# INTELLIGENT ORDER SCHEDULING AND RELEASE IN A BUILD TO ORDER ENVIRONMENT

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Submitted to the Sloan School of Management and the Department of Civil Engineering
In Partial Fulfillment of the Requirements for the Degrees of

**Master of Business Administration**
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By

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## Abstract

Dell's computer manufacturing process involves a complex system of material flow and assembly. This includes intelligent replenishment of sub-components from local warehouses according to the manufacturing schedule, just-in-time manufacturing of custom configured computer systems including hard-drive image and custom software download, packaging the unit for delivery, order accumulation, and finally, distribution and shipping to the customer.

This thesis examines Dell's current order fulfillment process and suggests methods that can help Dell meet or exceed customers' delivery time expectations at minimum logistics cost in the just-in-time environment. By manufacturing and shipping products based on certain times of the day, air shipments to certain destinations could be converted to less expensive ground shipments. However, this is only possible when the entire fulfillment process is integrated in such a way that eligible ground shipments meet their appropriate shipping windows.

This analysis shows that optimizing these windows not only requires an examination of the average cycle time in each phase but also of the impact that cycle time variations have on the success of this air-to-ground conversion strategy. Through the use of simulation models I found that the key factors in reducing logistics cost require setting appropriate scheduling rules for each order size and reducing the cycle time variation.

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# Table of Contents

## List of figures

# 1. INTRODUCTION AND BACKGROUND

The research presented in this thesis was completed during my six and a half-month internship in the Worldwide Fulfillment organization at Dell Inc. in Austin, Texas. This internship is a result of the partnership between Dell Inc. and the Leaders for Manufacturing program at the Massachusetts Institute of Technology.

## *1.1. Introduction*

Today's competitive business environment is forcing companies to continuously search for ways to improve their operations. To remain competitive, companies must not only constantly improve customer service but also at the same time improve efficiency and lower operational costs. In the past, most organizations have focused their efforts within a single facility and single departments. Thus, fundamental stages of supply chain procurement, production and distribution have been managed independently by different departments.

The single largest component of logistics costs for many companies is transportation, often comprising over half of the total logistics costs (Thomas and Griffin 1996). With recent advances in manufacturing flexibility and efficiency, together with sophisticated information technology systems, companies can reduce costs by coordinating different stages in the supply chain. Specifically, by coordinating production and distribution, companies have opportunity to reduce their logistics costs considerably. This approach is based on the integration of decision-making variables of these two functions into a single optimizing model.

At Dell, the main driver for logistics costs is transportation mode due to a significant price difference between air and ground shipments. The shipping mode, air or ground, is determined based on the promised delivery time and the actual time required to reach the customer. By scheduling orders with longest transportation time to be built first, the orders have a maximum time to reach customers within the promised delivery time. Thus, logistics costs can significantly be reduced by coordinating production scheduling and distribution resulting in fewer air shipments.

## *1.2. Project Definition and Goals*

The objective of the thesis is to determine how to meet or exceed the customers' delivery time expectations at minimum logistics cost in a just-in-time environment. Dell's Austin, TX based desktop manufacturing facility currently ships most of next day and second day service deliveries via air. However, for some order destinations, the opportunity exists to provide the same customer service via ground transportation by manufacturing and shipping its products based on certain times of the day. The key is identifying which orders can be shipped via ground and then scheduling their manufacture and shipment during the appropriate time window (at the start of the shipping day). This policy is called both Time-of-Day (TOD) routing and air-to-ground conversion. These two terms will be used interchangeably in this document. The TOD principle is illustrated in Figure 1.

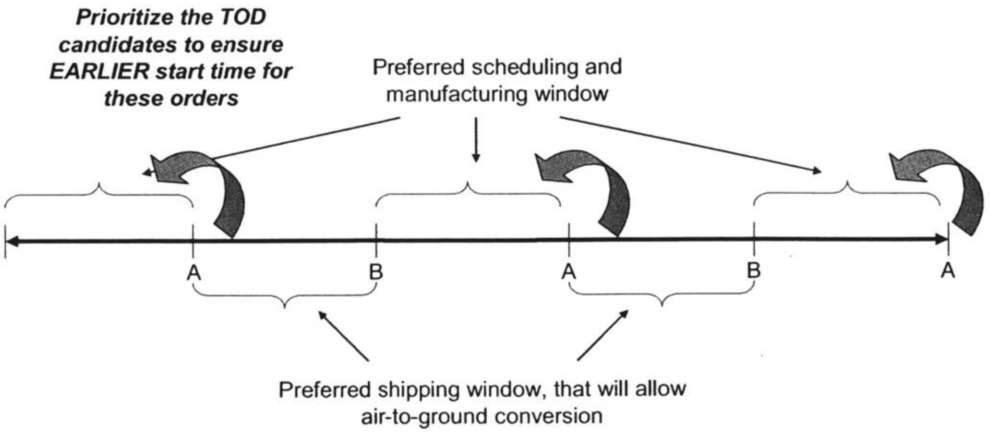


*Figure 1: The optimum manufacturing and shipping windows*

The goals of my research are summarized below.

- Define Dell's framework for identifying scheduling rules for Time-of-Day (TOD) routing and the optimum start time for each order size from 1 through 8 (orders containing from 1 to 8 computer systems) at Dell's Austin desktop manufacturing facility.
- Quantify the impact of manufacturing cycle time variation to TOD success rate both with and without intelligent order release.
- Identify high-level root causes for end-to-end cycle time variation starting at production scheduling and ending at shipping.
- Define intelligent order release criteria that will allow orders to be accumulated in the automatic storage and retrieval area and then released at the appropriate time to ensure optimal carrier selection.
- Quantify the trade-off between lower shipping costs and possible increased WIP.
- Investigate possibilities for geographic scheduling in order to maximize the efficiency and effectiveness of trailer loading and to minimize shippable WIP.
- Determine the impact of promising customers exact delivery date (Customer Committed Delivery, CCD) to the above scheduling and release rules.

The scope of this research includes analysis and recommendations for Dell's desktop manufacturing facility in Austin but the results and solutions are scalable and can be implemented in other Dell manufacturing facilities as well. Dell's just-in-time build-to-order environment and the direct business model provide a unique environment affecting all analysis.

## *1.3. Dell's Company Background and the Direct Model*

Dell Inc. was founded 1984 by 19-year-old Michael Dell on a simple concept: selling computer systems directly to customers. Dell soon became a tremendous success story; by 1992 Dell joined Fortune 500 and became one of the five largest computer makers in the world. Today Dell is the world's number one computer systems company based on market share and a Fortune 50 company. Revenue for the last four quarters totaled $39.7 billion and Dell employs approximately 44,300 people around the globe.

Dell's product offering has expanded from personal computers to a wide range of consumer electronics as the company has grown. Today Dell's product offering includes laptops and desktops, workstations, servers, storage systems, services, monitors, printers, hand-held computers, software and peripherals, appliances and switches and consumer electronics including LCD TVs, Projectors, Dell Media Experience and the Dell Jukebox.

Dell's advantage in the marketplace is a result of Dell's direct business model. Although Dell has grown dramatically in 20 years its business fundamentals have not changed: the direct model has remained the cornerstone of Dell's business strategy. In the direct model computers are sold directly to the customer with no middleman, such as retail stores. The direct model starts and ends with the customer and encompasses the whole value chain from the customer order to customer delivery. With its high focus on the customer, the model creates a unique way to build customer relationships highlighted by the five tenets of the model (www.dell.com 2004).

- **Most Efficient Path to the Customer**: The direct, close relationship with customers allows Dell to understand the specific needs of specific customers.

- **Single Point of Accountability:** Dell is the single point of accountability so that resources necessary to meet customer needs can be easily marshaled in support of complex challenges.
- **Build-to-Order:** Dell provides customers exactly what they want in their computer systems through easy custom configuration and ordering. Build-to-order also enables Dell to carry significantly lower inventories than their competitors and reduce operating costs accordingly. As a result, Dell can provide its customers the best pricing and latest technology.
- **Low-Cost Leader**: Dell's highly efficient supply chain and manufacturing organization, its concentration on standards-based technology and a dedication to reducing costs through business process improvements allow Dell to reduce costs and maintain very aggressive pricing.
- **Standards-Based Technology:** By focusing on standards-based technology Dell can provide customers with relevant, high-value products and services at a lowest price.

The direct model has given Dell an advantage and has allowed it to grow and operate profitably regardless of the flat or shrinking markets.

## *1.4. Current Order-Fulfillment Process*

Dell's order fulfillment process typically a general process. This process starts when the customer places an order directly with Dell either through the web, phone or face-to-face with a sales representative. Orders are then prioritized for scheduling purposes. A new schedule for manufacturing is made every two hours. The materials are also received from the suppliers every two hours according to the schedule. The orders are built based on customer requirements, and are then tested. Finally, orders are delivered to the customer when all computer systems belonging to the order are completed in manufacturing. The shipping mode is determined by the service level chosen by the customer (next day, second day, three days or three to five days) and time to reach the customer.

### *1.4.1. Order Entry and Production Scheduling*

Customer orders are entered to the Dell order management system either via one of the order entry applications or manually by the sales representative. After orders are in the order management system they receive "Order Pending Release" (OPR) status. After a credit check is completed the facility at which the order will be built is determined by specific rules (called download rules) such as product type (i.e., line of business), and destination of the order. Order entry and production scheduling processes are depicted in Figure 2.

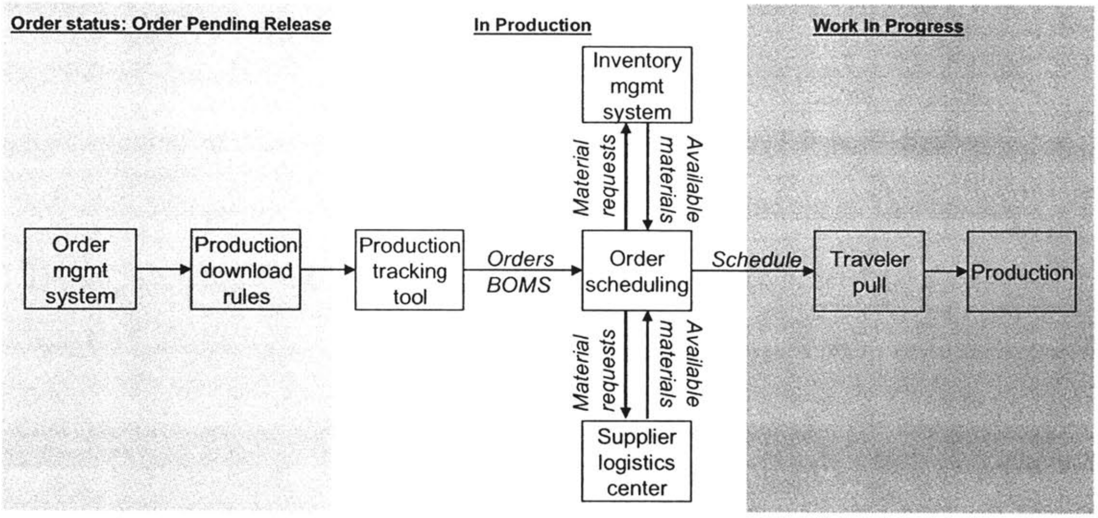


Figure 2: Order entry and scheduling

After that the order advances to "In Production" (IP) status and the order moves into to the production tracking system of the specific factory. The production schedule is created with a scheduling software tool called Factory Planner. Factory Planner creates prioritized and controlled schedules for each plant from the queue of orders in the order tracking system.

