THE ROLE OF FLEXIBILITY IN CONFIGURE-TO-ORDER MANUFACTURING: A FRAMEWORK FOR MANAGING VARIATION

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ABSTRACT

In this paper we examine a challenge that many companies are facing: how to respond to increased variation within their manufacturing operations. I posit that the challenges posed here are addressable with tools managers have within the four walls of their factory. Our goal is to better ensure that managers can keep their costs under control in times of turbulent change. Using Dell as an example of Configure-to-order (CTO) manufacturing at its extreme, and see how they are adapting their capabilities in order to become more flexible in this highly volatile marketplace.

Variation is inevitable, and a key driver for companies to move to configure-to-order manufacturing. Variation can take on many forms, but in most cases variation degrades the performance of an optimized system. Depending on the source of the variation (either predictable or not) and the firm's ability to react to the variation, the tools with which we address this variation change. Put another way, in order to do customization well, a firm must be adept at using flexibility to its advantage. "How effectively firms can use the flexible technologies that do exist, create new, more responsive processes and management methods, and use the inherent flexibility of workers to more quickly develop and produce new products and services that more closely match individual tastes is the key to the new paradigm." (Pine, 1992)

In order to be responsive to ever-changing customer demands, the modern firm must (1) understand the variation that confronts them and (2) have a strong grasp of how they provide value to their customers. Using the framework outlined in this thesis, the practitioner should be able to identify the type of variation they wish to address, and the price they are willing to pay in order to achieve a flexible result.

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Glossary

Attach Rate: a measure of how often a given component is used in a given product platform. Based on historic orders for that computer platform. Equals: # times used / # of systems built

ATB: Available to Build: Status of a customer order that has passed all initial checks and is ready to be scheduled into the production line.

BOM: Bill of Materials: List of parts associated with a given product, often in some hierarchical format including assembly structure as well as sub-assemblies.

CM: Contract manufacturer: Company under contract to manufacture products for other companies.

CPB: Cost per Box: Metric that measures cost of manufacturing one computer (not including raw materials).

DLCPB: Direct Labor Cost per Box: Metric that measures cost incurred due to human work at the plant.

CTO: Configure-to-order: Both a strategy and a capability of firms to produce products to direct customer orders. Implies that production is not completed until customer needs are known.

ULH: Unit Labor Hours: Metric that measures number of direct labor hours required to produce one computer. This is a calculated number based on all systems across one factory in a given time period, generally monthly. Equal to (Total direct labor hours) / (total computers shipped)

UPH: Units Per Hour: Metric measuring factory production rate. Number of systems produced in a given hour.

SLA: Service Level Agreement: contract between company and their supplier indicating the agreed upon service level. In the context of this thesis SLA refers to maximum time allowed for parts to be delivered to the factory from the warehouse.

VMI: Vendor Managed Inventory: Inventory owned by the supplier, usually in an offsite warehouse.

VMI Hub: Vendor Managed Inventory Hub: Warehouse were VMI parts are stored.

STC: Ship To Commit: Latest time an order can leave the factory in order to meet commitment to customer delivery promise. Usually referred to in terms of failures (how often the factory does not meet its promise date).

1 Background

Crisis can serve as the birthplace of innovation. Increased competition in the global market place coupled with the escalating financial crisis have driven many companies to re-evaluate how they meet their customers' needs. Dell Inc. is no exception to this trend. While competitors have been working hard to erode Dell's position as an industry leader, pressures from outside are giving Dell the opportunity to work on innovative ways to once again lead the pack.

To compete in this new environment, Dell is looking at creative ways to further leverage their manufacturing processes and supply chain to their advantage. A long standing pioneer in direct sales and one of the first companies to successfully build direct customization into their supply chain and manufacturing, Dell is in a position to build on their foundation of success and drive further process excellence. By driving cost out of manufacturing and operations in times of crisis, Dell has the opportunity to compound their advantage as they deploy these improvements across products and manufacturing sites around the world.

In this paper we will examine some challenges that many manufacturers are facing: how to respond to increased variation within their manufacturing operations. The challenges posed here are addressable with tools managers have within the four walls of their factory. The purpose is to better ensure that managers can keep their costs under control in times of turbulent change. We will then move on to highlight selected examples of how variation has affected Dell's operations, and what they are doing to manage their costs. We will use Dell as an example of Configure-to-order (CTO) manufacturing at its extreme, and see how they are adapting their capabilities in order to become more flexible in this highly volatile marketplace.

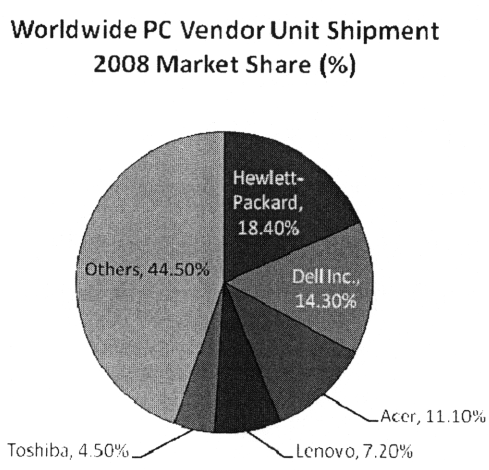
1.1 PC Industry Dynamics

No company can be understood without a basic understanding of the environment in which they operate. This section is provided to place Dell's operating model within the context of the global PC industry and to provide a sufficient background in the dynamics among the major players in the PC industry in order to understand the motivation for this thesis.

The history of the modern personal computer (PC) can be traced back to the first commercial super computers available in the 1960's. IBM's introduction of PCs into the marketplace in the 1980 was the first time that home and business users could easily access this technology in a way that was not cost prohibitive (Wu, 2006). These new machines combined spreadsheet applications, word processing, presentation graphics and a simple database application into one machine. Since that time, the market for personal computers has exploded; the current market for personal computers around the world in 2008 topped 300 million units shipped this past year (Gartner, 2009).

1.1.1 Market Dynamics

While the market was once dominated by just a few players, the number of competitors has skyrocketed. A recent report from Gartner provides insight into the current PC market. While five major players make up just over half of the market, the other 44.5% of the market is divided amongst many other players (as shown in Figure 1). This fragmented market structure for PCs has created a very cost competitive market, with each company trying to lower their cost of goods sold in order to offer customers a lower price.

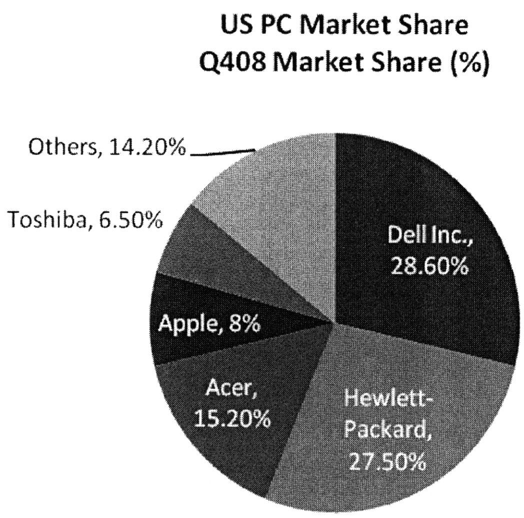


(Gartner, 2009)

Figure 1: 2008 Worldwide PC Market Share.

Though the market is highly fragmented, there are clearly recent winners and losers. Figure 2 below shows the relative change in market share for major competitors in the world PC market. While the market as a whole has grown by a mere 1.1% in the past year, major gains have been made by two prominent competitors; Toshiba and Acer, both Asian entrants who maintain smaller shares in the overall world market. This exemplifies the dynamic change happening in the PC industry. As the United States and European PC markets are becoming saturated, entrants from Asia are beginning to capitalize on growth opportunities in other parts of the world[1].

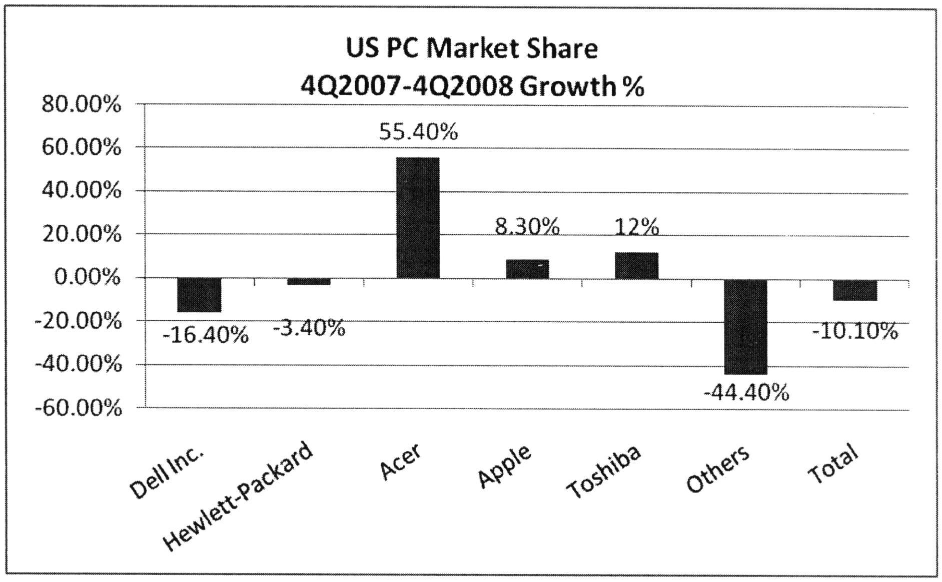
While the US market for PCs is a bit less fragmented, with major players Hewlett Packard and Dell alone capturing over 50% of the market, established firms here are also losing ground to new entrants. Figures 3 and 4 below show that in the declining US market, Toshiba and Acer are making significant strides to diminish the positions of powerhouses HP and Dell. While Dell has lost 16% of its US market share, Acer has increased its market share by 55%. It is important to note that although Acer and Toshiba experienced the highest US growth (55.3% and 8.3% respectively), they remain relatively small players both in the US and globally.



(Gartner, 2009)

Figure 2: 2008 United States PC Market Share.

[1] Major growth markets include Brazil, Russia, India, and China. These countries are collectively known as BRIC countries.



(Gartner, 2009)

Figure 3: Change in US PC Market Share Q42007-Q42008.

1.1.2 Manufacturing Strategy

Most PC makers today utilize contract manufacturers to produce high-tech electronic products. The business model for contract manufacturing generally involves the contracting firm approaching the contract manufacturer (CM) with a design, followed by negotiation and eventually agreement on a price. The CM acts as the hiring firm's remote factory. The CM identifies sub tier suppliers, procures the components and finally assemble PCs to the hiring firm's specifications. Depending on the contract, the CM will either ship the finished products to the hiring company's distribution center for final configuration, or in some cases ship directly to the channel customers or firm's direct customers.

Dell has found a very efficient way to provide products to customers by harnessing internet sales to provide customers with fully custom computers with a lead time of 5 days including delivery. (Ghiassi & Spera, 2003). Dell is one of the few American companies that still retain manufacturing facilities in the U.S. In the Dell direct model, customers are given the ability to customize several features of their computer. Manufacturing a fully integrated system in Asia and then shipping it to the US would be time-prohibitive given Dell's promised service level of under one week. On the other hand, holding an inventory of finished goods would be cost-prohibitive given the thousands of possible configurations that customers can choose from, and manufacturing a finished product and air-freighting it from Asia would be too cost-prohibitive if it is a heavy or bulky desktop product. Therefore, for Dell's desktop products, contract manufacturers in China produce and ship partially assembled products to Dell's factories in the U.S. Once the supply arrives and the complete customer orders are known, Dell factory workers assemble the PCs into their final configuration: build in the customized components (including the processor, memory, hard drive, speaker, etc.), install the necessary software application, perform final unit testing, and then ship the product to the customer in a timely fashion (Wu, 2006).

1.1.3 Technology Strategy

There are several trends within the PC industry that have changed companies' strategies in the past thirty years. The first of these is the rate of change of technology. Compared with many other industries, PC technology continues to change at a break-neck pace. In order to keep up with advances in technology and the resulting changes in customer preference, PC manufacturers are being forced to update their products at a faster and faster pace. New products are released every few months in order to keep up with changes in technology and changes in market demand. The rate of these product changes is forcing PC manufacturers to re-evaluate their entire supply chain as finished goods inventory is at a higher risk of obsolescence.

The second big shift in the industry is the commoditization of computer components. While a few computer manufacturers such as Apple are technology leaders, who incorporate proprietary technology into their market forward products, many manufacturers are market followers and incorporate technology into their products only after standard technology has been adopted. These fast followers use a stable technology platform and utilize their buying power to drive down the cost of this technology from all component manufacturers over time. This commoditization of computer components is a benefit to the firm, but has spillover effects for their competitors as the cost goes down for all players in the market. This provides a much more competitive low end market, driving down the margins on PCs as firms compete on price.

Dell's success in reducing inventory and providing lightning fast service has influenced other companies such as Gateway, Compaq and Hewlett-Packard to revise their operations paradigm and their corresponding CTO operations. This spillover effect of a successful supply chain strategy pushes the entire market towards continuous improvement in order to stay ahead of the competition. While this improvement is good for each firm individually, the net effect is also a lower-priced, higher-quality product that more closely corresponds to the customers' needs.

1.2 Dell Company Overview

Dell was originally founded as PC's Limited in 1984 by Michael Dell from his dorm room at the University of Texas. Dell pioneered the direct-sales model for computers and took the company from his dorm room to the top of the PC industry by keeping it focused on a simple formula: eliminate the middleman and sell for less. Dell's fundamental business model has not changed: selling directly to customers has become Dell's key strategy and strength. By building custom computer for their clients, Dell became the first successful computer manufacturer to incorporate individual customization for every product they manufacture.

Dell's close relationships with its suppliers have allowed the company to operate with nearly no work-in-process inventory. By working closely with suppliers, inventories of components and materials are minimized. Building systems to order means that there is no finished product inventory in the channel to manage. (Bowersox, Stank, & Daugherty, 1999). Dell's configure-to-order computers allow for lower inventories, lower costs, and higher profit margins; advantages that have served it well through PC price wars and IT spending recessions. Leadership in supply chain and the direct manufacturing model provided Dell with industry leading profit margins. Dell grew steadily through 1999 when they overtook Compaq to become the #1 computer manufacturer in the United States.

In the mid 2000s, Dell looked to increase market share further by focusing on the low-cost computer market. This strategy deteriorated margins and left Dell with eroded profitability. With the return of Michael Dell as CEO in 2007, the company has changed course to drastically lower operating expenses while distancing itself from the low-cost market. In order to drive these cost reductions, Dell is focusing on doing more with less. Relying on lean manufacturing techniques and working with ODM partners to create a more profitable future for the company and its shareholders.

The past few years have proven to be turbulent ones for Dell. The third quarter of 2008 was the first time that laptop PCs surpassed desktop PC in number of units sold. This shift in technology is a true paradigm shift in the computer industry. Because laptop PC's are much lighter and more compact, outsourcing or off shoring the manufacturing of laptop computers is a much more viable option. As desktop PC demand shrinks, Dell is faced with the prospect of closing U.S. manufacturing facilities. Figures 5, 6 and 7 show Dell's current sales data for geographic regions worldwide, as well as their product segmentation in those markets. In 2008 desktop sales still accounted for 32% of their overall sales. In the U.S., 83% of Dell systems are sold to businesses large and small, while 17% of sales are to consumers.

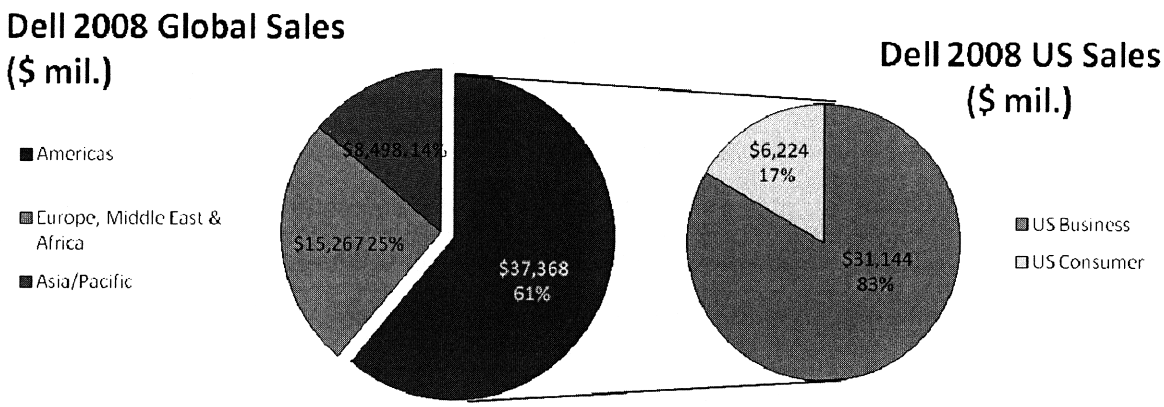
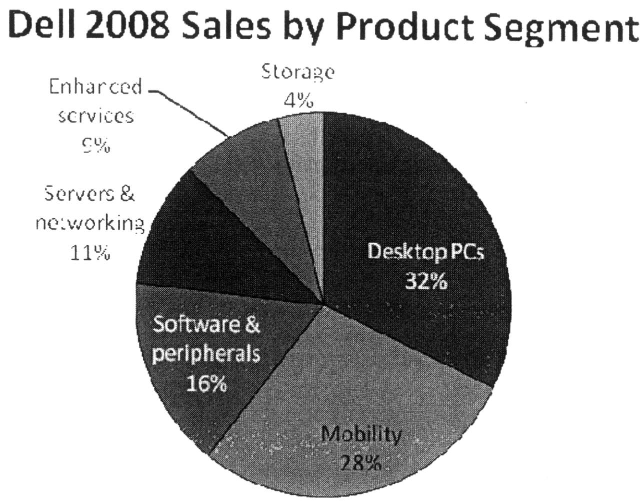


Figure 4: Dell 2008 sales by geographic region. US sales broken down by segment.



(Hoovers, 2008)

Figure 5: Dell 2008 sales by product segment

In order to say ahead of other computer manufacturers around the globe, Dell faces remaining challenges in their own manufacturing operations. In a Dell internal communication, Michael explains that "Dell has historically benefited from tough times and we can again by staying focused on our [top] initiatives, our customers and driving our competitiveness." In Chapter 4 we will examine in more depth how Dell is looking to additional flexibility in their manufacturing operations as an opportunity to a stay ahead of the market.

1.3 Desktop Computer Manufacturing at Dell

1.3.1 Facility Strategy

At the beginning of 2008, Dell was operating three desktop manufacturing facilities in the United States: Topfer Manufacturing Center (TMC), Eastgate TN (EG1), and Winston Salem NC (WS1). Each of these three factories fills a different position in Dell's overall facilities strategy. TMC was the first of these factories, and initially provided all desktop computers for the US market and abroad. It was developed with capabilities to fulfill all types of orders (including international shipping, special handling, custom parts) and evolved additional capabilities as Dell evolved to meet new customer needs. EG1 was developed as a lower cost manufacturing facility, producing desktop PCs that were less complicated and could be manufactured quickly. The site of EG1 in Nashville also helped Dell to reach their customers on the East Coast and in the Midwest a bit more quickly. This location decision directly supported Dell's strategy to compete on availability. The WS1 factory was built in anticipation of future desktop PC growth in the US and neighboring countries. This North Carolina facility was designed to take on a broader range of capabilities than EG1, and fewer than TMC.

