Juran's cost model shows how total costs are optimal at some percentage yield or conformance. Total costs are the sum of his categories above and in which costs of appraisal and prevention become prohibitive as a product reaches 100% yield and where the costs of internal and external defects become prohibitive as yield drops. Schneiderman [19], however, goes on to show how Juran's model can be mathematically treated to demonstrate that Juran's designated optimal quality point is merely the minimum cost point. He stresses that Juran's optimal point is the point where each additional dollar of appraisal and prevention reduces the failure costs by a dollar and is not the optimal quality point in terms of the "biggest bang for the buck." By investing in appraisal and prevention to achieve higher levels of quality, each dollar of appraisal and prevention now yields more than a dollar savings in failure costs. Schneiderman then goes on to show how understanding this relationship can promote radical improvement rather than incremental or continuous improvement that often arises from dollar for dollar justifications for quality improvement activities.

3.4.3 High-clockspeed

Dell's business relies on velocity. First, Dell relies on the velocity of technological change to promote new products more often and with cutting edge technology. Second, Dell relies on the velocity of its fulfillment process to deliver product in the predetermined lead-time (usually five days.) Finally, Dell relies on velocity of its raw materials through its pipeline to protect itself from inventory depreciation and to take advantage of its cash conversion cycle. Organizationally, Dell has a culture that promotes speed – top down management, strong problem solving, and a highly networked workforce.

Fine [6] coins the term clockspeed to address the speed at which companies and industries change in terms of product, process, and organization. Dell's clockspeed by Fine's definition is fast. While much of Dell's product, process and organization fit the model that Fine puts forth, it also places roadblocks to the very aspects that promote quality improvement. First, with a fast clockspeed, the time horizon over which continuous improvement and quality investment can achieve a return on investment is shortened creating a higher internal hurdle rate. Second, Fine stresses the importance of concurrent engineering along each of the three dimensions to support a fast clockspeed. However, with a faster clockspeed, gaining knowledge, transferring knowledge and then again meeting the hurdle rate required by the company can become an insurmountable task.

3.5 Populating the Defect Cost Model

The results of the new cost model framework are given in Section 4. Key cost data are first required, in order to populate this cost model. The following sections describe the aspects of these cost drivers and the associated cost calculations. Based on these, a lookup table is populated with the data and the proposed cost model results are identified.

3.5.1 Products

Each product within servers and storage is first documented. Each product belongs to a product platform that in turn belongs to a designated group based on product line. Servers, for example, could be grouped by Dell's two major product lines: PowerEdge® and PowerApp® servers. Storage, in turn, could be grouped by whether disks or tape were used in addition to other designators such as how the product interfaced with a network. Several levels of hierarchy would allow future cost model development to aggregate defect costs along several designations: product, product family, or product line.

3.5.2 Prices

Product prices can vary depending on customer chosen configurations. Base prices per product are instead obtained using Dell's published price lists. Base models are the most basic product configuration upon which options can be added. Product price is then used to estimate the revenue generated by shipping product from the factory. Component prices are also required to estimate quality related inventory costs and scrap costs. Dell's raw materials depreciate quickly which is why the pull system has so greatly impacted Dell's financials. However, since material cost does indeed change so quickly, only current prices are maintained. Without historical prices, aging inventory in Dell's pipeline is difficult to price exactly.

3.5.3 Volumes

Product volumes are required for several reasons. First, it helps determine the proper assignment of expected values. Second, it helps weigh any averages that will be calculated, and third, ultimately, Dell speaks in terms of cost per box defects per hundred units and any marginal costs will ultimately be compared to these units which include volume.

3.5.4 System Routings

As systems move through the factory floor, as seen in Figure 6, a series of routing positions are assigned. Most routings are associated with a physical location such as kitting, the build cell, or test. Other routings may give conditional information such as a system that is in test but is awaiting service or a system that is in EMR but is waiting to be rerouted. Routing positions guide much of the data reporting used for DPHU and cycle time reporting.

3.5.5 Component Routings

If EMR replaces a component during system service, the component will then be dispositioned and placed either in failure analysis, scraped or returned to the vendor. Component routings re used to calculate the value of each inventory contained in each "room" within the factory (each room associated inventory with raw materials, work in progress, the MRB, EMR, etc.) and also helps track the value and number of inventory destined for FA, scrap, or return.

3.5.6 Process Times

The process group maintains engineering standard times for all factory floor processes. Standard times are used to associate labor times with each process. These times are average times that take into account variation due to a wide variety of customer specified options and normal sources standard time variation. Normal variation can be attributed to fatigue, inexperience, etc. Nonetheless, the factory's capacity model runs off the standard times and thus the standard times were used for this project.

3.5.7 Test Times

Server/Storage test includes a simple "quick test" which checks for basic system assembly, functionality and connectivity and a group of extended tests which is called "burn." Referring back to Figure 6, test times per product exist for quick test and for each of the four sub-sections of burn: DOS-based tests, Windows-based tests, software download, and final test. QT generally lasts about 10 minutes while burn can last anywhere from about a half hour to many hours depending on the system complexity and software.

3.5.8 Labor Costs

Finance maintains the labor standards. Both burdened and unburdened rates exist. The former is used primarily when headcount reduction or reallocation to a different department is possible. Otherwise, the unburdened rate is used, particularly in factory capacity modeling. Unburdened rates helped represent more efficient use of labor, not necessarily headcount reduction. Labor rates are slightly higher for EMR and FA due to their expertise and their average seniority.

3.5.9 EMR Cycle Time

Since EMR associated labor is considered the major cost component associated with factory defects, EMR service or cycle time is required. EMR has average service times and equivalent service times per product. Equivalent service times are calculated by normalizing product service times by the average. These times can be as low as half the average for a few of the more simple products to almost three or four times the average. EMR technicians have a quota of some number of equivalent systems per day. The average service time for all products is used as a benchmark to evaluate service performance on all other systems.

3.5.10 EMR Hits and Repairs

EMR data has a wealth of information, albeit noisy, about defects. EMR data categorize repairs by:

- type - commodity replacement, repair a workmanship error, reseat or reconnect cables and components, etc.
- fault - Dell, vendor, or no assignable fault (unofficial, FA officially assigns fault)
- test from which the system failed to EMR - quick test, DOS testing, final test, etc.

EMR data are the foundation for DPHU reporting and analysis and drive much of the product engineering group's daily activities.

3.5.11 Commodities Replacement

EMR commodity replacements are tracked to their final destination. The commodity profile is used to help support a commodity based approach of attacking defects, helps uncover lower valued commodities that have a large dollar impact due to their relative percentage, and to helps address any systematic defect mechanisms.

3.5.12 Commodity Destination

Certain commodities do not have either the volume or price associated with it to make further diagnosis worthwhile. For others, FA capability or support do not exist and they are returned to the vendor for FA. Others are automatically routed to FA. The ultimate fate of commodities determine who bore the cost. To clarify, commodities could be scrapped (a cost to Dell), returned to vendor (a cost to the vendor), or returned to the flow (generally negligible inventory holding cost).

3.6 Data Mining and Analysis

Once the above dimensions of analysis are determined for the proposed cost model, data mining and analysis occur. There is a variety of manufacturing IT tools and associated manufacturing reports that facilitate data mining. However, data integrity becomes an issue that data analysts must grapple with in addition to shortcomings of the IT tools.