Factory Planner is connected to Dell's Supplier Logistics Center (SLC) and Dell's in-house inventory management system to ensure that only orders whose materials are in the stock at Dell are scheduled for production.

The scheduling algorithm in the Factory Planner takes the following steps to create the schedule:

1. Both orders and snapshots from on-hand inventory levels both at Dell and at the suppliers (SLCs) are loaded into Factory Planner.
2. The planner sorts all the orders based on priority, entry time and order quantity. The most important criterion is the priority, which is based on Dell's business rules. Orders with high priority, earliest entry time and largest quantities are scheduled to be built first.
3. Based on the schedule, material requests are sent electronically to the SLCs.
4. The SLCs confirm deliveries based on the on-hand inventory.
5. The Factory Planner assigns materials for the orders and communicates with the internal inventory management system, which makes corresponding updates to inventory levels.
6. Human intervention – The Production Control department at Dell can make changes to the generated plan based on various factors: delayed deliveries, SLCs' under-committed quantities, and any order-expedites that are requested, etc.
7. Material requests are sent to the SLCs. Suppliers have 90 minutes to deliverer the materials to the Dell facility.
8. The Factory Planner creates a detailed final schedule and assigns start times to each order.

The Factory Planner schedule governs the movement and transaction of inventory. Based on the schedule, suppliers deliver materials from the SLCs to arrive just before the start time. The Factory Planner is also integrated with inventory management system containing all Dell's internal material information such as in-house inventory amounts and storage locations. This information is updated when schedules are created, materials from SLC arrive and when orders are started. A final materials check is done before the schedule is released to production floor. The scheduling process is summarized in Figure 3.

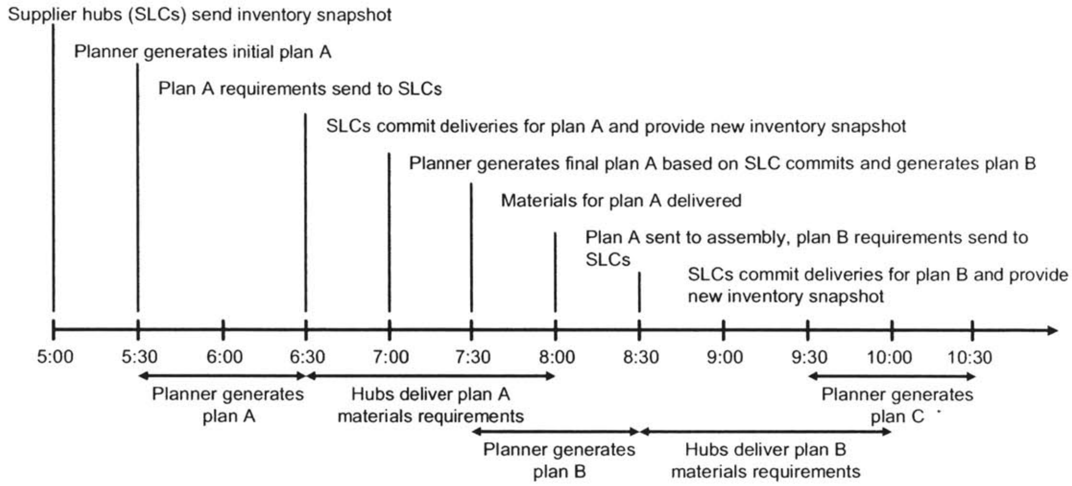


*Figure 3: Factory Planner scheduling process*

The Factory Planner only schedules the first production phase, which is called kitting, for each order. After kitting is completed the computer systems travel from one phase to the next phase according to the FIFO (First In First Out) principle.

At the factory the production of an order is initiated when a bar code that contains specifications for a particular computer system is printed in the kitting phase. This is called "traveler pull". Traveler equals the bar code linked to the order information. The order status now moves to the Work-In-Progress (WIP) status.

### *1.4.2. Production, Order Accumulation and Shipping*

As mentioned above, production starts with travel pull in kitting. The production process is illustrated in Figure 4.

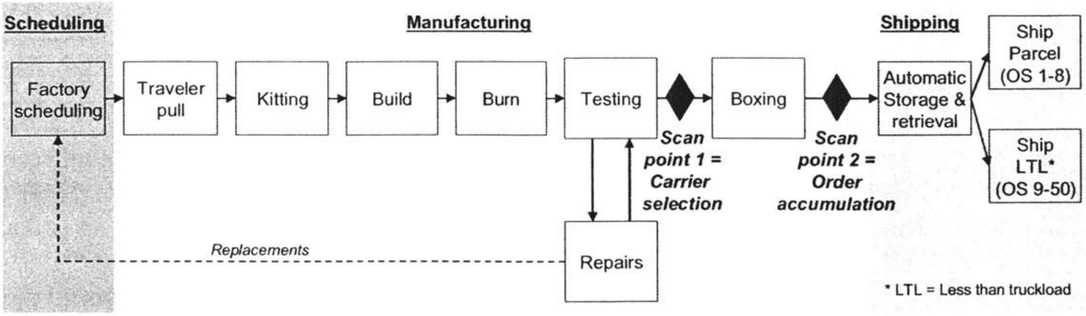


*Figure 4: Production and shipping process*

In the kitting phase, all components belonging to a specific computer system are picked, placed in a special tray and sent along the route to build. The complete order is started simultaneously in kitting phase but after kitting individual systems travel through the process independently. The order then moves into a build phase where one person completely assembles the system and performs basic quality test by turning the system on to ensure that it is functional. Then the system is placed on a burn rack where all the software is downloaded into the system and a thorough testing is performed. After this burn phase a final testing is performed. If problems occur in any of the above mentioned tests an electromechanical repair (EMR) specialist will be called in to investigate and repair the possible failures. If a system cannot be repaired a replacement system is scheduled.

After the burn phase the system passes scan point 1, where its bar code is scanned. Scan point 1 is linked to carrier selection software, speedway, which selects the transportation mode (i.e. carrier) to the order the system belongs to. All the information related to carrier selection is downloaded into carrier selection software, Speedway. A dynamic rating and routing algorithm selects the optimal carrier based on order size (number of systems), shipment weight, ship-to address, and requested service level in order to minimize the transportation costs. Carrier for the order is selected only when the first system of an order passes scan point 1.

The last phase in manufacturing is boxing in which the completed system is placed in a box together with all the peripherals such as keyboard, mouse, documentation and power cords. After boxing, the system then passes scan point 2 where it is sent either to an automated storage and retrieval system (ASRS) or directly to trucks for delivery. The decision to send an order to shipping or to the ASRS is made based on the following criteria. An order will be stored in the ASRS if:

- It is not complete, i.e., another system or systems in the same order have not yet been completed.
- The carrier chosen earlier at scan point 1 is not available (i.e. the truck is not at Dell facility).
- The carrier is available but there is not enough space in the truck for the whole order.
- SPAMs (Speakers, Monitors and other peripherals ordered with the computer system) are not yet available.
- Pallet build (i.e. if the order is sent using a less-than-truckload (LTL) carrier it needs to be palletized before loading) location is not available (i.e. all pallet build locations are reserved by other orders)
- An engineering hold is placed on an order (e.g. due to quality-control reasons)
- Overpacks associated to an order (all peripherals, etc. ordered by the customer that do not fit in the computer system box) are not yet available.
- Some orders with special shipping requests or international destination can not be shipped with automatic shipping system Speedway. These orders are all directed to the ASRS as default and then manually released and shipped with a manual shipping system.

If all the above criteria are met, an order is released and shipped with the carrier chosen at the scan point 1. For computer systems diverted to the ASRS, separate software automatically rechecks the order every three minutes to ensure that all orders are released as soon as all criteria are met. When an order is released all components (Systems, SPAMs and overpacks) are released at the same. Systems stored in the ASRS, and SPAMs stored in a separate area, travel then at the same time to the shipping area where the shipping documents and package slips are attached. The orders are considered complete after the shipping documents are attached.

Dell uses two different shipping networks. All the orders that contain from one to eight computer systems are sent loose-loaded (i.e. these orders are not palletized) to customer. These loose-loaded shipments are parcel shipments. All orders containing 8 to 50 systems have to be palletized (this is called pallet build) and are sent as Less Than Truckload (LTL) shipments. If an order contains more than 50 systems it is broken into several smaller orders and sent to customers in batches of 50 (due to historical business reasons).

## *1.5. Dell's New Global Fulfillment System*

The legacy system that executes carrier selection and the shipping procedure is called Speedway. Speedway is being replaced by a more scalable and stable software tool that includes a warehouse management system (WMS) that interfaces with a transportation management system (TMS).

TMSs are typically used as decision support tools in two areas: planning and optimization and transportation execution. During planning and optimization efforts, TMSs determine the transportation mode(s) and also manage freight consolidation operations and coordinate company shipments, including continuous freight moves. When used in the execution or operations modes, TMSs are either directly or indirectly responsible for carrier load tendering, routing and scheduling, shipment tracking and tracing, and freight payment and auditing (Gilmore and Tompkins, 2000).

As both WMSs and TMSs are the primary tools used in supply chain execution, they are the key in integrating the physical flow of goods along the extended supply chain. The most promising opportunity for achieving efficient management of the extended supply chain is through a full systems integration of WMS and TMS (Gilmore and Tompkins, 1997).

### *1.5.1. Goals of the New Fulfillment System*

The goal of the new fulfillment system is to reduce supply chain costs while enabling advanced supply chain processes by integrating WMS and TMS. Dell's warehouse management system includes activities related to inbound logistics such as receiving, inventory control, physical count and inbound quality assurance. The goals of the new WMS are listed below.

- Reduce labor associated with receiving and inventory control functions,
- Reduce on-hand inventory, eliminate write-offs, and improve order fill rates through increased inventory accuracy,
- Improve space and equipment utilization, and
- Enable advanced distribution functions such as cross-docking, vendor performance tracking, work order management and returns processing.

The transportation management system focuses on outbound logistics activities such as loading, pallet build, carrier selection and shipping. The new TMS system will also replace two existing shipping systems, Speedway and the manual shipping system with single system. The goals of the new TMS are summarized below.

