Inventory Decisions in Dell's Supply Chain

Roman Kapuscinski
University of Michigan Business School, Ann Arbor, Michigan 48109, roman.kapuscinski@umich.edu

Rachel Q. Zhang
Johnson Graduate School of Management, Cornell University, Ithaca, New York 14853, rqz2@cornell.edu

Paul Carbonneau
McKinsey & Company, 3 Landmark Square, Stamford, Connecticut 06901, paul_carbonneau@mckinsey.com

Robert Moore, Bill Reeves
Dell Inc., Mail Stop 6363, Austin, Texas 78682 {robert_a_moore@dell.com, bill_reeves@dell.com}

The Tauber Manufacturing Institute (TMI) is a partnership between the engineering and business schools at the University of Michigan. In the summer of 1999, a TMI team spent 14 weeks at Dell Inc. in Austin, Texas, and developed an inventory model to identify inventory drivers and quantify target levels for inventory in the final stage of Dell's supply chain, the revolvers or supplier logistics centers (SLC). With the information and analysis provided by this model, Dell's regional materials organizations could tactically manage revolver inventory while Dell's worldwide commodity management could partner with suppliers in improvement projects to identify inventory drivers and to reduce inventory. Dell also initiated a pilot program for procurement of XDX (a disguised name for one of the major components of personal computers (PCs)) in the United States to institutionalize the model and promote partnership with suppliers. Based on the model predictions, Dell launched e-commerce and manufacturing initiatives with its suppliers to lower supply-chain-inventory costs by reducing revolver inventory by 40 percent. This reduction would raise the corresponding inventory turns by 67 percent. Net Present Value (NPV) calculations for XDX alone suggest $43 million in potential savings. To ensure project longevity, Dell formed the supply-chain-optimization team and charged it with incorporating the model into a strategic redesign of Dell's business practices and supervising improvement projects the model identified.

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Dell and Our Project

Dell is the largest computer-systems company based on estimates of global market share. It is also the fastest growing of the major computer-systems companies competing in the business, education, government, and consumer markets. Dell's product line includes desktop computers, notebook computers, network servers, workstations, and storage products. Michael Dell founded the company based on the concept of bypassing retailers and selling personal computer systems directly to customers, thereby avoiding the delays and costs of an additional stage in the supply chain. Much of Dell's superior financial performance can be attributed to its successful implementation of this direct-sales model.

While the computer industry has grown tremendously over the past decade, firms in this industry face their own challenges. First, rapid changes in technology make holding inventory a huge liability. Many components lose 0.5 to 2.0 percent of their value per week, and a supply chain packed with yesterday's technology is nearly worthless. With its direct sales,

however, Dell carries very little inventory: the whole organization concentrates on speeding components and products through its supply chain. Dell delivers new products to market faster than its competitors and does not have to sell old products at a discount, because it has none. Second, the traditional model of vertical integration that the original equipment manufacturers (OEMs) follow to manufacture all of the major components of their products has almost disappeared in the computer industry. Research and development (R and D) costs are too high and technology changes too rapid for one company to sustain leadership in every component of its product lines. Dell has close-relationship agreements with its suppliers that allow them to focus on their specific components. At the same time, Dell concentrates its research on customer-focused, collaborative efforts to leverage the collective R and D of its partners (Dell and Magretta 1998), which includes cultivating its supply-chain competence.

Dell management was concerned that, although the firm carried almost no inventory, its suppliers might

be holding much more inventory than was needed to provide desired customer service. For this reason, Dell asked a team from the Tauber Manufacturing Institute (TMI), a partnership between the engineering and business schools at the University of Michigan, to study this issue. Dell sought recommendations for a sustainable process and decision-support tools for determining optimal levels of component inventory to support the final assembly process.

Dell bases its business model on integrating five key strategies: rapid time to volume, products built to order, elimination of reseller markups, superior service and support, and low inventory and capital investment. We designed our project and the resulting tools to support Dell's low-inventory and low-capital-investment strategy and to extend its impact beyond the plant floor into the preceding stage of its supply chain. Tom Meredith, at the time chief financial officer, said in the May 18, 1999 earnings conference call: "Customers see no advantage in a manufacturer lowering inventory to six days if there are still 90 days in the supply line." Our project was the first step taken to combat the "90 days in the supply line."

Dell's Supply Chain

Dell's supply chain works as follows. After a customer places an order, either by phone or through the Internet on www.dell.com, Dell processes the order through financial evaluation (credit checking) and configuration evaluations (checking the feasibility of a specific technical configuration), which takes two to three days, after which it sends the order to one of its manufacturing plants in Austin, Texas. These plants can build, test, and package the product in about eight hours. The general rule for production is first in, first out, and Dell typically plans to ship all orders no later than five days after receipt. There are, however, some exceptions. For example, Dell may manipulate the schedule when there is a need to replace defective units or when facing large customers with specific service-level agreements (who have non-standard quoted manufacturing lead times) for their orders.

In most cases, Dell has significantly less time to respond to customers than it takes to transport components from its suppliers to its assembly plants. Many of the suppliers are located in Southeast Asia and their transportation times to Austin range from seven days for air shipments to upwards of 30 days by water and ground. To compensate for long lead times and buffer against demand variability, Dell requires its suppliers to keep inventory on hand in the Austin revolvers (for "revolving" inventory). Revolvers or supplier logistics centers (SLCs) are small warehouses located within a few miles of Dell's assembly plants. Each of the revolvers is shared by several suppliers who pay rents for using their revolver.

Dell does not own the inventory in its revolvers; this inventory is owned by suppliers and charged to Dell indirectly through component pricing. The cost of maintaining inventory in the supply chain is, however, eventually included in the final prices of the computers. Therefore, any reduction in inventory benefits Dell's customers directly by reducing product prices. Low inventories also lead to higher product quality, because Dell detects any quality problems more quickly than it would with high inventories.

Dell wishes to stay ahead of competitors who adopt a direct-sales approach, and it must be able to reduce supplier inventory to gain significant leverage. Although arguably supply-chain costs include all costs incurred from raw parts to final assembly, Dell concentrates on Dell-specific inventory (that is, parts designed to Dell's specifications or stored in Dell-specific locations, such as its revolvers and assembly plants). Because assembly plants hold inventories for only a few hours, Dell's primary target, and ours in this project, was the inventory in revolvers.

Dell has a special vendor-managed-inventory (VMI) arrangement with its suppliers: suppliers decide how much inventory to order and when to order while Dell sets target inventory levels and records suppliers' deviations from the targets. Dell heuristically chose an inventory target of 10 days supply, and it uses a quarterly supplier scorecard to evaluate how well each supplier does in maintaining this target inventory in the revolver. Dell withdraws inventory from the revolvers as needed, on average every two hours. If the commodity is multisourced (that is, parts from different suppliers are completely interchangeable), Dell can withdraw (pull) those components from any subset of the suppliers. Dell often withdraws components from one supplier for a few days before switching to another. Suppliers decide when to send their goods to their revolvers. In practice, most suppliers deliver to their revolvers on average three times a week.

To help suppliers make good ordering decisions, Dell shares its forecasts with them once per month. These forecasts are generated by Dell's line of business (LOB) marketing department. In addition to product-specific trends, they obviously reflect the seasonality in sales. For home systems, Christmas is the top time of the year. Other high-demand periods include the back-to-school season, the end of the year when the government makes big purchases, and country-specific high seasons for foreign purchases (foreign language keyboards are especially influenced). Dell sales also increase at the ends of quarters (referred to as the hockey stick).