3.6.1 Manufacturing IT

Many of Dell's IT tools, like most manufacturing companies, are homegrown applications that are built around the specific information needs of a company or department. While these systems have been highly optimized for certain needs, many gaps exist both in the data each system obtains as well as the data that is shared between tools. Nonetheless, Dell has placed itself at the forefront of IT development with its strategic use of ERP software for inbound logistics and has plans to further integrate its information systems and value chain. The following list describes the IT systems employed for data collection

- DOMS – Dell's order management software is the initial portal into the factory. Sales representatives enter system configurations (the base model plus customer defined options) and order quantities. Any illegal configurations are caught only if specified by DOMS.
- Factory Planner – Dell employs i2's factory planner ERP software. Factory planner downloads DOMS information and first checks the SLC for part availability. Factory planner runs every two hours to pull required raw materials from the SLC and to schedule orders and systems for the factory.
- Glovia – Dell's inventory control system not only tracks inventory levels but also inventory rooms, piece part costs, and SKU information.
- WTCS – WIP (work in progress) tracking and control system that tracks systems through the factory primarily based on routing positions. Operators annotate failures and repairs by entering comments to WTCS comments field.
- DPS – Dell's product support software is the main software used for customer support. Although most of the relevant data pertains to customer, order, and system information, it also contains information on inventory that either gets associated or disassociated with an order. This helps track commodities with prior failures or that that have several intermittent failures that never result in a hard failure. Dell closely monitors this marginal material and removes it from raw materials when repaired material fails or when intermittent fails have been observed three times.
- BROMs – Dell's burn rack order management systems helps track and prioritize systems within the burn-rack. BROMS notifies operators of failed systems residing in the burn

rack that need to be routed to EMR and creates a priority system for EMR routed systems based on order quantity associated with the system, system age, and other factors.

- AGT – Automatic Green Tag software creates a tracking code and entry for all parts that are pulled from production and that require disposition. AGT tracks where commodities are routed while in disposition and tracks failure responsibility (Dell, Vendor, or Cannot Duplicate).

3.6.2 Manufacturing Reports

A flurry of manufacturing reports occurs on a daily, weekly, and monthly basis. Each group has several data analysts dedicated to running reports, maintaining databases, and scrubbing data for use by the factory associates, engineers, and management. BRIO, a tool that creates a graphical user interface (GUI) to the databases, facilitates much of the data extraction as opposed to cumbersome structured query language (SQL) queries. These databases are usually divided into historical data and current manufacturing data. The data have integrity issues with which the data analysts are intimately familiar. Many of their pre-analyses involve addressing these issues.

3.6.3 Data Integrity

WTCS tracks the diagnostic fail code created by the various tests run during production. For purposes of tracking defects, however, the diagnosis only specifies what component the test is targeting and does not necessarily correlate to the failure mode. The build and EMR associates enter the fail code that WTCS reports use. Several issues arise here. EMR technicians comment failures to varying degrees and may choose from a wide variety of similar failure codes available from the pull-down menu provided. This discretion also creates differences between operators. Different operators may describe the same defect differently. Finally, only one fail mode can be described, so if a system undergoes several repairs, only the last repair is recorded. WTCS works mostly off routing information, so data analysts must also decipher historical routings of a system through the flow.

3.6.4 Data Analysis and Tools

The data analysts helped provide a majority of the data that are used for the project. The most prevalent data analysis tools for both reporting and for this project include:

- P-charts – used as a base line for the project to compare project results to the current approach to quality improvement.
- Simple average – the expected value or true mean of a sample distribution.
- Weighted average – averages are also calculated by weighting factors including percent population and percent occurrence.
- Median – the mid-value of a density to check if the density is symmetrically weighted.
- Standard deviation – to check the spread of the distribution.
- Pareto analysis – charts which address the relative frequency of the arguments to identify a prioritized order of issues.
- Cumulative plots – charts which show how successively ranked arguments contribute to the total population.
- Decision tree and expected value – a node network of possible decisions or outcomes and related probabilities to help compare decisions (or possibilities). An expected or weighted average value of all possible outcomes can also be calculated.

Both Brio and Microsoft Excel provide the statistical functions and manipulations to perform all of the above analyses.

Three quarters worth of data are analyzed which address the current fiscal year through the end of the 3rd quarter. Initially, a robust cost model using yield analysis was investigated. Populating this model using the above data sources and tools drove an in-depth study of what quality factors drive costs, an external study of how defects impact other organization and stakeholders, and the relative frequency systems that fail repeatedly or after all completed tests. As many of these second order effects were negligible compared to the first order effects of systems that fail once and fail into EMR from burn and quick test, the final yield analysis diagram is presented with the tactical results in Section 4.

4 TACTICAL RESULTS

The final cost model evaluates the first order costs related to labor, inventory, and cycle time. First order costs help to bring attention to the magnitude of the problem of internal defects. The value of knowing this cost, however, come from translating the results to key learnings and recommended actions.

Section 3 provides the building blocks for the proposed model. The manufacturing flow determines where defects can occur and whether a system or component from a defective system. The associated costs are incurred when:

- Systems are serviced by EMR (labor costs)
- Components are scrapped (inventory costs)
- Systems are shipped late (cycle time costs)

These costs are also related to metrics such as DPHU and STT. Total costs for an average per incident defect are given using the three costs associated with defects. This marginal cost divorces defect costs from the average or CPB. In doing so, the true magnitude of internal defects can be understood. Once the total costs are reported, the implications and recommendations to the factory are given.

Figure 10 is provided to illustrate how the manufacturing flow incurs these costs and whether the manufacturing flow is concerned with systems or with individual components. Solid lines track systems through the factory and dashed lines track components. The flow also brings attention to another aspect of the cost model that will be fundamental to understanding the strategic importance of defects. Defective systems can potentially belong to an order. The order accumulates in burn waiting for the defective system. While cycle time plays a minor role in the discussion of the tactical results, it has resounding influence on how manufacturing should attack internal quality both within its factory walls and upstream with its partners in design, procurement, and with its vendors.