This facility strategy is graphically represented in Table 1 below. You can see that each factory was developed to fit a different part of Dells strategy in terms of production volume and range of products produced at each factory. In the case of Dell, the range of product mix is relative to their overall selection; though EG1 was created as a low-mix site for Dell, it had the capability to produce several thousands of product combinations. Dell's facility strategy is counter of what is usually seen in industry. Many firms account for mix and volume by allocating one factory to take on high-mix low-volume[2], and others to focus on only a few products and make large numbers of those[3].

	Low ⟵	Total Process Volume	⟶ High
High Variety of Products ↑			TMC
Range of product mix		WS1	
↓ Low variety of products	EG1		

Table 1: Dell's desktop manufacturing facility strategy (cerca 2004).

1.3.2 Evolving Methods

As with any company, Dell is not a static system and has evolved their strategy and methods over time. Beginning in 2006, Dell's EG1 factory started down a path towards "lean

[2] Generally more of a job shop, or R&D type manufacturing facility

[3] Closer to mass production conditions

manufacturing". The "traditional" means of manufacturing at Dell included the following process steps: kitting (collecting all of the components needed for one system), build (one worker assembling the whole computer), burn (software install), box (assemble shipping boxes and fill with relevant CDs and brochures) and finally shipping (sorting boxes to their appropriate trucks and applying all applicable shipping documentation)[4]. The new approach spearheaded at EG1 involved the use of one central material supermarket supplying components to single-piece-flow lines, each set up to run multiple product platforms with minimal setup time. Burn, box and ship remained similar to the older system. Using lean manufacturing techniques, EG1 was able to reduce their production costs by roughly 40% per system and reduce the footprint of their manufacturing operation by over 50%. Because the change was so successful, other Dell sites have begun to adopt the process: WS1 started down their own lean journey in 2008, and sites in Poland and Brazil are investigating lean manufacturing now.

At the same time that lean manufacturing has increased the effective capacity at EG1 and WS1, the global demand for desktop computers has slowly been declining. This has left Dell with more capacity than they need. Given the current economic situation around the world, it is not surprising that Dell and many other manufacturers are being faced with declining demand for their products. This decline in demand is not a smooth ramp-down, but rather a sharp decline punctuated by higher variation in demand.

Dell's strategy to build only after a customer order is complete makes the company much more vulnerable to volatility in the market. As stated by Michael Dell, "because so much of our sales are directly to customers, we see changes in demand before others who have a longer distribution channel". The repercussion of this are twofold: first, Dell factories have to be much more agile in order to manage costs and capacity as demand changes; second, with a shorter supply chain and a CTO manufacturing strategy Dell will not be left with large amounts of inventory that could negatively affect the bottom line. In short, in hard times it is much more important for Dell to manage cost and capacity in their factories, and that is the focus of this thesis.

In the past twelve months, Dell has shut the doors of TMC and also stopped the production of desktop computers at EG1. WS1 and Dell's outsource partners remain to provide desktop

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[4] A more thorough description of this process is available in Appendix A

capacity for the North American market. Without the capacity buffer of the other two plants (TMC and EG1), WS1 is responsible for being flexible enough to deal with the entire variation of the market. Although the business environment has changed, Dell is still driving to provide the best quality, service and cost its customers in the US and abroad.

1.4 Project Background

Once a factory is designed and built, there are not many large scale changes that can be done to change capacity or the flexibility of that capacity without major capital investment. For the most part, management has to make decisions within the confines of the factory in the condition that it exists. Short of adding equipment, changing the layout of the plant or doing a major overhaul of the supply chain, there is very little that can drastically change the capacity of a factory. Not only do these options involve large capital investment, but the time scale for implementation of these changes is very long. More relevant to the actual manufacturing environment is to understand the adjustments that can be made on a shorter time scale in order to react to changes in demand as they occur.

In the context of configure-to-order manufacturing at Dell, visibility into actual demand is at most a one week into the future. Dell's CTO model is an acute case of low service lead times which makes these relevant grounds to understand how flexibility can be used to a company's advantage in dealing with variation within a condensed time horizon.

Faced with sporadic but declining demand, Dell is looking for additional capabilities to compliment their existing CTO strategy:

- Ways to better match single factory capacity to real-time demand.
- Ability to reduce overhead costs in order to be more competitive when running below full capacity.
- Tools to better anticipate variation of inputs, and control those variations to their advantage.

At the time this project began, both TMC and EG1 were still in operation. TMC was in the process of ramping down production and transferring process knowledge to WS1 which would take on most of the additional volume and complexity. EG1 was still at full capacity utilization, looking to take on more of the work from TMC. The major work for this thesis was conducted at the EG1 facility as they experienced the full spectrum of demand; from over capacity, through downsizing, to closure. This thesis aims to capture and share much of learning gained through observation and problem solving inside one of the most dynamic and resilient computer manufacturers on earth. The internal capability of Dell to react to change will be explored, as will new approaches that were developed over the course of my time at EG1.

1.5 Project Objectives and Approach

As with most projects in corporate America, the objective of the project discussed here is to reduce cost without creating any negative effects to the customer. Though "cost cutting" is indeed an important objective; this term does little to describe how it was to be accomplished and how the outcomes will be measured against then-current performance.

Dell factories are judged using a defined set of metrics. These metrics include the following:

- Cost per Box (CPB): The cost of manufacturing one computer (not including raw materials).
- Direct Labor Cost per Box (DLCPB): The cost incurred by human work at the plant.
- Unit Labor Hours (ULH): The number of direct labor hours required to produce one computer. This is a calculated number based on all systems across one factory in a given time period, generally monthly. Equal to (Total direct labor hours) / (total computers shipped)
- Units Per Hour (UPH): Factory production rate. Number of systems produced in a given hour.
- Ship to Commit (STC): Latest time an order can leave the factory in order to meet commitment to customer delivery promise. Usually referred to in terms of failures (how often the factory does not meet its promise date).

Within the context of these metrics, the objectives of this project include moving each of the above metrics in the direction favorable for Dell (lower costs, more productive workforce, and greater reliability to the customer). These metrics are driven by three major forces within the factory: labor productivity (DLCPB, ULH, and UPH), fixed costs (CPB), and operational efficiency (STC). In order to meet the goal of reduced costs, each of these forces were analyzed to understand the cost drivers within Dell manufacturing. Major opportunities were identified in terms of scenarios that the factory commonly faced. These scenarios and the assessment questions used to approach them are identified below in Table 2.

Scenario	**Assessment Questions - Approach**
Demand > Capacity	What can be done to streamline operations and reduce waste in the manufacturing process?
Demand < Capacity	How can flexible labor pool be used more effectively? When should capacity be cut in order to reduce labor costs?
Limited demand information	Can existing information be leveraged to provide early indicators? How can communication be improved to reduce delays in information sharing?
General	What waste exists in the manufacturing system that can be eliminated to provide benefit no matter that situation? What are drivers of production downtime?

Table 2: Common scenarios that detract from factory cost objectives

Improvement activities based on the answers to the above questions are almost limitless. Looking to lean principals we can begin with the "five whys", starting with an obvious problem and digging deeper by asking the question "why?" five times, each time arriving closer to a root cause (Ohno, 1988). Each problem scenario may have multiple root causes, and the scenarios above provide ample opportunity to understand many of the root causes leading to strife within the factory. In order to limit the scope of this work to something manageable in my six month timeframe, these exercises were practiced only in the upstream portions of the factory (incoming materials and assembly). Though there were certainly many improvement opportunities in other portions of the factory, resources were not available to complete this work in all areas.

Using the output from the root cause analysis, new approaches were developed using available data and existing best practices. Historically, Dell has pushed back on outside influences with a "not made here" mentality. Because this project leverages tools that were developed within Dell, I am better positioned for success within this environment. Leveraging existing processes and information allowed for greater adoption of the new projects within the company, as well as more efficient use of time than creating solutions from scratch.

1.6 Chapter Summary

The computer industry is evolving at a rapid clock speed, and those firms who do not adapt to changing conditions are at risk of being overtaken. Though 50% of the global market is dominated by a few major players, the other half of the market is fragmented with new entrants quickly gaining ground on the dominant players. This shift in the industry highlights the need for older existing firms to adapt their strategies in order to become more agile and adaptive as consumer demands are changing ever more rapidly.

Within this market, Dell was designed and evolved to become a lean, mean computer making company. Starting with the novel approach of direct sales to customers, Dell evolved a highly connected supply chain that allowed them to follow through on their promise to provide custom computers in a fraction of the time of their competitors. Further adaption of their strategy has included the adoption of lean manufacturing and a greater connection to outsource manufacturing partners.

In the current market, many companies (Dell included) are finding themselves with orders far below their designed manufacturing capacity. The central premise of this work is that configure-to-order manufacturing companies need to utilize flexibility in new ways in order to deal with variation in a way that controls costs. How can these companies create additional flexibility with little capital, that can then be used to manage their operations on a daily basis. These fine control mechanisms will allow companies to tune their operations as variation occurs, as well as provide a more robust system that will accept more varied inputs.

Using Dell as an example of CTO manufacturing in a declining market, I will approach this problem by looking at sources of variation both within and outside of the firm. Using lean principals I will identify knobs to handle this variation in order to minimize costs associated with unexpected demand.

2 Literature Review

This section is included to give the reader a familiarity with three terms used throughout this thesis: configure-to-order, variation, and flexibility. At this time we will lay out the basic definition and role of each of these concepts in the manufacturing context. Building further on these concepts in Chapters 3 and 4 we will explore the intersections of CTO with variation and then with flexibility. Finally, in chapter 5 we look at examples of where variation and flexibility come together in case studies.

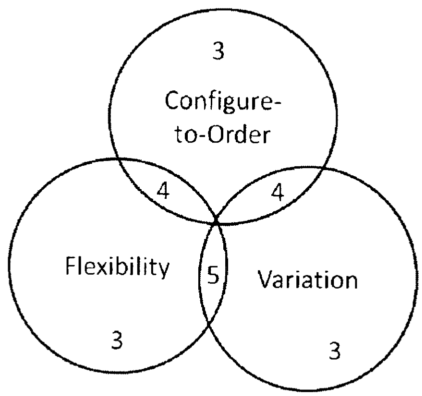

Figure 6: Structure for describing the main concepts of the thesis

2.1 CTO Supply Chains and Manufacturing

2.1.1 Predecessors to CTO

The drivers for configure-to-order manufacturing can be linked to the concept of mass customization. Mass customization is based on the notion that each customer has different needs. Rather than fitting the customer to the product, mass customizers adapt their products, processes, services to the customer. The shift to mass customization in the 80s and 90s is in stark contrast to the earlier practice of mass production. In the book Mass Customization, Joseph Pine (1992) does a very good job of walking through the history of manufacturing thought; from the industrial revolution through to modern manufacturing. Table 3, provided by Pine, highlights the major changes in thinking between mass production and mass customization. Major differences include the move to smaller batch sizes, as well as a shift to much larger numbers of product offerings in order to meet the needs of each customer.

	Mass Production	Mass Customization
Focus	Efficiency through stability and control	Variety and customization through flexibility and quick responsiveness
Goal	Developing, producing, marketing, and delivering goods and services at prices low enough that nearly everyone can afford them	Developing, producing, marketing, and delivering affordable goods and services with enough variety and customization that nearly everyone finds exactly what they want
Key Features	• Stable demand	• Fragmented demand
	• Large, homogenous markets	• Heterogeneous niches
	• Low-cost, consistent quality, standardized goods and services	• Low-cost, high-quality, customized goods and services
	• Long product development cycles	• Short product development cycles
	• Long product life cycles	• Short product life cycles.

Table 3: Mass Customization Contrasted with Mass Production. Adapted from Pine (1992)

2.1.2 Characteristics of CTO

Tyan, Wang and Du (2003) identify configure-to-order as an efficient way to deal with the trends of mass customization. Configure-to-order is just what it sounds, a process by which products or services are not built or configured until the customer has ordered it. This process allows "retailers and manufacturers to shorten planning cycles, compress manufacturing lead times, and expedite distribution" (Tyan, Wang, & Du, 2003). These benefits enabled by configure-to-order manufacturing are also the market drivers that have lead to mass customization in the first place. In Mass Customization, Pine describes the reinforcing dynamics that led to and then fueled the continuation of mass customization. This cycle can be seen in Figure 7 below. If we start with the customer, the cycle looks like this:

- Customers have differing needs that lead to demand fragmentation.
- Heterogeneous markets form to supply the needs of the customer base.
- Competition in the markets lead to low-cost, high-quality, custom products.

- Advances in process technology allow for greater flexibility in manufacturing, and greater ability to customize new products.
- Product lifecycles shorten as product technology changes at a faster and faster pace (also spurred by mass customization). Product development speeds up to facilitate this process.
- Customers are offered a greater diversity of products and come to expect customization.

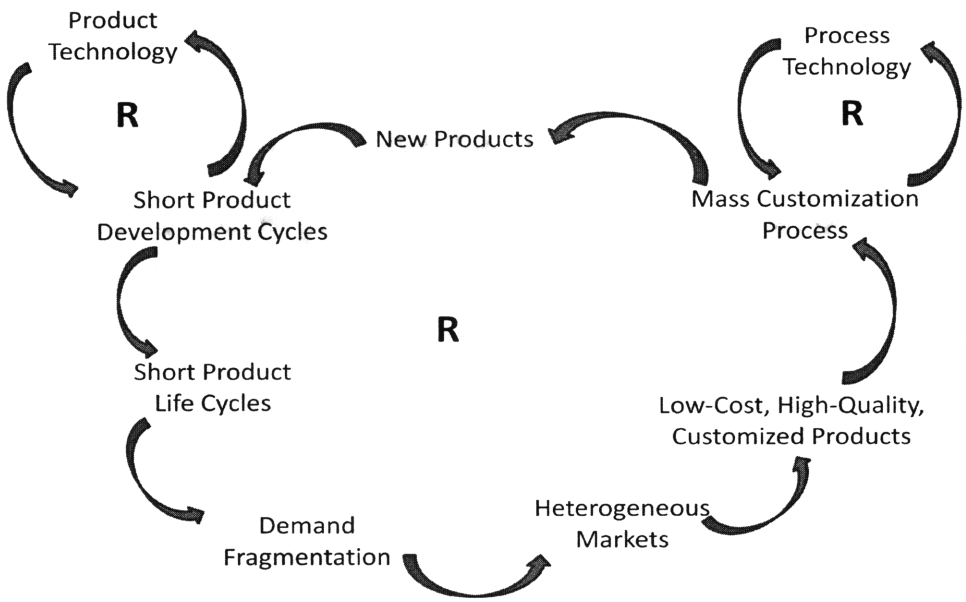

Figure 7 System Dynamics feedback loop representation of Mass Customization. Adapted from Pine (1992).

This progression can thus be seen to feed back positively on itself, creating a reinforcing loop of greater variety, through increasing flexibility, more quickly – the exact opposite of mass production (Pine, 1992).

2.1.3 Requirements for CTO

In the previous section we highlighted the advantages of CTO as shorter planning cycles, compressed lead times and expedited distribution. At this point it is important to describe some of the underlying capabilities and tenants that make CTO successful in this way.

Wagner, Guralnik & Phelps (2003) line out the requirements of CTO as "no work in process at the end of the day, zero finished goods inventory, [and] building products to order only." But again, these are just the manifestations of a working configure-to-order system. If you were to eliminate the WIP and the inventory on day one, you would not by default come to the CTO process you desire. Simply implementing the tools does not guarantee success, as CTO must be approached as a system with all parts working in harmony.

CTO implies that some level of sub-assembly components are complete and stocked, ready to be differentiated on demand. Configure-to-order is similar to its cousin build to order, with the exception that it is generally made from parts that are ready for assembly, rather than made to specification. Many of these systems rely on a push-pull interface at the point of product differentiation. This interface is the boundary between a buffered supply and the location where pull materials flow begins. Simchi-Levi, Kaminsky and Simchi-Levi (2008) suggest that industries that have high demand uncertainty and low economies of scale are most appropriate for a pull type strategy. In the case of CTO, because the jobs are not processed unit an order is confirmed this leads those processes to be more at the mercy of the market and therefore higher demand uncertainty. In the case of economies of scale, one of the real enablers of CTO is flexible manufacturing; driving down the setup costs between products and therefore reducing the effect of economies of scale. As the push-pull interface is moved closer to the customer, the more responsive the system will be to the customer's needs in terms of lead time. To balance this, the further downstream the interface is, the more the firm will likely pay in inventory holding costs.

In order to accommodate the need for fast product development cycles and multiple product offerings, a firm must make specific choices about the products it makes. First, by reducing the complexity of product design and manufacturing, the firm can use those saved resources for deploying other products. Second, the use of modular product design allows the firm to leverage design resources across products as well as pool risk associated with demand variation. By simplifying and leveraging common designs, the firm can enhance the effectiveness of CTO by driving down cost and variation.

The CTO production system relies strongly on the tight integration of the upstream supplier of parts, the midstream manufacturer and assembler of components and the downstream distributor of finished goods in the supply chain. This integration necessitates a timely and efficient channel of communication (Chen, Lu, Yu, Tzent, & Chang, 2003). In Chapter 4 we will explore in more depth some examples where communication has proved to be vital in the success of a CTO operation.

For each part of an organization, there are associated behaviors that allow CTO to be successful within the firm. Traditional supply chain models and CTO supply chains differ in their level of flexibility and responsiveness to changing market requirements. Many of these concepts can be seen in Table 4 which compares traditional supply chains to build-to-order supply chain characteristics in different parts of the organization (Gunasekaran & Ngai, 2005). It is clear that for a company to transition to configure-to-order operations there is a tremendous shift that must occur in almost every aspect of its operations.

Reference	Traditional Supply Chain	Build-to-order supply chain
Marketing	Push - sell from stock	Pull - build to customer order
Production	Focus on level and stable schedules: fixed order lineup	Customer demand focused on supply chain flexibility
Logistics	Mass approach - non-differentiated	Fast, reliable, customized
Customer relationship	Dealer-owned	Shared across the extended enterprise
Managing uncertainty	Finished goods inventory buffers	Strategic part buffers and information management
Finished goods inventory	High stock control	Low, condensed dealer tock levels
Suppliers	Long lead times	Collaborative/responsive

Table 4: Differences between traditional and build-to-order supply chains

2.1.4 Common Issues in CTO

Although the CTO supply chain appears to be better in many ways than traditional supply chain, there are several issues that arise in CTO that would not be an issue otherwise. According to Gunasekaran & Ngai (2005), many of these CTO specific issues are associated with the pace of product development as well as the complexities of scheduling. For starters "order-processing is time consuming and costly, multiple revisions of specifications are required, delivery dates are often not met, last minute changes take up and increasing portion of resources, production plans are often inaccurate and over ruled, and the more often this happens, the more profits decline" (Gunasekaran & Ngai, 2005). Keeping these types of issues in mind, we will explore later on how robust flexibility can help to error proof CTO processes and reduce the negative effects of these common issues.

Many of these pitfalls are the indicators of a company's inability to deal with uncertainty. By studying the root causes of these characteristic problems within a firm, it is possible to reduce inefficiencies and allow a firm to look past their internal points of friction and start to proactively understand external sources of variation and how to address them.

2.2 Variation

Variation is a broad concept, and means various things in different circumstances. Both the causes of variation and the effects of variation on manufacturing have been well documented in the literature. Hopp and Spearman (2001) define variation as "the quality of nonuniformity of a class of entities". This definition is as accurate as it is broad; through defining the specifics of those nonuniformities as well as the characteristics of the "entities" we can better understand the details of the variation. This distinction between the source of variation and the manifestation of variation is important to keep in mind as we later explore a framework for dealing with variation.