After the center of competence (COC) checks a forecast for predicted availability of components, the forecast goes to Dell's commodity teams and becomes the basis for a six-month rolling forecast that they update weekly. The commodity teams make generic forecasts for systems and components and break those forecasts down to a level of the specific parts that need to be ordered. If the forecast is not feasible, the LOB marketing department revises it, although such revisions are very rare. The buyer-planner for each commodity receives an updated rolling forecast weekly; suppliers receive forecasts monthly.

The objectives of our project were to recommend target inventories for the revolvers to minimize inventory-related costs subject to a service-level constraint and to develop a process and tools for identifying and updating target levels for inventories of the items in the revolvers. (Suppliers who make the replenishment decisions attempt to follow Dell's targets and guidelines.) Dell had been setting inventory targets based on empirical data and judgment with no clear reference to any desired service levels. Dell hypothesized that it could reduce revolver inventory markedly by using a more rigorous approach and gaining better visibility of the inventory throughout the supply chain. Once it determined an optimized inventory level, Dell could collaborate with its suppliers to eliminate excess inventory.

Dell emphasized that it wanted to sustain any changes over the long term, which would require integrating them into its informational infrastructure. ValueChain is a program intended to extend Dell's successful direct-sales approach back into the supply chain with the goal of increasing the speed and quality of the information flow between Dell and its supply base. The corresponding Web site valuechain.dell.com is an extranet for sharing such information as points of contact, inventory in the supply chain, supply and demand data, component quality metrics, and new part transitions. Dell envisions using this site to exchange with suppliers current data, forecasted data, new product ideas, and other dynamic information that might help it to optimize the flow of information and materials in the supply chain.

By integrating the process and associated tools that we developed with valuechain.dell.com, we want to make the tools part of Dell's and its suppliers' procurement-business processes. Dell and its suppliers through ValueChain can share such information as target inventory levels to support collaboration on future improvements.

Our Approach

We concentrated on the last stage of Dell's supply chain, the revolvers, where the inventories of all components are Dell specific. Dell believes that inventory savings at this level will produce comparable supply-chain savings. Also, analysis of this stage is a necessary first step to further improve the whole supply chain. We looked at the inventories of an important component, XDX, in the revolvers themselves and in transit to revolvers. XDX is one of the major components of PCs, supplied by a few suppliers, that is fully interchangeable (customers do not choose the manufacturer of this component when ordering the final product).

In our analysis, we made several simplifying assumptions. Because the supply chain provides a fairly high service level, simultaneous shortages of multiple components are very infrequent, and thus, we could ignore them without significantly altering the results. Although Dell regularly updates its forecasts of demand and hence its desired inventory levels, we assumed stationary demand and inventory targets during a rolling forecast horizon of 10 business days. We realized that the behaviors of demand and inventories at the beginning and the end of a product's life cycle differ from those mid life cycle; however, we handled them separately and do not describe them here. (Kurawarwala and Matsuo 1996 describe ramp-on using the Bass 1969 model.) We call the inventory in the revolvers the *revolver inventory* and the revolver inventory plus any inventory ordered but not yet delivered the *system inventory*. Although revolver inventory determines the availability of parts, Dell can control it only by placing new orders (increasing the system inventory).

Currently, Dell's suppliers order in batches (to offset fixed ordering costs incurred every time an order is placed) when inventory levels drop. However, the actual order (batch) sizes and points (levels) at which the suppliers reorder are quite inconsistent. Our first task was to develop a tool that would bring consistency to suppliers' ordering decisions. (Our estimates of the benefits do not include benefits from eliminating existing inconsistencies.) We considered using continuous-time, discrete-time (time buckets), or fixed-time-period approaches. Because suppliers and buyer-planners react to changes in conditions as they occur, we used a continuous-time approach and the corresponding optimal policy, a (Q, R) policy. Also, we found that (Q, R) policies are far easier for the managers at Dell to understand and use than the (s, S) policies used in periodic settings. In a (Q, R) policy, R denotes the reorder point and Q is the size of the order (that is, we order a batch of size Q whenever system inventory drops to R). Consequently, $R + Q$ denotes the order-up-to level. We also used the newsvendor ratio to heuristically find the best reorder point, R. We focused on identifying the optimal reorder point R for XDX and assumed that the order size Q would remain at its current level.

That is, based on long-term data, we estimated the order size Q suppliers were using and assumed it would not change.

The reorder point is closely related to safety stock, which is the extra inventory held to buffer against multiple sources of variability. Specifically, *safety stock* is the difference between the reorder point and the average requirements during replenishment lead time (the latter is also called *pipeline inventory*). Assuming normal distributions of forecast error and of replenishment lead time and independence of forecast errors, the safety stock level for (Q, R) policy is given by $Z * \sqrt{\mu_f^2 \sigma_l^2 + \mu_l \sigma_f^2}$, and the reorder point is the sum of the pipeline inventory and safety stock. That is,

$$R = \mu_l \mu_f + Z\sqrt{\mu_f^2 \sigma_l^2 + \mu_l \sigma_f^2}, \quad \text{where}$$

μ_f is the average of the daily forecasted demand during replenishment lead time,

σ_f is the standard deviation of daily forecast error during replenishment lead time,

μ_l and σ_l are the mean and standard deviation of the replenishment time, and

Z is a score that links safety stock with required service level. For a desired service level defined as the probability that demand is met from stock, $Z = \Phi^{-1}$ (service level), where $\Phi(\cdot)$ is the cumulative standard normal distribution.

Safety stock protects against variability of demand during lead time. Here, we control safety stock through the total *system inventory* (the inventory in the revolvers and the inventory on order), as these two differ only by a constant. We can approximate the optimal safety stock using the newsvendor logic (Nahmias 1997). According to this approximation, the probability of satisfying all demand (or the service level) needs to be equal to the critical fractile $c_u/(c_u + c_o)$, where c_u is the cost of not being able to satisfy one unit of demand (underage cost), and c_o is the cost of maintaining an unused unit of inventory between consecutive ordering decisions (overage cost). The critical fractile is thus the same as the service level that balances the costs of carrying one too many items versus one too few items in inventory. With $\Phi(\cdot)$ being the cumulative standard normal distribution, optimal $Z = \Phi^{-1}(c_u/(c_u + c_o))$. To calculate the optimal service level, we needed data to estimate c_u and c_o.

After specifying the model, we decided how to estimate the input parameters (for example, demand data and cost coefficients) and focused on the supply chain for XDX. For all of the input parameters, we used historical data.

We developed a user-friendly spreadsheet template, the revolver inventory model, which allows a buyer-planner to set target inventory levels and track actual inventory levels daily. The spreadsheet uses historical data to estimate demand. It also estimates such parameters as the costs of underage and overage, calculates the suggested policy, illustrates the historical behavior, and permits numerical and graphical analyses of scenarios. The revolver inventory model also serves as a strategic or diagnostic tool by relating components of the total-required-inventory levels to the various underlying causes. For example, we could determine what portion of the required inventory is due to variation in the forecast error. We collected historical data for XDX for each of the variables identified by the model and performed our original analysis for the period from December 1, 1998 through May 27, 1999 (we included a methodology for daily updates). In the final step in this portion of the project, we used the analysis of the data and the model to identify areas for improvement.