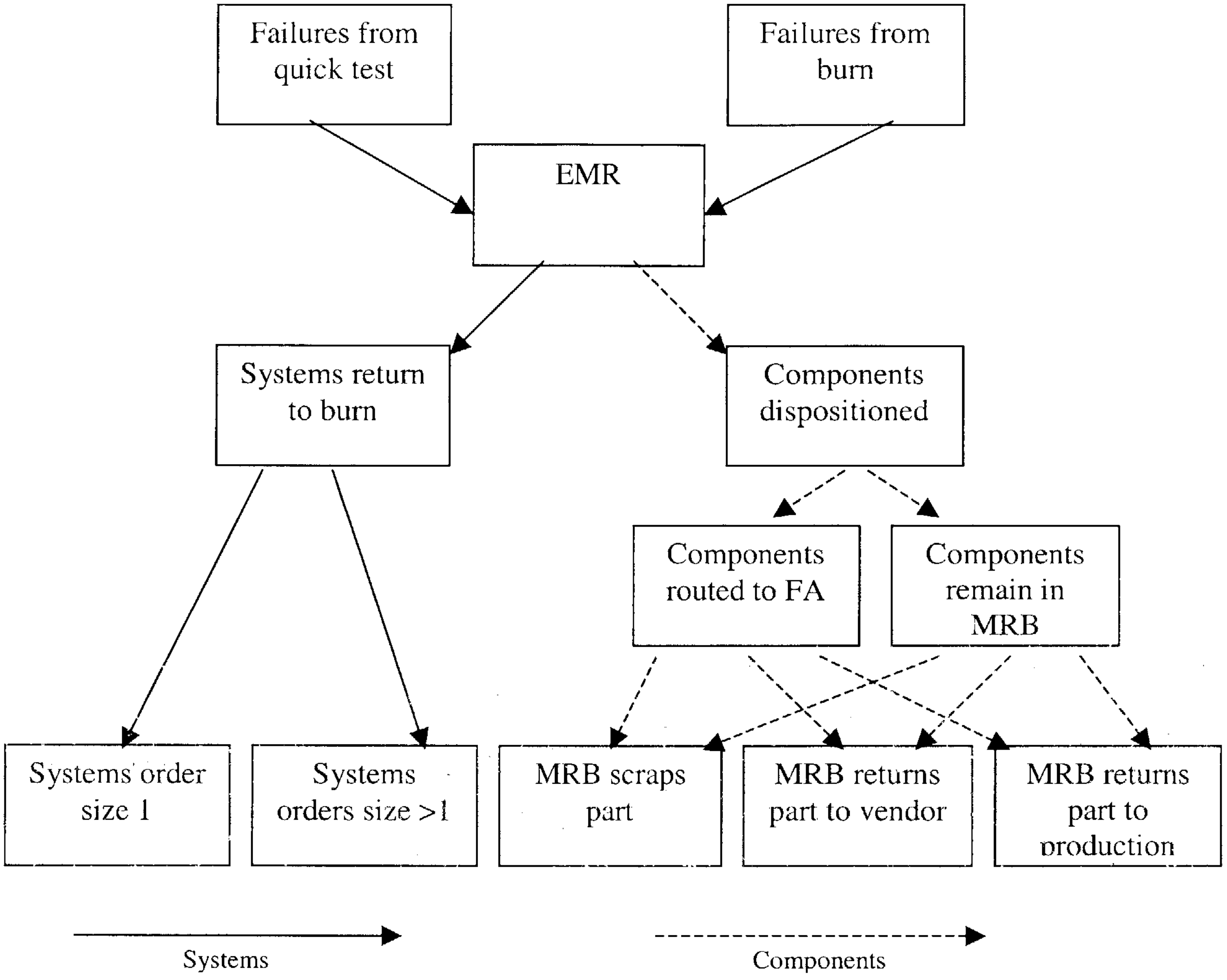

Figure 10. Final cost analysis yield diagram

4.1 Labor

Labor costs are incurred when a system is routed into EMR. The product of the EMR service time and EMR labor costs yields the labor cost per system. Since a significant reduction in DPHU is required to reallocate EMR heads to other positions within the factory, the unburdened labor rate is used. Although EMR service times rely on WTCS routing positions in and out of EMR, EMR management has carefully scrubbed data to remove data integrity issues such as nights, weekends, breaks, and end of shift. This average time is used to calculate the labor component for the average per incident cost of defects.

For the three quarters, Figure 11 shows how the volume weighted DPHU values, the traditional approach to defect control, correlate to the percentage of total labor related costs as obtained from the proposed cost model. A scatter plot of these pairs of data along with a best-fit line obtained from linear regression yields an R-square value of less than 0.2.

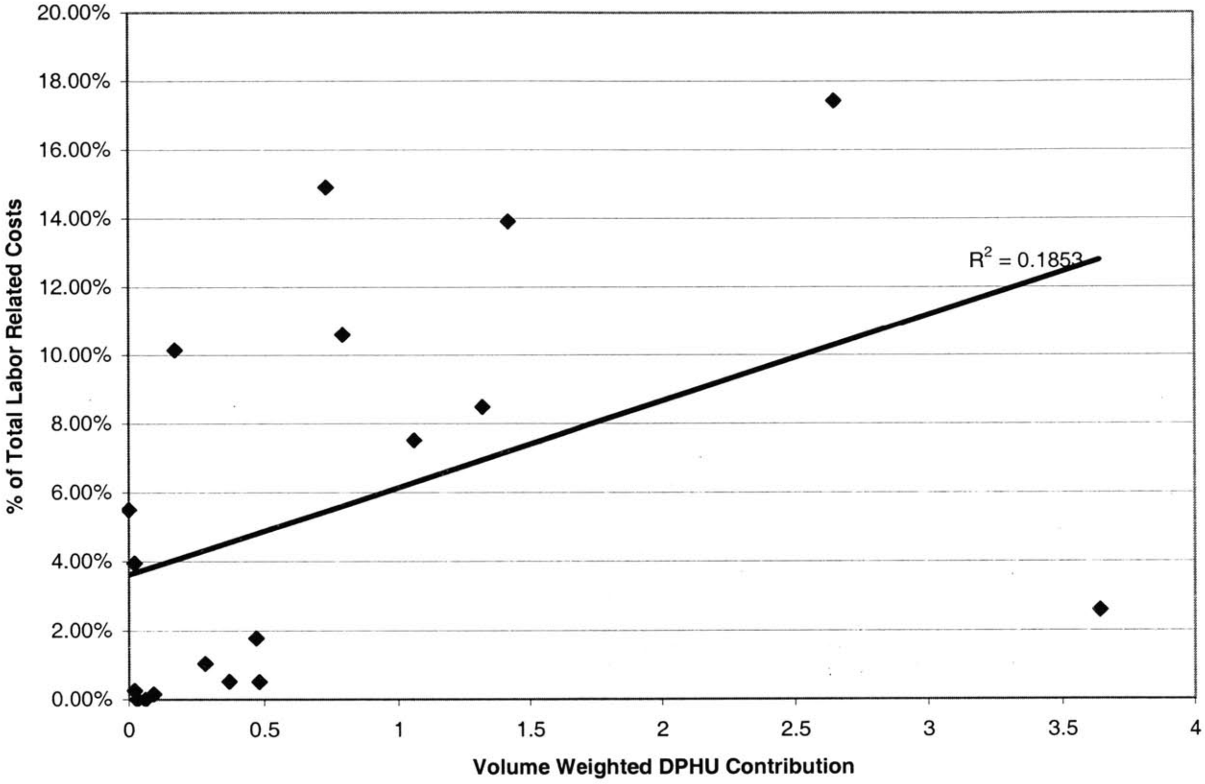

Figure 11. Correlation of Volume Weighted DPHU and Cost via EMR Labor

DPHU, therefore, is not a significant proxy for labor cost. Although cost is driven by the EMR labor associated with DPHU, labor cost is a combination of service times and the absolute number of units that flow through EMR. EMR is already tasked to bring service times down across the board. However, with limited factory resources, evaluating drivers of relatively long EMR service time and products with large absolute numbers of systems requiring EMR service will provide the most direct benefit to reduce total labor costs.

This example is one of several that show how a metric such as DPHU that is useful for management purposes can be less useful if not misguided for management decision-making. DPHU is a worthy data point in the general health of either a product or the factory, but is less useful in directing resources and valuable engineering time.

EMR also addresses the repair type for a system. Many repair codes exist, but the most relevant are *replacement, process, general, connection, CND* and *workmanship*. Replacement refers to at least one component being replaced and routed to MRB for disposition. Process and workmanship refer to Dell specific issues. *Connection* is related to package pins, wiring, and other various connections made between components. *General* includes false failures. Figure 12 shows a pie chart with the relative percentages of the repair categories for the three quarters worth of the EMR systems. Section 4.2 will address the largest portion, replacements, by following replaced commodities through MRB to their final destination.

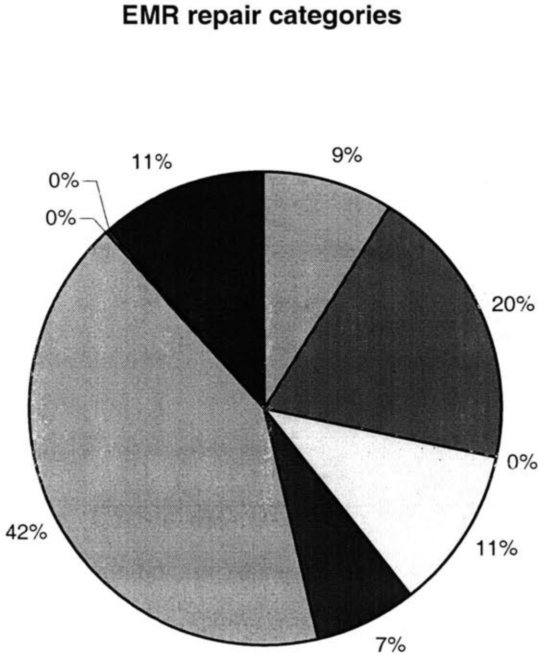

Figure 12. Relative contributions of EMR repair categories for all EMR systems

4.2 Inventory

Dell's inventory turns are testament to the rapid pace at which Dell processes both productive and unproductive inventory. Productive inventory is converted from raw materials to product, usually with a five-day turnover period. Unproductive inventory primarily resides in MRB awaiting further disposition.