In Lean Thinking, Womack and Jones (1996) walk us though the types of waste associated with any process, pointing out that variation in a process can be considered "muda" or waste. An understanding of variation based on this analysis allows the practitioner to focus their attention on the elimination of variation rather than spending a lot of time trying to define the variation as suggested previously.

Variability is closely associate with, but not identical to, randomness. Here we can make a distinction between predictable variation and unpredictable variation. Although any aspect of an operation may be variable, there are many instances where those variations are well understood.

For example, if ambient temperature is an important factor in your operations, a weather report can help to predict that variation well in advance. Additionally, some variation can be a consequence of bad control. These distinctions will become more important as we evaluate the causes of variation and the countermeasures necessary to address them. Different causes of variation need to be dealt with in different ways (see Chapter 3)

Hopp and Spearman continue on to group the sources of variation into two categories: either controllable or random. Controllable variation is defined as variation that is a direct result of a decision. Because controllable variation has a cause/effect relationship with some defined action, it can be controlled or at a minimum predicted. In contrast, random variation is the consequence of events beyond our immediate control. Random variation drives the need for more resilient systems which can handle a large range of inputs, where controllable variation points us in the direction of removing the source of the variation.

Within the context of manufacturing, Beckman and Rosenfield (2008) nicely lay out categories that help define the manifestations of variation within the firm. These categories include the following: demand variability, supply variability, product or service variability, process variability, and workforce and equipment variability. These are not mutually exclusive categories as a single variation can create outcomes that manifest in more than one way. "All five types [of variation] may occur simultaneously. The particular mix of variability experienced varies for each company depending on its industry and competitive environment" (Beckman & Rosenfield, 2008)

- Demand Variability is generally attributed to direct customer activities. Can manifest in the forms of product mix, or volume. Includes seasonal variation, weekly variation, etc.
- Supply Variability is generated by the supplier. This variation can be manifested in the quality and timeliness of materials deliveries.
- Product or service variability links directly to changes in the product or service itself. Changes can be linked to product customization as well as changing market preference.
- Process Variability can be caused by technology changes, management changes or process changes anywhere in the value stream.
- Workforce and equipment variability can result in variation in quality, output, and reliability. In the case of workforce and equipment, these variations can occur spontaneously and are only partially controllable.

Once a reasonable descriptive language has been selected to define the variation within a system, it is important to understand the reprocussions of the variation. Hopp and Spearman (2001) state as a law that "increasing variability always degrades the performance of a production system." This assertion implies that an increase in variation of any sort must harm some measure of performance. They acknowledge that variation in a system may be a benefit to the system in certain ways, but always at the tradeoff of other measures of performance.

Tradeoffs between variation and other performance measures can be controlled in various ways. Hopp and Spearman suggest the idea of variation buffering, where variability in a production system can be buffered by some combination of inventory, capacity, or time. This proposition allows the firm to identify and control how variation in one input can impact the system. Tradeoffs give us the ability to build our operations response in alignment with the overall corporate strategy.

2.3 Flexibility

In "The Management of Manufacturing Flexibility," David Upton (1994) describes flexibility as "the ability to change or react with little penalty in time, effort, cost or performance." This description links flexibility to the desired outcomes of its application. Does this imply that flexibility is an ability, a set of tools or a set of outcomes? Here we begin to get a sense of the ambiguity associated with the term flexibility throughout the literature. In many cases the term flexibility is described in relation to a particular system or environment. Here, Upton is defining flexibility by the range of desired outcomes.

Within the manufacturing context, Tsubone and Horikawa (1999) posit that "flexibility is the ability of a system to adapt quickly to any changes in relevant factors such as product, process, workload, or machine failure." Here we are adding the concept of changing inputs, possibly equivalent to the concept of variation explored earlier. While this definition adds more richness to our understanding, it fails to identify the possibility of flexibility as a proactive pursuit that may pre-empt changes in those input factors.

The Aberdeen group reports on manufacturing flexibility as it relates to the shop floor operations. Aberdeen defines flexibility as "convergence of supply chain visibility, production capacity, and dynamic decision making" (Aberdeen Group, 2007). This definition begins to guide us in the direction of sources of flexibility, such as increased supply chain visibility and rapid, multi-dimensional decision processes.

Beckman and Rosenfield (2008) begin to encompass the multi-dimensional nature of flexibility. "Flexibility is a cross-cutting capability that allows and organization to be responsive or readily adjustable to changing conditions." This definition allows us to understand that the capabilities known as flexibility can come from any corner of an organization. In addition, this passage implies that changing conditions are inevitable and should be planned for. Rosenfield and Beckman (2008) continue on to point out that customers are generally not directly aware of flexibility, rather they make choices based on the outcomes of flexibility: cost, quality, availability and selection. To this point, Upton (1994) points out that flexibility can be seen as both a set of capabilities (what can we do) and a source of competitive advantage in a particular environment (what the customer sees). This distinction highlights the difference between the market need for flexibility and the actual ability of a firm to execute to that need.

Flexibility is both an internal pursuit as well as a strategic necessity. Gunasekaran & Ngai (2005) discuss flexibility in relation to the speed or responsiveness of the capability. In their formulation, agility is the sum of both flexibility and responsiveness. In recent history, this agility has proven to be a competitive weapon for capturing market share in global markets.

Upton (1994) also touches on the speed or agility component of flexibility. He posits that flexibility can be defined as either agile or robust. Agile flexibility is the quality of adapting quickly to an external change. While robust flexibility is the ability to "maintain a status quo despite a change (which may be internal or external to the firm)" (Upton, 1994). This can also be stated as reactive or proactive flexibility; most situations require some level of each of these types of flexibility.

In order to better comprehend the multidimensional nature of flexibility, Upton (1994) suggested a list of flexibility "categories" that can be applicable to manufacturing. Figure 9 below lists Upton's categories of manufacturing flexibility.

Routing Flexibility	Volume Flexibility	Machine Flexibility
Product Flexibility	Program Flexibility	Labor Flexibility
Mix Flexibility	Long-Term Flexibility	Design-change Flexibili
Action Flexibility	Short-term Flexibility	Operation Flexibility
State Flexibility	Expansion Flexibility	Process Flexibility

Figure 8: Adapted from Upton's categories of manufacturing flexibility (1994)

Upton (1994) continues to define flexibility in terms of a different framework: three characteristic dimensions by which flexibility can be described and then measured. These dimensions are range, mobility, and uniformity and are described in more detail below and also in Chapter 4.

- **Range:** measures the range of products or services an operation can provide by measuring the set of values the operation is able to deliver along a given dimension
- **Mobility**: measures the cost or effort of making a change within the range
- **Uniformity**: assesses the ability of the system to provide consistent performance across the range.

Even after the dimensions of flexibility are defined and measured, it is still important to go one level further and translate these measures into some form of benefit to either the customer or the company. Only by quantifying the benefits of flexibility can you make value judgment between differing alternatives and methods to achieve flexibility. This valuation of flexibility can be used to understand the cost/benefit of investing in flexible infrastructure (Beckman & Rosenfield, 2008). Upton (1994) suggests to measure flexibility in terms of key outcomes. The three key performance indicators he suggests are on time delivery, finished goods inventory, and manufacturing cycle time. By measuring the outcomes, the practitioner tracks overall operational success rather than a specific flexibility competency.

2.4 Chapter Summary

In this chapter we have explored the concepts of CTO manufacturing, variation and flexibility. In each case taking a look at how these concepts are defined in the literature, how they relate in the context of manufacturing as well as exploring how these concepts might be useful as a framework to explore interdependencies.

CTO manufacturing is one common manifestation of mass customization. This CTO set of tools allows firms to provide their customers with custom products in a reduced period of time in comparison to mass production. Driven by fragmented customer demand, companies employing CTO are able to provide a greater product variety and condensed lead time to support the evolving needs of their customers. In order to implement a successful CTO strategy, organizations must drive for reduced complexity in their products and their processes. By tuning each part of the organization to be responsive to real-time information, CTO operations give firms an advantage in today's rapidly changing marketplace.

Variation is defined as non-uniformity within a system, and generally accepted as a detractor to efficient operations. Variation needs to be recognized as either controllable or random; each classification with its own course of actions. Controllable variation is caused by an action, and can be managed or predicted. Random variation in a system can be countered by designing systems that are robust to variation. Variation can manifest itself in any area of a supply chain, and is often described by where it is identified within the system[5]. If variation cannot be eliminated at the source, there is the some ability to "buffer" the variation with some combination of time, inventory or capacity.

Finally, we discussed flexibility and its role in manufacturing. Similar to variation, flexibility is somewhat ambiguous and often defined by the situation and set of tools used to implement flexibility. In short, flexibility is a set of skills that allow a firm to either proactively or reactively adapt to change/variation. In the best cases this flexibility is executed with very little impact on inventory, lead time or capacity[6]. By measuring key indicators such as delivery, finished goods inventory, and manufacturing cycle time, it becomes possible to link the effects of flexibility to customer value. This valuation then allows the firm to proactively balance investments in flexibility with a payoff to the customer.

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[5] Example: materials variation, product variation, etc

[6] Thesethe buffers described in relation to variation

3 Role of Variation in CTO Manufacturing

"Mass Production depends on stable, steadily growing demand to keep its wheels turning" (Pine, 1992). In the past twenty years, markets have become more turbulent and the resulting variation has proved problematic for traditional manufacturing as sales forecasting and production planning have become harder to accurately judge. As markets become more unpredictable, it becomes harder to maintain multibillion-dollar plants designed to employ economies of scale to produce large production runs at a low price. The economics of the situation begin to fall apart as customer demand shrinks or simply becomes less predictable. This is precisely the driver for CTO manufacturing.

We can see that CTO manufacturing is the industry's response to the phenomenon of increased variation. A system designed precisely to be robust to variation and agile enough to adapt to many changing environments. Through the application of technology and new management methods, companies have created a new paradigm by creating variety and customization through flexibility and quick responsiveness.

3.1 Overview of Variation

Variation can be caused by any number of factors both internal and external to the firm. In this analysis we will investigate the manifestation of variation in the manufacturing environment. We will investigate the different ways that variation is seen within the manufacturing environment, and try to understand internal and external sources for that variation. As we identify upstream drivers of variation will then investigate how to address them through different methods we will describe as flexibility (Chapter 4).

One framework that is helpful in understanding the role of variability in a manufacturing system can be seen in Figure 9. Previous thesis work at Dell done by Erik Dolak (Dolak, 2007) describes variability and flexibility as balancing forces. Bringing together the concepts from Chapter 2, we can begin to see how a variability shock (either internal or external) has two paths in order not to tip the balance: either to directly respond with flexibility to counter the variation, or to translate the variation into some sort of buffer so that the variation is not felt beyond the point of impact.

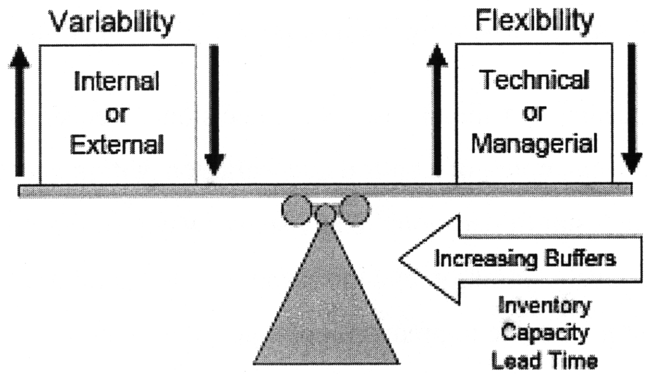

Figure 9: Interaction between variability, flexibility and the use of buffers. Adapted from Dolak (2007).

Variation can build up through a manufacturing system, or be dissipated as it moves through. Similar to shocks on a car, variation buffering is a mechanism designed to dissipate the variation. By adding buffers of inventory, time or capacity, the variation is absorbed by these complimentary metrics. This transfer of variation to decreased performance leads to one of Hopp and Spearman's (2001) "laws" of factory physics: "Increasing variability always degrades the performance of a production system." Although either response can protect the firm from feeling the implications of variation, the use of flexibility directly supports a CTO strategy while buffers often drive up costs and can cause a company to be less responsive to its customers.

3.2 Types of Variation

In order to avoid ambiguity, variation needs to be discussed within the context that it is experienced. The concept of "low" variation only has meaning in relation to some "high" variation. Descriptors such as timeframe, frequency, location, and any other characteristics of a specific variation are in order to communicate it to others, as well as in formulating a solution. Defining the problem is the first step in understanding what a solution will look like.

In this section we will look deeper into several classifications of variation: controllable, predictable, uncontrollable, external and random variation. While some characteristics of variation (frequency, intensity, location) are straightforward to describe, the ones listed above require some clarification before they can be useful in our discourse about variation. These characteristics help us classify variation by its cause rather than its effect. This distinction will guide us in the right direction for assessing the means to fix them later on.

Controllable variation occurs as a direct result of a decision. Decisions about batch size and replenishment cycles are examples of controllable variation within the system. Controllable variations can also be the result of decisions[7] many steps away. Similar to controllable variation is predictable variation. Cyclic variation due to seasonality, temperature, business cycle, etc. are not be controllable, but it is possible to predict these types of variation.

Uncontrollable variation has its root either outside of the firm or due to some form of randomness. External sources of variation such as general economic conditions, inflation, political instability, industrial policies and wage laws fall outside of the direct control of the firm. Random variation is also uncontrollable, but the sources are not known. One interpretation of randomness is that because we have imperfect (or incomplete) information, systems appear to behave randomly (Hopp & Spearman, 2001).

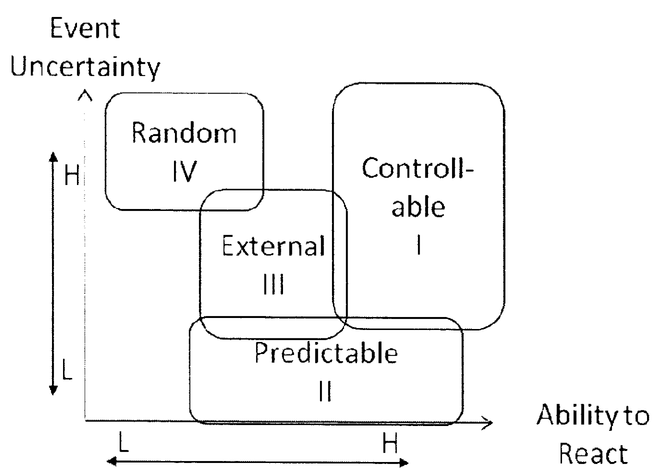

Figure 10: Variation defined by event uncertainty and the ability to react

[7] Or set of many decisions

If we classify these types of variation by the methodology suggested in Figure 10, we begin see that variation has some component of uncertainty (predictability) as well as a dimension associated with the firm's ability to react. Both controllable (I) and predictable (II) variations can be addressed with proactive and agile responses within the firm. By anticipating these drivers of inconsistency, variation can be proactively addressed to minimize its effects on the manufacturing system and the customer. In addition, when there is a direct correlation between an action and the resulting variation it is possible to use that action as a "knob": actively leveraging that decision to either turn on or turn off the resulting variation.

Uncontrollable factors should be accounted for when developing the strategies of a business organization. In the case that a firm cannot control the sources of variation or those sources are not known (the area above the diagonal in Figure 12), the operations strategy should be one which allows the firm to be robust to variation. Allowing for many possible inputs to a given process will mean that the system will not be overwhelmed when variation is inevitably experienced. Because the set of conditions will change without notice, there is no real way to get to an optimal solution, since the optimal scenario will only exist a small amount of the time. A robust policy is almost never optimal, but performs better over the loner time period.

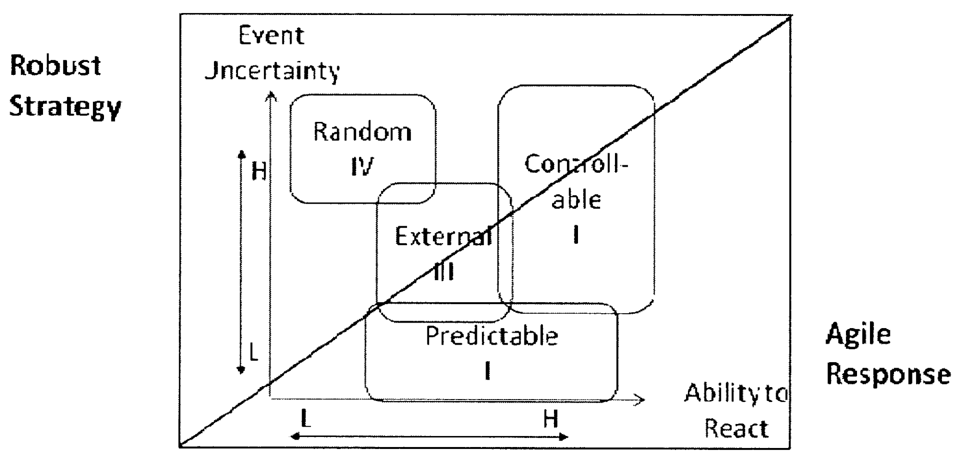

Figure 11: Proactive/reactive responses to variation

3.3 Sources of variation Associated with CTO

These examples are ones that I have observed to have the largest impact on configure-to-order manufacturing, though they are not exclusive to CTO.

3.3.1 Variation in expectations

Lean manufacturing teaches us that value should be assessed from the perspective of the customer. Variation is only an issue if it begins to manifest itself to the customer in a way that detracts from their value proposition. Customers judge a company on the company's ability to provide them with the product they desire at the right cost, quality, availability and features that the customer cares about. (Beckman & Rosenfield, 2008). Once variation begins to erode any of the indicators that a particular customer is interested in, that variation has become a problem. For example: if variation of incoming material causes a decrease in manufacturing yield and a resulting increase in manufacturing cost, the customer may feel that variation in the price they pay for the product.

On the other hand, if variation is left unchecked and there is no appreciable effect to the customer, it is fair to say that there is no need to deal with the variation. Some level of variation is either not detectable by the customer or does not change their willingness to pay for that product or service. In these cases it is foolish for the firm to chase after variation that is neither adding nor detracting value for the end customer.

On the other hand, customer expectations can also change over time. Customer expectations fall into five main categories: cost, quality, availability, features and environmental performance (Beckman & Rosenfield, 2008). The next time a customer goes to buy a product their minimum buy expectations are likely to have changed. The metrics and systems that exist to meet current customer needs may become outdated as customer needs change. This is also a function of the competitive marketplace; as competitors improve their offerings, the rest of the market must either keep up or compete on a different dimension such as quality or availability instead of cost.

3.3.2 Demand Variation

Variation in demand is likely *the* most important variable in any supply chain. The "fit" of a firm's strategy to the structure of their market often defines the success of the entire supply chain. We understand from earlier that highly volatile markets are best addressed with a configure-to-order strategy. "Everything else being equal, higher demand uncertainty leads to a preference for managing the supply chain based on realized demand: a pull strategy" (Simchi-Levi, Kaminsky, & Simchi-Levi, 2008).

The success of CTO in the face of high demand uncertainty is the ability to vary production output in accordance with actual customer demand. In the case of Dell, demand variation is intentionally buffered by an increased capacity in the system. In order to promise a short lead time for customers (5-7 days for desktop computers), Dell has to ensure that even at peak demand times their capacity is sufficient to meet promised lead times.