The Golf Analogy at Dell

While many people at Dell understand inventory-replenishment concepts, we found that they had no knowledge of formal operations-management theories. To explain these ideas, we used an analogy from golf, employing terms from the sport to describe the expressions and conditions commonly found in basic inventory equations. A golf course provides many physical obstacles, such as sand traps, water hazards, and the long distances to the hole. All of these elements are completely out of the control of the golfer, and they must accommodate these perils throughout the game. Like water hazards and sand traps, several factors can hinder a smooth delivery of components in a supply chain, such as road construction or congested highways. The distance between the tee and the hole is analogous to the distance from suppliers to the OEM. In golf, each hole has a standard, or par that the course designer sets based on a variety of factors. This par will not change unless the designers of the course return and make fundamental alterations to the layout. The interesting thing about par is that it gives golfers a target to strive for. They have constant feedback on how they are doing, compared to a set standard. With no variability in the system, the inventory necessary to maintain steady production depends on only three factors: demand, replenishment time, and shipping frequency (or the size of shipments). We dubbed this level of inventory as par, based on the notion that a problem-free manufacturing environment should run efficiently with a certain natural level of inventory just as an average, problem-free golfer should achieve an expected score on a course. We calculated the par

level of inventory for several points in the supply chain:

$$\text{total system par}$$
$$= \text{forecasted demand for time period}$$
$$* (\text{replenishment time for the supplier}$$
$$+ \text{time between shipments}/2).$$

The first part of the total system par is sometimes called the pipeline inventory, that is, the average inventory ordered but not yet delivered, while the second part is the cycle inventory, inventory due to batching. By Little's law, the average time between orders is given by Q/μ_f (Nahmias 1997) for given order quantity Q and forecasted average daily demand during replenishment lead time μ_f.

Dell's Handicap

In golf, a handicap is a measure of a golfer's performance relative to an expected baseline, the par. As a golfer improves over time, his or her handicap score decreases. We used this term and found it very effective to describe safety stock and the reasons why the organization might carry extra material.

Safety stock insures against potential variations on both Dell's side and the supplier's side of the supply chain. To gauge improvements and to determine causes of variation, we separated the sources of variance. We referred to the safety stock required to cover problems and variance within Dell's portion of the supply chain as Dell's handicap, and we referred to the remaining inventory needed to guard against the supplier's failures to deliver quality goods consistently on time as the supplier's handicap. For the project, Dell and its suppliers agreed to outline the elements that would constitute the supplier's handicap. We planned to make the supplier's handicap part of the supplier scorecard.

Important elements of Dell's handicap are forecast error and pull variance. We use *variance* in the statistical sense as the expected value of the square of deviations from target values. Dell forecasts its need for individual components in two stages. In the first stage, it forecasts an aggregate number of final products; in the second, it estimates the mix of components (corresponding to different features). An error is associated with each of the two stages. The absolute difference between the number of units actually sold on the aggregate level and the number forecasted is called the *aggregate deviation*. The difference between the actual units and the forecasted units that incorporate a specific component (feature) is another forecast error, labeled the *attach deviation*. Both are absolute differences, not fractions. Outside of the forecasting process, a deviation also exists between what Dell

pulls out of the revolver daily and what the supplier expected Dell would pull based on the production schedule. This is the *pull deviation*.

While aggregate demand is generally predictable and not a major contributor to the safety stock, the attach rate varies noticeably. Customer preferences change every day, sometimes drastically, despite Dell's amplifying or reducing demand through sales and price reductions or increases for various components. The attach deviation is the difference between the expected demand for a component and the actual number of components Dell uses, assuming that Dell pulls at the predetermined percentage and has made no aggregate-level error. For example, suppose that Dell forecasts an aggregate demand for 4,000 units, 2,000 of which would have XDXs attached, representing a 50 percent attach rate. If the actual demand turns out to be 3,200 units, then the forecasted demand at the aggregate level deviates from the actual by 800 units. However, suppose that demand perfectly matches the forecast of 4,000 (resulting in an aggregate deviation of 0), but only 1,500 computers need an XDX. In this case, the actual attach rate is only 37.5 percent and the attach deviation is $2{,}000 - 1{,}500 = 500$. This attach deviation can be calculated for each supplier. If Suppliers A and B each have 50 percent of Dell's business for this device, Dell would plan to consume 1,000 of A's XDXs and 1,000 of B's XDXs. If the pulled quantities are proportional to the allocated ratios (50 percent for each supplier), then each would provide 750 units. In this case, the attach deviation equals $1{,}000 - 750 = 250$ for each supplier. (The actual pull is 250 units less than the forecasted pull of 1,000 units.)

Safety stock is driven by variances (in the square-root formula for safety stock), and therefore, we translate all of the deviations into corresponding variances. Our objective is to examine the total variance and to attribute it to specific causes. Because it is more difficult to forecast on the component level than on the aggregate level, we expect that the attach variance will be greater than or equal to the aggregate-level variance. By subtracting the aggregate-level variance from the attach variance, we can estimate the incremental contribution of attach rates to the variance, even though these effects are obviously not independent.

If the commodity in question is multisourced, Dell must further allocate the attach rate forecast to individual suppliers. Dell tends to pull material from competing suppliers in batches, switching from one to the other, rather than taking a fixed percentage from each one. Thus, even without any aggregate-level variance or attach variance, the suppliers' inventory is different than forecasted. This is referred to as the pull variance (Figure 1). Dell pulled different numbers of units of XDX from two suppliers' revolvers. Dell's
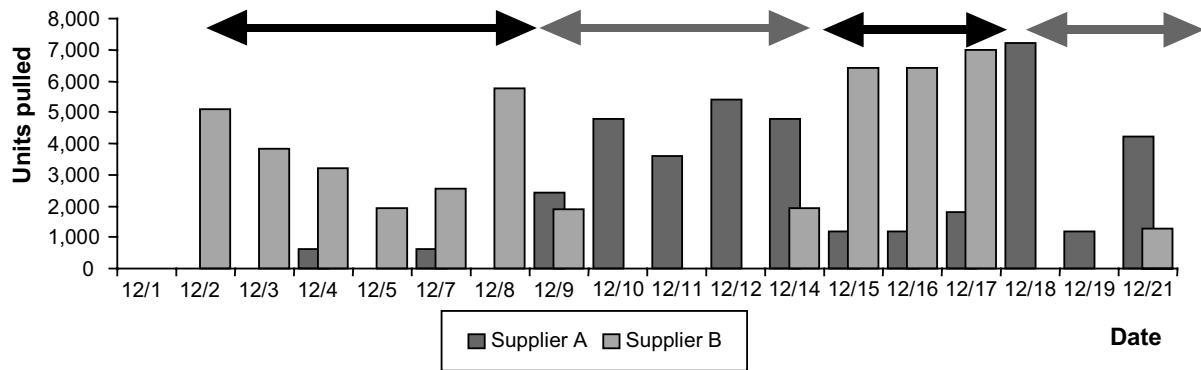
Figure 1: Dell pulled different numbers of units of XDX from two suppliers' revolvers. Light bars and dark bars correspond to quantities pulled by two different suppliers. The arrows above the graph denote the range of days during which Dell pulled predominately one supplier's goods. Dell's pulling in batches of different sizes results in a larger forecast error than would be the case if it used all components in a fixed ratio (level schedule or level pull).

pulling in batches of different sizes results in a larger forecast error than would be the case if it used all components in a fixed ratio (level schedule or level pull). Even though the suppliers do not order every day, they continuously monitor the inventory levels and, therefore, the pull variance influences their decisions.