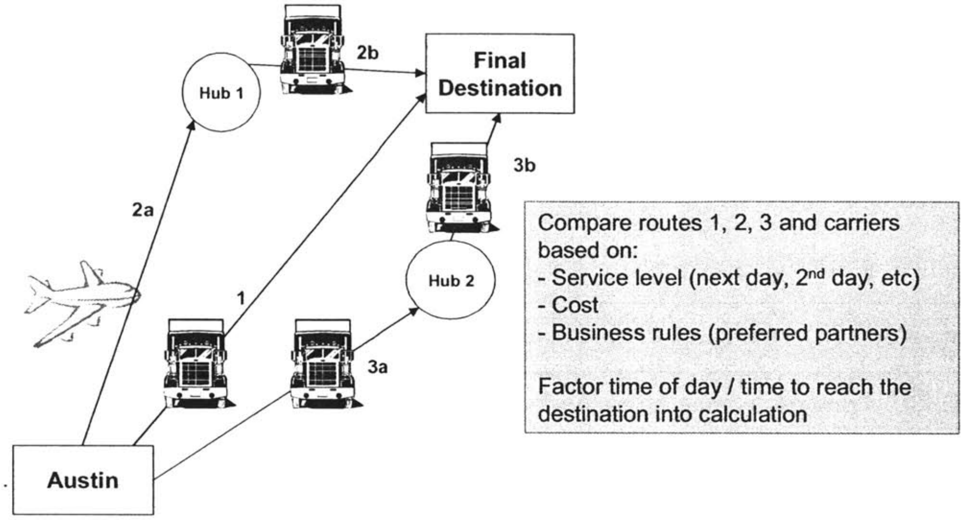
- Lower outbound logistics costs by enabling carrier re-evaluation after an order is completed,

- Reduce labor associated with order release, picking, packing, Value-Added Services (VAS), staging, and shipping,
- Improve customer service by reducing shipping errors, improving lead times, ensuring customer compliance and enabling VAS, and
- Increase throughput by optimizing fulfillment processes.

### *1.5.2. New System and Carrier Selection*

Currently, carrier selection occurs when the first computer system of an order passes scan point 1 and cannot be modified at the order release point (from the accumulation area). The problem with this process is that the carrier is selected without accurate information about the actual shipping time because shipping is always executed on an order-level (not for individual computer systems). If an order includes multiple systems it might take hours, sometimes over a day, before the whole order is completed and the order can be shipped. Similarly, regardless of the order size, it can take several hours after the order passes scan point 1 before it can be shipped if the SPAMs are not available or other release criteria are not met. This delay has two disadvantages. Firstly, Dell can not assign carriers that are only available within certain times of the day because the actual shipping time is not known when the carrier selection is made. Secondly, there is a risk that Dell will miss the customer delivery date if an order completes significantly later after a first system of an order passes the scan point 1.

The new shipping system will allow carrier re-evaluation when the order is released from accumulation area and the complete order is ready for shipping. The carrier re-evaluation will enable Dell to accurately select a carrier based on both the primary criteria (order size, shipment weight, ship-to-address, time-of-day/day-of-week, and requested service level) and delivery time to customer as depicted in Figure 5. Further, order expediting is possible in case there is significant time lag between initial carrier selection (scan point 1) and re-evaluation. Carrier re-evaluation at the point of order release and thus, the new shipping software, is a pre-requisite for the new scheduling and release rules recommended in this thesis.



Compare routes 1, 2, 3 and carriers based on:
- Service level (next day, 2nd day, etc)
- Cost
- Business rules (preferred partners)

Factor time of day / time to reach the destination into calculation

*Figure 5: Dell routing process*

## *1.6. Scope and Limitations*

My original research scope (intelligent order release) focused primarily on the release to carrier, i.e., how to manage the ASRS accumulation release process to ensure maximum air-to-ground conversion. After the initial process analysis, however, the scope was broadened and to determine how best to manage the entire order-fulfillment process to achieve maximum air-to-ground conversion and cost savings. It became obvious that successful implementation of TOD routing requires that all four elements of the order-fulfillment process – scheduling, manufacturing, accumulation and shipping – are tightly coordinated to achieve on-time deliveries with minimum logistics costs. This thesis investigates how Dell manages these elements and how decisions made in each phase impact the fulfillment process as a whole (Figure 6).

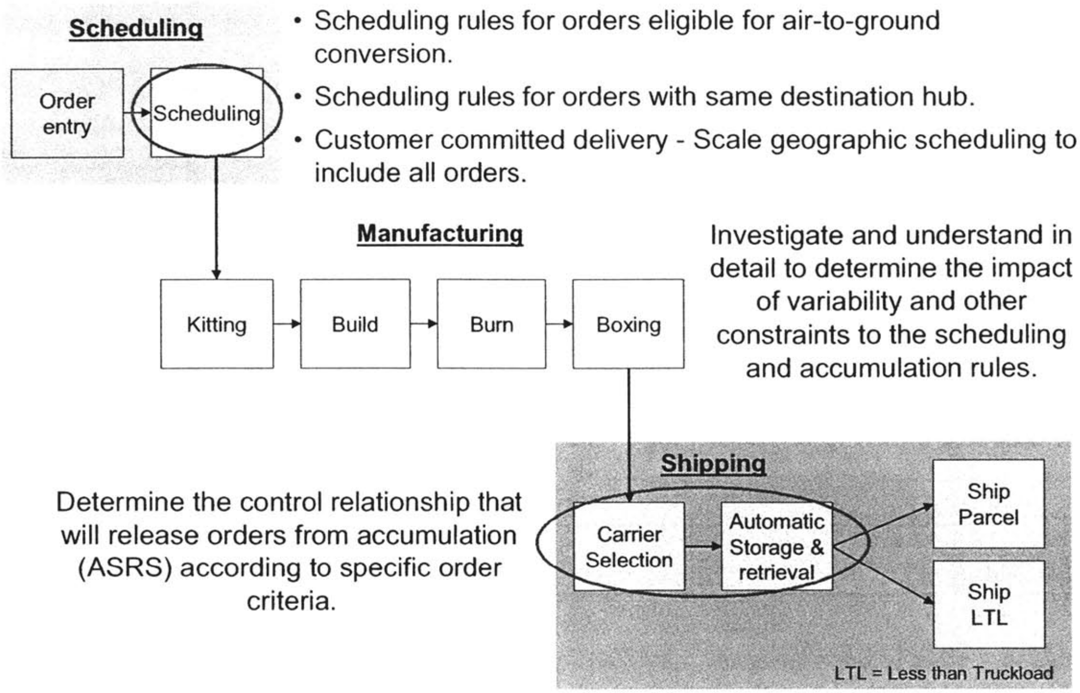


*Figure 6: Project overview*

In scheduling, the objective is to ensure that orders with express service level (next day, 2nd day deliveries) are scheduled to be completed within a specified time window in order to ensure lower transportation rates by using ground instead of air shipments. Currently, the optimum start time for each order size and destination hub are based on the cycle times and carrier cut-off times. Some of these scheduling rules are already in use in Dell's desktop manufacturing facility in Nashville, TN. However, as the manufacturing process and the average order quantities are different in Nashville and Austin there needs to be proper analysis of the optimum scheduling rules for Austin.

The manufacturing department executes the plan created by the Factory Planner. Variability in cycle time directly impacts the ability to meet the optimal manufacturing and shipping windows. Thus, it was critical to investigate and understand not only the average cycle times but also the variation around the cycle times in each phase.

Cycle time variation decreases the probability of completing orders within a certain time window regardless of the optimum start time. Thus, to achieve the targeted cost savings Dell must manage orders that miss the targeted window. This can be achieved by adding intelligent ASRS order release criteria that will ensure optimum carrier selection at the point of release (from ASRS). The intelligent release criteria is a controlled relationship between the Warehouse Management System and Transportation Management System that will allow orders to be accumulated and then released according to the specific criteria that take into account the promised delivery date so that customer satisfaction will not suffer from a delayed release.

My research focuses on both the current order-delivery process and Customer Committed Delivery as depicted in Figure 7. Currently delivery time is defined as a combination of the manufacturing lead time and the shipping time (i.e., service level). In the future, however, customers will no longer choose service level but delivery date that includes both the manufacturing lead time and shipping time. This is called Customer Committed Delivery (CCD). My research determines appropriate release and scheduling rules for both current and CCD environment.

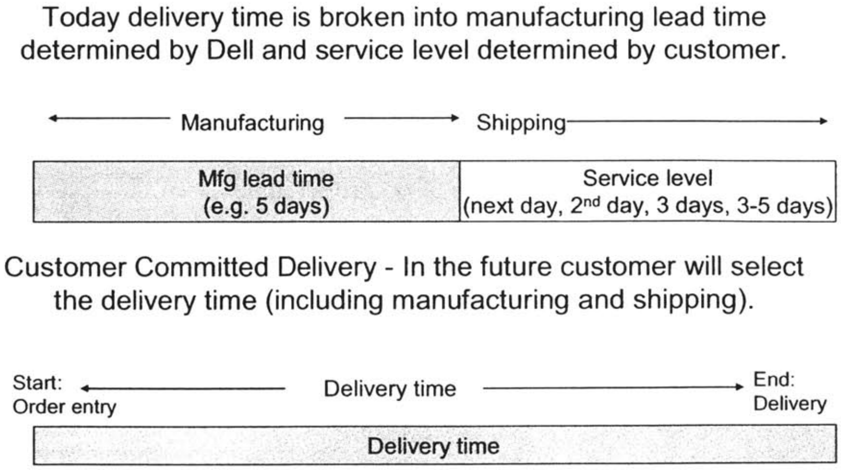


*Figure 7:Customer Committed Delivery (CCD)*

# 2. LITERATURE REVIEW

In this section, I first review the literature on integrated production/scheduling and distribution/logistics models to explore how these models operate and how widely implemented integrated production and distribution systems are today. Additionally, the goal is to study to what extent these systems are used to optimize existing logistic networks, i.e., tactical level logistical decisions and how effective they are. Following this I explore methods that companies use to manage uncertainty and the variability of manufacturing processes because cycle time variability is one of the most important factors influencing air-to-ground conversion success.

This literature review is not intended to be exhaustive, but rather it is directed toward identifying how other companies approach the problems that Dell faces in managing order-fulfillment process more effectively.

## *2.1. Integrated Scheduling and Logistics*

This section reviews the literature on integrated analysis of production and distribution functions. The main interest is on the following two questions: (i) How have logistics aspects been included in the integrated analysis? (ii) What competitive advantage has been obtained from integrating the distribution function into other order-fulfillment functions within a company?

The production-distribution integration can take many forms. The literature addressing both production planning and distribution planning is rich. However, only a few models attempt to address these models simultaneously. One reason might be that the production and distribution processes are often separated by the finished goods inventory. In addition, both production scheduling and distribution planning are most often managed independently of each other by two different departments. Production schedules are based on set-up costs and inventory costs, while transportation schedules are based on freight charges and loading costs.