The lead time vs. capacity relationship can be quantified with Little's Law (Hopp & Spearman, 2001):

$$\text{Cycle Time} = \text{Work in Process} / \text{Throughput}$$

Where cycle time is the time from order input through order received, work in process (WIP) is the total number of orders in the system, and throughput is the rate at which orders can be processed through the system. In order to guarantee a short cycle time when there is little control over WIP (due to demand variation), the firm must control the throughput of the system. To push orders through the system faster, additional capacity is needed.

Predictable variation in demand is most easily understood when thinking about seasonality of products. For Dell the major predictable spikes in demand are seen at Christmas as well as back to school. For sales to their enterprise customers, large orders would often be seen at the beginning of a new fiscal year when budgets are big. These variations in demand are seen year after year, making it easier to anticipate changes in demand and plan for capacity accordingly. On a larger time horizon, Dell understands that customers are shifting their purchases from desktop computers to laptops; this is a slow decrease over a longer time period. This change in demand is predictable, but not cyclic. Unpredictable demand is also felt at Dell, and at most companies. This unpredictable portion of demand variation may be a combination of external variation as well as fully random variation. The current economic slowdown is a good example of unpredictable demand that has become somewhat predictable. This demand fluctuation was once unexpected, but has proven to be a trend. Astute observation and modeling may be helpful in moving "unpredictable" demand information into the predictable category.

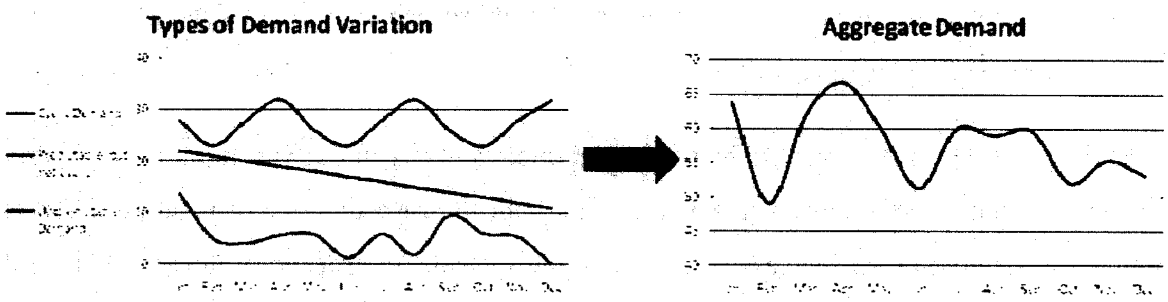

Figure 12: Aggregation of different types of demand variation

In Dell's version of CTO manufacturing, the production schedule is not created until customer orders are final. Every two hours the production schedule is re-optimized to take into account any new orders that may have been received. In this way, any swing in customer orders causes an equivalent swing in production scheduling. At times this is experienced as very slow time (low demand) followed by periods of overtime and weekend work (increased capacity). Unlike a build to stock model, gaps in the schedule cannot be filled with predicted demand. With thousands of product configurations in the case of Dell, building unordered product to the finished state would create enormous amounts of finished goods inventory. This is the opposite of CTO strategy.

3.3.3 Workforce Variation

Due to the quickly changing nature of Dell's industry, and their need for extreme capacity flexibility, much of their assembly work is done by skilled operators. There is typically more natural variability in a manual process than in an automated one. Automated machine assembly is generally more costly to achieve the same level of flexibility as compared with human capital. Flexibility in this case refers to both capacity flexibility as well as the ability to easily change between products and processes.

Worker capabilities: Not every employee has the same basic capabilities. It may not be possible for each employee to do the same job in the same way or at the same pace. For example, shorter operators may require a step in order to be in an ergonomic position for performing their job. Workspace that is adaptable to varying operator needs will allow for a larger pool of workers capable of doing those jobs.

Worker skills: Different jobs within the process require different sets of skills. As operators gain training and experience, it is possible that they can become proficient at multiple jobs. This leads to variation in the abilities of the individual workforce. When scheduling the manufacturing plant it is important to not only make sure all hours are staffed, but staffed with workers with the correct skills.

Variation within an operation: Inherent variability exists when one person does the same task again and again. Though they may get faster over time, there will still be variation from run to run.

3.3.4 Order Complexity

Each system that Dell assembles is matched to a specific customer order. Due to the large number of configuration options and the unpredictable nature of customer needs, an almost limitless number of combinations exist. This affects the factory in terms of work content and part attach rates. Work content describes the amount of assembly work necessary to complete a job, and part attach rate is a measure of how often a given part is used in a system (expressed as a percentage). This range of work content and part demand pose a particular challenge on Dell's lean manufacturing lines.

Lean manufacturing is based on balancing work content along the manufacturing line in order to achieve a smooth pace. Variation in work content between individual orders leads to unevenness in the manufacturing process, and decreased productivity.

For a labor capacity constrained system, the maximum capacity of a line staffed by n cross trained operators with identical work rates is (Hopp & Spearman, 2001):

$$Throughput_{max} = \frac{number\ of\ workers}{raw\ process\ time}$$

This is the maximum capacity of the line, but any variability in work rates between workers will cause capacity to decrease because the rate of the line is set by the slowest operation. Here we can see the compounded effect of differences in order complexity with workforce capability variation.

To address order complexity variation, Dell distinguishes orders by product family (sharing common parts) as well as by work content (high, medium and low). Scheduling decisions then create "batches" of orders with similar characteristics. By batching work with similar work content, Dell is able to reduce much of the variation in raw process time that leads to reduced capacity. Batching has its detractors as it is a tradeoff between the setup time between products and the full flexibility of being able to run any order at any time. Depending on the size of the batch (and length of the run), other orders are required to wait in queue before they can be manufactured. The longer batches are, the less frequently each product family/work content combination is run.

One final type of order variation that is worth mentioning here is Dell's venture into retail. In contrast to configure-to-order, their retail strategy involves manufacturing large runs of computers with the same configuration to be sold to large retailers. This type of order has zero variation from system to system, so it has the capability of running through the factory near the theoretical maximum rate. The difficulty in this situation is that flexibility has been built into every aspect of Dell's operations, from scheduling to materials handling to shipping. By sending standard retail systems through the factory, infrastructure is being used that adds unnecessary handling and processing to this retail flow.

3.3.5 Materials Variation

By definition, each process has a set of inputs, some form of transformation of those inputs yielding some output. In the case of manufacturing, incoming materials make up a large portion of the inputs to the process. Variability in the inputs to a process can then impact the transformation and the resulting output. The earlier in a process that variation occurs, the more likely it is to cause issues. Variation in incoming materials can be quite detrimental to a process. In many industries, any change to "form, fit, or function" is the threshold for unacceptable variation. Once inconsistencies in material can be identified as affecting the final product or the customer they need to be addressed.

There are many ways in which materials can exhibit variation to CTO manufacturing. The most obvious materials variations are one that can be seen, such as changes to the size or shape of the incoming material. Other physical variations include quantity, quality, color, etc. Any physical characteristic of the material can also be a source of variation. This very broad range of physical variation is the driver for the use of geometric dimensioning and tolerancing (GD&T). This system allows a firm to define not only the physical characteristics of a part being ordered, but also the range of variation that is allowable in those parts. GD&T becomes the language by which materials variability moves from the subjective to the objective.

Materials variation can be manifested in the cost of materials. Cost variation has the ability to change a product from profitable for the firm to unprofitable. Materials with large fluctuation in price are often bout under long term contract in order to provide stability for the firm.

Availability is likely the most important attribute of a given material in a manufacturing environment. While physical variation may mean a part can't be used, if the part is not present in the first place it most certainly cannot be used! Availability of materials is equivalent to service level. The materials team provides parts to their customer, manufacturing. When parts are not available to the customer when they need them, it is a stock out.

Within the context of Dell manufacturing there are four levels of availability: available for use (in the right place), available in the factory (somewhere else), available outside the factory (delay), or not available in any reasonable time period. Only "available for use" provides the manufacturing line the service they need, where each other case represents a stock out. Computer systems within Dell alert the materials team when parts are not available in the building. This prevents orders from being scheduled when parts are not available to complete the order. Parts are tracked at the stockroom level (eg, manufacturing, boxing, etc) but not down to their physical location. Problems do occur when the part IS available, but not in the right place.

Part demand variation is of particular importance to CTO manufacturing. Unlike build to stock, where orders (and their materials) are planned in advance, customer order variation in CTO leads to variation in the demand of materials. Even if overall demand is stable, the makeup of parts necessary to fulfill that demand is changing. At Dell, the frequency of usage for a single part is called its attach rate. Expressed as a percentage, attach rate describes how often the part is used. Though attach rate can give us a first pass approximation of usage over time, it does little to tell us about the variance of that demand.

Example: Part X is classified as a 2% attach rate part (suggesting 1/50 orders requires this part). After 2 hours of no demand for Part X, 10 orders in an hour all require Part X. If the manufacturing line is stocked with parts based on historic attach rates there is likely to be a stock out when many orders call for that low attach rate part.

3.4 Chapter Summary

Variation is inevitable, and a key driver for companies to move to configure-to-order manufacturing. Variation can take on many forms, but in most cases variation degrades the performance of an optimized system. Depending on the source of the variation (either predictable or not) and the firm's ability to react to the variation, the tools with which we address this variation change.

Within CTO manufacturing, major sources of variation include customer expectation, demand variation, workforce variation, order variation and materials variation. These categories are by no means mutually exclusive or collectively exhaustive, but rather help to describe a large number of issues that are faced in CTO manufacturing. These different sources of variation often interact with each other, building into more complex forms of variation as they travel through the production process. While it is impossible to remove all variation from a system, in the next chapter we will examine ways to use flexibility to either anticipate variation or become robust to its influences.

4 Role of Flexibility in CTO Manufacturing

As we began to explore at in Chapter 3, the introduction of variation into a system can be countered in three distinct ways: removal of variation, variability buffering or the use of flexibility. According to Hopp and Spearman's laws of factory physics, the corollary to the Law of Variability Buffering is Buffer Flexibility:

"Flexibility reduces the amount of variability buffering required in a production system"

While flexibility is one answer to buffering, the approach a firm takes should be in alignment with their corporate strategy and their market positioning. Buffering and flexibility are both tools that address variation, and each tool may be chosen based on the desired effect. By starting with the customer to understand the performance metrics that are important to them (cost, availability, quality, etc), the firm can chose a response to variation that aligns with the customers' needs. For example: if availability is of top importance to the customer, variation in demand can be buffered with a either increased capacity, or increased finished goods inventory. This approach will ensure that the effects of variation are counter to the customers' desire for availability. It is important to remember that value is in the eye of the customer, and the firm should focus on their customers while developing a flexibility strategy.

It can be stated that one of the great benefits grained through the use of flexibility is customization. Put another way, in order to do customization well, a firm must be adept at using flexibility to its advantage. "How effectively firms can use the flexible technologies that do exist, create new, more responsive processes and management methods, and use the inherent flexibility of workers to more quickly develop and produce new products and services that more closely match individual tastes is the key to the new paradigm." (Pine, 1992)

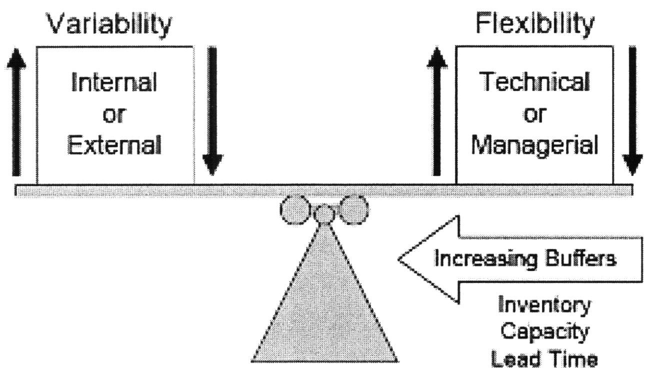

Figure 13 : Interaction between variability, flexibility and the use of buffers. Adapted from Dolak (2007)

The model above illustrates the forces of variability and flexibility acting on a given operational strategy. A shock to the system, such as in increase in variability, requires a response by one of the other forces in order to keep the system balanced. We can reduce the effect of variability on the manufacturing line with one of the following generic responses:

- Reduce or eliminate the source of the variation
- Create buffers to insulate manufacturing from the effects of variation
- Develop a flexible infrastructure that can balance the variation

To truly achieve the balance illustrated in Figure 15, the economic costs of developing the flexibility must be favorable when compared with the additional revenue (or avoidance of lost revenue) that the firm experiences. It is important to make sure that changes made in the name of flexibility are not so nearsighted to damage the company in the future. Long term viability of the company is the ultimate goal of any organization, and decisions made for a positive outcome today may be at the expense of doing the right thing for the future. "When all decisions are based on only the short term, the results are predictable: people become dispensable, vendors are ruthlessly pitted against one another, and the name of the game becomes getting today's job done" (Jennings, 2002). Truly productive companies understand that while a business must deliver in the short term, the real focus must be on providing long term value to the customers and shareholders.

4.1 Framework for Evaluating Flexibility

The first step in developing any application to solve a real world problem is to define the problem. A clear understanding of the elements we plan to address will help us define our path of action as well as the success criteria. The framework proposed here is an adaptation of work published by David Upton called "The Management of Manufacturing Flexibility". This framework for evaluating flexibility in configure-to-order manufacturing involves defining flexibility in four dimensions: direction, dimension, time horizon and element. These distinctions will allow for greater clarity as you think about addressing variation with flexible solutions in your firm.

A brief overview of this framework is outlined below as well as in Figure 14:

- Identify the type of variation you are looking to "deal with"
- Define the dimension of change upon which flexibility is necessary (be specific here)
- Understand the time period that flexibility is required to be evaluated
- Define the elements which will provide the appropriate type of flexibility to your system

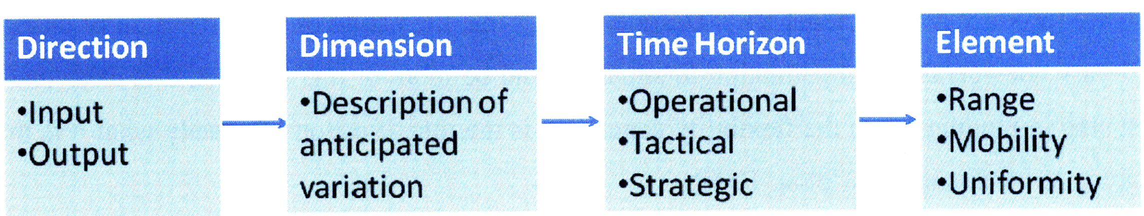

Figure 14: Framework for evaluating flexibility.

Direction of Flexibility: Flexibility can either be defined as the ability for a process to accept a range of inputs and produce a set output, or the ability for a single process to produce multiple outputs. We will distinguish these two directions of flexibility as input and output flexibility. Figure 15below demonstrates these two directions of flexibility. Though this represents a mutually exclusive set of directions, it is entirely possible and likely that the flexibility solution desired will have some combination of input and output flexibility. It is of value here to separate the two directions in the definition phase, as each can lead to a different set of solution. After the definition is complete, the solution sets can be combined to create the combined flexibility solution.

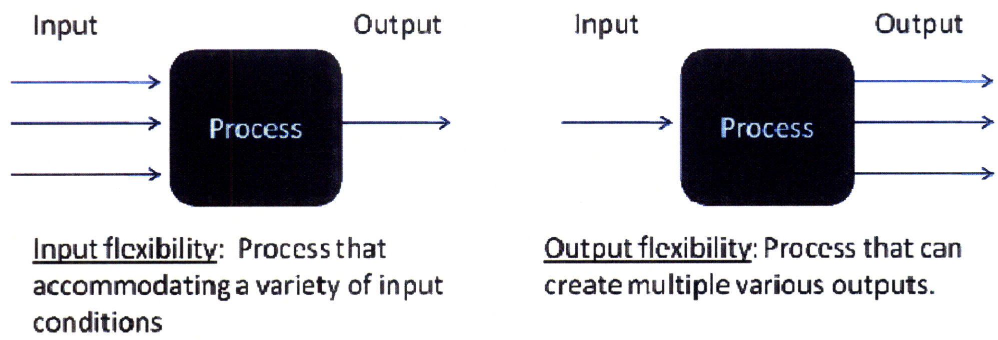

Figure 15: Direction of flexibility: input and output flexibility

Dimension of Flexibility: In this part of the framework we identify the magnitude and type of variation we are planning to address with flexibility. The outcome is a detailed description of the nature of variation that is to be performed or tolerated in the new system. From our discussion of variation in Chapters 2 and 3 this dimension can range from materials thickness, order frequency, product variety, etc. The dimension can be either continuous (range of input dimensions) or discrete (product A vs. product B). "Despite the fact that the nature of the dimension of change will vary considerably from situation to situation, and be more or less abstract, it is clear that a first step in pinning down the flexibility concerned is the identification of exactly what it is that is going to be changing" (Upton, 1994).

This may not correlate to the full range of variability we experience. We can build a system that addresses a broader range of variation than has been experienced (precautionary) or a more narrow range (conservative). The driving force for this decision is the value proposition of adding a large range of flexibility. It may be worth limiting the range of variation accommodated if adding a larger degree of flexibility is cost prohibitive or of diminishing returns.

Flexibility Time Horizon: This descriptor allows us to define how often changes or adaptations will occur, ranging from continuous adaptation to strategic decisions made every couple of years.

Decisions made over long time horizons (such as factory sizing) tend to be associated with a higher commitment level and flexibility that is at a more strategic level. Decisions made on a more continuous basis are often more operational in nature and commitment level to this change is low. Tactical flexibility falls in the middle of this range, with changes occurring weekly or monthly and have some intermediate level of commitment.

In defining the flexibility time horizon we specify both the frequency of change as well as if it is operational, tactical or strategic in nature. Table 5 below outlines several time scales for flexibility and some associated characteristics of those options.

Time Scale	Control Mechanism	Type of Flexibility	Type of Change
Daily	On the Floor	Operational	Continuous
Weekly	Site Management	Operational or Tactical	Semi-Continuous
Quarterly	Central Planning	Tactical	Discrete
Yearly	VP Level	Strategic	Discrete

Table 5: Proposed framework for understanding timescale of flexibility

<u>Flexibility Element</u>: Once we have defined the dimension of variation as well as the time horizon of the changes we can begin to evaluate the type of flexibility that will be needed to address the defined situation. Here we are defining the expected outcomes of our flexibility solution. Upton proposes three characteristic dimensions by which flexibility can be described and then measured: range, mobility, and uniformity (Upton, 1994).

- **Range:** Defined by the range of products or services an operation can provide by measuring the set of values the operation is able to deliver or accept along a given dimension. Examples include being able to accommodate a materials thickness variation of +/- 2mm, or the ability to produce three different products on a given manufacturing line.
- **Mobility**: Measures the cost or effort of making a change within the range. This describes the transition penalties (in time or cost) associated with making a change. Low values of mobility cost are associated with a low penalty to change. From Upton's original definition of flexibility – mobility assures "little penalty in time, effort [or] cost."
- **Uniformity**: assesses the ability of the system to provide consistent performance across the identified range of flexibility. Once the range of inputs has been defined, uniformity

measures how well the system can produce a uniform output given an input within the range. This is particularly relevant to input flexibility, as the goal is to produce a standard output from a range of possible input streams. Uniformity allows flexibility with "little penalty in … performance."

<u>Use of Framework</u>: Now that we have defined the elements necessary to complete this framework we can begin to understand how it is used. Table 6 illustrates one way to use this framework as a checklist in defining your variation as a flexible solution.