We compute the pull variance using the same underlying logic as the other two variances except that it derives from the build-pull error instead of the forecast-build error. So, if Dell expected to use 2,000 XDXs per day and it actually used 2,000, the aggregate and attach deviations would be zero. If each of the two suppliers has 50 percent of the business, then each would expect to supply 1,000 units during the day. However, if Dell ignored the percentage of business and pulled all 2,000 units from Supplier A and

none from Supplier B, it would cause high levels of forecast error (and confusion) for both suppliers. If, on the other hand, Dell pulled according to the forecasted business percentage for each supplier, it would eliminate the pull deviations (and consequently variance). The data clearly indicate that the variance from Dell's pulls is greater than the variance in the attach rate, which is greater than the aggregate variance, thus leading to inflated inventories.

Using these three variances as inputs to the model results in three different inventory requirements. Even though interdependencies exist among these variances, by calculating the differences between these inventory requirements, Dell can estimate the cost of error propagation from the aggregate level, through the detailed component level, to the actual variance of pulls from the revolvers (Figure 2). The inventory

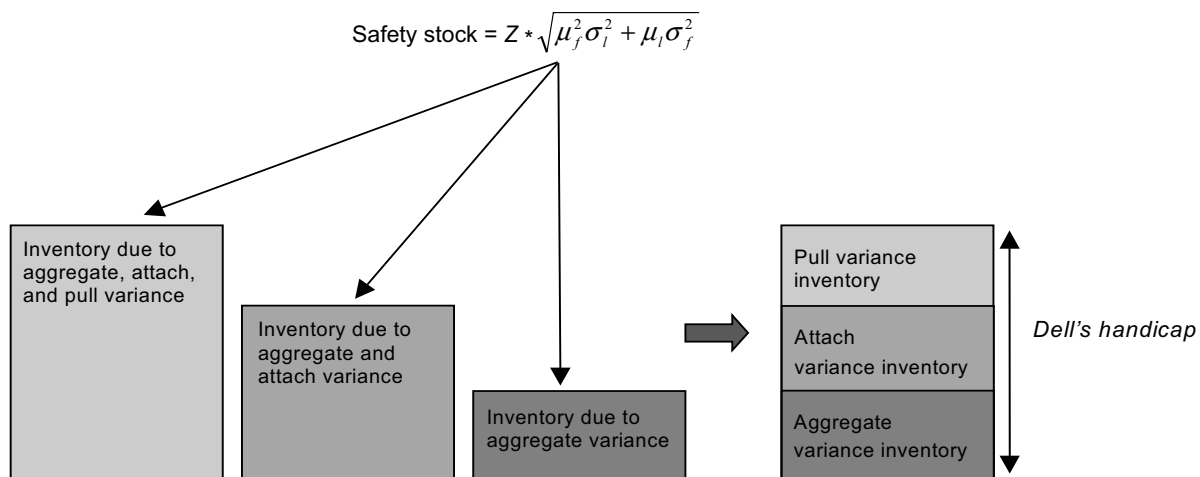$$\text{Safety stock} = Z * \sqrt{\mu_f^2 \sigma_l^2 + \mu_l \sigma_f^2}$$

Figure 2: In this breakdown of Dell's handicap, the left side shows the levels of inventory required due to the accumulation of variance. The right side illustrates how we associate the inventory with each of the underlying causes. We interpret the incremental inventory as a result of the three causes.

Figure 3: We developed a total inventory breakdown assuming the current sources of inefficiency, and we call the inventory driven by aggregate variance, attach variance, and pull variance Dell's handicap.

driven by aggregate variance, attach variance, and pull variance is called Dell's handicap (Figure 3). Our next logical step was to attack this level of inventory through various improvement initiatives.

Data Collection and Analysis

The model provides Dell with a scientific tool to determine the revolver inventory levels and hence to manage its supply chain in a systematic way. The model can also create a reference point for future improvements and estimate the savings Dell can obtain by changing its current manufacturing system. Specifically, buyer-planners can use the model to manage their inventory at a desired service level, and commodity managers can use it to measure improvements in the supply chain. To implement the model, we needed to gather historical data and create a self-contained, user-friendly spreadsheet template buyer-planners can use daily.

Data Collection

We collected data for the period from December 1, 1998 through May 27, 1999. Three companies (A, B, and C) supplied XDXs to Dell during this period. Supplier A supplied two different XDXs, Supplier B and Supplier C each provided one part number but many versions of that part. The parts supplied by A, B, and C are labeled as XA1, XA2, XB, and XC.

We used two groups of data in our analysis: data related to the economics of safety stock (mainly the costs of underage and of overage) and data related to historical estimates of the variance of lead-time demand.

The Cost of Underage

We calculated the cost of underage by evaluating the impact of not having an XDX in inventory. We did not consider the costs of switching among suppliers but instead concentrated on the cost of running out of XDXs altogether. Consequently, we based lost margins on cancelled orders and compensation for the expedited shipping costs for delayed orders. The data included estimates of

—the lost profit from a canceled order,

—increased shipping cost for not having a component when needed (the product is express shipped to the customer or the shipping charges are reduced or waived or both),

—the portion of customer orders that results in a lost profit, and

—the fraction of orders that incur higher shipping costs.

Several costs (for example, for substitution and for air freight) are caused by part shortages, and they are not easy to quantify; many have a greater impact on profit than lost sales. We advised Dell to try to quantify all of these costs in the future. They include

—providing a better part at the same price as the requested part,

—paying a penalty, for example, a percentage of the price of the system for each day above the standard lead time (as specified in some of Dell's contracts),

—making price concessions on future orders because of noncompliance with stated lead times,

—losing sales opportunities with disappointed customers, and

—losing sales when sales representatives call customers to explain delinquent orders instead of calling other customers to make new sales.

The Cost of Overage

In calculating the cost of overage, we recognize that the effect of current ordering decisions is limited to the time between consecutive deliveries of the component. During that time, capital is tied up, price erosion occurs, and the revolver assesses a storage charge. We considered the following data in determining the cost of overage:

—We assumed that the supplier's annual cost of capital was slightly higher than Dell's.

—We estimated price erosion based on empirical data on price decreases for XDXs.

—We estimated that the average time between deliveries was two days based on conversations with sales representatives from all suppliers. Most said that they order from their factories approximately three times per week. Dell's need for the parts and suppliers' presumptions about the size of the order, and not preset schedules, drive their ordering.

Lead Time Demand Variance

We collected the following data for use in our historical study of variance of lead-time demand for XDXs:

—Dell's daily pulls from the revolver for production but not other pulls (for replacement parts or for quality issues), although they were still used to determine the inventory level in the revolver,

—daily receipts of suppliers' components at the revolver,

—daily quantities of in-transit inventory between the suppliers and the revolver,

—daily sales or builds of systems needing XDXs,

—Dell's forecasts to its suppliers specifying the quantity of each supplier's XDX that Dell expects to use during the next month, and

—the suppliers lead times for XDXs obtained from the suppliers' representatives in Austin (including day stamps indicating when parts became Dell-specific), transport times, and the amount of Dell-specific finished-goods inventory suppliers held at their manufacturing and configuration sites.

We could not calculate the standard deviation of supplier lead times with the data collected; we estimated it based on anecdotal evidence. Also, in many cases, suppliers made deliveries of more than one batch, which meant that average lead time could be an inappropriate variable. Because the purpose of safety stock is to reduce the risk of running out of inventory, we used the lead time for the first batch as an estimate of the relevant variable.