Sarmiento and Nagi (1999) distinguish two broad areas in the integrated analysis of production-distribution systems research: inventory-distribution planning and production-distribution planning. The classification is based on the decisions made in a model (e.g., production, distribution, inventory management). The inventory-distribution models typically consider warehousing/distribution process as first-echelon and retailer or end customer as second echelon. The objective of these models has commonly been the minimization of total costs, including inventory costs at both supply and demand points as well as transportation costs. The decision variables in these models are usually shipment sizes, inventory levels and optimum routes. These models are most often used in situations where a large amount of inventory builds up between production and distribution thus decoupling the two functions. As companies move towards lower inventory levels, the focus moves from the inventory-distribution problem to the production-distribution problem. This review focuses on the production-distribution models because of Dell's just-in-time manufacturing (JIT) environment and minimum inventories.

The production-distribution models date back to 1980's. Williams (1981) studied dynamic programming based on algorithms for simultaneous minimization of production and distribution costs in assembly-production and conjoined-distribution networks. The algorithm connects the production and distribution networks and aims to minimize average costs per period in the entire system over an infinite horizon. The optimization focus, however, is on determining the optimum production and distribution batch sizes and minimizing the processing and inventory holding costs rather than using optimum transportation modes. In addition, the demand in each destination node is assumed to be known, constant and continuous.

Benjamin (1990) considers the choice of transportation mode in a production-distribution network with multiple supply and demand points. He looks at the problem from the entire supply chain point of view including inbound and outbound logistics. He analyzes the process of choosing a mode of transport for the distribution of materials in terms of setup, inventory, and order costs as well as the transportation cost. He finds that the choice of transportation mode has implications for shipping patterns throughout the network. In particular, adoption of special shipping strategies, such as the just-in-time (JIT) inventory policy, depends on the comparative total costs for each link in the network. When using the JIT strategy, the cost of production at the demand point must also be considered. He suggests that the total cost of shipping, storage, and production should be the decision criterion wherever shipping options are available, and that costs for an entire network should be considered when transport decisions are made. Even though this model is not directly not applicable to this problem it is one of the few models found that takes into account different transportation modes.

Blumenfeld and Burns (1991) examine whether it is cost-effective to synchronize production and transportation schedules on a production network involving one production facility and multiple shipping destinations. The research focuses on a simple system where one plant produces parts that are shipped directly to each destination (one destination by part type). This reduces the complexity so that the network can be modeled analytically allowing the basic problems in synchronized schedules to be addressed. Decision variables include production set-up, freight transportation and inventory costs on the network whereas the common objective is to minimize the total costs. The production and transportation schedules are considered synchronized if the production lot size and shipment size are equal. Therefore a shipment departs from the origin as soon as the production run for the destination is completed thus reducing inventory at the origin. This simple synchronization strategy can also be generalized to allow more than one shipment per production cycle. The schedules remain synchronized if the shipment size is a sub-multiple of the production lot size, so that shipment still departs immediately at the end of a production run. The results indicate that the cost savings from synchronizing production and transportation schedules for a wide range of set-up and freight costs are between 15 and 40%. The savings increase as the number of destinations on the network and the value of parts produced increase. However, the model assumes ground transportation and direct shipping for each destination.

Chandra and Fisher (1993) present a single plant, multi-customer, multi-product model that combines production scheduling and vehicle routing problems to investigate the value of coordination between these functions. They consider a plant that produces a large number of products over time and maintains an inventory of finished goods at the plant. The products are distributed by a fleet of trucks to a number of retail outlets at which the demand for each product is known for every period of a planning horizon. They compare two approaches to managing this operation, one in which the production scheduling and vehicle routing problems are solved separately, and another in which they are coordinated within a single model. Chandra and Fisher then conduct an analysis using different values of the basic model parameters including the length of the planning horizon, the number of products and retail outlets, and the cost of setups, and inventory holding. Additionally, the conditions under which companies can consider the organizational changes necessary to support coordination of production and distribution are researched. The model assumes finished goods inventory and does not consider different transportation modes other than ground transportation.

The few models that focus on integrated production and distribution in the JIT environment seem to concentrate on the inbound logistics and on ensuring the raw materials/parts supply for production. For example, Yano and Gerchak (1989) analyze this problem. They present a solution methodology to simultaneously determine safety stock levels at the location in the second echelon (customer), number of trucks required for regular delivery and time between shipments so that overall operational costs are minimized. These costs include inventory holding, shortage at the second echelon, and transportation costs.

In addition, another type of models focuses on the design aspects of the supply chain. These models concentrate on optimum facility (warehouses, plants, distribution centers) location as well as inventory and production quantities at each location. Clearly, these approaches are applicable for strategic aspects of the supply chain, not for tactical optimization of an existing supply chain. Thus, these models were excluded from my literature review.

Based on this literature review it can be concluded that the analysis of production-distribution systems remains a wide open area. Most of the existing research focuses on minimizing the total system wide costs by optimizing the inventory levels at each phase. Very little research focuses on optimizing the logistics within a current network in the JIT environment where manufacturing is based solely on customer orders and no excess inventory exists. Additionally, many models assume fixed transportation costs or use linear transportation cost functions. While linear functions simplify the analyses they fail to examine cost and time differences between various routings and transportation modes.

However, the literature shows that integrating production and distribution (i.e., logistics and scheduling) in most cases enables companies to gain a competitive advantage even if the integration is performed at different levels.

## 2.2. *Does Variability Matter?*

I will start by quantifying variability. *Variance*, commonly noted as $\sigma^2$ is a measure of absolute variability, as is the *standard deviation* $\sigma$, defined as the square root of variance. Often, however, absolute variability is less important than relative variability. For instance, a standard deviation of one hour would in most cases indicate low variability if the mean cycle time is 5 hours, but would represent a very high variability if the mean cycle time is 30 minutes. A reasonable relative measure of the variability of a random variable is the standard deviation divided by the mean, which is called the *co-efficient of variation* (CV).

Hopp and Spearman (2000) divide variability into three classes based on the CV: variability is considered low if the CV is under 0.75, moderate if the CV is between 0.75 and 1.33 and high if the CV is higher than 1.33. Cycle time probability distributions with low variability look typically like a bell-shape curve as depicted in Figure 8. Most of the area under the curve is distributed near the mean. In the case of moderate variability, the most likely values are actually smaller than the mean, but it tails off further away than low variability distribution. In this case the means are identical but the variances are much different. An example of the high variability distribution is, for example, an exponential probability distribution that typically has a larger "spike" close to zero and a tail further away from the x-axis than in a moderate variability distribution.

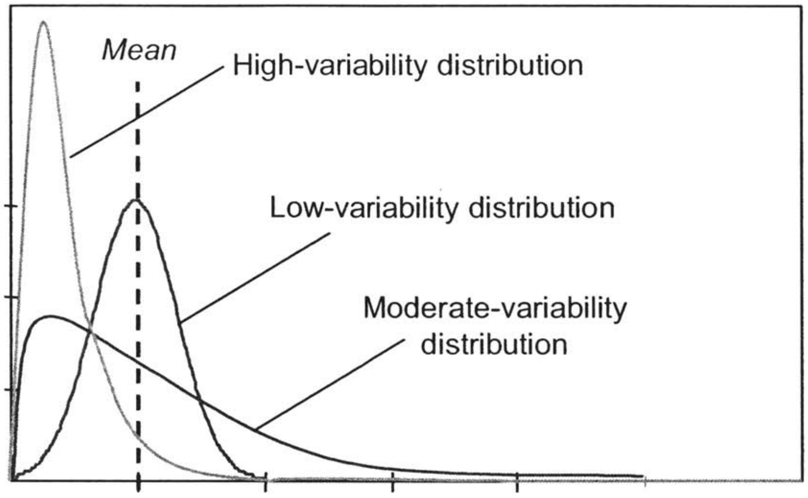


*Figure 8: Low and moderate variability distributions*

Cycle time variances have not typically been the focus of the corporate managements. Rather, most studies in the vast literature on manufacturing process performance evaluation focus on measures such as average cycle times and average work-in-progress inventory. However, there is a growing number of studies to demonstrate the significant impact of variance on process performance, especially in just-in-time manufacturing environments. The importance of this topic is highlighted by the fact that empirical studies and factory observations show that the standard deviations of the output in a given time period are often more than 10% above the mean (Tan, 1998a). The motivation for this research derives from key finding that any variability in cycle times directly impacts Dell's ability to meet optimal manufacturing and shipping windows.

Sarkar and Zangwill (1991) examined the effect of variance in production systems utilizing the cyclic queue system. A mathematical model based on the cycle queue system allows a number of features of stochastic multi-product production to be calculated, including expected inventory, waiting time and cycle times. The variance of setup time, processing time and arrival rate is shown to have a powerful impact on system performance. Sarkar's and Zangwill's research shows that in the presence of setup or processing time variance, the reductions in the average processing time do not guarantee WIP reduction and may even cause WIP levels to increase which automatically lengthens the cycle times accordingly. Sarkar and Zangwill study two examples that not only contradict the usual insights into production systems but also highlight the role of variance. In the first example, the average processing time is cut by speeding up production machines. It was expected that the inventory waiting for processing would decrease accordingly. However, the opposite occurred. The second example demonstrates that, without decreasing the variance, cutting the average setup-times can also increase WIP rather than decrease it.

The paper demonstrates that whereas average processing time and setup-time reductions might help in a deterministic system they can make things worse in a stochastic system. Thus, variance can cause the inventory to increase. By reducing the average setup or processing time the expected cycle times decrease. If the variances are not reduced proportionally, however, a number of longer processing/setup times will remain and (the tail of the cycle time distribution) increasing the relative variability, i.e., coefficient of variation. As a result, the WIP in the system will increase leading to longer cycle times.

Albino and Garavelli (1995) propose a methodology to evaluate the effects of variability on just-in-time system performance. Specifically, it provides a framework for the evaluation of performance sensitivity to unexpected events by pointing out how JIT systems are disrupted. This approach can be used to point out the weaknesses of JIT systems and to suggest prevention measures as well as to help management to design system controls and adopt of suitable measures. Albino and Garavelli analyzed two industrial applications to show how the vulnerability concept can be applied in practice, how to focus on the most critical aspects, and to provide guidelines for the methodology implementation.

Buss and Lawrence (1995) investigate mean-variance interactions of processing times as applied to capacity planning and process improvement by applying results from the queueing theory. They provide a formal framework to examine the interaction of processing-time means and variances and their marginal effect on costs. The model is specialized to a case of a queueing model with linear and separable mean and variance costs and with total costs proportional to the mean queue length. The model demonstrates that a production process will fall into one of six mean-variance regions, each with its own policy implication. A simulation example of a production network taken from the industry is used to demonstrate the applicability of the model in a general, realistic setting. Figure 9 represents these six regions for the example examined by Buss and Lawrence.