MRB monitors its total inventory as well as its inventory for specific commodities. End of quarter places specific pressures on MRB to move inventory to its final destination as shown in Figure 10: scrap, return to vendor, or return to flow. Scrap occurs for commodities whose cost does not reach a threshold value. This threshold can apply to either a single piece part, or the total value of a commodity residing in MRB. Scrap also occurs for material damaged by Dell that is either irreparable or does not have vendor support for repair. Return to vendor occurs for parts that are vendor damaged either at the supplier's factory or during shipment. Return to flow occurs for parts that failure analysis deems cannot duplicate, or CND.

Since MRB has a similarly fast inventory turn for returns, the inventory holding costs and associated labor are not included in the inventory related defect cost calculation. Instead, only scrap is considered for the average per incident cost. Figure 13 shows a Pareto of scrapped commodity values for the three quarters. 90% of the total scrap value is associated with the top four commodities.

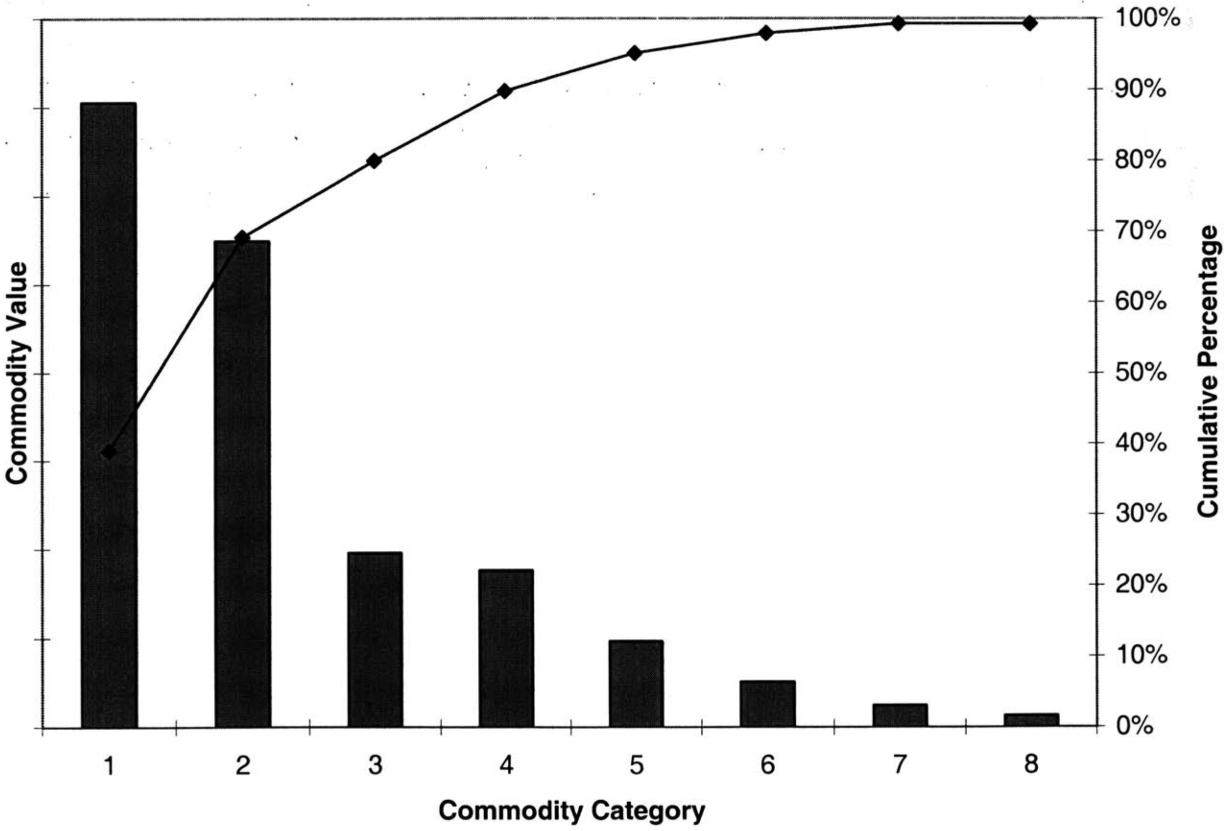

Figure 13. Server/Storage Scrapped Commodity Pareto (in relative $)

The reported values and Pareto are pulled from the AGT tool. To emphasize this total scrap value in terms that other disciplines can appreciate, the total server/storage scrap is also translated to days sales inventory (DSI). DSI represents the total value of raw materials that are converted to production during a day. Over 18 DSI worth of inventory has been scrapped as of the end of the 3rd quarter.

The top four commodities can largely be addressed through improved handling and processes. Handling issues occur in the kitting area as well as build. Processes also address dropped systems and components, dings, scratches, and other stresses and damage. While this addresses Dell induced damage, the failure analysis rate must also be addressed. Failure analysis cannot fiscally support all commodities nor could it in a timely manner, but should strive to achieve 100% for these top four commodities.

Now that replaced commodities have been traced to scrap, the fate of systems exiting EMR need also to be addressed via cycle time.

4.3 Cycle time

Cycle time impact was originally assumed to be purely a matter of cost of capital. Delayed orders accumulating in burn awaiting systems that have been in EMR mean delayed revenue. Some of the server and storage products retail in the thousands and in the tens of thousands of dollars. Cost of capital, around 16% annually for Dell, is calculated from the order cycle times that exceeded one-day due to defects. Section 2.7.2 has described how STT allots the factory one day from traveler pull to ship.

The factory rarely violates this time allotment. Figure 14 supports this assertion. The server/storage facility has maintained close to 90% compliance to this metric. Average cycle times reports that are published on a weekly basis also paint a similar picture. A more careful look at how DPHU drives cycle times variation points to a different story; revisiting Figure 14, the long tail is of interest.