Direction	Dimension	Time Horizon	Element	
			Range:	
			Mobility:	
			Uniformity:	

Table 6: Template for defining flexibility

With the framework now in place, we can begin to see how variation and flexibility interact with CTO manufacturing system and how they can be defined and addressed. Figure 16 is a schematic of how long term variation can manifest itself in multiple time horizons. Here we see how demand variation in the long term can be addressed by building new factories, in the medium term it can be solved by increasing flexible capacity inside existing factories, and in the short term adjusting scheduling practices on the shop floor. Each of these manifestations of flexibility are viable responses to a single source of variation.

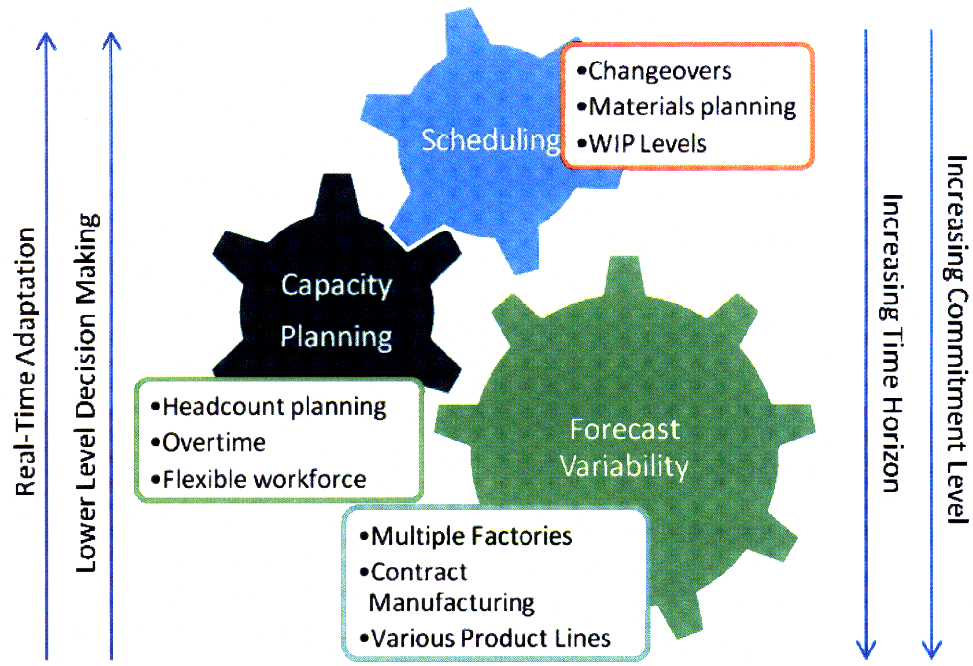

Figure 16: Interactions between variation and flexibility

Using the framework as we have described it here, we can evaluate the issue of variable demand using Table 7 below. We define demand variability as a type of input flexibility, the ability to accept a range of demand to the system. Dimension of change is the range we expect for incoming order variation, in this case between 2,000 and 10,000 orders per day. Our time horizon for making the change we chose to be weekly[8]. The outcome we desire includes being able to accept any input from the range of 2,000 to 10,000 orders per day while minimizing the time required to achieve this flexibility without any noticeable impact on our promised lead time. The solution I have proposed here involves building flexibility within the workforce, with three days notice we gain the ability to flex our capacity to accommodate the appropriate level of orders. This solution allows us a medium level of flexibility as it requires a delay of several days.

[8] We could react slower or more quickly to this variation if we choose. Each different time horizon defines the outcome in a different way.

Direction	Dimension	Time Horizon	Element		How to achieve
Input	Incoming demand ranges from 2,000 orders per day to 10,000 orders per day	Weekly, tactical.	Range:	2k orders to 10k orders manufactured in a day	Scale worker hours to the demand for the week. With three days notice we can ask workers to work overtime. Can backlog orders for 2 days as we adjust worker flexibility
			Mobility:	Need to be able to scale production quickly	
			Uniformity:	No change in promised lead time to customer	

Table 7: Example of framework used on demand flexibility

4.2 Forms of Flexibility

By this point we are fully capable of describing the variation we experience (or expect to experience), and then using our framework to define the solution we are looking to create with flexibility. The one aspect that remains for us to understand is how we can achieve the flexibility that we desire. Our final goal is to develop flexibility solutions that both meet the customers' needs and allow the firm to be agile in the market place

"The situation of uncertainty (instability) in [CTO manufacturing] can be eliminated by developing suitable strategic alliances and leveraging people and information technology." (Gunasekaran & Ngai, 2005). This is so well put that it is worth repeating: flexibility is achieved through "developing suitable strategic alliances and leveraging people and information technology." In this section we will explore different ways to leverage this approach in terms of physical flexibility, operational flexibility and also information flexibility. Each manufacturing environment and situation will require a different implementation of flexibility; this discussion is meant to incorporate broad concepts rather than specific solutions.

4.2.1 Physical Flexibility

Physical flexibility is represented by any part of the physical environment that can either accommodate different inputs, or deliver several types of output. One elegant example of this is the use of flexible rope lines used in movie theaters and at amusement parks. The ropes and stantions that define the shape of a queue can easily be reconfigured to accommodate changes in the length of the line and can be moved to change the placement of the line. With only the investment of time, the physical environment of the line can be changed easily and quickly.

4.2.1.1 Manufacturing Flexibility

Newman et al. (1993) observed that "manufacturing flexibility is the most obvious response to external uncertainty, because of its accommodating nature" (Newman, Hanna, & Maffei, 1993). The accommodating nature he refers to is the ability of a manufacturing system to either accept input variation or produce a variety of outputs[9].

The use of tooling that is not specific to a single product, but can be re-configured to suit the needs of multiple manufacturing processes is an example of manufacturing flexibility. Here we are trading off the efficiency of equipment that is optimized for a given process with the value of being able to change either the inputs or outputs from that equipment with little penalty. For manufacturing processes that are expected to run large volumes of a single product for a very long time and do not anticipate much variation in either input or product output, this type of flexibility is of little use. On the other hand, with the advent of mass customization and configure-to-order, manufacturing flexibility is a key enabler for being able to produce small runs of varied products in order to match customer demand.

The acquisition of flexible process technology is a strategic decision that often requires significant capital and planning. It is important to first understand the range of inputs and outputs desired from the manufacturing system before the purchase of flexible process technology and tooling. In a configure-to-order manufacturing environment, this technology can include flexible automation, re-configurable work stations, and human labor. As each industry requires different types of technology, it is of little value here to provide an exhaustive list of specific flexible technology.

<u>Automation</u>: Robotic automation provides flexibility in that it can be programmed to perform multiple tasks. This flexibility can take the form of being able to process different types of products in a single time period, or simply be re-purposed when the next product is introduced.

[9] Directional flexibility as defined by our flexibility framework

This tooling is generally quite expensive, but provides the flexibility to use the same tool for multiple product cycles.

Work Stations: Flexible work stations assemble much like Lincoln logs. Modular structural components can be attached in any number of configurations with little penalty in time. This allows for adaptation of the work environment to accommodate processes changes. New work aids can also be created as continuous improvement dictates. This configurability is also applicable to conveyor systems. If the work environment will be changing dynamically, the firm would do well to consider a conveyor system that is equally adaptable.

Human Labor: Arguably the most flexible manufacturing tool available is human ability. While costly machines use specialized tools to produce specific outputs, humans can produce any number of motions and tasks with very little change over time. The flexibility and adaptability of human motion surpasses the abilities of most robots. The variation of human motion is greater than variation seen with automation. This imprecision of human motion can be countered by designing with assembly in mind. Design for Assembly (DFA) uses design techniques to make the assembly process more robust for human and robot assembly.

In a manual assembly environment, capacity is often proportional to the number of workers doing the assembly. By adding additional workers or shifts it is feasible to increase capacity 2-3 fold without adding physical capacity. The same is true of decreasing capacity.

4.2.1.2 Capacity Flexibility

Capacity was described by Hopp and Spearman as one of three main tools for variation buffering. Extra capacity can be used to dampen the effects external variation inside the manufacturing environment and eventually to the customer.

In the previous section we discussed the flexibility of human labor for scaling capacity quickly. A good working relationship with the workforce is essential if you plan to use labor flexibility extensively. Workers expect some level of stability in work and in pay. Frequently changing the size of the workforce might scare away potential workers.

Another way to gain flexible capacity is to contract external capacity. In Chapter 1 we discussed the extensive use of contract manufacturers (CM) and original design manufacturers (ODM).

Outsourced manufacturing allows a firm to add capacity in small increments to accommodate additional capacity. Once demand grows large enough to warrant another factory capacity can be build internally and orders moved back in-house. Contract manufacturing may be more difficult for CTO manufacturers as the IT that enables CTO must be able to communicate orders to the contract manufacturer as well.

A further strategy for leveraging contract manufacturers is to outsource more of the upstream manufacturing. By outsourcing parts of the process downstream from the push-pull interface, contract manufacturers can build-to-forecast for components used in final assembly. Because the lead time from Asian contract manufacturers is often longer due to ocean travel, this strategy can help accommodate the additional time due to the demand pooling associated with common components.

4.2.2 Operational Flexibility

In Mass Customization, Joseph Pine comments that in CTO manufacturing "processes are more important than products". In his argument, a stable and consistent process allows for fast paced product innovation and manufacturing. In practice, companies that have successfully implement configure-to-order manufacturing spend quite a bit of time focused on process improvement activities. "Customers in increasingly heterogeneous markets demand customized products, which creates the need to re-engineer processes for mass customization. Individual new products then flow from these flexible, responsive but long-term and stable processes." (Pine, 1992)

Earlier we discussed the role of people in making flexibility a reality. This workforce has the power to enable process improvements in the organization and drive a culture of continuous improvement. "At the heart of the ability to respond to process change or to take on process changes is the ability of the organization to learn" (Senge, 1990). By engaging the learning power of the workforce, a firm can amplify the success of its CTO manufacturing.

There are several innovations that have helped enable flexible processes necessary for a CTO manufacturing process to work more effectively. These include the following (Pine, 1992):

- Just-in-time delivery and processing of materials and components that eliminate process flaws and reduce inventory carrying costs
- Reducing setup and changeover times, which directly lowers run size and cost of variety (As setup costs go down, the optimum lot size will also decrease.)
- Compressing cycle times throughout all processes in the value chain, which eliminates waste to increase flexibility and responsiveness while decreasing costs
- Producing upon receipt of an order instead of a forecast, which lowers inventory costs, eliminates fire sales and write-offs, and provides the information necessary for individual customization.

We will go into more depth in this section looking at flexible supply chains, standard work, and reduced setup time.

4.2.2.1 Flexible Supply Chain

The ability of the supply chain to react in coordination with the needs of the firm is a strong competitive advantage if it can be achieved. By integrating with suppliers to share real time demand information the firm can reduce the impact of the bullwhip effect[10], instead coupling demand all the way down the supply chain.

At its extreme level, the arrival of parts just-in-time (JIT) reduces the total inventory to almost zero. In JIT, replenishment is initiated only when requested by a downstream operation. By integrating these signals all the way up and down the supply chain, movement of parts is controlled by final customer demand. This reduces the amount of parts inventory held in stock and hence the holding cost and obsolescence costs associate with that inventory.

An additional step towards a more flexible supply chain is the use of vendor managed inventory (VMI). Under VMI, the manufacturer's suppliers will hold, manage, and deliver materials to the manufacturer as needed to support production. The VMI partnership requires close cooperation between both the manufacturer and the vendor. This purpose of this partnership is to reduce

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[10] The bullwhip effect describes the systematic increase in variability that occurs as we travel up the supply chain. This effect is caused by mistrust as well as delays in demand communication.

This relationship is quantified by the economic order quantity (EOQ) model expressed in below (Hopp & Spearman, 2001):

$$Lot\ Size = \sqrt{\frac{2 * (Setup\ Cost) * (Demand\ rate)}{(Annual\ holding\ cost)}}$$

A visual representation of EOQ is provided in Figure 17. You can see that the economic lot size is defined by the minimum point on the total cost curve. This total cost curve is the relationship between holding cost and setup cost. As setup cost is decreased, the economic lot size also decreases. The theoretical limit of this relationship culminates in a lot size of one correlated to zero setup cost.

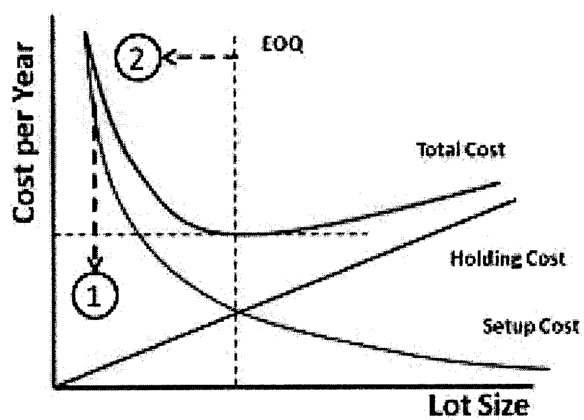

Figure 17: Graphic example of Economic Order Quantity (EOQ).

In order to approach a setup cost of zero, changeover time must be minimized. This has two major implications for moving to more flexible operations:

- First, in order to be more fully flexible with varying demand it is important to understand your set-up costs either in terms of time or money spent.
- Second, in order to drastically reduce lot size it is important to first focus on reducing the setup time between runs.

By studying the product changeover process closely, there are likely opportunities to make that process faster and more efficient. Use of lean tools such as value stream mapping will allow you to better understand the relevant steps necessary for the setup, as well as how much time is spent inventory and improve service levels on incoming materials. In addition, the supplier has the ability to reduce safety stock levels and smooth out production (Smith, 2000).

One final form of supply chain flexibility worth discussing is the strategic use of pooled inventory. By strategically position inventory within the supply chain, reduced lead times and robust availability can be better attained. This inventory positioning strategy takes advantage of stocking inventory upstream of differentiation steps. In this way fewer distinct parts need to be stocked and demand variation is aggregated over fewer parts, buffering the variation experienced downstream.

4.2.2.2 Standard Work

Taiichi Ohno famously stated that "without standard work, there can be no improvement." This statement is a central truth of the very successful Toyota Production System. This standard work focuses on the workers and the steps they must take to produce the product or service (Whitmore, 2008). Standard work involves codifying the best work practices and following those instructions every time. Standard work enables consistent product quality and is the baseline for continuous improvement. Therefore, conformance to standard work helps to create the results that allow a firm to stay competitive. In order to counter the variation inherent in a human workforce, standard work can help to make abnormalities visible.

Once standard work is in place, the workforce can be enabled to understand how to improve the current work performance. In this way "regular work is tightly coupled with learning how to do the work better. These principles lead to ongoing improvements in reliability, flexibility, safety and efficiency, and, hence, market share and profitability" (Spear, 2006).

4.2.2.3 Product Changeover and Setup

Determining optimal lot size in manufacturing is accomplished by balancing inventory holding cost of finished goods with the cost of changing the setup to run a different product. The more costly it is to change production, the more a firm will want to manufacture between changes.

adding value to those steps vs. wasted time. Even if you decide not to take lot size down to the smallest size possible, any gains you can make in setup time will be a direct benefit to your line capacity and to the company's bottom line. "When the changeover costs are drastically reduced, the EOQ moves down the curve to a run size of one, resulting in a much greater variety at much lower costs. Particularly when customers' desires are changing rapidly or demand is uncertain, the cost savings of eliminating changeover time can be tremendous." (Pine, 1992)

4.2.3 IT Flexibility

As we discussed earlier in this chapter, flexible supply chains are enabled by highly integrated communication. "the instant application of information throughout a firm's value chain allows it to respond quickly to changes in demand and designs" (Pine, 1992) If the firm is competing on availability they will benefit from "investment in IT that links the members of the supply chain with information that allows rapid decision making and response." (Beckman & Rosenfield, 2008). Full IT integration requires is a highly strategic decision that cannot be easily reversed.

This IT integration may manifest itself all the way up and down the supply chain. Starting with the customer interface, information technology can allow the customer to enter their own orders through the internet. Once an order is entered into the IT system all or some of the follow-on processing such as product specification checking, financing, BOM verification and production scheduling can be performed automatically.

In order for IT flexibility to give the firm a strategic advantage, it must be founded on IT that cannot easily be replicated by competing firms. To gain a sustained advantage, companies like Amazon.com have created proprietary internal software to integrate their factory and supply chain. In some cases proprietary setups of packages such SAP or Oracle can provide a competitive advantage.

Flexibility enabled with IT:

- <u>Material Tracking</u>: This type of IT application will allow a company to know in real time how much material exists and where it can be found. This information is only as complete as the IT system supporting it and requires integration of tracking mechanisms[11] throughout the factory.

- Order Management: The interaction with customers can be controlled with internet infrastructure. Dell has successfully implemented their direct model using the internet to track orders as well as to direct customers to certain preferred products. This concept is known as demand shaping and will be explored further in Section 5.1.1.
- Dynamic Scheduling: Integrating IT into the production scheduling and manufacturing yields the ability to optimize production sequence in near real-time. By dynamically assessing run lengths and changeovers based on actual orders in the queue, efficiencies are gained in production.

5 Examples of Flexibility within Dell

Returning back to the topic at hand, we want to understand how a factory that is already in existence, can avoid some of the major pitfalls that come along with variability by utilizing its inherent flexibility in near real-time. How can managers on the floor use short term flexibility in order to make the effects of inevitable variation less evident to the customer and to the bottom line? Most often these managers are held accountable to the operating cost of the factory, these examples from Dell will help you get a feel for what their management has been doing to manage costs when variation inevitably occurs.

5.1.1 Demand Management

"Most companies assume that they do not have any control over demand. However, demand can be managed by exercising control over prices promotional efforts and the quality of the services offered" (Gunasekaran & Ngai, 2005).

For the CTO strategy to be successfully implemented demand management techniques must be taken into consideration to manage fluctuations in volume. Such techniques include marketing incentives, pricing strategies, and an increased flexibility with suppliers, all of which help to balance supply with demand and allow the pipeline to change right along with the demands of

[11] Such as barcode scanners and computer workstations

the consumer (Gunasekaran & Ngai, 2005). This concept turns the idea of demand variation on its head. Instead of thinking of demand as an external source of variation, companies can reach outside of the firm boundary and interact with their customers in a new constructive way. By proactively guiding the customer in the direction that is most convenient for the firm, both parties can be better satisfied with the resulting service.

Dell practices a form of demand management known as "demand shaping". At the tactical level, the focus is on understanding demand patterns and then influencing customers' demand toward available supply, using the levers of price, promotion and products/services bundling (Dey & Singh, 2007). This practice relies heavily on coordination between supply chain planning, marketing and IT for its success. Without a smooth flow of information across the company, and real-time feedback to the customer it would not be possible to fully utilize demand shaping principals.

Within the context of our flexibility framework demand shaping has the following attributes:

Direction	Dimension	Time Horizon	Element		How to achieve
Input	Incoming materials availability. Certain parts not available	Continuous, operational	Range:	Some standard parts not available for customer choice	Use IT integration to alert sales of part shortages. Price available options such that customer choice is moved away from less available products.
			Mobility:	Need the ability to influence customer demand	
			Uniformity:	No change in customer perception of the product	

Table 8: Flexibility framework for demand management

5.1.2 Dynamic Work Allocation

In Chapter 1 we discussed the dynamics between the different manufacturing facilities within Dell. The factories EG1, WS1 and TMC work together to produce desktop orders for the North American market. Redundancy in certain capabilities allows for factories to back each other up when one is over capacity, or has other issues prevent it from meeting demand.