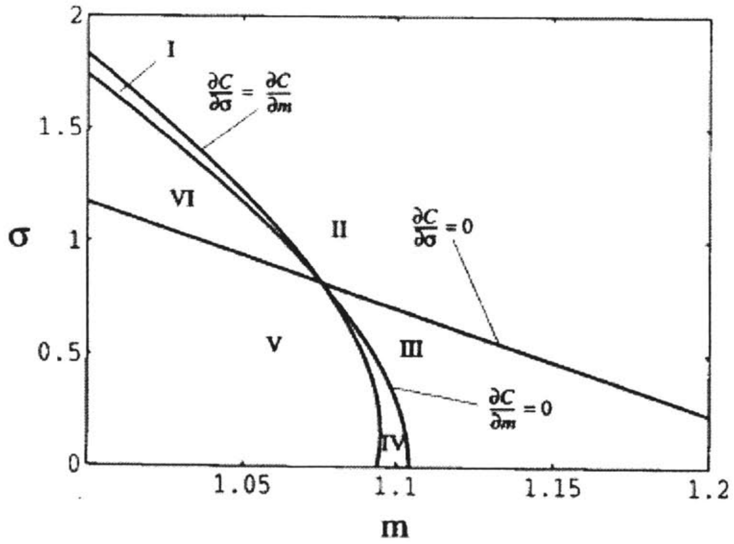


*Figure 9: Mean-variance curves and regions for an industrial example (Buss and Lawrence 1995)*

As shown in Figure 9, In regions I and II cost improvement can be obtained by decreasing either the mean (m) or standard deviation ($\sigma$) since $\delta C/\delta m > 0$ and $\delta C/\delta\sigma > 0$. However, in region I $\delta C/\delta m < \delta C/\delta\sigma$, so improvements in process variance produce larger cost reductions since costs decrease at faster rate with $\sigma$. Conversely, in region II, $\delta C/\delta m > \delta C/\delta\sigma$, indicating that decreasing the mean processing time provides superior cost reductions.

In regions III and VI, $\delta C/\delta m$ and $\delta C/\delta\sigma$ have opposite signs, demonstrating the interaction between processing-time means and variances: one should be improved at the expense of the other. In region III, $\delta C/\delta\sigma < 0 < \delta C/\delta m$ so, in this region, management should focus on decreasing the mean but the variance can be allowed to increase. On the contrary, in region IV, $C/\delta\sigma > 0 > \delta C/\delta m$, so firms can increase the mean whereas variance must be decreased. In regions V and IV, $\delta C/\delta\sigma < 0$ and $\delta C/\delta m < 0$, so increasing the mean and/or variance will improve costs. In region IV, $\delta C/\delta m > \delta C/\delta\sigma$, so increasing variance will be more cost effective than increasing the mean. Conversely, in region V, the opposite is true.

Obviously, many companies today believe that they operate in regions I and II as they focus on maximizing utilization while ignoring processing variances. On the contrary many Japanese companies that operate under the just-in-time philosophy run their machines at a slower but steadier pace indicating that they believe they operate in region VI. On the other hand, many companies attempt to increase speed without regard for variance showing that they believe that they are operating in region III. In summary, process improvements can be achieved by reducing both the mean and variance of processing times. In addition, the interaction between these two factors is a critical factor. Thus, it important for a firm to be aware of the region in which it is operating to make effective decision regarding improvements and to understand which process improvement efforts will not be cost-effective.

Tan (1998b) studies the effects of variability on the production system structure, and also the effect of processing time variability on the performance of a manufacturing system. He utilizes a simple model of a synchronous production line with identical stations and random processing times. More specifically, Tan investigate the effects of the coefficient of variation of processing times, the number of stations on the production line, the mean, the variance, and the squared coefficient of variation of the inter-departure times of the products leaving the manufacturing system, the production rate and the asymptotic variance rate of the number of parts produced. The results indicate that the structure of a manufacturing system, the variability of the processing times, and the operational decisions can profoundly affect the variability of the performance. For example, as depicted in Figure 10, when the coefficient of variation (cv[X]) of the processing time is zero, the cycle time is equal to the processing time (i.e., the processing time is deterministic) but as the coefficient of variation increases, the cycle time increases dramatically until cv[X] becomes 3. Additionally, Figure 11 depicts how the number of stations in a production process affects the variance of interdeparture times.

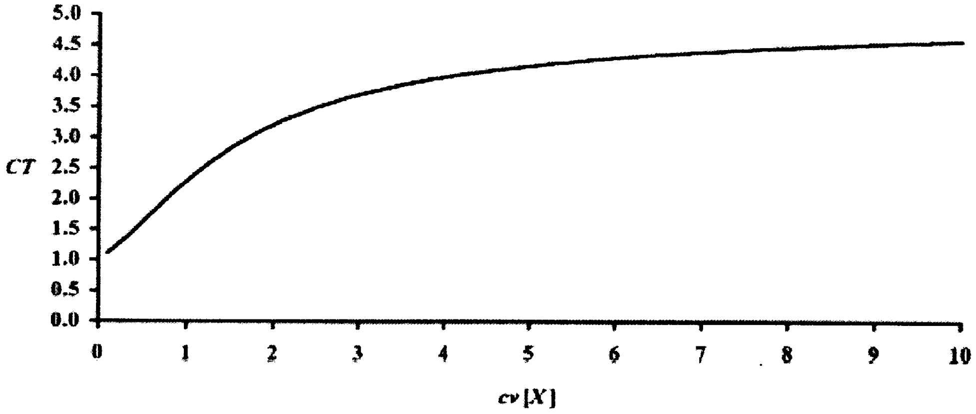


*Figure 10: The cycle time CT vs. the coefficient of variation of processing time for a production line with five stations (Tan 1998b)*

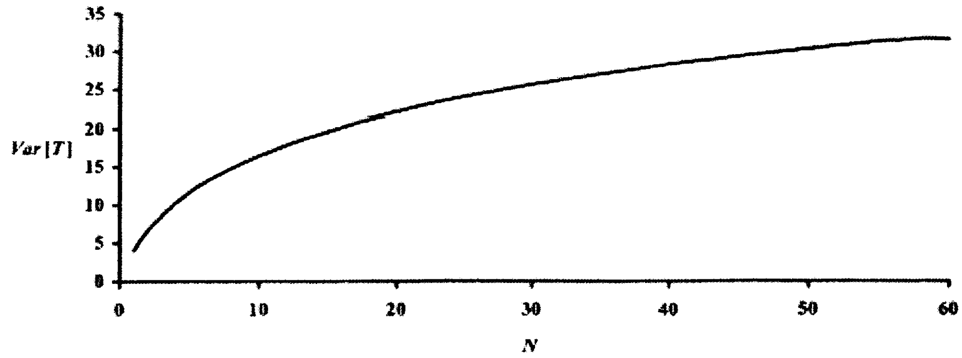


*Figure 11: The variance of the interdeparture times Var[T] vs. the number of stations N (Tan 1998b)*

The results show that even a simple analytical model provides valuable information that clarifies the relationship between the system parameters, the structure and the variability of the output in a given time period.

This literature review clearly demonstrates that even though variability has not been traditional performance measure in production, its importance is growing. This is especially true for companies that operate in the just-in-time environment. This reinforces my hypothesis that cycle time variability is a key component affecting air-to-ground conversion success.

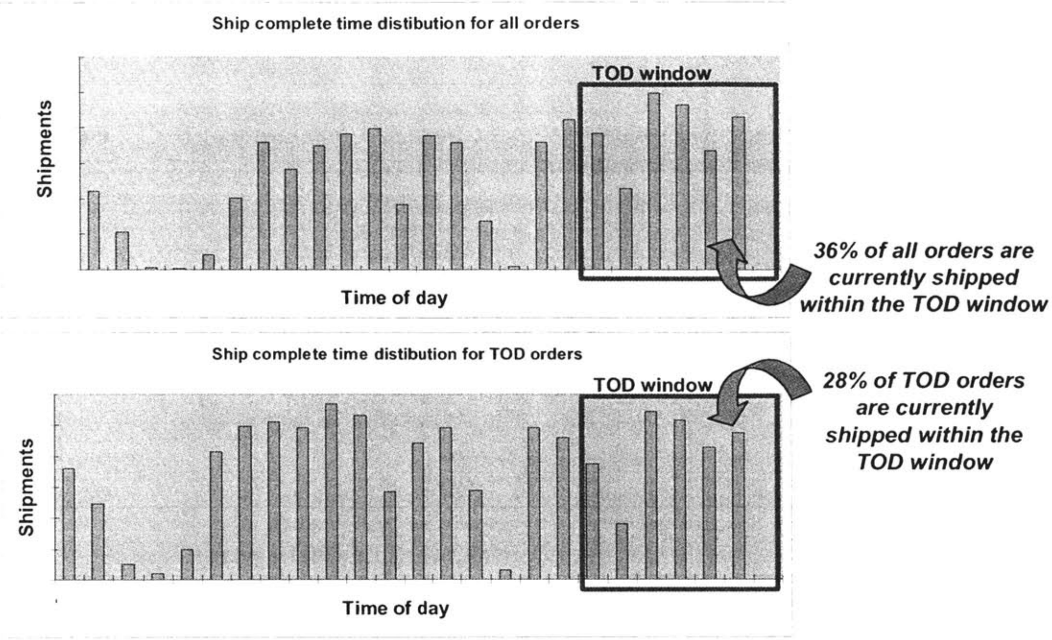
# 3. ANALYSIS

This chapter analyzes the air-to-ground capabilities and constraints of Dell's current order-fulfillment process. Firstly, current shipping times are analyzed in order to identify at what times orders are shipped each day in order to devise new scheduling and release rules. Secondly, current scheduling rules, manufacturing processes and release rules are analyzed. Next I investigate high-level causes for the cycle time variation. Finally, I conduct ASRS capacity utilization analysis.

This analysis is a vital step in order to understand the number of changes needed at each process step. This is important when determining the recommendations and constructing an implementation plan.

## *3.1. Current Shipping Times*

To understand the need for changes in the order-fulfillment process, current ship times were investigated. Based on the analysis of shipments for the past 6 months, it can be concluded, that with the current process, 36% of all the orders were shipped within the TOD window without any scheduling or release rules (Figure 12). Looking at only next-day and second-day orders (TOD candidates) the percentage of orders shipped at the appropriate time window drops to 28%. This demonstrates that without new scheduling and/or release rules TOD success can not be higher than 28%. This confirms the need for new scheduling and release rules at Dell and was an important analysis to ensure credibility and to highlight the importance of this project for optimizing logistics.