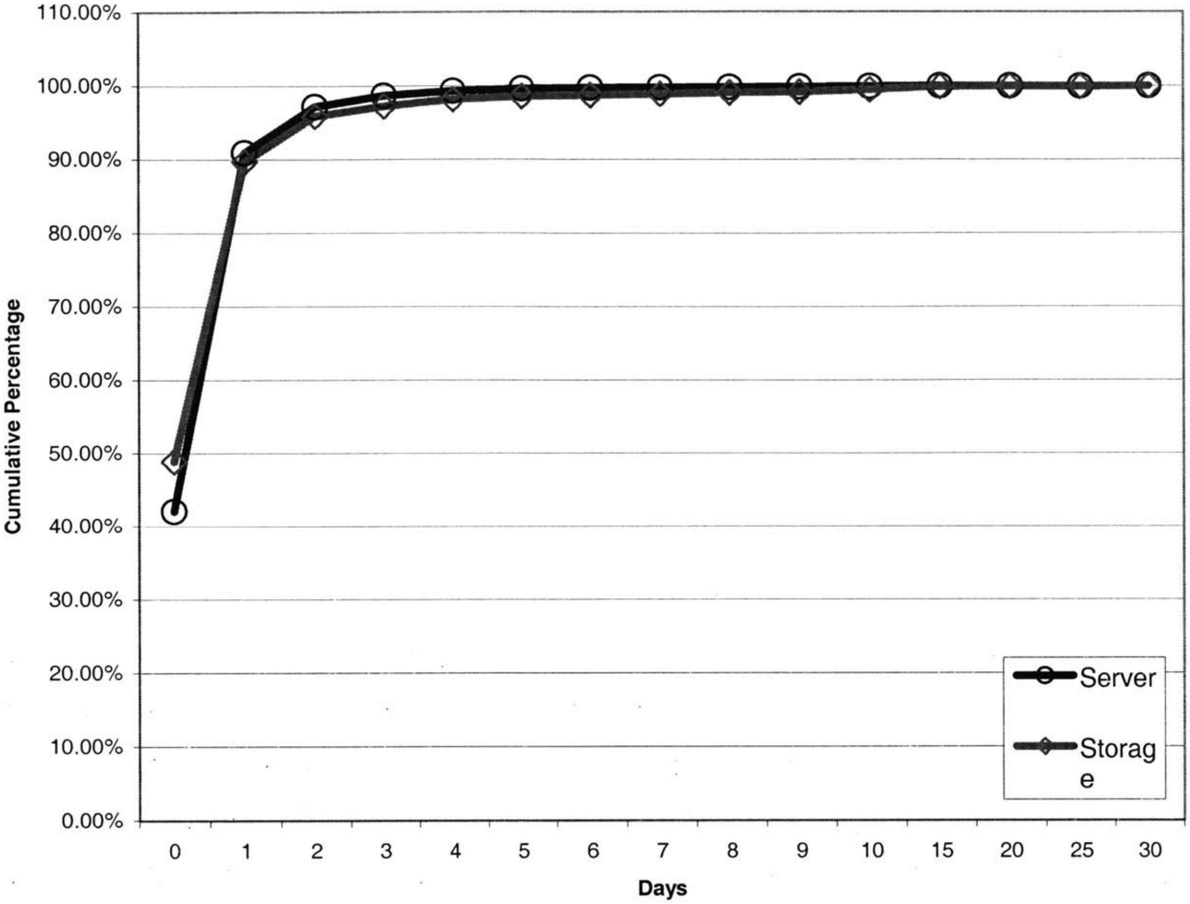

Figure 14. Dell STT metric compliance

Cycle time for orders with and without at least one system failing into EMR is analyzed in BRIO. The analysis shows a drastic order cycle time variation between the two samples. Due to accumulation in burn, orders that have systems that fall into EMR are impacted by the exception flow cycle time. The exception flow includes time until a burn or QT operator recognizes a failure and routes the system to EMR, system time in the EMR queue, EMR service time, and subsequent rerouting to burn. A virtual DPHU is calculated for each product line that indicated how many systems are impacted in this way. Figure 15 shows how this difference arises.

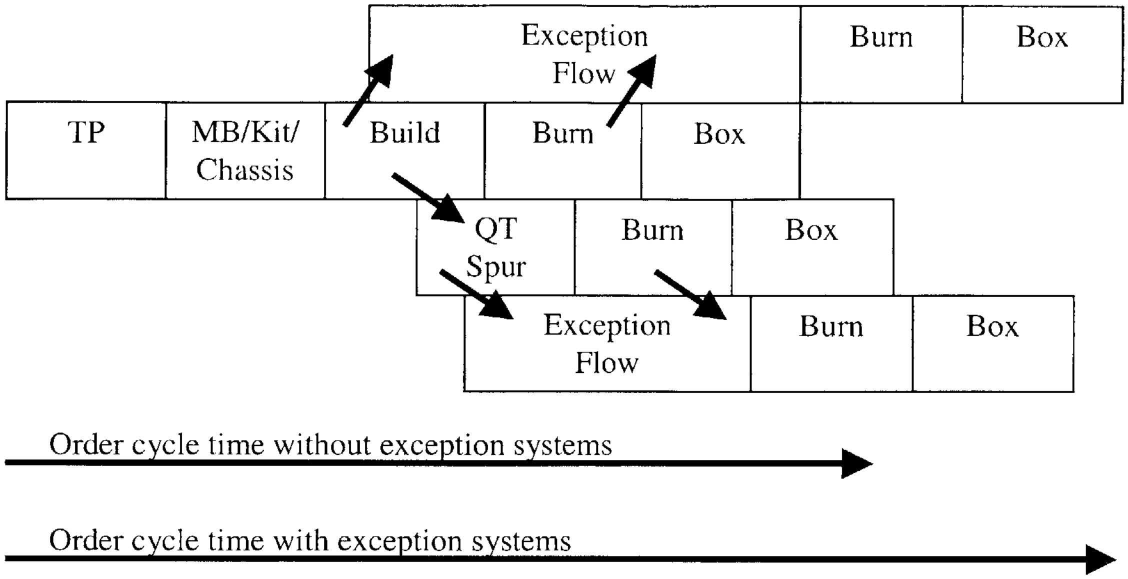

Figure 15. Order cycle time variation

Systems flow right from TP (traveler pull) through to box. In some instances, systems are pushed out of the build cell and QT is performed at the end of line QT spur. This is the first potential time delay that is introduced since build verification is now performed separate from the builder. Builders eventually receive feedback on build related issues, but it does not happen instantaneously as it would if the builder himself performed the QT. Systems can fail into the exception flow from QT within the build cell, from the QT spur, or from burn. The later in the test sequence the systems fail, the more the entire cycle time is impacted. The order cycle time is as long as the longest system cycle time.

While DPHU generally ranges from the 1's to 10's of percent, virtual DPHU, the number of systems impacted due to orders with at least one exception system can reach upwards of 30%. Cycle time is impacted by several hours for each product, enough to represent a shift delay (if the defect occurred during 1st shift) and a day delay (if the defect occurred during 2nd shift). The velocity of the order, not individual systems, determines the impact to revenue and STT.

Since STT as metric is rarely violated, cycle time is largely considered to be a process that is under control. Average cycle times, which are weighted heavily by systems with no exception flow processing, also fall into a reasonable range for the factory. It is only the examination of the variability that uncovers a strong relationship between cycle time variation and defects. The impact, though in the 1's of dollars in terms of cost of capital, is huge in terms of its effect on ship to commit, as discussed later in section 5.3.3.

4.4 Total Cost

The total cost per defect takes each of the three categories: labor, inventory, and cycle time and calculates an expected value for defects. The expected value is the weighted costs associated with all system and component related issues from Figure 10. Table 1 reviews each cost contribution, the cost calculation, results, and relevant notes.

Table 1. Summary of cost contribution calculations for average per incident cost of poor quality

Cost Categories	Cost Calculation	Data Sources	Data Analysis Notes	Relative Dollars
Labor	average EMR service time * unburdened labor rate e.g. 2 hours* $10/hour = $20	WTCS, EMR management, finance	EMR labor receives a premium labor rate compared to other associates	10's of dollars
Inventory	Weighted sum of commodity costs calculated by sum of : average cost per commodity * percent of AGT inventory the commodity represents e.g. $100*40% + $50*45% + $2*15% = $58.30	AGT, Glovia, production control	Median scrap values greater than mean scrap values per commodity barring processors. Thus, average scrap is a conservative estimation of the inventory contribution to cost.	10's of dollars (about twice the cost of labor)
Cycle Time	Weighted sum of delayed revenue for products whose exception flow cycle time exceed 1 day calculated by sum of: # of days revenue is delayed * cost of capital * product base price e.g. 1 day * 16%coc*$10K = $4.50	WTCS, production control	Only products whose exception flow impact cycle times exceed 1 day were use. This value is conservative compared to all delays that exceed a shift which could delay revenue. Base price is also conservative.	1's of dollars

4.5 Implications for the Factory

The analysis to find the average per incident defect cost helps to address the nature of quality control within the factory. The following sections address several recommended quality control and improvement activities within the factory and the implications this analysis has on how best to reduce cost related to defects and poor quality.

4.5.1 Relation of DPHU and Cost

The most important result of the project is to underline the nature of DPHU as it relates to cost. Products, which contribute most to factory DPHU, draw most of the factory resources focused on quality. Not all defects are created equal, however. The labor analysis shows that DPHU does not drive EMR costs in isolation. The EMR service time must also be considered. Thus, a combination of product complexity and product volume drive the labor related defect costs. The inventory analysis shows that scrapped commodities impact cost not just through the relative number of replacements but also through the average commodity value. Scrap value is managed as a separate issue and had not been previously tied back to EMR hits. Finally the cycle time impact of defects also is a novel approach to estimating defect costs.

The impact of DPHU had also never been understood at a marginal level, but rather only through average costs as calculated by cost per box. Cost per box dilutes the cost impact that defects create by distributing quality related costs across all units of production. While ultimately sales only requires the average, or CPB, value to decide pricing and quantity strategies, the factory can best attack the costs related to DPHU through the cost contributions highlighted by this analysis. A few factory centric recommendations also arise.

4.5.2 Recommendations

Although the new defect cost model provides a per incident cost, its contribution comes more readily from the guidance the model's framework provides as to how to most effectively push the factory frontier related to cost and quality.