Other Parameters

We collected the data to derive values for other needed parameters.

—We calculated the daily quantity of inventory in the system (the system inventory) by adding inventory in the revolver to that in transit for each part number on each production day.

—We calculated the forecast error for demand during lead time by directly collecting data on the quantity analyzed. That is, we considered buckets of time equal to the lead time and calculated the forecast error for each bucket by summing the forecasted demand for all days in the bucket and subtracting Dell' actual pulls over the same period. Then, we calculated a standard deviation of these errors. To express the error as a portion of average demand, we divided the result by the average of the forecasts for the next 10 days, a number we believed was appropriate after observing some real data.

—We calculated the days of inventory Dell held (a measure common at Dell) by dividing a given day's inventory level by the average of the forecasts for the next 10 days. In addition to expressing a given day's inventory in terms of inventory days, we also calculate the average inventory in units.

—To assess Dell's method of making ordering decision, we translated the system inventory levels just before orders into corresponding Z-scores. That is, we used the system inventory to solve for the Z-score for each lead-time bucket and then converted the Z-score into the corresponding service level, using the standard normal distribution. The resulting quantity described the imputed service level.

—We determined the optimal XDX inventory levels, in transit and system inventory levels, for the aggregate and for individual suppliers that should have been carried. These values were calculated using the following formulas:

average in-transit inventory $= \mu_l \mu_f$, and

average system inventory $= R + Q/2 = (\mu_l + L/2)\mu_f + Z\sigma_{D,LT}$,

where Q is the order size, L is the average time between shipments received at the revolver, $\sigma_{D,LT} = \sqrt{\mu_f^2 \sigma_l^2 + \mu_l \sigma_f^2}$ is the standard deviation of demand during the lead time, and $R = \mu_l \mu_f + Z\sigma_{D,LT}$ is the reorder point.

—We calculated the optimal number of days of XDX that Dell should have held by dividing each day's optimal inventory by the average of the forecasts for the next 10 days. We calculated these figures for each part number for each date included in the study. (We wanted to compare the optimal number of days with the actual number of days of inventory in the system.)

Data Analysis

Although interested in the inventory savings, Dell's management wanted to be very cautious and to overestimate, rather than underestimate, inventory needs to avoid damaging customer service due to unavailability of components.

Although our model can handle all the factors listed below, we initially ignored some factors that would have reduced inventory needs even further. First, Dell assembles most of its products two or three days after receiving an order. To be conservative, we ignored this extra lead time. We can easily incorporate its effects by reducing suppliers' delivery times to the revolvers. Second, Dell wanted to run the model at its current average service levels for each component before making any further changes. Third, pooling might provide benefits because three firms were supplying interchangeable parts. For all three suppliers combined, to achieve a 98 percent service level, each would need to achieve a much lower service level (about 70 to 75 percent if they were of comparable sizes). Before exploiting the benefits of pooling, Dell wanted to eliminate the current operational disadvantages caused by clumpy pulls. Also, we ignored ramp-up and ramp-down effects.

Part number	System Z-score	System service level (%)
Aggregate	2.26	98.80
XA1(A)	1.50	93.27
XA2(A)	1.51	93.49
XB(B)	1.25	89.35
XC(C)	0.93	82.42

Table 1: In this table of historical average system service levels (as of May 27, 1999), the parts supplied by A, B, and C are labeled as XA1, XA2, XB, and XC.

Given these simplifications and Dell's requirements, we started by investigating the historical service levels and then the forecast error.

Service Level

The aggregated imputed historical service level of 98.80 percent was surprisingly close to the optimal service level of 98.66 percent provided by the model (Table 1). Individual products, however, had significantly different average service levels, and actual service levels (and the corresponding Z-scores) varied significantly over the course of the study (Figure 4). Inventory theory would suggest a fairly stable level of service. If demand were stationary, both the reorder point and the inventory order-up-to levels would be constant. Even when demand forecasts vary from period to period, because the costs of underage and overage are very stable, the expected service level and the corresponding Z-score, where $Z = \Phi^{-1}(c_u/(c_u + c_o))$, should remain constant (unless there are substantial nonstationarities). We therefore expressed the inventory levels just before orders were placed as Z-scores. Our results show major swings of the Z-scores, which indicates that Dell's suppliers do not follow a (Q, R) policy. We understood that they used

ad hoc techniques, and we were not able to capture them formally. We suspect that these swings were caused by suppliers overreacting to current situations and possibly by long-term trends. (We performed the same analysis for inventory order-up-to levels, which should also remain stable, yet they were equally volatile.) While individual orders varied widely during the study period, the average service level for all three suppliers combined was very close to the optimal.

Our estimates of the average historical service level are very close to the estimates of optimal service levels, and thus the average service level should remain at the current level. However, because in the past inventories shifted erratically and Dell had no consistent policy, it should be able to reduce average inventory by following a consistent policy.

Forecast Error

We gathered information on historical forecasts for XDX and the actual Dell pulls and compared the two for each of the replenishment periods. Forecast error is a critical input in determining the optimal inventory level. In our model, we assumed the errors to be random. However, it was apparent (and confirmed by formal analysis) that at the commodity level the errors are not independent from period to period. The error showed strong linear trends (Figure 5).

The strong error trends could arise from several factors, including forecasting. Like many companies, Dell passes forecasts through various internal organizations before disseminating them to suppliers. While innocently acting with the company's best interest in mind, each group used its own judgment and biases to modify the forecasts of demand. Such iterative hedges and adjustments can erode the quality of the original information. Dell's supply-chain
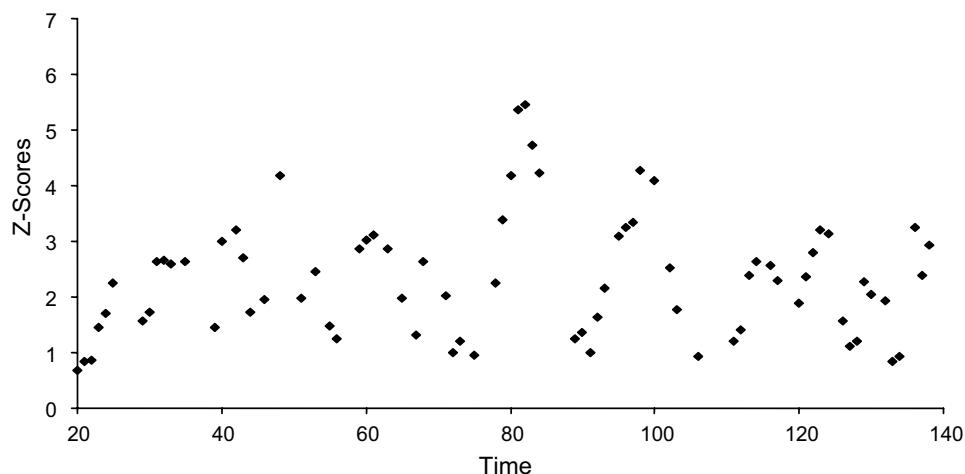
Figure 4: In this graph of Z-scores for system inventory associated with historical service levels over the course of the study, each point corresponds to a placed order.
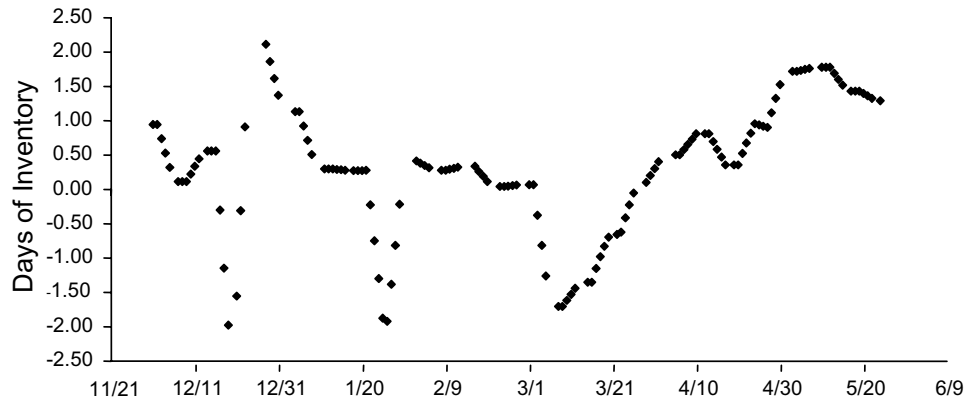
Figure 5: The forecast error for XDX over the course of study showed strong linear trends.