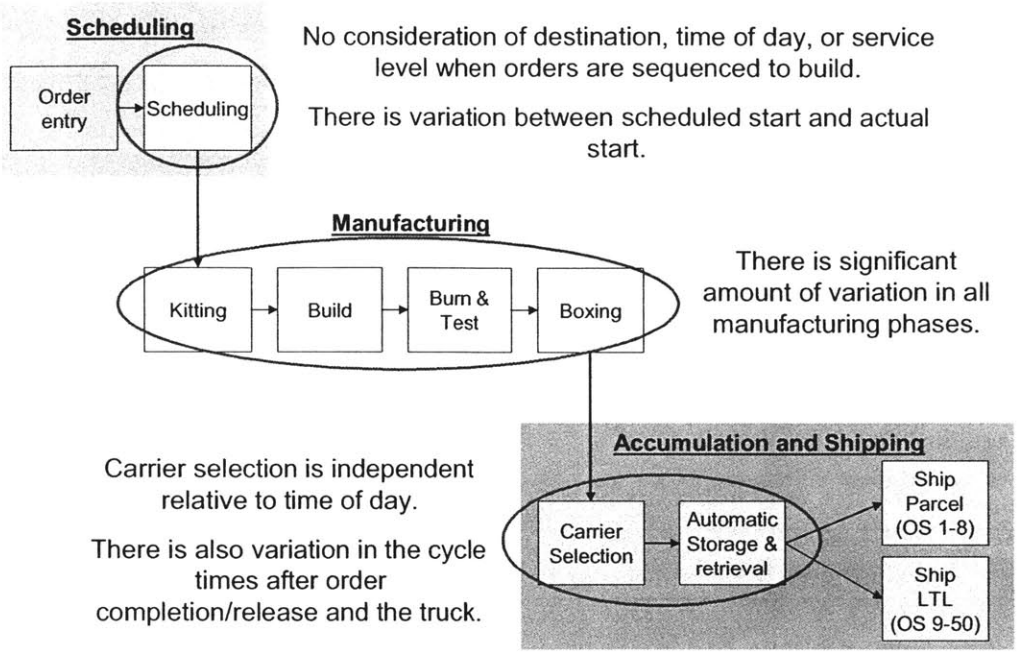
36% of all orders are currently shipped within the TOD window

28% of TOD orders are currently shipped within the TOD window

*Figure 12: Histogram of shipments between 3/1/03-8/1/03*

## *3.2. As-Is Process Regarding TOD Routing*

Looking at the four building blocks of the order fulfillment process – scheduling, manufacturing, accumulation and shipping –several factors influence the potential TOD routing in Austin (Figure 13).



No consideration of destination, time of day, or service level when orders are sequenced to build.

There is variation between scheduled start and actual start.

There is significant amount of variation in all manufacturing phases.

Carrier selection is independent relative to time of day.

There is also variation in the cycle times after order completion/release and the truck.

*Figure 13: As-Is process at the Austin desktop manufacturing*

In scheduling, the Factory Planner does not factor order destination, scheduling time (i.e. time of day), and service level, the variables that determine whether an order is an air-to-ground candidate, into the scheduling algorithm. In addition, there is variation between the scheduled start and the actual start of an order due to several reasons. The root causes for the variation will be explained in the section 3.3.

As the computer systems progress through manufacturing a significant amount of cycle time variation affects the order completion and order cycle time. There is, however, a formal expediting process that reduces the variability. All orders that are older than 4h appear automatically in the aged orders list and are expedited. Expediting happens separately at each phase as the supervisors of each phase (kitting, build, burn and test, and boxing) have separate expediting lists. This process helps to complete orders but there is also a risk that different phases may not expedite same orders at the same time.

The carrier selection that occurs right before the accumulation is not dependent on the time of day. No matter what time air-to-ground conversion candidate order is completed, air shipment is selected by default. In addition, the carrier is selected when the first computer system of an order is ready for boxing. This can be too early in some cases, as there is no certainty at this point about when the whole order will be completed and when it will be ready for shipping. Due to the cycle time variation, there may be a significant time difference between the completion of the first and last system of an order.

In accumulation (ASRS) the release algorithm does not consider whether the optimum shipping window for eligible time-of-day orders is open. On some occasions, it would be more cost effective to wait until the preferred shipping window is open.

Lastly, cycle time from the accumulation area to the trucks varies. This can impact TOD success if the cut-off time is close to the end of the preferred shipping window. In that case, the orders that are released at the end of the preferred shipping window may not make it to the truck on time thus compromising on-time delivery.

## *3.3. Sources of Cycle Time Variation*

The Factory Planner creates a new schedule every two hours. Factory Planner divides orders with multiple configurations into different sub-orders called "order ties", so that each tie includes only one type of configurations. Thus, if a customer orders two different configurations of computer systems the order will be broken into two different order ties. The historical reason for this is that certain configurations can only be built on certain kitting lines because some special materials are available on select kitting lines. Different order ties are most often scheduled to start on different lines at different times. The longer start time differentials between systems within the same order the longer the total cycle time will be for the whole order because all the ties need to be completed for an order to be complete. This increases the order-level and cycle time variation. Further, operators in kitting can override to the Factory Planner schedule causing an order to be delayed or starter earlier than the scheduled start time. This changes the original plan and can shorten or lengthen the expected cycle time of an order.

In manufacturing, several factors affect order completion, order cycle times and cycle time variation. Firstly, if materials are not available regardless of the automatic materials check, orders are started but then get pulled away from the line until the missing materials arrive. Or only some systems within an order are started if there are materials available only for a part of an order. While this will ensure line productivity it will at the same time compromise the order completion time. Further, Factory Planner schedules are based on loading the kitting lines, which is not the real process bottleneck. Historically, burn has been considered to be the bottleneck of the production system due to limited capacity of the burn racks and highly variable process cycle time. This mismatch causes occasional order overflow in kitting, lengthening the order cycle time. Due to the serial processing of orders on a kitting line any delays/downtime will result in cumulative order completion delays.

This analysis of Dell's manufacturing cycle times provide the coefficient of variation for each manufacturing phase (Figure 14). The coefficient of variation for an order size of 1 is relatively high in each order phase. For an order size of 8, the coefficient of variation is highest in the kitting phase, much higher than in any other phase. This is extremely dangerous because any delays/variation in kitting will result in cumulative order completion delays at the downstream processes. Additionally, currently no expediting procedure is in place in the kitting phase for uncompleted partial orders that had parts shortages and were pulled off the line.

**Coefficient of Variation (standard deviation devided by the mean)**

| | Order size 1 | Order size 8 |
|---|---|---|
| Kitting | 2.79 | 2.24 |
| Build | 2.32 | 1.44 |
| Burn and test | 1.40 | 0.97 |
| Box | 3.28 | 1.05 |
| Accumulation | 4.86 | 1.03 |
| Total | 0.96 | 0.77 |

*Figure 14: Coefficient of variation in each production phase*

The next phases of manufacturing are build, burn and test. Because the Factory Planner only schedules kitting, all stations after kitting use first-in first-out principle to prioritize the queue of computer systems waiting for processing. This causes deviation to the original production schedule because the sequence of orders changes. As a result, the actual cycle time of an order becomes shorter or longer than expected. As systems proceed to the burn and test phase quality failures add further delays for the order completion. Even though the first-pass yield in the burn/test phases may be high for the individual systems, the probability of a delay increases exponentially as the order sizes grow. For example, if the burn process has a 98% first pass yield, then an order consisting of 50 systems has only a 36% (0.9850 x 100%) chance to successfully complete the burn and test.

The last phase in the manufacturing process is boxing. Similar to kitting, boxing involves selecting the parts belonging to an order. Thus, material shortages resulting from inaccurate inventory levels and missed deliveries will have an impact on the boxing cycle times. In addition, boxing is partly automated so all the downtime in the automated boxing line affects boxing capacity and throughput. Lastly, all the variation that happens before the boxing phase is affects the boxing cycle time. Whenever upstream phases have highly variable cycle times, the downstream phases will also have highly variable cycle time as the variability is amplified in the downstream phases.

After boxing, a few sample computer systems are taken out of their boxes and examined thoroughly, just as customer will do upon receiving the system, to simulate customer experience. This is called the out-of-box-experience. This out-of-box testing process, when conducting on orders with more than one system, will also impact the speed of order completion.

ASRS has only a limited capacity and can create a bottleneck in the production if the order completion rate is significantly lower than the production rate. If ASRS becomes full all the additional boxes are diverted into a manual storage area and must be manually returned to the conveyor. This time-consuming and labor-intensive process causes significant delays in order completion. In addition, it should be noted that quality problems in any phase can significantly affect variability.

To measure the current cycle time variability, cycle time data for previous 6 months (3/03-9/03) was analyzed for both the individual systems (order size = 1) as well as for orders of up to 8 systems. The cycle time probability distribution for an individual system (i.e., order size 1) is shown in Figure 15. The shape of the probability distribution shows that the variation is high. In the low-variability distribution, most values are concentrated around the mean. Here, the most likely values are only few hours and, actually, lower than the mean. But because the distribution tails off very far from the mean, in most extreme cases systems spend days in production. If these systems are a part of a larger order, all the other systems have to wait in the ASRS until the last one is completed before it can be shipped. Because Dell only ships complete orders, the order level cycle times must also be analyzed.

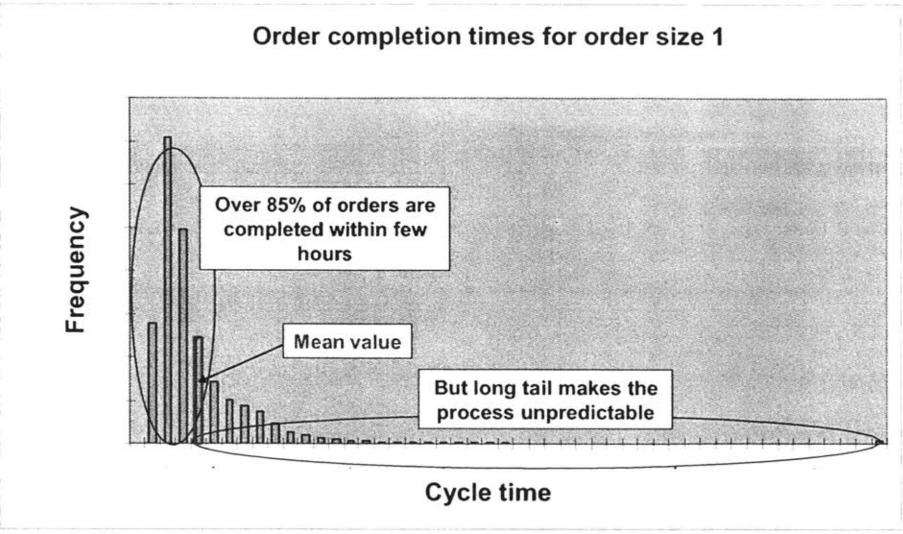


*Figure 15: Order completion times for individual computer systems (order size of 1)*

The effects of the system level variability become quite visible when comparing system level cycle time to the cycle time of orders with multiple systems. For example, Figure 16 illustrates the order completion times of an order size of 10.