	Low ← Total Process Volume → High		
High Variety of Products ↑			TMC
Range of product mix		WS1	
↓ Low variety of products	EG1		

Table 9: Dell's desktop manufacturing facility strategy (cerca 2004).

In once recent example, necessary IT updates at WS1 took longer than expected. Instead of holding up production of orders scheduled to WS1, both EG1 and TMC took on additional capacity in the form of extended work shifts to help relieve the pressure. In this way customer demand was fulfilled out of a flexible network of factories. The combination of a network of factories and a flexible workforce allowed customer demand to be fulfilled in the face of a manufacturing interruption.

Direction	Dimension	Time Horizon	Element		How to achieve
Input	Variation in effective capacity (factory down or slow)	Weekly, operational and tactical	Range:	30% of capacity not available	Redundant factory network structure provides backup. Flexible workforce can surge capacity in case of shock.
			Mobility:	One day response to a shock	
			Uniformity:	No change in customer perception of the product or service.	

Table 10: Flexibility framework for dynamic work allocation

5.1.3 Flexible Workforce

5.1.3.1 For Cost Reduction

The primary cost incorporated into EG1 metrics is direct labor. Labor cost is justified when it is balanced by available orders and efficient scheduling methodologies. In order to drive for excellence in cost and productivity metrics, Dell must insure that scheduling is done in a way to minimize downtime due to product changeovers while meeting the needs of their customers. Current detractors to the metrics of Cost Per Box (CPB) and Unit Labor Hours (ULH) include materials changeovers, low production build rate, as well as low order backlog.

Earlier in Dell's history they utilized a one man build process[12]. With this manufacturing technique each "builder" was required to know how to manufacture several different types of systems from beginning to end. Because of the specialized knowledge necessary to be able to build many different systems, these builders took many months to bring up to full speed. This individual build system worked well for early Dell when there were fewer types of systems to build. As more product families entered Dell portfolio, this type of assembly process became much harder to manage.

In the past 2 years Dell has been transitioning many of their factories to a modular flow model where 6-8 people were assigned to a flow line where each person is responsible for a sub-section of the system. Requiring fewer specialized workers overall, training time was reduced down to 2-3 days[13]. Additionally, these new flow lines used much less floor space to produce the same amount of output. This Lean transition allowed Dell to substantially reduce the square footage required as well as reduce the supporting workforce. This reduction in workforce was partially driven by materials being placed at point of use, rather than kitted one by one at the beginning of the line.

The example of changing from one man build to flow line is not meant to be something that is done overnight. This example is used to illustrate the flexibility that can be gained by reducing waste in the manufacturing system and utilizing the inherently flexible nature of human ability.

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[12] Full description of old process can be found in Appendix A

[13] Interview with training staff, March 2009

Direction	Dimension	Time Horizon	Element		How to achieve
Input	Cost variation due to inconsistent demand	Yearly +, Strategic	Range:	Flexibility to arrange manufacturing to accommodate new product demand	Implementation of single piece flow lines to reduce labor necessary for production. Define value added steps and reduce all other waste.
			Mobility:	Modular change over the course of several months	
			Uniformity:	No change in customer perception of the product or service.	

Table 11: Flexibility framework for cost reductions associated with flexible workforce

5.1.3.2 For Flexible Capacity

We have discussed at length the use of human labor to augment capacity. In this section I will address the drivers that allow a firm to use labor in this way and specific methods that are employed at Dell.

<u>Collaborative work environment</u>: While many industries are plagued with labor issues, Dell has been able to maintain a collaborative work environment with their employees. Though Dell does not oppose their employees from joining a union, they do proactively try to provide the workers with a sense of community and stability that a union also provides.

> "We work hard on developing an open direct relationship with employees. We try to communicate with employees and keep them informed regarding why the business needs to change. In this industry, we need to be able to not only maintain flexibility but to move quickly."[14]

The result of this open relationship is that Dell can ask more of its workforce than most other companies can. When business needs require, Dell can ask their staff to work extra hours, even weekends. At the end of the year when demand is at its peak, it is not uncommon for the workers to work 10 hour shifts, 7 days a week. In a more labor restrictive environment this extraordinarily workforce flexibility is rarely heard of. Because Dell does not need to provide very much notice to call overtime, they are able to flex their capacity much more nimbly than many of their competitors.

[14] Interview with HR representative, March 2009

The flip side of this flexibility is the necessity to manage the relationship with the employees. Though specific laws don't limiting how work is allocated, it is important to treat the workers equitably. Example: if shifts are being cut early every day, workers might not be getting earning money to pay their bills. Flexibility for the company comes at the expense of flexibility for the employees. It is important to understand the limits of your workforce because they have a choice in employment as well.

<u>Use of temporary workforce:</u>

We discussed earlier in this section about the benefits of moving from "single builder" to "modular flow" manufacturing at Dell. One of the big benefits gained from that transition was the ability to more easily rotate different employees into those once specialized positions. In effect this move has lowered the minimum requirements to get a new employee onto the build line. This shorter ramp time for new workers makes it easier for Dell to use temporary workers to offset changes in demand.

At points in Dell's past, substantial portions of their workforce in a given factory has been made up of temporary workers. The use of temps allows Dell to quickly respond to upswings in demand. By holding a baseline number of temps they can also flex downwards when demand is lower than expected. These temporary workers act as a capacity buffer with a very short lead time to implement. At times when it is known that demand will be unusually high (holiday season, end of quarter), Dell can work with the temp agencies in advance to make sure the workforce will be available.

Direction	Dimension	Time Horizon	Element		How to achieve
Input	Variation in incoming demand. Resulting variation in headcount.	Weekly, operational	Range:	+/- 50% in capacity	Work collaboratively employees so they will be willing to work extended shifts and weekends. Bring on temporary workers to allow for larger swings in capacity.
			Mobility:	One day notice to bring on 10%, one week notice to bring on additional capacity	
			Uniformity:	•Minimal employee turnover •No change in customer perception of the product.	

Table 12: Flexibility framework for capacity variation enabled by flexible workforce

5.1.4 IT Systems

Use of internet:

One of the key differentiators, and strategic strengths, at Dell is their use of the internet to interact directly with the customer. This internet presence allows for a large volume of information to be collected about each customer (order specifications, address information, billing, what they looked at and didn't buy, etc). On the upstream side, Dell uses the internet to communicate with their suppliers as well. This end-to-end ubiquitous interface both frees up humans from doing this work, and ensures that information is transmitted with very little delay. "Internet reduces the lead time for order processing and transportation; and effective inventory management, and pickups and deliveries of shipments can be more accurately monitored" (Gunasekaran & Ngai, 2005).

Use of internal IT systems:

Because Dell has historically used the direct model to create computers to customer demand, their IT systems have also developed around the direct model. As Dell's business has grown and become more complex, so too has the informational infrastructure that enables it. Rather than use off the shelf software, Dell has tailor made IT solutions that fit their particular needs.

IT solutions are only as flexible as they are designed to be. Many of the systems and interfaces that were precisely what Dell needed 10 years ago have become outmoded as business is changing faster than their IT solutions. As is the case in many companies, Dell's IT system is configured in a way that was best suited for its past. Due to competing business priorities, funds for IT projects have been reigned in. Compounded with the current economic climate, most corporate spending has slowed substantially; including spending on IT.

Data Octopus[15]:

In order to make all parts of Operations, Sales, Marketing and Supply Chain fully integrated, Dell maintains many different IT solutions and packages, each with a certain area of specialty.

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[15] A jumble of arms

While "Glovia" can manage inventory levels in the factory, "HUB Collab" is needed to coordinate with vendor managed inventory, and Factory Planner is then used to schedule work into the manufacturing line. The number of systems and their unique ways of operating make it difficult to collaborate between the systems as well as with the outside world. In most cases the output of one system needs some help to become the input for the next; this often requires human intervention.

While it may sound straightforward for Dell to move on to a new IT infrastructure, it is far from easy. At this point they are almost too big to change. The cost and difficulty of switching such a large IT infrastructure to a new system would be enormous. One possible solution we will explore in Chapter 5.1.6 is the advantage of outsourcing and its positive effects on the IT system.

Direction	Dimension	Time Horizon	Element		How to achieve
Input and Output	Variation in needs of an IT system	Every Decade, Strategic	Range:	Account for larger range of future options (demand, customers, products, manufacturing processes, geographies)	Solution unknown. One possibility includes outsourcing the majority of production to another company. This reduces the demand on the old IT system.
			Mobility:	Quite costly	
			Uniformity:	•Minimize impact to the business •No change in customer perception of the product	

Table 13: Flexibility framework for Dell's IT system

5.1.5 Inventory Management

Dell's use of vendor managed inventory (VMI) is a key enabler to their CTO supply chain. While long term planning is still conducted as collaboration between Dell's forecasting department and the supplier, short term materials planning can be done in a reactionary manner almost on a continuous basis. The ability to pull material from the suppliers with 2 hours notice allows for very adaptable manufacturing strategy. With the implementation of Lean Manufacturing and many of their manufacturing sites, VMI provides materials on a just-in-time basis. Part of VMI agreement includes a stipulation that vendors keep their inventory within certain proximity of the Dell factory. In this way VMI parts can be delivered with a turnaround time as low as 2 hours. This allows Dell to hold about 3 hours worth of inventory on their premises, reducing their need for warehouse space. Dell does not own most of their inventory until it is delivered to the factory, so this also reduces the financial burden of inventory.

Dell "pulls" parts from suppliers just as they are needed for production. Communication technologies such as fax or phone messages with replenishment requirements are forwarded to suppliers based on actual orders (Bowersox, Stank, & Daugherty, 1999). Strategic compliments to this low inventory model include product modularity, risk-pooling, e-procurement, and strategic alliances. (Gunasekaran & Ngai, 2005)

Direction	Dimension	Time Horizon	Element		How to achieve
Input	Variation in part demand	Continuous, Operational	Range:	Along any common component of the system	Partner with vendors to allow for Vendor Managed Inventory. Service level agreement of delivery within a 2 hour period.
			Mobility:	Two hour notice to bring in necessary quantities of needed parts	
			Uniformity:	•Very high service level to Dell •No change in customer perception of the product	

Table 14: Flexibility framework for Dell's inventory management system

5.1.6 Outsourcing

Outsourcing is playing an increasing role within Dell, but not in the way you might think. In this context we are referring to third party providers of services to Dell[16]. More and more, Dell is looking to outside partners to help them manage their day to day operations. Third part logistics providers (3PLs) work behind the scenes to perform tasks such as warehouse management, shipping, stocking, and returns. Dell management management is looking for ways to outsource tasks that are not core to their business in order to free up their employees to work on things that *are* core to Dell's business. In this way Dell is using outsourcing as a tool not just to reduce cost, but to be flexible in how you use your human resources. This is a move away from vertical integration to focus more on the capabilities that cannot be done as efficiently as by others.

[16] While parts that are sourced from abroad come from <u>vendors</u>

How is this flexibility??

- If outsourcing is done as a true partnership, the companies can influence each other's policies and practices in order to co-optimize the process. Instead of optimizing each part of the process separately, blurring the lines allows for a larger scope across which to optimize.
- Ability to learn best practices from other firms
- Flexibility requires some extra capacity – in this case manpower capacity to work on the correct emerging projects instead of maintaining the business as usual tasks.
- Dell can contract for a certain service level from their outsource vendor. While a given service level might be difficult for Dell to achieve internally, the partner is now contractually obligated to perform.
- Outsourcing may be costly, but the ability to react quickly in times of heavy variation may far outweigh the cost.

5.2 Chapter Summary

In each of the sections of the chapter we have explored different ways that flexibility is used within Dell's manufacturing environment. Applying the flexibility framework, we have identified the sources of variation as well and the desired outcomes. In looking at a broad range of examples I hope that this section has allowed the reader to understand the methods of the flexibility framework and that you will be able to apply it to your own sources of variation.

6 Case Studies

In the course of my work at Dell's EG1 and WS1 factories I approached their processes with the framework I have described in the previous chapters. By investigating the causes of variation and downtime in their existing factory systems I identified opportunities to improve Dell's flexibility in the face of variation. In the following case studies I will describe the situation as it presented itself, outline the issues that I identified and walk you through the solution and the outcome.

First, we will use see an example of variation caused by differences in incoming materials. The case is a combination of work done by Johnson Wu at Dell in 2006, as well as my experiences at Dell's EG1 manufacturing facility in 2008.

Second we will examine the use of communication along the supply chain in an example from both the EG1 and WS1 factories. We will see how improved communication can help a factory become more nimble and flexible. The output of this case became the major contribution of my internship at Dell.

6.1 Case Study: L5/L6 Chassis Integration at Dell

This case study is an example of an iterative approach to flexibility. Once the problem at hand was addressed, other more subtle forms of variation were discovered and addressed in a subsequent application of the flexibility framework.

6.1.1 The Situation

Computer assembly at Dell's EG1 facility begins with a chassis. This is the structural box that houses the rest of the components that go on to become your PC. As discussed briefly in Chapter 1, Dell and other computer manufacturers often look to Contract Manufacturers (CM) to produce some part of the final product. In this case, Dell uses a CM to assemble the motherboard of the computer into the chassis. This is done at a factory in Asia and then shipped as an assembly to Dell factories in the US. The level of integration with a montherboard+chassis is called "L6", while the motherboard and chassis separately are called "L5". Each higher level of integration is closer to the finished product, which is finally known as L10 integration.

Due to certain planned and unplanned circumstances, Dell will on occasion receive L5 chassis (w/o a motherboard) when they had ordered L6. This failure to integrate the motherboard can be caused by several reasons listed in Figure 18. If for some reason there is a problem with the chipset (which lives on the motherboard), the chassis will be sent separately from the motherboard and they will meet in the US for L5 to L6 integration at a Dell facility. L5 chassis also arrive when there is a New Product Introduction (NPI), since the motherboard is often the last part to be finalized for production.

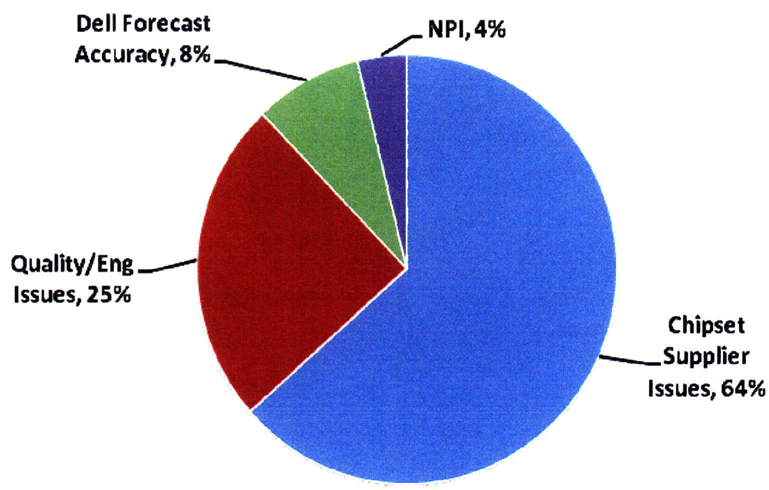

Figure 18: Breakdown of L5 causes as defined by cost of expediting[17]

Problems at EG1 arise when the production line is expecting to receive L6 chassis and L5 chassis arrive instead. The extra work associated with integrating the motherboard into the chassis throws off the balance of the assembly lines. Figure 19 shows how the assembly line works together to manufacture computers.

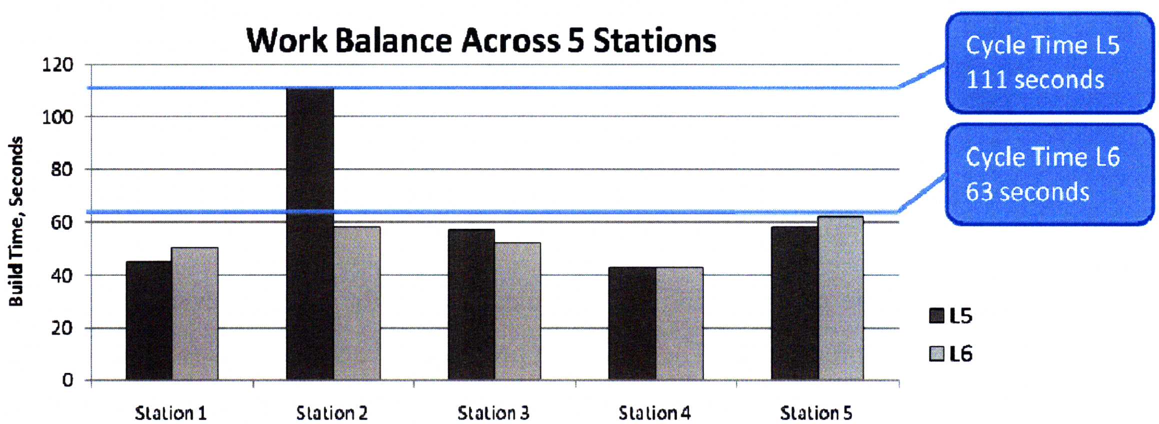

Figure 20shows how the increase of work at station 2 increases the cycle time of the entire assembly line. Because computers roll off the assembly line every 111 seconds instead of every 63 seconds, capacity is effectively cut in half when L5 chassis arrive instead of L6.

[17] Adapted from Johnson Wu (2006)

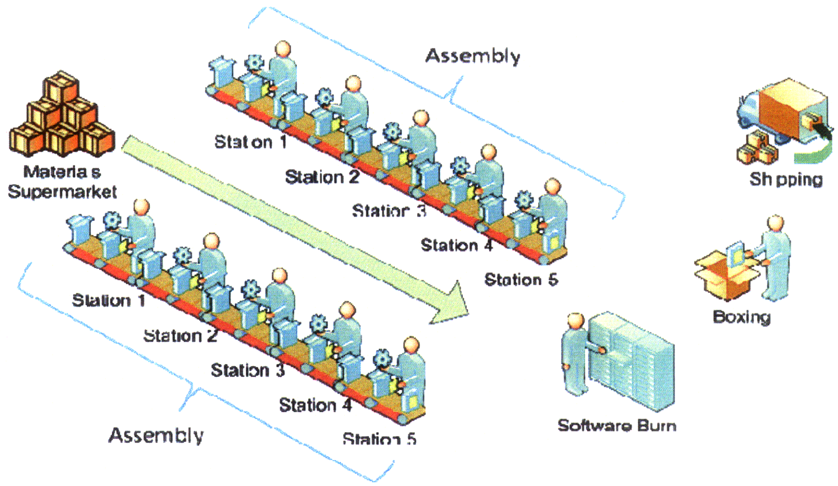

Figure 19: Representation of manufacturing line setup at EG1

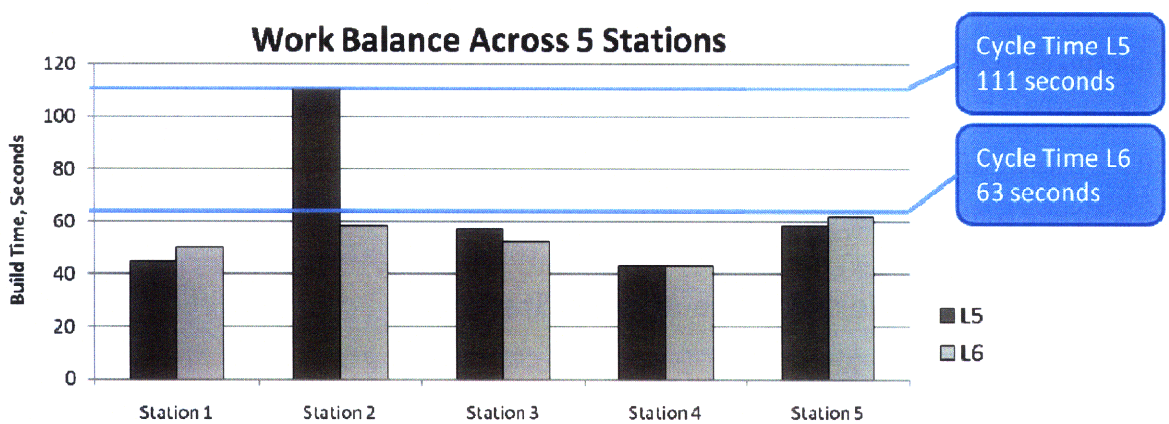

Figure 20: Example of L5 work balance. This line balance creates a bottleneck at Station 2.