optimization team has targeted these forecasts for process improvement. Despite this concern, we used the forecast data to estimate inventory levels. We exercised extra caution, however, and to reduce potential inaccuracy, we dealt with the lack of independence heuristically (as described in the data analysis section). In this way, we believe that we did not compromise the results from the model, even though the lack of independence reduced the accuracy of the model's recommendations.

In graphing forecast error for XA2, we observed strong cyclic behavior (Figure 6). This can be attributed to the frequency and format of the data Dell provides to the suppliers. The information is provided weekly in monthly buckets. Suppliers generally divide these aggregate monthly figures evenly into four weekly buckets but do not divide it further by days of the week. Sometimes they may even consider the forecast for two weeks as demand needed in one day (the first day of the two weeks). As a result, the forecast for cumulative demand becomes a step function, while it actually grows linearly.

Several other factors (most related to human errors) can contribute to forecast inaccuracies beyond normally expected levels. Ultimately, these forecast errors could prompt Dell to investigate its forecasting procedures and possibly adopt a more quantitative approach.

Results Analysis

After analyzing the data required for the model, we created an Excel-based tool for the buyer-planners. This spreadsheet-based tool was self-contained and included an overview of an input area, actual calculations, suggested decisions, and explanations of the logic for each step. To provide detailed information on each component, we created a series of charts dynamically linked to source data. These charts depicted

—current inventory versus recommended inventory in units,

—current days of inventory versus recommended days of inventory (the above output translated into days),
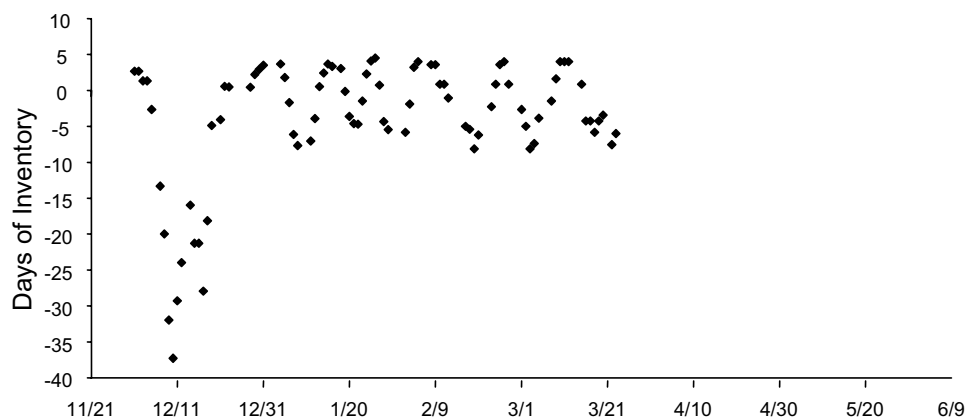

Figure 6: The forecast error for XA2 over the course of study showed a difference between actual orders and forecasted values before Christmas in December of 1998.

—current service level compared to the recommended level,

—inventory drivers, that is, inventory units broken down into causes (such as aggregate error, attach rate error, and pull error), and

—inventory percentage drivers, that is, inventory units broken down into causes and listed as percentages.

Data at this moment must be manually (copy and paste) entered, but Dell is independently proceeding with automating this link.

Service Levels

After developing a format for the data and determining the historical service levels, we examined what the model's recommendations would have been for the past six months. Because the levels of service for individual products were significantly different from those the model would have recommended, Dell and the TMI team agreed to implement the model. The implementation, however, would be split into two stages. In stage 1, historical service levels would be imposed and used as an input to the model; in stage 2, service levels for individual products would be adjusted in accordance with the model's recommendations. Not surprisingly, in stage 1, the model's outputs were close to the average historical levels (Table 2).

Optimal vs. Actual Inventory Levels

While the order-up-to levels that we calculated using the model remained fairly stable over time, the actual

Part number	Average historical level		Average level suggested by the model	
	Units	Days	Units	Days
Aggregate	81,606	11.0	77,643	10.7
XA1(A)	32,351	11.2	24,625	8.4
XA2(A)	26,625	22.1	27,147	23.7
XB(B)	21,111	9.8	18,186	8.2
XC(C)	44,109	9.6	43,414	9.3

Table 2: The historical average inventory levels were fairly close to average inventory levels suggested by the model as of May 27, 1999.

system inventory levels fluctuated widely (Figure 7). The average system inventory levels were close to those suggested by the model, but the actual number of units in the system at any time differed drastically from the number required. For example, around February 1, 1999, the model showed that the system should have held nine to 11 days of inventory to handle expected fluctuations in demand and supply. However, the actual number in the system was close to 18 days of inventory. The extra seven days of inventory in the revolver were costly for the supplier. Likewise, in the beginning of March, Dell was carrying five to seven days worth of inventory, while the model showed that eight to 10 days were required. This means Dell was at a much higher risk of stocking out during that period. Clearly Dell should avoid such huge fluctuations. The systematic ordering policy we proposed will eliminate most of them and make Dell aware of the remaining ones.
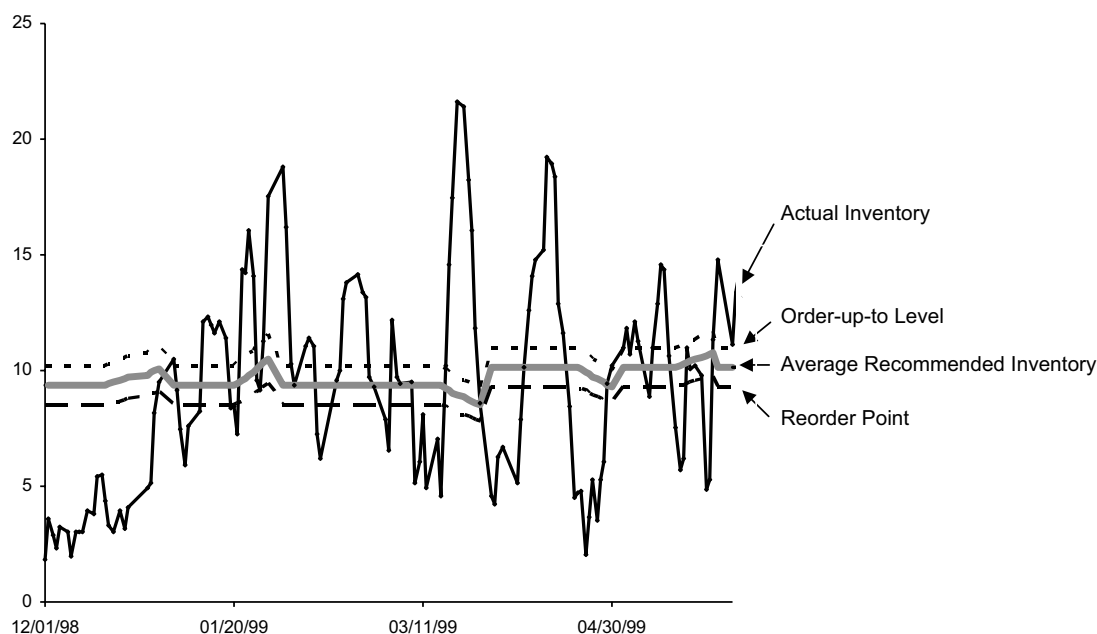
Figure 7: Although on average actual XC inventory was close to the average recommended by the model, the individual observations indicate that most of the time the actuals differed from the recommended levels significantly.