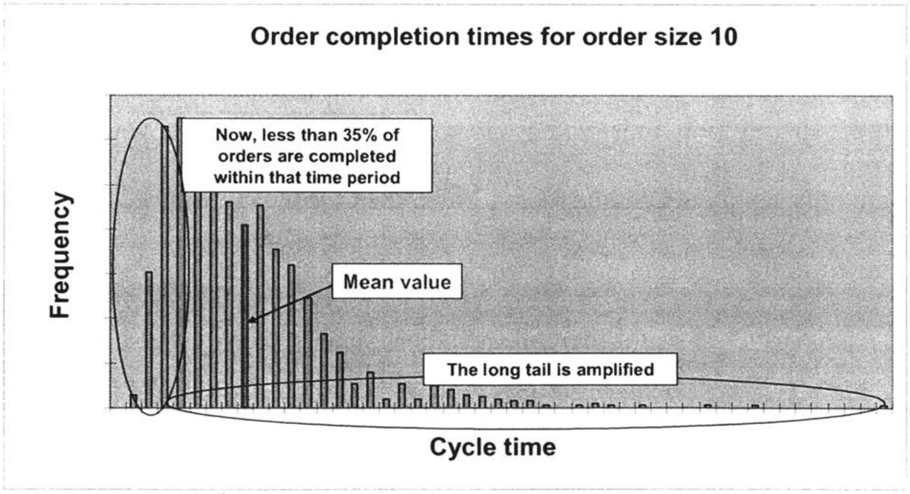


*Figure 16: Order completion times for order size 10*

Now, less than 35% of the orders are completed within the same time period due to the variability in the process. The mean has more than doubled and the long tail is amplified. This clearly impacts production predictability and makes it extremely hard to estimate how long it will take to complete an order.

## 3.4. *Automated Storage and Retrieval System (ASRS) Capacity Analysis*

Sufficient capacity in the ASRS is a pre-requisite for adding new release criteria because it decreases the probability of release at certain times of day. To understand the current utilization of the ASRS, current usage of the ASRS was studied for the previous six months (3/03-9/03). The results are summarized in Figure 17.

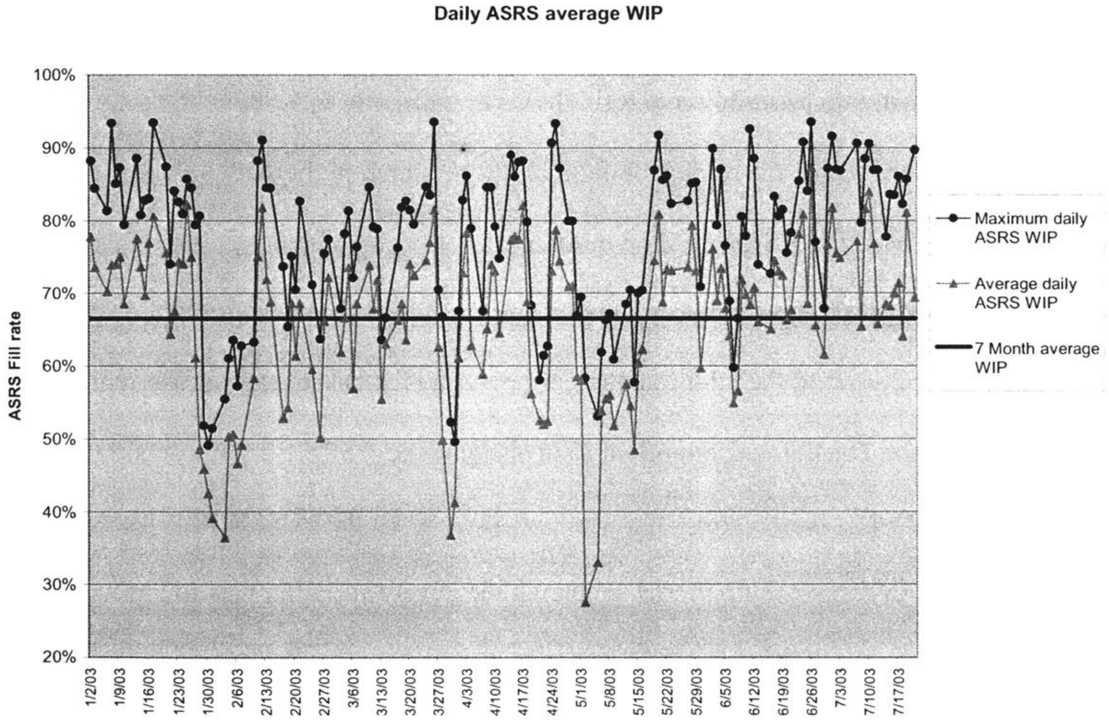


*Figure 17: ASRS daily usage*

The average fill rate for ASRS is 67% and generally, ASRS is filled somewhere between 60% and 90% as shown in Figure 18.

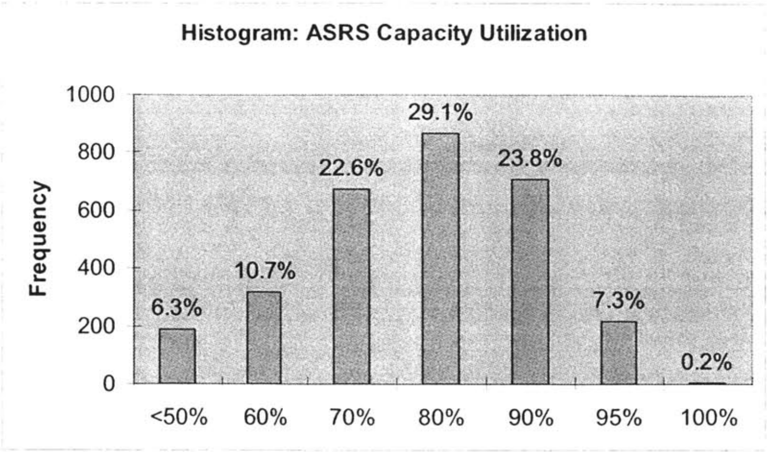


*Figure 18: ASRS capacity utilization*

Dell strives for ASRS utilization lower than 90% in order to prevent ASRS from causing a bottleneck in the upstream assembly process. However, currently in 7.5% of the time ASRS is more than 90% filled. Thus, the extra amount that can be stored in the ASRS is limited and the amount of extra WIP in the ASRS must be minimized.

In addition, my task was to understand whether the ASRS fill rates correlated with the time-of-day. The purpose of the additional release criteria is to ensure the release within the appropriate window. Thus, it was important to investigate the ASRS fill rates outside that window, especially a few hours before the window opens when the extra WIP is likely be at its highest level. However, no clear patterns appeared; the hourly variation was found to be only about 10% as depicted in Figure 19.

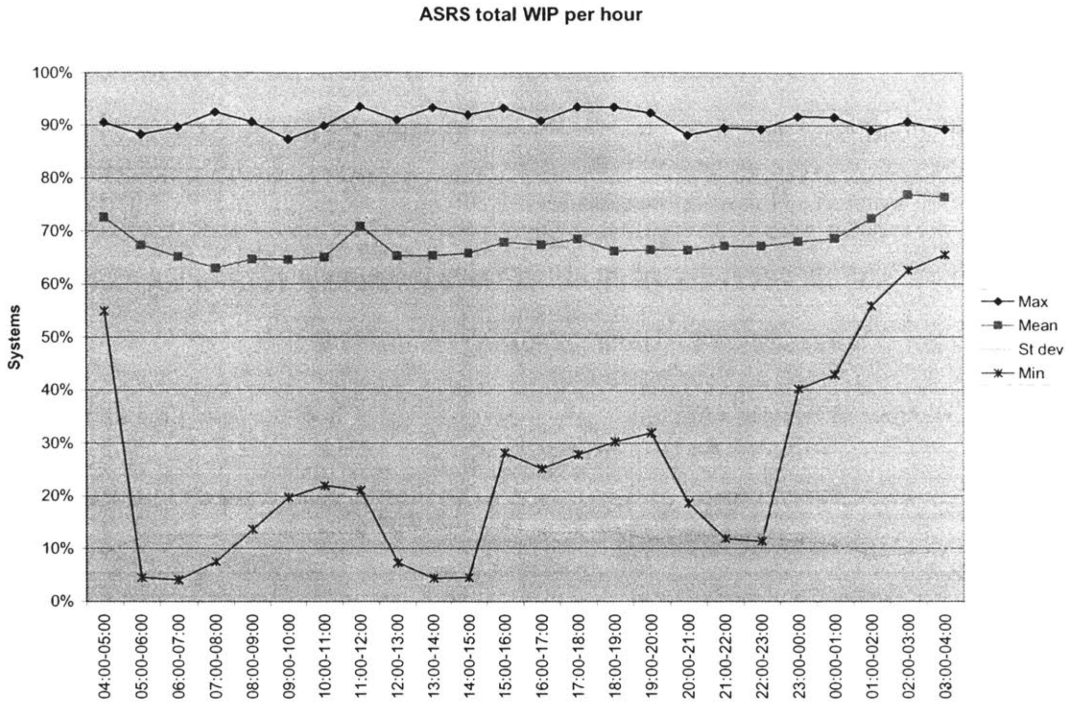
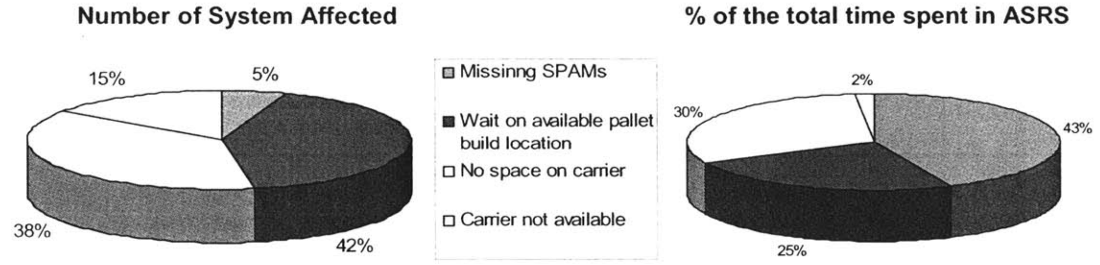


*Figure 19: ASRS hourly fill rates*

To further understand the ASRS capacity utilization, the main contributors to the ASRS WIP were investigated. ASRS WIP can be divided into two major components; order completion WIP and shippable WIP. Order completion WIP includes all the computer systems that are waiting for other systems within the same order, i.e., order completion. Shippable WIP includes all the orders that are complete but can not be shipped before manual shipping is completed or one of the remaining release criteria (e.g., SPAMs, overpacks, pallet build or carrier is not available) for the order is not met. Typically, shippable WIP average 23% of the total WIP in the ASRS.

All orders consisting of 9 or more systems must be palletized in a separate pallet build area. Since there are a limited number of pallet build stations, the amount of free capacity available at the pallet build phase must be checked before orders are released from the ASRS.