The severity of this issue prompted EG1 management to call for a kaizen event to reduce the impact of L5 chassis in production. The following problem and solution cycles were performed over the course of one week, with a working prototype system implemented in the same timeframe.

6.1.2 Problem to address – Round 1

By our earlier definition, the cause of the L5 chassis variation is external to Dell, and not one that can be controlled by the EG1 factory. This rules out trying to eliminate the variation – it must be dealt with! If L5 chassis are a given in the system, the problem becomes variation in cycle time through the manufacturing line.

Using the tool of the 5 whys:

Problem: cycle time variation

1) Why: Assembly stations do not have a balance work load.
2) Why: Station 2 does additional work of motherboard integration.
3) Why: There are no other stations to do the work[18].
4) Why: Work area not designed for additional stations.
5) Why: There has never been a need.

Based on this analysis, it seems that the work load imbalance causing cycle time variation can be addressed by including an additional station to integrate the motherboard into the chassis.

6.1.3 Flexibility Framework – Round 1

Direction	Dimension	Time Horizon	Element		How to achieve
Input	Variation in Chassis Config. Either L5 or L6.	Continuous, Operational	Range:	Either L5 or L6 chassis as inputs to assembly	Create additional work station that will do the L5 -> L6 integration. When L6 chassis are input, leave station empty. Requires one additional headcount to run L5 assembly line.
			Mobility:	•Change between L5 and L6 in same time as product changeover time •No penalty in takt time	
			Uniformity:	No change in customer perception of the product	

Table 15: Flexibility framework for L5/L6 variation, Round 1

In order to put this scenario into our framework, we will look at each area separately:

Input Flexibility – Here we are trying to address variation caused by multiple inputs

Dimension – Variation in incoming chassis. Either L5 or L6 integration.

Time Horizon – Production occurs continuously. L5 chassis could be introduced at any time in the day

Range – Must be able to accept either L5 or L6 chassis.

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[18] Motherboard integration must be done before other components are attached. Station 1 is used for initiating the assembly process and applying regulatory stickers.

Mobility – Change between manufacturing with L5 chassis and L6 chassis must not take longer than the rest of the changeover process[19]

Uniformity – Ideally we would like to have cycle time of the L5 systems at the same rate as the L6 systems. This would ensure smooth capacity capability.

6.1.4 Solution Definition and Implementation

In order to reduce the extra burden of work on Station 2, the team determined to add a station between 1 and 2 to do the motherboard integration. This new station was dubbed "1.5" and included only a torque driver and a screw presenter. Dell's EG1 facility employed a modular work station environment that could be reconfigured in one day. Within the course of a week, all of the manufacturing lines were converted with this additional "half station". The cost to do this was simply the cost of the team (15 people) working on this project for one week plus the additional torque drivers and screw presenters.

The addition of this station allowed the L5 integration work to be moved away from the bottleneck, allowing for a cycle time equally fast as the same system starting with L6 chassis. The addition of the station did, however, require one additional worker for each manufacturing line running L5 at any given time. If the additional worker were not available, the station would remain empty and L5 work would be just as slow as before.

6.1.5 Problem to address – Round 2

Unfortunately, the addition of labor into the factory could not be accomplished as quickly as the variation in L5/L6 chassis occurred. Based on existing workforce contracts, Dell held a weekly meeting to request additional/fewer workers for the following week. This meant that to add additional head count for L5 integration required at least one week's notice.

Problem: Not enough warning of L5 chassis arrival

1) Why: Weekly L5 forecasts are only correct in aggregate (not day by day).
2) Why: Schedulers plan L5/L6 changes without understanding the needs of the factory.
3) Why: Incomplete communication between planning department and factory.

[19] Generally 10-20 minutes depending on the product

4) Why: The multiple groups are geographically dispersed and do not have a strong relationship.
5) Why: Previously not deemed necessary to connect headcount planning with L5 integration.

The work of moving from one level of "why" to the next required quite a bit of digging into the chassis supply chain through Dell. The process map that the team developed can be seen in Figure 21. A larger version of this same diagram can also be found in Appendix B.

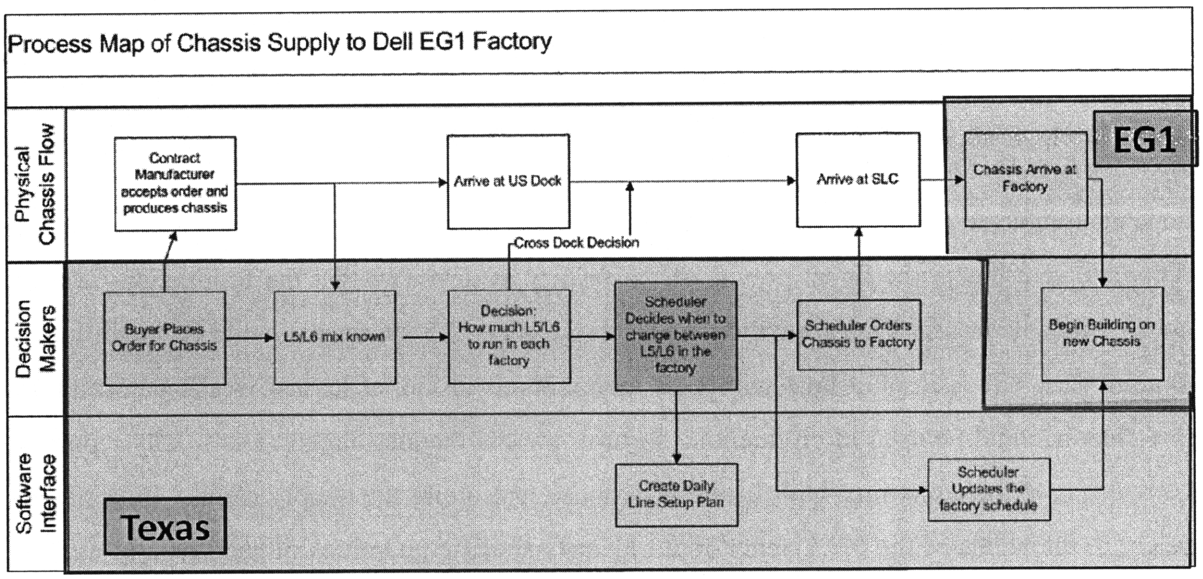

Figure 21: Chassis supply chain from contract manufacturer through Dell factory

6.1.6 Flexibility Framework – Round 2

Direction	Dimension	Time Horizon	Element		How to achieve
Input	Variation in amount of labor needed to run production (more needed when L5 runs)	Weekly, Tactical	Range:	Either L5 or L6 chassis mix	Create direct communication path between PC Planner and Operations manager at EG1. Weekly meeting to coordinate headcount with the need for L5 integration in the upcoming week.
			Mobility:	Existing ability to bring on additional headcount with one week notice	
			Uniformity:	No detriment to factory capacity	

Table 16: Flexibility framework for L5/L6 variation, Round 2

In order to put this scenario into our framework, we will look at each area separately:

Input Flexibility – Here we are trying to address variation of multiple inputs

Dimension – Variation in incoming chassis. Either L5 or L6 integration.

Time Horizon – Headcount planning decisions are made on a weekly basis.

Range – Possibility of adding additional headcount in order to meet L5 capacity needs. Not to exceed 20% additional assembly workforce[20].

Mobility – Cost of change is the hourly rate of the temporary worker. No additional penalty should be incurred if planning takes place in the given one week window.

Uniformity – Outcome would allow all L5 to run at the factory standard L6 rate. This requires staffing station 1.5 every time L5 chassis are run on that line.

6.1.7 Solution Definition and Implementation

The team conducted research to better understand chassis supply chain. Although long range L5 shipments were not in the direct prevue of the factory, it turns out that the Production Control Planner was able to see this information weeks in advance. L5 shipments could be identified at the point they left Asia on a boat without a motherboard inside, at least 4 weeks before those same chassis could be used in production. In turn, the PC Planner already ran a daily report to assess the L5/L6 chassis mix both in the warehouse and along the supply chain. Information already in the hands of the PC Planner could identify specific quantities of each type of chassis (L5/L6) for each product in each of the factory warehouses.

Once it was identified that the information the manufacturing needed was already available, it became important to understand how the operations team would use that information. The major factor of interest for manufacturing was the total number of additional headcount that would be needed to run L5 production at high speed.

By looking ahead in the supply of chassis (both L5 and L6) it became possible to provide a best case and worst case scenario for headcount planning. By agreeing on the use of L5 or L6[21] one week in advance with the PC planner, the factory now had a feedback into the mechanism that fed them chassis. On weeks when more headcount capacity was available, EG1 could request that additional L5 be run in that week. Conversely, on weeks when there was a shortage of

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[20] 20% is based on one additional worker in five. This will only be the case if every manufacturing line is running L5 at the same time.

[21] When both were available

headcount (or that headcount was needed for other capacity) it became possible to request a shift towards L6 chassis.

Weekly meetings were set up between the PC Planner (in Austin), the Operations Manager (at EG1), and the Ops Cell Manager (at EG1). In these meetings they would agree on the outlook for L5 and L6 chassis for the upcoming week, with those numbers they could plan headcount requirements.

My input to this project was the tool that converted the output from the PC Planner into information useful to factory management. An example of this dashboard can be seen in Appendix C.

6.2 Real time order scheduling for materials replenishment

6.2.1 The Situation

Full flexibility of manufacturing lines is constrained by the number of chassis that can be put on a line as well as the number of pick faces[22]. Therefore, product line changeovers must be done to change from one computer platform to the next (as defined by the combination of chassis and motherboard). During the changeover, unneeded components are taken off of the production line, and new parts are then added (both physically, and within the materials tracking system). The materials team is held accountable for the time it takes them to get the line back up and running (changeover time). To shorten this changeover time they begin by stocking the fresh line with parts that have a high attach rate and are more likely to be used on the first orders to be produced on that line. In many cases, the materials department will allow the production line to start again before all of the lowest attach rate parts are placed onto the line. As we discussed in Chapter 3.3.4 about order complexity, attach rate is only a metric of long term demand and not the short term variance of that part usage. As the materials depart allows production to proceed, there is a high likelihood there will be a need for at least one of those low attach rate parts. Once a low attach rate part is needed on the line and has not yet been stocked a stockout situation occurs. In this case the line is temporarily stopped while the part is found somewhere in the factory.

[22] Number of different components that can be stocked in a given work station

The evidence of this part demand variation was the occurrence of manufacturing downtime due to "part shortage". This detractor to productivity accounted for 73% of all the downtime attributed to materials stocking issues. This was contrary to the belief in the factory that changover events were the main driver of materials downtime.

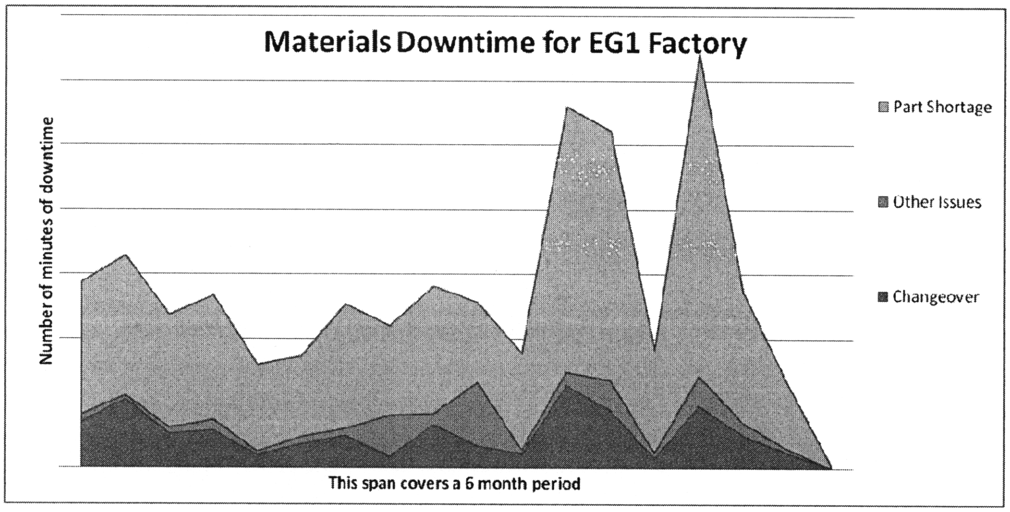

Figure 22: Materials department weekly downtime at EG1

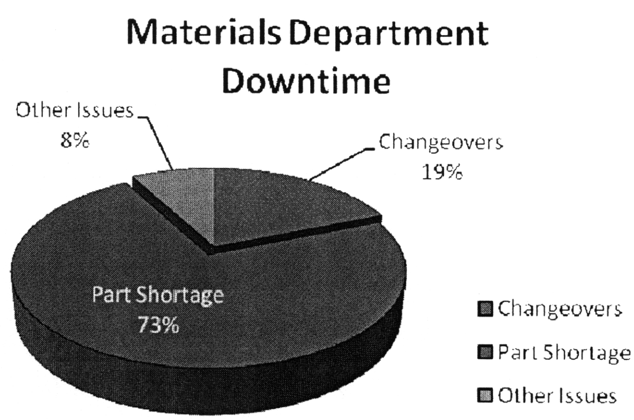

Figure 23: Aggregate materials department downtime by cause code

This "part shortage" situation will also occur when the production line is in full operation (not just right after a changeover). The expectation of a materials "part runner" is to replenish the production lines every 30 min. Once again, part runners will often check the status of the line by looking first at the high attach rate parts then moving on to low attach rate parts. In the case when there is a higher demand for a part than usual, the kanban stock[23] will at times run out before the line is replenished and cause a stockout situation that will be reported as downtime.

It is poignant to mention here the importance of data integrity. The downtime database where EG1 keeps information about downtime events is a self reporting system. Downtime information is added manually by managers on the floor. There is the potential within this system to assess blame for downtime events to other departments, in this way pointing fingers and keeping blame away from your own department. That being said, many more incidents were reported as "part shortage" issues as compared to "changeover" downtime.

6.2.2 Problem to address

From the description above, it is clear that Dell's EG1 was experiencing a large amount of downtime due to "part shortage" situations. Although most people were concerned with changeover time, part shortages accounted for over 3x more downtime.

Using the tool of the 5 whys:

Problem: part shortage

6) Why: necessary parts are not available when they are needed.
7) Why: parts have not been restocked in time.
8) Why: Materials parts runners are not aware of which parts are needed most quickly.
9) Why: Order data is not available to the materials department in a format they can use to stock the production lines.
10) Why: Tools are not available to deliver this information to the materials department in a useful manner.

Based on the answers to the 5 whys, one possible solution to our part shortage problem is to create a tool that provides order information to the materials team in real time.

[23] A pull system of stocking that contains the anticipated quantity of parts necessary for a given time period. This stock level is determined by long term demand history of each part.

6.2.3 Flexibility Framework

Direction	Dimension	Time Horizon	Element		How to achieve
Output	Variation in materials demand across assembly parts. Local stock outs a problem.	Continuous, Operational	Range:	Any combination of orders in the same product family and work content grouping	IT Integration: Integrate five hour look-ahead schedule with factory materials availability and current line setup. Provide a tool to materials handlers for prioritizing materials orders to prevent stock out.
			Mobility:	Anticipate demand within the SLC window for VMI Hub. In this case 2.5 hours	
			Uniformity:	•No stock outs on the line. •No change in customer perception of the product.	

Table 17: Flexibility framework for materials stock out

In order to put this scenario into our framework, we will look at each area separately:

Output Flexibility – In this case we are looking for the ability to produce many different types of systems off or a single production line, without holdups due to materials stock outs.

Dimension – We are experiencing variation due to materials stock outs that occur when parts demand does not occur at an even rate. We do not have visibility into actual part demand.

Time Horizon – New production schedules are run every 2 hours. The ability to know part demand over time would need to be refreshed every 2 hours.

Range – We are looking for the ability to run any combination of orders in a single product family and work content group (example: Flambé family and medium work content).

Mobility – Need to be able to identify material needs and then materials shortages within the window that orders can be placed for new parts. If the materials team can identify a shortage with enough time to spare, they can avoid the stock out situation.

Uniformity – Zero downtime due to stock outs. This materials stocking should have no detrimental effect on the production line.

6.2.4 Solution Definition and Implementation

Information already existed within the planning and scheduling department to be able to tell with some certainty which orders are scheduled to the production line for the next 5 hours. Separate from the schedule information, another IT system had the ability to present the BOM for each order. With the two types of information together, it became possible to identify which parts are needed for which systems when (and where).

With the help of the IT analyst[24] at Dell headquarters and an innovative project manager[25], an existing solution was identified at another plant within Dell. The PN1 facility that manufactured servers had already devised a way to obtain this data from the databases and update it in real time. By leveraging a solution that was developed within Dell, I was able to overcome much of the "not made here" mentality that often accompanied change. In addition, I was able to add functionality to the tool to allow the materials managers to see when materials should be ordered from the vendor managed hub. This solution was successfully implemented at EG1 before they ramped down production, and also rolled out at WS1 to help them enable their ramp up. An example of this real-time materials planning tool can be seen in Appendix D and E.

7 Conclusion and Recommendations

7.1 Basic Conclusions for Flexibility

The most basic take-away from the work of this thesis is the key role of flexibility in ensuring the success of configure-to-order manufacturing. In order to be responsive to ever-changing customer demands, the modern firm must (1) understand the variation that confronts them and (2) have a strong grasp of how they provide value to their customers. Using the framework outlined in this thesis, the practitioner should be able to identify the type of variation they want to address, and the price they are willing to commit in order to achieve a flexible outcome.

Even before flexibility is explored as a solution, practitioners should study carefully the <u>sources</u> of the variations they identify. It is faulty to implement flexibility in cases where variation can be reduced or eliminated at its source. This brings up the related concept of "flexibility for flexibility sake". More than a buzzword, flexibility is used to its best outcomes when treated as a tailored solution for a well defined set of possible outcomes. Additionally, even after a flexibility solution has been identified, it is important to weight the cost of implementation against the ultimate benefit to the customer. This benefit can be assessed against increased profits or minimized losses.

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[24] Thank you Thang

[25] Thank you Paul

From the perspective of my work at Dell, it is interesting to consider the opportunities that are available at the Factory Manager level to modulate factory flexibility on a daily basis. In the context of the current economic crisis, factories are being held accountable to hit operating cost targets while demand is inconsistent and declining. Configure-to-order manufacturing plants are particularly vulnerable to variation. Truly managing supply chain variation to your advantage can keep a company strong in the face of turbulent times.

In order to understand the ways that variation flows through a process or product, metrics must be in place to monitor performance over time. Metrics should be established as leading indicators of variation at key process steps. Early indication of variation will allow your facility to respond proactively to input or output variation. It is all a matter of knowing when things are going to change, and using the knobs that are available to counter the negative consequences of that variation.