These two examples illustrate the potential benefits of a management tool like the proposed inventory model that can quantify the inventory needed in the system at any time. Dell's buyer-planners who monitor the inventory levels should communicate with suppliers and require inventory levels based on the model's recommendations to prevent Dell from risking a stock-out or paying for unnecessary inventory.

Inventory Percentage Drivers
One of the important features of the model is its ability to categorize causes of required inventory. We analyzed the historical data for XDX and found that attach variance and pull variance each contributed 20 to 25 percent to the total inventory. After hearing several suppliers complain about the clumpy pull, we expected the pull variance to be nonnegligible. The attach variance shows that Dell's forecasts at the commodity level leave room for further refinement (Figure 8). We broke down the drivers for inventory based on the following assumptions:

—The supplier handicap was one day based on the procurement team's experience with supplier delay,

—the replenishment time variance was (one day)^2, and

—the aggregate variance we assumed to be zero because no data were available. (Should the data become available, they would not change the aggregate level of inventory recommended but would alter the breakdown percentages.)

Around 15 percent of the total inventory is associated with par. If there were no variance in the entire manufacturing system, Dell would need only 15 percent of the inventory it needed at the time of our study. Granted, problems and fluctuations will always exist, but this lower bound shows that Dell has tremendous

room for inventory reductions if it can implement and sustain the recommended improvements.

Days of Inventory vs. Units of Inventory
Dell and its suppliers describe inventory levels in terms of days of supply. Days of supply is a much more stable measure than units of inventory. As long as target service levels remain unchanged over a given period and demand does not change dramatically, days of inventory will not vary significantly. (When the coefficient of variation is constant, days of inventory should remain constant.) However, the actual units of inventory may change over time as demand changes (Figures 9 and 10). The component has a recommended inventory level of close to 60 days for nearly the entire product life span, yet the actual reorder points fluctuate widely. In particular, there is a dramatic drop in recommended days of inventory in early January 1999. Although the recommended days of inventory decrease, the units recommended do not because the average demand per day is rapidly increasing (Figure 10). The day calculation is an average of 10 future days' forecasts; in this case, the forecasts were increasing rapidly. Furthermore, two more factors amplify the level of fluctuation: the historical service level of 99 percent and the tremendous supplier pull variance. This example shows why it is important for the buyer-planners to manage inventory in terms of both units and days. The combination of the two charts will allow better understanding and improved decisions, which should translate into decreased costs for Dell and its suppliers. While we believe that days of inventory will remain the primary tool for deciding how much to order, buyer-planners can use graphs of units of inventory to see whether the requirements for a given part are stable or changing. They can interpret any difference between the targeted number of days and the actual number of days of inventory into monetary exposure from holding too much or too little inventory.

Our model does not capture ramp-up and ramp-down scenarios. XA2 was in its ramp-down phase between late March and early April of 1999, after which Dell ceased using the product. Looking at both graphs of units of inventory and days of inventory, however, one can easily recognize such ramp-down and ramp-up periods.

Our results highlight the degree of error in the forecasts suppliers were using and should encourage Dell to investigate why the error was higher than expected (for example, Dell may not have informed the suppliers promptly of changes or Dell may have delayed a product launch because of a quality problem). This should spark Dell's immediate action to correct data frequently and improve its business process.

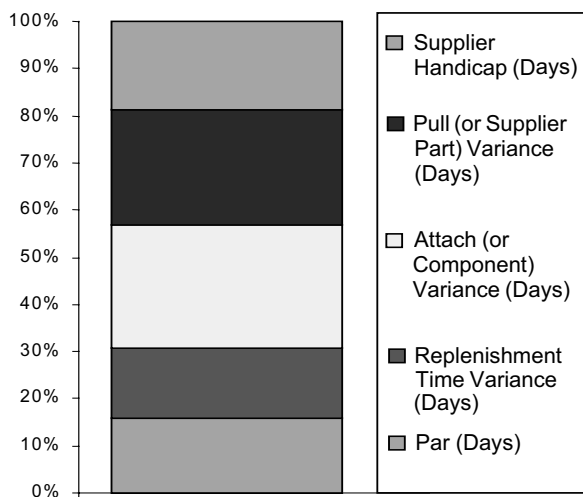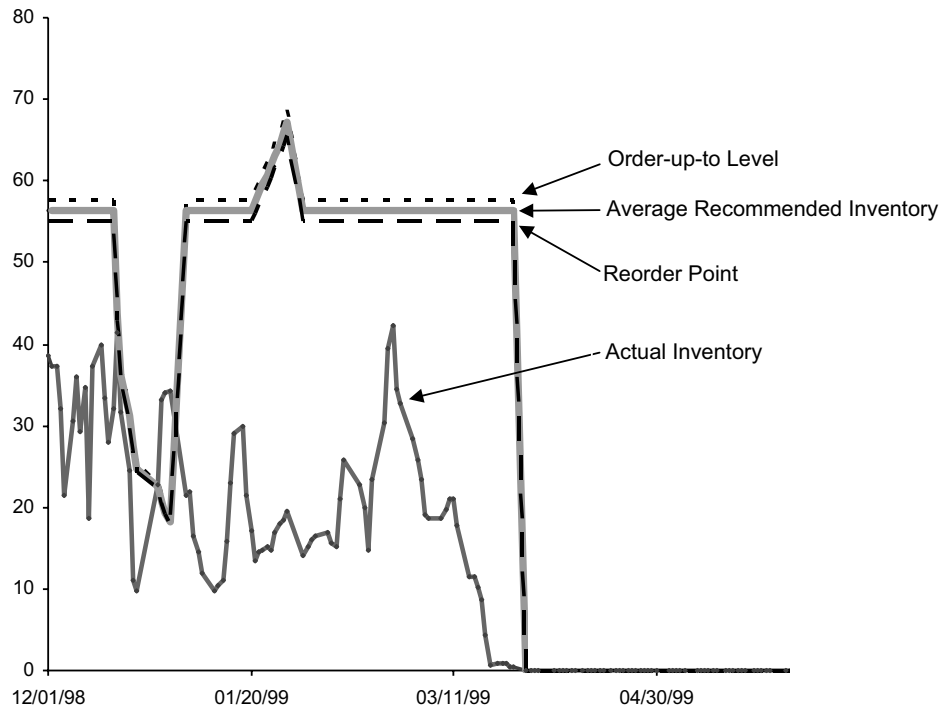Furthermore, the high inventory level should encourage Dell to reconsider the optimal service level

Figure 8: This breakdown of total inventory shows the inventory associated with the drivers of inventory (based on historical data).