Low Hanging Fruit - Several of the cost contributions point to areas of improvement that can impact total quality related costs significantly. Reviewing the significant drivers of cost, the recommendations include:

- Inventory or scrap related to defects was twice that of labor and should be thought not as a separate operational cost but a cost inherent to poor internal quality. Dell induced defects comprise half of the scrapped commodities' value and are largely due to handling issues as reported by FA technicians and supplier quality engineers. Minimizing touches, promoting proper handling at all times, and processes and packaging, which insulate these commodities from mishandling opportunities, are required. Furthermore, 90% of total scrapped value is addressed with four commodity types. This Pareto should promote commodity centric focus teams in addition to those that already exist for high DPHU related commodities.

- EMR cycle time – as this time impacts both cycle time costs and labor costs, EMR bears a large burden to reduce times across the board. EMR has limited control over several of the factors that make up the exception flow. The only ways in which EMR cycle time can be explicitly reduced is by tearing down failing systems and pulling another system, by having EMR technicians work faster, or by preventing defects from failing systems into EMR. The first requires additional touches which has been linked to commodity damage; the second promotes commodity replacements for a quick system turnaround, which can lead to scrap and to unproductive inventory, and last requires the factory to continue to control factory related issues but emphasizes the need for radical improvement upstream for design and vendor related defects. The final recommendation is of strategic importance is expanded in Section 5.

Failure Analysis - Appropriate failure analysis both at the EMR system level and at the FA commodity level has two major areas of improvement:

- EMR technicians have nothing more than their vast experience and a few process flows to trouble shoot potentially complex systems and inextricable problems. Providing EMR with appropriate diagnostic tools can help reduce system service time as well as reduce the potential for unnecessary commodity replacements that can lead to scrap and unproductive inventory.
- The analyses that occur in EMR and FA need to provide more real time feedback to builders and other associates. This feedback is also of value to vendors and designers. Much of this dialogue occurs, however, after vendors have been chosen and after the design have been completed. The need for further acknowledgment of the factory's role in concurrent engineering is required corporate wide at both a tactical and a strategic level.

Resource Allocation - The new product-engineering role has the intent of integrating the roles of product introduction with quality engineering to create a more potent engineering resource to affect design. Ironically, factory quality has drawn the engineering resources more closely to the factory. In conjunction with the model results and the low-hanging fruit, the thesis recommends:

- Within the factory, resources can better be aligned with products and commodities that drive costs instead of purely along their DPHU impact. The sporadic variation that is inherent to the DPHU metric creates "fire fighting" that drains a significant portion of the product engineer's time that is not value added in actually reducing DPHU, much less defects themselves which drives costs.
- In addition to ensuring customer quality issues do not escape the factory, product-engineering resources are best directed at driving DFX related quality improvements. In line with the EMR recommendation, defects must be prevented to effectively reduce the factory-incurred costs related to quality. This recommendation is also included in the strategic discussion that follows.

Process Engineering - The project has attempted to work with the process engineering capacity model to attribute capacity related costs to defects. The capacity model is found to have a fudge factor that includes typical issue such as breaks, fatigue, and downtime that also incorporate defects. Defects are not explicitly addressed in the capacity model since the build cell is the designated factory bottleneck and the exception flow allows systems to be expelled from the normal factory flow to prevent failing systems from impeding non-failing systems in the build cells and in the burn racks. This dynamic begs two recommendations:

- Process engineering should not only concentrate on system velocity, but also on the exception flow cycle time. Regardless of how fast a system can make it through the flow, failing systems in the same order are the bottleneck for order delivery.
- Factory dynamics are significantly impacted by failures and EMR capacity. The capacity model should continue its efforts to integrate EMR headcount and cycle time into the overall factory capacity model to note impact the system level impact failures have to the factory.

5 STRATEGIC IMPLICATIONS AND RECOMMENDATIONS

The prior section discussing tactical results and recommendations made several references to the strategic impact of how defects and their costs are addressed as well as the role of the factory in driving quality improvements upstream. These strategic implications are explored more fully in this section and are followed by related recommendations.

5.1 Understanding the Nature of Cost of Quality

Cost of quality is a daunting task. While this thesis proposes a new first order defect cost, the model requires looking at costs at a much deeper level. Although it helps to bring intuition to how costs are generated, a deeper look at quality costs often does not constitute the dollar values that would seem to justify quality improvements. Quality related costs are often controversial (different stakeholders place varying values on quality issues), are soft (either related to cost avoidance vs. cost savings or cannot be assigned a dollar amount), or are not currently captured by IT tools or metrics.

In addition, Dell's business model places a tremendous hurdle in front of a "business case" approach to internal quality improvement. By performing simple, ROI analysis, again, the cost of obtaining quality will rarely justify the improvements. Dell's business model, which provides 800% return on invested capital, creates a huge window for viable internal rates of return, but it also skews expectations on return well away from the 16% cost of capital. Understanding how quality related costs are incurred can help guide resources to most efficiently affect transformation and warranty costs, as demonstrated by the tactical implications of the project. Furthermore, cost analysis shows that defects are less costly when caught upstream and when quality is approached at an enterprise level as demonstrated by the rule of 10's and by concurrent engineering as discussed below. But dollar values signify only a portion of the total cost of quality. Quality can impact strategic plans, can tarnish brand, and drive lifetime costs that undermine Dell's strategic advantage but to which it is difficult to assign dollar values.

5.2 Sources of Quality Issues

A careful examination of where quality issues can be stemmed identifies many areas outside of the factory's influence. These sources include:

- Design changes – the high-clockspeed often drives changes to the last minute and design changes often occur after vendor component development and factory qualification. These changes create new opportunities for quality issues as the components may not have been fully tested or new specifications are not clearly communicated to the vendors.
- Vendor changes – vendors may source from different geographies based on internal capacity needs to or to meet Dell's cost reduction requirements. Changes usually create a spike of quality issues within the factory as the new geography usually faces a learning curve to bring quality up to the prior source's levels.
- Procurement – procurement makes many sourcing decisions concentrating on design as its primary stakeholder. Cost is the most overriding of these concerns despite the attempts of using balanced scorecards.
- Customer – the customer is priority one at Dell. As such, many of Dell's processes and products are centered on satisfying the customer. In the case of servers and storage, this results in an explosions of SKU's, product proliferations that builders must learn, the number of configurations that should be qualified, and other manufacturing complexities. In addition, an 80-20 rule holds where 20% of the configurations represent 80% of the volume.

The factory, which deals with the brunt of this quality burden, is in an inextricable dilemma by being both the catchall for defects and the champion of quality. With little monetary ammunition and limited influence on many quality issues that impact their quality levels, the factory role as a quality champion should be readdressed.

5.3 Readdressing the Role of the Factory

The factory has a wealth of knowledge and experience with defects. Without the proper outlet for knowledge transfer and the equal weighting of factory concerns with other disciplines, the factory is limited to continuous improvement of its own costs and quality. Factory costs contribute to Dell's bottom line directly as it is the foundation upon which Sales and Marketing establish pricing and sales goals. Factory quality also contributes to Dell strategically in several ways including being later in the value stream in regards to the rules of 10, of possessing the knowledge base to practice further concurrent engineering, and in other strategic initiatives at Dell including ship to commit.

Dell must recognize the strategic importance of transferring knowledge effectively from the factory upstream towards design and vendors. The factory must be allowed not only a voice but also the power to create change in when DFX is addressed and with how vendors are selected.

5.3.1 Rules of 10

Many attempts have been made to correlate in time external defects with internal defects. While that proves useful to predict warranty issues and cost, it disregards an even more important relationship – the rules of 10. Referring back to Figure 8, quality improvement literature for decades have shown how costs decrease by an order of magnitude the further back in the value stream defects can be contained. The average per incident cost of a factory defect is on the order of 10's of dollars compared to the per incident cost of customer or warranty defects which is on the order of 100's of dollars.

Two recommendations arise from this relationship. First, warranty costs can be significantly reduced by identifying quality issues that arise before the first knee of the bathtub curve and by catching these issues in the factory. This includes identifying factory escapes for time-zero failures as well as early lifetime failures that can be captured through traditional production reliability tests including accelerated lifetime stresses. Likewise, factory costs can benefit from capturing design and vendor related defects upstream via appropriate factory knowledge transfer and concurrent engineering.