7.2 Recommendations and Next Steps for Dell

> "A company can't be productive if it tries to focus on too many things simultaneously. The attempt defies the definition of "focus"" (Jennings, 2002)

The purpose of my time at Dell was to help them do more with less. By working to understand sources of variation within the manufacturing organization I identified opportunities to become more flexible in their operations.

Dell's strength lies in its ability to respond quickly to stimulus. If they can focus their efforts on fewer more effective leverage points within their organization, Dell can use their skills to their advantage. Beyond the projects that we have already discussed I have a few recommendations that may allow Dell, Inc. to take better advantage of the assets they already have.

7.2.1 Knowledge Capture

Dell does great work at putting together task forces to deal with specific problems. Both BPI and Lean are prominent within Dell culture and continuous improvement is always the overarching theme. In order to better leverage the learning from these individual events, Dell should consider investing more in the discrimination of best practices across the organization. Leveraging breakthroughs across Dell will shorten the learning curve and make the corporation more efficient.

Although teams are often rewarded for breakthrough improvements, those teams are not engaged to show their findings to the larger organization and share learning between groups. This type of learning culture would benefit Dell when confronted with systemic change[26].

In order to be an extremely responsive firm, Dell might consider implementing Lean principles into their office processes. Much of what Dell does is off of the shop floor and more involved with customer care, sales, information flows, design and management. Within each of these groups, standard work definitions would be appropriate in responding to variation in quality and throughput of human processes. Some work has been attempted within the sales organization and it is likely to be helpful in other parts of the organization. For an example of engineering standard work in a large organization please see the Harvard Business School Case "Pratt & Whitney: Engineering Standard Work" (H. Kent Bowen, 2004).

7.2.2 Communication

Work past organizational silos:

From 3 Lens analysis of the Dell culture: Each of three functional groups (materials, operations and production control) maintain competing metrics which puts those groups at odds to quite often. Though this system has been described as "checks and balances", the tension that it creates in the organization can become un-productive.. In order to facilitate real dialogue and learning, the organization must recognize the patterns of interaction in teams that undermine learning. The patterns of defensiveness are often deeply ingrained in how a team operates. If

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[26] As described here in terms of reactions to variation

unrecognized, they undermine learning. If recognized and surfaced creatively, they can accelerate learning. Unless teams can learn, the organization cannot learn. (Senge, 1990)

In order to facilitate better communication and understanding between related groups, Dell Inc. could benefit from rotation exercises between groups. Actively rotating employees between planning, materials, scheduling and operations will facilitate a much richer understanding of the entire Dell system. Rotation will also result in a more rounded appreciation for what is required to provide excellent service to the customer[27]. Also a better understanding of the metrics that drive each of the otherwise siloed organizations. In addition, rotating employees allows for a more rapid diffusion culture and of best practices throughout the firm. This can also be accomplished on a smaller scale with relate groups visiting each other on a rotating basis (i.e., round robin of reverse logistics facilities).

7.2.3 Strategic Communication

As an employee of a large firm, it is important to know what direction the ship is heading. Better communication about what the strategic direction of the company has the possibility to better engage employees at all levels. It is much easier to motivate a group of people if they understand the larger goal and how they can help. Alignment of effort across the firm can accomplish tremendous amounts, and in a down turn it is especially important to apply motivated employees at maximum PSI.

7.2.4 Prevention

Based on the work of Joseph Juran, we can put several of these improvement suggestions into the category of the "prevention costs of quality". According to Juran these costs include the following:

[27] internal and external customers

- Quality planning
- New products review
- Training
- Process control
- Data analysis
- Reporting

Although none of these tasks adds value on its own, they collectively help to ensure that gains won through continuous improvements and breakthrough improvements will not be lost with time. Although Dell, Inc. does a good job in quality planning and new product review, the remaining items should continue to receive attention. It is easy in down times to cut investment in the systems that support manufacturing. With a larger systems view, it is these same capabilities that will allow the firm to rebound from a downturn most nimbly. One example of this shows a company trying to ramp up production without enough trainers on staff anymore to onboard the new employees. These background quality functions play an important role in maintaining improvements over a long period of time. Rigorous process control is one enabler of continued quality that can reinforce a lean culture in times of variation.

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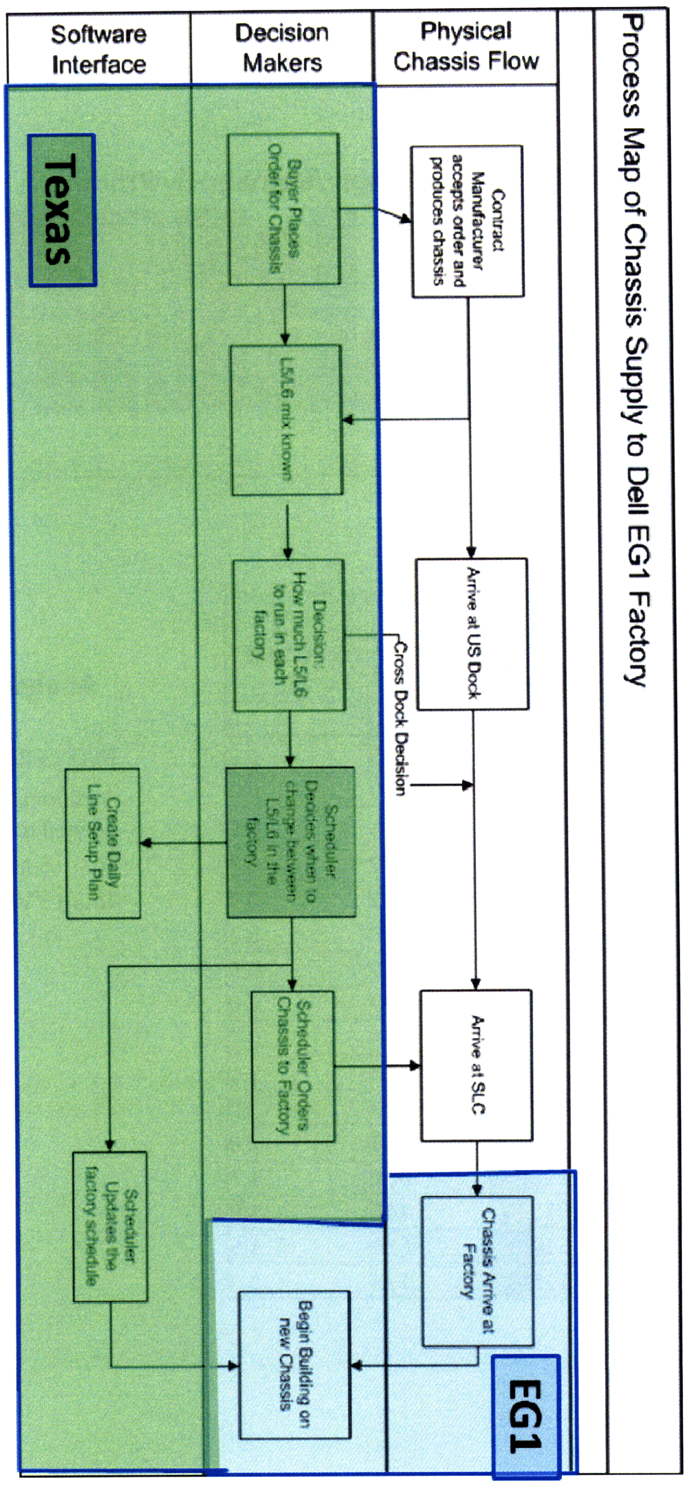
APPENDIX

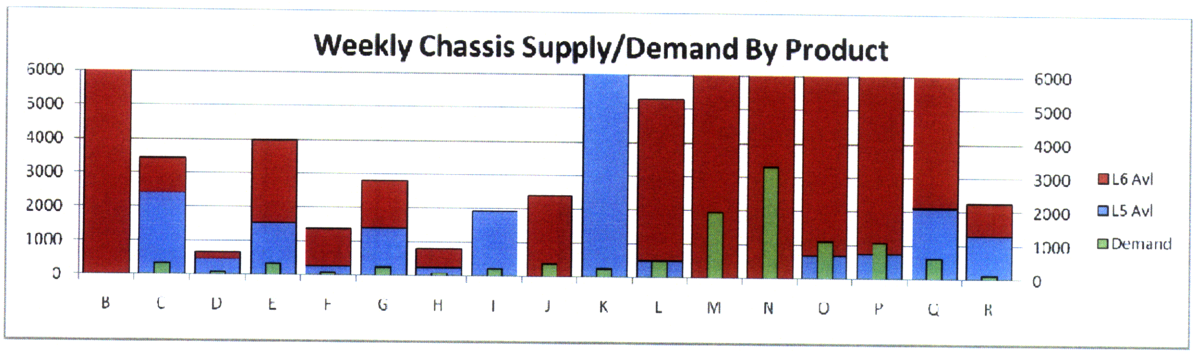
APPENDIX A: Traditional build process at Dell

1) Kitting: A customer Bill of Materials (BOM) is received by the materials team and each individual component required for that system is gathered and put in a tote along with the appropriate chassis for that system.
2) Build: Next, the tote and chassis are delivered to the next available operator who is trained to build that platform of computer. Either individuals or a team of two builders then assemble the customer specific components into the chassis.
3) Burn: Assembled computers are plugged into large racks where software is downloaded and diagnostics are performed on the system. This process helps assure that all customer requested components are present and plugged in.
4) Box: Completed systems are wrapped for safety and put into a box. Additional parts such as keyboards and brochures are added to correspond to the specific customer order.
5) Ship: Routing decisions are made electronically and boxes are assigned a shipping method (and time). Computers that are part of a larger order accumulate with their sibling systems before being shipped out to the end customer. Individual boxes are routed to the outbound dock doors to be shipped.

APPENDIX B: Chassis supply chain from contract manufacturer through Dell factory



APPENDIX C: Tool developed to provide chassis visibility to EG1 factory



Average L5 UPH Rate 55

Product	L5 Avl	L6 Avl	L6 Dmd	Max L5 we CAN run	Mods*Shifts L5
B	0	6281	0	0	0
C	2409	1019	335	335	0.8
D	456	216	100	100	0.3
E	1530	2475	345	345	0.9
D	294	1083	100	100	0.3
G	1407	1407	260	260	0.7
H	251	534	85	85	0.2
I	1915	0	240	240	0.6
J	0	2393	385	0	0
K	8997	12233	260	260	0.7
L	513	4757	450	450	1.1
M	0	17558	1950	0	0
N	0	50038	3320	0	0
O	684	8150	1115	684	1.7
P	746	5839	1075	746	1.9
Q	2114	4692	610	610	1.5
R	1301	964	125	125	0.3

Analysis for WW20

MAX L5 RUN

Additional headcount needed to run Max L5	2.44
Total L5 hours production	176.8
Total L5 Volume	9748

APPENDIX D: Tools developed to help Dell Material's Team overcome part shortages on the manufacturing line.

Reschedule Time: 4/8/2009 16:19 Save Plan: 4/8/2009 17:10

Home

Material Demand for I

PrimaryResource	ASSIGNED_PART	DESCRIPTION	COMMODITY	Use in 5 hrs	0	1	2	3	4	5
WS1-I_LEAN_MOD	C120D	CRD,GRPHC,256,LP,OPGA6	BDS	71	2		2	40	27	
WS1-I_LEAN_MOD	X398D	CRD,GRPHC,256,FH,OUGA6	BDS	6	1			5		
WS1-I_LEAN_MOD	Y104D	CRD,GRPHC,256,LP,OUGA6,2	BDS	16	1		4	11		
WS1-I_LEAN_MOD	YP477	CRD,GRPHC,2400,PRO,LP,OUGA5	BDS	96					48	48
WS1-I_LEAN_MOD	FH439	ASSY,CBL,FLEX-BAY,MCSF/MND	CBL	52				26	26	
WS1-I_LEAN_MOD	W5775	ASSY,CBL,ATAPI,MND	CBL	133	1			15	69	48
WS1-I_LEAN_MOD	D9901	ASSY,SPKR,2W,40X28.5,6.5CBL,UL	HDW	293	73	17	12	46	97	48
WS1-I_LEAN_MOD	CT364	LBL,COA,OS,VHB32,V#2007	LBL	52			1	25	26	
WS1-I_LEAN_MOD	HY385	LBL,COA,OS,VB32/64,V#2007	LBL	183	61	17	26	58	21	
WS1-I_LEAN_MOD	T938F	LBL,COA,OS,VB32/64,EMRP,LATAM	LBL	25	7		15		3	
WS1-I_LEAN_MOD	TU490	LBL,COA,OS,VU32/64,V#2007	LBL	5	5					
WS1-I_LEAN_MOD	W448F	LBL,COA,OS,VHB32,EMRP,LATAM	LBL	96					48	48
WS1-I_LEAN_MOD	HX727	ASSY,CAGE,RSR,MND,PCI,CMB,2.0	MCH	6	1			5		
WS1-I_LEAN_MOD	JY385	ASSY,HTSNK,SHRD,MND	MCH	362	74	17	42	83	98	48
WS1-I_LEAN_MOD	UC635	ASSY,SWT,PB,NTRSN,GX520	MCH	20				17	3	
WS1-I_LEAN_MOD	X837C	ASSY,CHAS,MND,760,APFC,L6,TPM	MCH	362	74	17	42	83	98	48
WS1-I_LEAN_MOD	CM633	DIMM,1GB,800,128X64,8,240,1RX8	MEM	518	120	34	56	68	144	96
WS1-I_LEAN_MOD	HT212	DIMM,512,667,64X64,8,240,1RX16	MEM	16	12		4			
WS1-I_LEAN_MOD	YG410	DIMM,2G,800M,256X64,8,240,2RX8	MEM	173	17		19	85	52	
WS1-I_LEAN_MOD	D306F	PRC,E7300,2.66,3MB,WFD,65W,M0	PRC	57	16		23	16	2	
WS1-I_LEAN_MOD	D782J	PRC,E5200,2.5,2MB,WFD,65W,M0	PRC	14			11	2	1	
WS1-I_LEAN_MOD	F007F	PRC,E7200,2.53,3MB,WFD,65W,M0	PRC	2	2					

I-M

This software tool allows workers to know which parts will be needed on the production line and when. Boxes in grey indicate that the part will not be used in that hour.

APPENDIX E: Tools developed to help Dell Material's Team anticipate shortages in the materials supermarket (across all mfg lines). Real-time priority list to check for shortages.

HOME | Lean Line Kitting Stock Room 5 Hr Demand 4/8/09 4:18 PM

Pink Cells Indicate parts have run out

ReschedTime	PART#	DESCRIPTION	COMM	Avail	Need	4:18 PM 5:18 PM	5:18 PM 6:18 PM	6:18 P 7:18 PM	7:18 P 8:18 PM	8:18 P 9:18 PM	9:18 PM 10:18 PM	Runout Time	Order By:	
4/8/09 16:18	H341D	ASSY,CHAS,L6,MBSF,960,EPA,TPM	MCH	98	133	72	61					5:43 PM	4:13 PM	CST
4/8/09 16:18	N860C	ASSY,HTSNK,SELES	MCH	127	153	72	70	11				6:05 PM	4:35 PM	CST
4/8/09 16:18	J075D	PRC,T2390,1.86,1MB,2C,PMER,M0	PRC	18	21	14	5	2				6:06 PM	4:36 PM	CST
4/8/09 16:18	N385D	PRC,T8100,2.1,3MB,CPEN,M0	PRC	41	47	29	15	3				6:06 PM	4:36 PM	CST
4/8/09 16:18	H224H	KIT,BRKT,2.5,HD,CADY,FX160/160	MCH	39	150		42	57	51			6:13 PM	4:43 PM	CST
4/8/09 16:18	RU772	ASSY,DVD,8,12.7,SATA,SLCY,TEAC	STR	205	508	105	107	51	98	74	73	6:14 PM	4:44 PM	CST
4/8/09 16:18	UH650	ASSY,FD,1.44M,SONY,05,BLK	STR	186	736	55	124	99	112	109	237	6:22 PM	4:52 PM	CST
4/8/09 16:18	C976J	PRC,I7-920,2.66,8MB,BLM,C0	PRC	256	476	171	47	45	79	64	70	7:08 PM	5:38 PM	CST
4/8/09 16:18	CP825	ASSY,HTSNK,FAN,MNTW	MCH	355	691	71	136	176	150	114	44	7:08 PM	5:38 PM	CST
4/8/09 16:18	N031F	HD,80GB,FFS,7.2K,9.5,HIT-FALC	NBD	103	149		42	57	50			7:22 PM	5:52 PM	CST
4/8/09 16:18	F405H	PRC,E8500,3.16,6MB,WFD,65W,E0	PRC	167	363	15	55	80	111	6	96	7:27 PM	5:57 PM	CST
4/8/09 16:18	K262D	ASSY,DVD,16X,SATA,HH,BARE,HLDS	STR	177	312	41	40	78	59	57	37	7:36 PM	6:06 PM	CST
4/8/09 16:18	C118D	HD,640GB,S2,7.2K,WD,XL320	STR	156	271	80	30	13	60	55	33	7:51 PM	6:21 PM	CST
4/8/09 16:18	CP187	CRD,GRPHC,G92,HMGA16,EM	BDS	38	45		19	10	16			7:51 PM	6:21 PM	CST
4/8/09 16:18	X696G	PRC,E8400,3.0,6MB,WFD,65W,E0	PRC	872	1506	243	237	191	338	242	255	7:53 PM	6:23 PM	CST
4/8/09 16:18	FH868	ADPT,GRPHC,DVI,2,LP,ULD	BDS	222	351	24	49	81	98	2	97	7:59 PM	6:29 PM	CST
4/8/09 16:18	XN068	ASSY,FSD,USB,RDR,ENH,BARE,TEAC	STR	253	394	81	50	37	93	84	49	8:12 PM	6:42 PM	CST
4/8/09 16:18	H425H	ASSY,DVD+/-RW,16X,HH,HLDS,DVDM	STR	683	1210	166	120	191	185	294	254	8:22 PM	6:52 PM	CST
4/8/09 16:18	CM633	DIMM,1GB,800,128X64,8,240,1RX8	MEM	5044	7314	1067	1085	1356	1419	1226	1161	8:23 PM	6:53 PM	CST
4/8/09 16:18	D306F	PRC,E7300,2.66,3MB,WFD,65W,M0	PRC	506	789	169	61	160	77	189	133	8:30 PM	7:00 PM	CST
4/8/09 16:18	X837C	ASSY,CHAS,MND,760,APFC,L6,TPM	MCH	625	924	95	17	160	227	234	191	8:50 PM	7:20 PM	CST
4/8/09 16:18	JN738	ASSY,HTSNK,SHRD,MSMT	MCH	683	967	158	124	160	122	202	201	8:53 PM	7:23 PM	CST
4/8/09 16:18	NR694	HD,80G,S2,7.2K,3.5,WD-UNIC	STR	2006	2598	394	343	418	510	535	398	8:56 PM	7:26 PM	CST
4/8/09 16:18	DU689	PRC,440,2.0,512KB,CEL,A1	PRC	223	339	3	1	52	96	102	85	8:59 PM	7:29 PM	CST
4/8/09 16:18	U717D	HD,160GB,S2,7.2K,WD,XL320	STR	848	988	224	148	180	145	180	111	9:08 PM	7:38 PM	CST
4/8/09 16:18	JY385	ASSY,HTSNK,SHRD,MND	MCH	739	1078	95	17	160	227	269	310	9:11 PM	7:41 PM	CST

APPENDIX F: Visual Representation of the themes in this Thesis