Figure 9: The XA2 component has a recommended inventory level close to 60 days, but the actual reorder points fluctuate widely. The recommended days of inventory decreased at the end of December and beginning of January because the forecasts were growing rapidly.
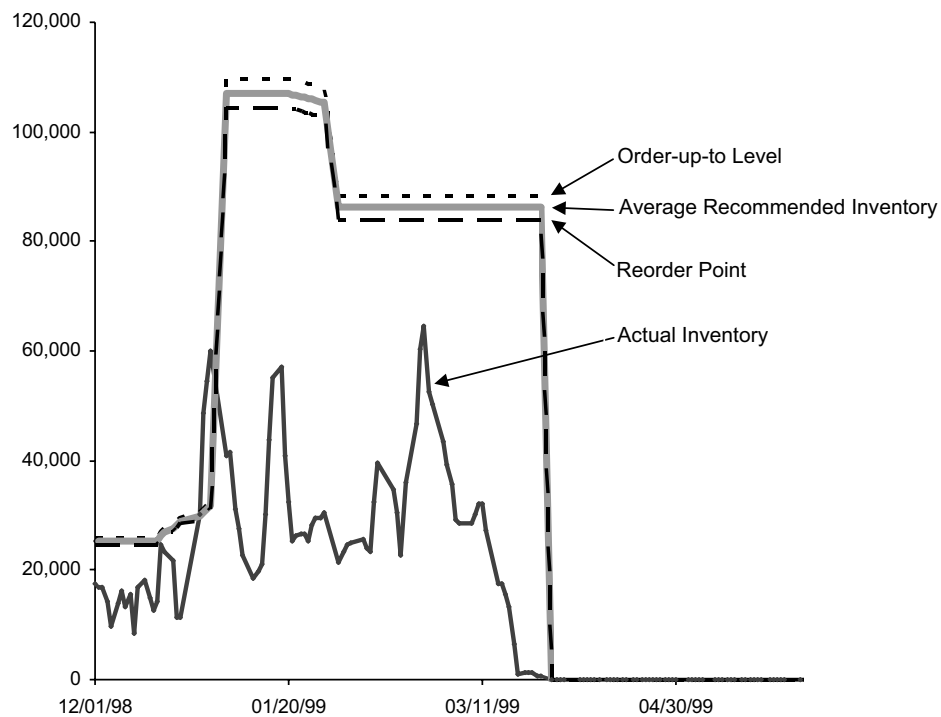
Figure 10: The recommended units of XA2 inventory increase in January due to increased demand.

for a supplier. Dell specified that it wanted to maintain the existing service levels initially. A service level of 99 percent is extremely high and most likely excessive given the data we collected. For this component, Dell could operate with a lower level of supplier service.

Trial Implementation and Impact

After we analyzed the data and developed the tools, we moved to initial implementation. We conducted several tutorials, during which we discussed the theory behind the model and the specific instructions for using the tools (in Excel format).

The goal of the tutorials varied depending on the group targeted. For instance, in training the buyer-planners of XDXs, we focused on using the tactical tool (to set inventory levels and track them); whereas in training the supply-chain-optimization team, we stressed the theory behind the model and the drivers of inventory levels (so that they could conduct improvement projects and quantify their impact). In a tutorial for all of the XDX suppliers, we concentrated on Dell's efforts to reduce the inventories it required them to hold and asked them to help Dell to collect the data needed to run the model.

We also assessed the improvement projects we identified earlier. Other supply-chain-optimization team members were identified as leaders for these projects, and we roughly quantified the effects some of the improvement projects will have on Dell and its suppliers.

Finally, we discussed our project with teams for commodities other than XDX with the idea of finding commodities most appropriate for analysis with our model and validating the model's assumptions for other commodities.

The vocabulary we introduced in our project persists at Dell, particularly *par* and *handicap*. Dell has started other projects to eliminate elements of its handicap. It has defined sources of variability and linked various variance-increasing and variance-decreasing actions to costs and benefits. On a tactical level, our project led to Dell's implementing tools to identify optimal inventory levels.

We analyzed a number of scenarios to estimate the financial impact of various improvement projects. Using the model to extrapolate savings across all XDXs, we calculated the cost savings Dell could achieve by reducing inventory. We used inventory drivers and the corresponding breakdown of inventory costs to estimate the reductions in inventory that could be achieved through various improvements. Eliminating the clumpy pull, reducing the replenishment time by 25 percent, doubling the delivery frequency, and reducing the attach-rate error through

scheduling methods would all help to decrease inventory. Using specific estimates (for price erosion, storage charges, and costs of parts), we estimated that Dell could reduce the current 10.5 days average inventory level by 38 percent. By removing approximately four days of safety-stock inventory, Dell could achieve perpetual savings for all XDXs that will pass through the revolver in the future. The resulting NPV of savings is $43 million, at an eight percent cost of capital. While the actual implementation for XDX is still under way, Dell has used the model to set target inventory levels for networking accessories at the revolvers. So far Dell has decreased inventories for its PowerConnect line of business from 20 days to between 10 and 15 days, which is close to the target of 10 days recommended by the model, and it expects estimated annual savings of $2.7 million.

These benefits are likely lower than the true savings possible as they ignore the facts that Dell does not implement the current inventory policy consistently (the Z-scores are not stable) and does not set service levels correctly, basing them on historical service levels. Consequently, we expect actual savings to be even higher than our estimates.

Throughout the project, we concentrated on a basic solution and showed its use as not only a tactical, but also a diagnostic tool. If such a tool yields savings for a fairly sophisticated manufacturer like Dell Inc., most likely it would also benefit other companies with similar supply-chain issues.

We presented the model to all the stakeholders and prepared the buyer-planners to use it before we departed. Also, the project was awarded the second prize at the Spotlight (a formal festive presentation of results from all TMI projects) held at the University of Michigan in September 1999. A second TMI team continued the project, focusing on decreasing variance on the suppliers' side, and a third team focused on an efficient process for collecting and maintaining the inputs to the model.

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Dick Hunter, Vice President, Americas Manufacturing Operations, Dell Inc., One Dell Way, Round Rock, Texas 78682-2244, writes: "Thank you for the

opportunity to describe the benefits that Dell Computer Corporation has experienced by implementing the Inventory Analysis model in our supply chain. A team of University of Michigan Tauber Manufacturing Institute students and professors developed this model with us in 1999. This model and corresponding logic changed our thinking by directing us to focus on the drivers of variation in our supply chain as a key method to reduce inventory and improve velocity.

"Understanding the variation drivers quantified in this model, we have taken action to change how we pull inventory from supplier logistics centers into our factories. As a result, our suppliers see a more linear, predictable pull of product. For Dell, this means that supply continuity becomes more robust as suppliers are better able to handle unforecasted upsides.

"Supplier logistics center inventory levels have not been reduced so far; rather we have increased our service level to our factories and customers. Dell's ability to deliver quality systems to our customers has increased since inventory previously in place to handle pull-variation is now able to extend our implementation time for quality improvements. Similarly, exogenous factors such as overseas natural disasters are less likely to impact the velocity with which we deliver our systems.

"A systematic reduction of inventory using this model requires an integrated solution with a significant I/T investment. Dell is working towards that direction based on the model algorithms to minimize channel inventory and reap the benefits of increased service levels through reduced variation."