5.3.2 Concurrent Engineering

Fine's clockspeed model stresses the importance of concurrent engineering in overcoming the hurdles prescribed by high-clockspeed. Often attempts for design for assembly, manufacturability, etc. (DFX) face defeat themselves by being delayed until the design has matured at which point many DFX changes cannot be easily justified economically. High-clockspeed only exacerbates the issue. Dell's rapidly increasing pace of product development and decreasing development times will only push DFX further away from incorporation.

DFX must be concurrently engineered and placed as an initial priority with design so that the necessary accommodations can be absorbed into the system design.

5.3.3 Ship to Commit

Although the cycle time impact to products costs is smallest of the three contributions, it has a large impact to Dell's strategy. Many people both external and internal to Dell have questioned Dell's ship to target logistics strategy. Value can be extracted from the market by segmenting it into customers with precise lead-time requirements and charging accordingly. This logistics strategy, called ship to commit, has become the next nirvana for Dell. It requires further integration and innovation of its already cutting edge supply chain. What it also implies is that order fulfillment now has a market value, and delays to orders due to defects can no longer be absorbed as it was by the STT metric.

To resolve the issue, EMR can make marginal service time improvements. This service time, however, is small portion of the total order cycle time impact. The most efficient way to control the ship to commit related cycle time impact is to prevent defects from occurring in the first place.

In summary, the factory will continue to protect the customer from quality issues, but it can no longer sustain the role of "catchall". Defects must be captured at the design and vendor stage not only for cost reasons but also for the strategic reasons related to ship to commit.

5.4 Reevaluating Quality

Quality at Dell is truly undergoing a change. However, that change is incremental due to the apparent burden that low-cost and high-clockspeed creates to quality investment. Referring back to Crosby, it is quality that costs nothing, and only noncompliance that costs. Likewise, this thesis shows how low-cost and high-clockspeed in fact do not prevent quality investments but emphasizes the dramatic need for it.

5.4.1 Branding and Competition

Dell's former president and COO, and current vice chairman, Dr. Vanderslice, has been a primary champion to reevaluate quality at Dell. As a 33-year veteran of IBM, his extensive experience at a mature company brings along with it the many lessons these companies have already uncovered about the nature of quality improvement.

Quality is rarely a strict matter of dollars. Quality is essential, in his words, to Dell's branding and competitive sustainability. The server and storage factory manager, Perry Noakes, further explains the competitive sustainability issue by viewing Dell's competition as a much broader industry than computer and server manufacturers. Within this limited realm, Dell is indeed a leader in quality. However, when the product that Dell delivers is compared to all sources of data and entertainment, Dell is ultimately up against the likes of Sony, Disney, and Time Warner. Consumers will no longer deal with intermittent failures, reboots, and component failures that are commonplace and grudgingly accepted in the computer industry.

Dell's commitment to quality thus must transcend the customer to include its own organizations and dollars to include a quality culture.

5.4.2 Process Improvement

Lean manufacturing can be revisited to uncover several important lessons about process improvement. Continuous improvement does indeed eliminate waste and create value. Business process improvement (BPI) at Dell largely follows this approach. The business case approach that BPI encourages is meant to emphasize the cost savings associated with quality. It is often used against itself, however, based on the many examples this thesis offers as reasons why quality improvements do not readily justify the investment required. Furthermore, Dell's quality control, specifically DPHU, is in a state of vast fluctuation, not of minute process control. While quality issues remain internal, the factory bears much of the total cost, as it is mostly done through detection (DPHU) and by appraisal (product engineering, EMR, FA, etc.). Continuous improvement appropriately addresses processes that have already been fixed or controlled. Radical improvement upstream will help the factory benefit from factors that are otherwise out of their direct control, unlike workmanship. Finally, the thesis has pointed out the need for quality improvement further upstream and the need to move defects from containment to prevention. Quality improvement at Dell is primed to go from an evolution to a revolution. Radical improvement is thus an alternative path to process and quality improvement that should be embraced not only to address the importance Dell places on quality along many dimensions but also the nature of quality improvement in a low-cost, high-clockspeed environment.

Lean manufacturing also refers to a Japanese quality term – poka-yoke. While it is defined as "mistake-proofing" devices and procedures to prevent mistakes from moving further along a production flow, it has implications beyond just stopping a mistake when it happens. At best case, it prevents mistakes from happening at all. Poka-yoke can ultimately be an element of design for assembly and design for manufacturing that virtually eliminates workmanship problems. Workmanship issues will always remain a detriment to Dell's quality until this is achieved. Workmanship problems can be reduced through rules, monitors, and metrics, but they will always exist due to the limitations of training, the turnover of associates, and the very limits of humans. As Dell's cost structure has not promoted large capital expenditures on automation, a poka-yoke approach to product development is required to finally eliminate workmanship related issues.

The final process-related issue is similar to the case based comparison of Burger King and McDonald's [15, 16]. Many will argue that Burger King's burgers are better quality since the customer can configure sandwiches to their specifications and sandwiches are made to order. McDonald's, in contrast, offers burgers that are generally pre-made and pre-configured to very exact specifications. McDonald's has many process controls that create consistent burgers not only at a particular restaurant but also at any McDonald's around the world. Others would thus argue that McDonald's provides a better quality product and quality experience. Burger King sandwiches can vary between employees, shifts, and restaurants due to the process variation. Despite few obvious similarities between fast food and computing products, Dell faces a similar issue with its products, especially with servers and storage. Dell must address to what limit it will let variation and complexity drive defects within its own process given the potentially broader scope in which quality, competition, and brand can be viewed.

5.4.3 Enterprise Approach to Quality

Dell has already begun to address the lifetime costs of poor quality. At the end of this project, procurement had initiated an analysis to understand how its decisions affect warranty costs. The approach was confined, however, to lifetime costs. Again, the cost of quality is difficult to address even in a small context. Development of a corporate wide lifetime cost is an insurmountable task. A corporate-wide approach is indeed what Dell requires, but in terms of knowledge transfer and concurrent engineering. An enterprise approach also helps link the interpretation of quality, helps varying disciplines understand how local decisions that seem well justified can be detrimental to Dell as a whole, and helps devise goals and metrics that drive the entire organization towards a solution.

5.4.4 Metrics

Specifically in regard to metrics, several recommendations can be made. The first addresses the nature of distributions. Averages by themselves do not describe distributions. Distributions must also be described by the amount of variation from that average, the amount of symmetry, and even the seemingly negligible tails. The devil is often in the details, and metrics will normally only supply averages that gloss over sources of variability. From the analysis, DPHU and cycle are both shown to have as much information in the nature of the variability as it does in the reported averages. Quality related issues should address issues without subsidy by conforming material, should address variability, and should have metrics that separate management control from management decision making as the date one requires is seldom useful to the other.

Zimmerman [25] stresses that corporate cost accounting, no matter how well thought out, creates trade-offs between decision-making and decision control. Metrics, likewise, can be used to measure performance, reward performance, and guide behavior. However, very seldom are all three done equally well with a metric. Often, complimentary metrics are used to balance these requirements, but any one stakeholder can easily place emphasis on one over the other. Again, DPHU can serve very well as a monitor of factory health, but the metric itself is a poor guide in reducing cost and in resource allocation.

Furthermore, Zimmerman established the need for corporations to develop three equally weighted systems:

- A system that measures performance
- A system that rewards and punishes performance
- A system that partitions decision rights

He calls this overall system the "three-legged stool" and warns that problems occur when they are not weighted equally. The factory faces many of these inequalities. Velocity and throughput are often emphasized (or at least interpreted) to be of a higher importance than quality since that is what the factory is generally rewarded and punished for. Factory management has recognized this and is reevaluating the incentive structure to divorce it from how performance itself is measured. The factory also is responsible for cost per box and DPHU but has little decision rights over design and procurement to affect issues that are outside the. These metrics are also not valuable in guiding resources to reduce cost as this thesis has shown. This strategic implication leads to the final discussion around quality improvement – that of the organization.

5.5 Quality Organization

Total quality management and other quality frameworks demonstrate how quality should transcend an organization and should help drive organizational dynamics. Quality is indeed part of Dell's mission statement and is an element of every task; however, corporate values and metrics must also reflect the importance of quality. Cost, quality, and speed have a natural tension in every organization. Competing metrics do not suffice to keep these concerns in balance. The entire organization must embrace a commitment to quality that goes beyond dollars and metrics.

Juran's philosophy underlines management's role in creating a quality culture. This role includes communication, setting priorities, and aligning incentives along the many contingencies and stakeholders involved in quality improvement. Dell's senior management is showing a great deal of dedication and thought to this role, but the strategy should harness the entire enterprise rather than be goals associated with individual disciplines. The latter creates local optimizations and synthetic trade-offs that prevent simultaneous optimization of cost and quality.

Within Dell's factory, the responsibility lies also with the new product engineers and factory associates. Again, there is a tension between sustaining quality in existing products and improving quality for future products. While containing defects that jeopardize the customer should continue to be pursued, attacking high value added improvements within the factory and promoting knowledge transfer to the design teams and to vendors best utilize the engineering resources. Likewise, until designs include poka-yoke that eliminate workmanship problems, operators play a significant role in factory quality. With the significant turnover in operators, training and discipline is a constant battle. Appropriate incentives and clear management priorities become a powerful guide in eliciting the proper behavior as described in the section regarding metrics.

Outside of the factory, procurement and supplier quality engineers are beginning to examine the lifetime costs associated with vendor related decisions. Many of these decisions are based primarily on monetary decisions. Other issues must be addressed such as the importance of supplier relationship and supplier learning in a cohesive quality strategy. Although different vendors may have inherently different quality levels due to process control and quality management, each supplier undergoes a learning curve as it produces new products for Dell. These learning curves extend over several components' lifetimes. Dell often makes a component-by-component decision for suppliers that prevent vendors from achieving the learning that may occur for more continuous or longer lasting relationships than what Dell currently maintains. Collaborative supplier relations have repeatedly been foundations for successful quality improvement and should become an element of the balanced scorecard that tempers the stringent cost and quality schedules that Dell requires from its vendors.

6 CONCLUSIONS

Every company faces managing the tension between many conflicting goals. In particular, this thesis examines the tension between quality control and improvement and Dell's business attributes of low-cost and high-clockspeed. Dell's time to market and price-performance strategy has to be balanced with the need to control and improve quality and warranty costs, to limit design complexity, to improve reliability, and to keep quality vendors.

Quality control and improvement in such an environment has been pursued incrementally. The metric that guides this improvement, DPHU, does not have a per incident cost associated with it beyond the associated EMR labor. Furthermore, it is shown to be a poor proxy for these associated costs.

EMR labor serves as a foundation for a more extensive and novel cost model. The novel aspects of the model include:

- Unsubsidized or marginal cost analysis opposed to average costs related to CPB.
- Several new first order cost contributions not previously attributed to defects directly, namely scrapped inventory and cycle time.
- Analysis in terms of cost as well as in terms of customer and factory metrics.
- Justification of radical improvement in addition to continuous improvement.

The significance of the per incident costs and particularly the process of obtaining it are many including:

- Often quality costs are soft costs, go unmeasured, or are immeasurable. While cost of quality is important to understand, the impact of quality goes well beyond dollars. A pure business-case approach to quality improvement rarely justifies the investment required for quality improvement.
- Not all defects are created equal; while different defects may impact the yield numbers in the same way, they have significantly different cost impacts via excessive rework time, excessive material scrap, or excessive cycle time impact.
- The Pareto of each cost contributor reveals how best to impact cost of quality both internally to the factory and externally with design and procurement – often contrary to the current approaches to quality improvement.

- Many decisions may be locally optimized, but may be a detriment to Dell as a whole.

Finally, the cost model also helps address the strategic questions posed by the thesis and problem statement. In regard to how best to leverage the factory resources, the cost model provides several process control tool evaluations to then recommends strategies within the factory as well as upstream with the design and vendors. This strategy addresses the factories role both as the final insulator to the customer and its role as quality champion. In regard to how Dell should approach total cost of ownership, the model proposes the importance of leveraging factory knowledge, of thinking both strategically and tactically, as well as the requirement of an enterprise level solution. Most importantly, the thesis addresses that like most companies, Dell is not at a point at which internal quality investments contradict low-cost and high-clockspeed. Quality investments are in fact crucial to reducing factory costs as well as enabling flexibility and order velocity within the factory. Dell's innovation in other operational expertise such as supply chain, flexibility, and cost has actually allowed internal quality to be further optimized simultaneously.

For decades, quality experts and the relevant literature have provided many frameworks in which to view quality: waste reduction, manufacturing to specification, controlling variability, and corporate values, to name a few. While the cost model results and consequent recommendations within this thesis only repeat these messages, justifying quality improvement in terms of internal metrics and data as well as showing how radical improvements upstream are of strategic importance despite the apparent constraints of low cost and short life cycle will aid Dell move forward with it quality evolution. In fact, this does not contradict much of the momentum Dell already has in pursuing this evolution, now - potentially a revolution.

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APPENDIX A: GLOSSARY OF ACRONYMS

Activity Based Costing (ABC)
Automatic Green Tag (AGT)

Bill of Materials (BOM)
Business Process Improvement (BPI)

Cannot Duplicate (CND)
Cash Conversion Cycle (CCC)
Cost Per Box (CPB)

Days Sales Inventory (DSI)
Defect Per Hundred Units (DPHU)
*Design for * (where * refers to assembly, manufacturing, service, test, etc.)* (DFX)

Electromechanical Repair (EMR)
Enterprise Resource Planning (ERP)
Excess and Obsolete (E&O)

Field Incident Rate (FIR)
First In First Out (FIFO)

Graphical User Interface (GUI)

Initial Field Incident Rate (IFIR)

Lower Control Limit (LCL)

Motherboard (MB)

Personal Computer (PC)

Redundant Array of Independent Disks (RAID)
Return on Investment (ROI)

Ship to Target (STT)
Structured Query Language (SQL)
Storekeeping Unit (SKU)
Supplier Logistics Center (SLC)
Statistical Process Control (SPC)

Upper Control Limit (UCL)

Work in progress (WIP)
WIP tracking and control system (WTCS)

APPENDIX B: DELL SERVER MANUFACTURING FLOW

1) Dell makes a sale.
2) An order is entered into Dell's order management software.
3) The order is downloaded to the factory during which time the order is BOM'ed out or exploded into barcodes with the requisite parts into the lecture servers.
4) The traveler is pulled.
5) The traveler is given to the Ram cabinet where the processor and memory are pulled.
6) At the same time the Kitting lights up to pick the parts for the system.
7) The memory and processor is installed on the MB at MB prep.
8) The MB is sent down the conveyor to a waiting chassis where it is installed.
9) Meanwhile, in the kitting line, operators are picking parts and placing it in a tote assigned for the system.
10) The chassis and the tote move on a converging conveyor until they meet and head into an empty build cell.
11) In the build cell, operators install the parts from the totes into the chassis.
12) The operator generates a step disk and Quick Tests it at a separate module.
13) Once Quick Test is completed it is sent down the conveyor where operators use mobile racks to move the system into the burn racks where Extended Test 1 & 2, SW download, and Final Test is run.
14) If it is a Dell Plus system it will go through the SI spur, during which DSI technicians perform manual configurations and install needed labels.
15) Once completed the system is moved to Wipedown where the system is inspected for any cosmetic defects.
16) If it does have a cosmetic defect the system will be sent to visual repair.
17) The system is then sent through the pick to light boxing line where Docs and parts and kitted with the system.
18) The system is boxed, and once the entire order is collected shipped to DC to be sent to the customer.
19) A failure could occur anytime during this process. Should this occur, the system is sent to EMR.