This will ensure that orders can be palletized and shipped immediately after release. I identified pallet build unavailability as the biggest reason for shippable WIP (Figure 20). The data below does not include missing overpacks because that information is not stored in any database and thus, cannot be tracked. However, overpacks are often considered a major contributor to shippable WIP. This data is collected on orders using the automated shipping system (Speedway) but is fairly similar for orders requiring manual shipping.



1. Pallet build unavailability – 42% of systems and 25% of total time
    - → Problem especially with large orders only complete orders can be released → up to 3 pallet build locations must be available at the same
    - → Auditing process slows down pallet build (pallets need to be audited before release)
    - → Scanning the whole pallet rather than individual boxes may result in "missing" boxes
2. Missing SPAMs – 5% of systems and 43% of total time
3. No space on carrier – 38% of systems and 30% of total time
4. Carrier unavailability – 15% of systems and 2% of total time

*Figure 20: Causes for shippable WIP*

In summary, several factors contribute to the relatively high utilization of the ASRS. Clearly, the air-to-ground conversion cannot rely only on adding new release criteria as the ASRS capacity is already highly utilized. Adding new ASRS capacity is expensive and as Dell's strategic objective is to decrease inventory, that strategy is not feasible. Managing the process and the factors causing variation in the manufacturing and scheduling cycle times will not only ensure a minimum increase in the ASRS WIP (caused by additional release rules) but will also reduce both the shippable WIP and the order completion WIP in the ASRS.

### *3.5. Summary*

This analysis of order-fulfillment process indicates that a new set of scheduling rules, together with changes in carrier selection and release rules, are needed to implement the TOD routing. Managing the end-to-end process rather than individual phases, scheduling, manufacturing, accumulation and shipping, now becomes important. This analysis clearly shows substantial cycle time variation in each of these phases that causes delays in order completion. Thus, some orders are completed outside the optimum shipping window even with optimum scheduling rules. This phenomenon can be seen in Dell's Nashville desktop manufacturing plant. They have achieved limited air-to-ground success because they are using only scheduling rules without any changes in managing the order-fulfillment process. Additionally, due to the limited ASRS capacity, air-to-ground conversion success cannot be achieved by managing just the release either.

However, the question remains, what are the drivers for air-to-ground conversion and what is the impact of each of the proposed changes? To analyze this problem I build a discrete event simulation. This simulation model and simulation results are presented in the next chapter.

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# 4. DISCRETE-EVENT SIMULATION

I chose discrete event simulation as the analytical tool to aid in quantifying the key drivers of air-to-ground conversion success. Discrete event simulation involves the modeling of a system as it evolves over time by representation in which variables change instantaneously at separate point of time. The points in time include when an event occurs, where an event is defined as an instantaneous occurrence that may change the state of the system (Law & Kelton 1991).

According to Chang and Makatsoris (2001) discrete-event simulation allows the evaluation of operating performance prior to the implementation of a system since it: (a) enables companies to perform powerful what-if analyses that could lead to better planning decisions; (b) permits the comparison of various operational alternatives without interrupting the real system and (c) permits time compression to enable timely policy decisions.

The purpose of the simulation model used in this study is to answer the following questions:

- What are the key success factors driving air-to-ground conversion and TOD success?
- What impact do appropriate Factory Planner scheduling rules have on the TOD success rate?
- What is the right TOD scheduling window for each order size from1 to 8?
- How will the release rules/intelligent release impact TOD success rate?
- How will the release rules impact ASRS?
- How will the cycle time variation impact air-to-ground conversion success?

## *4.1. Simulation Strategy*

The first step in the simulation strategy was to build a simulation that would serve as a baseline. The baseline should be constructed based on a specific subset of operations, at one factory, during a specific time period (Shannon, 1998). In my study the base line was the current order-fulfillment process without any TOD routing principles (no scheduling rules and no release rules) at the desktop manufacturing facility in Austin, Texas. In addition, the order sizes were limited to parcel order sizes, i.e., order sizes between 1 and 8, which provided the opportunity build a manageable model within the 6.5 months internship time frame.

The next step was to validate the simulation model. The reliability of the simulation had to be at a high enough level to capture the relevant characteristics of the process but ignore characteristics that could be safely ignored. It is generally neither necessary nor possible to match each element of a system to each element of the model. The level of detail must be derived from the purpose of the simulation model as the models need not be universally valid but designed for specific purposes (Law and Kelton 1991). For example, a simple model of a manufacturing system might accurately predict throughput but be inadequate for determining the required floor space for work in progress. The level of detail must also be balanced with the resources and time available to develop the simulation and the run time needed to conduct studies.

Validation included model debugging and comparing the model output data to the output data from the actual system. A more qualitative verification and validation of the simulation was performed at the factory with employees involved in the order-fulfillment process.

Following successful simulation construction and validation, I conducted a what-if analysis using various TOD routing characteristics and then compared the results to the baseline. The primary focus of the what-if analysis was to determine the key TOD success factors. Additionally, the impact of reducing variation on both TOD success and overall system performance was investigated.

I built the simulation model using Simul8 Corporation's "Simul8" software. The simulation package offered a "drag and drop" user-friendly interface and the option to code additional functions that were not included in the simulation package with a language called Visual Logic. However, as the simulation package lacked some very basic functions the amount of model-specific coding required turned out to be high. This delayed the model construction significantly.

## *4.2. Simulation Model Assumptions*

As mentioned above, a significant assumption in the model I built was the parcel order sizes, i.e. order sizes from 1 to 8 only. This assumption simplified the model and provided a manageable scope for the simulation. This also ensures that the results can be used to improve the TOD routing in the Nashville desktop manufacturing as they ship mostly parcel orders. In addition, the parcel logistics network is considered to be more stable than the LTL (Less than Truckload) network (which is for order sizes 9-50). Lastly, as Dell's manufacturing process is similar for LTL orders (order sizes 9-50) the results for the parcel network would also provide good insights into the possible results for higher order sizes.

Factory Planner schedules were modeled on the existing Factory Planner cycles, i.e., a new schedule would be produced every two hours. The variability between the scheduled start and actual start was taken into consideration when scheduling the TOD orders. In the model, all the TOD orders were assumed to be started within an hour even though the scheduled start would be within a half an hour of the two-hour schedule. While this might be a conservative assumption it was considered appropriate for this study.

Production volumes were estimated using the actual data for the second quarter of fiscal year 2004. The TOD volumes for each order size (number of air-to-ground candidates) were estimated using the next- and second-day attach rates and the Austin parcel network ground transportation times. The manufacturing process for multiple order sizes (from 2 to 8) were simulated using order-size-1 cycle times in the individual manufacturing phases. Orders were constructed by assigning order numbers to each individual computer system. After the kitting phase the systems traveled through the manufacturing independently and were then combined into orders again in the order accumulation area so that only completed orders were shipped.

Manufacturing was broken into four basic phases. The first phase was kitting which included all the internal routing positions, from the traveler pull to actual start of build. The Second phase, build, included all the internal routing positions from build to the start-of-burn process. The next phase, burn, included the software burn and testing as well as the travel time to boxing. The last phase, boxing included all the routing positions between the start of boxing and the accumulation area (ASRS). Considering the simulation objectives, adding further details to the model was not necessary.

### 4.3. *Simulation Modeling and Validation*

The cycle time distributions were modeled using historical data (3/03-5/03) and Palisade's "Bestfit" software, which enables the input of 100,000 historical data points and provides the closest distributions to the original data. In addition, all the significant statistics and goodness of fit (GOF) were evaluated using the Bestfit software. The last two weeks of May (5/03), the end of that quarter, were excluded from the cycle time input data because of the unusually high order and shipping volumes.

Manufacturing was divided into four basic phases. The manufacturing cycle time data used to model the cycle time distributions included the waiting time between the different phases. Thus, capacity constraints leading to the waiting time between the individual manufacturing phases were excluded from the model to avoid double counting.

Next, the distribution process (DC) from the accumulation area to the truck was modeled. The CD cycle time distributions were determined also by using the Bestfit software. In the simulation model, all orders were given a 'DC time stamp' which was then added to the manufacturing time to calculate the total cycle time.

The simulation model constructed in this study and described above is depicted in Figure 21.

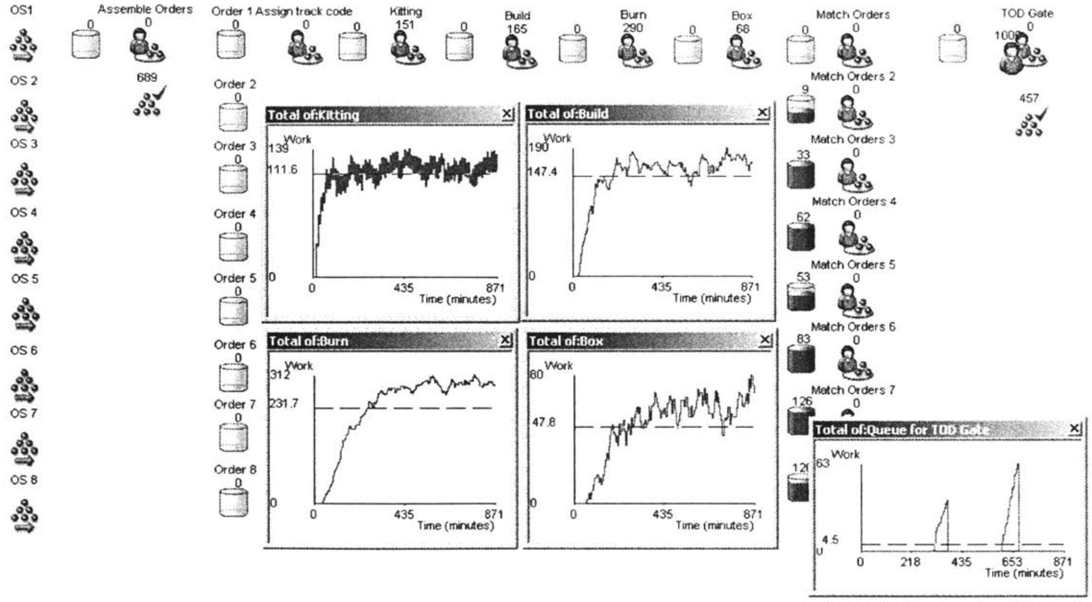

*Figure 21: Simulation model*

Although validation should be done throughout the entire simulation study, it is particularly important to validate the model thoroughly before any as-is and what-if analysis. It is important to define the measures for the evaluation as the models are not universally valid but designed for specific purposes. Validation is the most important part of a simulation and often takes the most time. During this project, validation consumed about 60-70% of the total time commitment.

Several techniques can be used to debug a simulation model. One of the most powerful techniques to debug a discrete-event simulation model is a "trace". In the trace, the state of the simulated system is printed out just after each event occurs and it is then compared to hand calculation to see if the program is operating properly (Law and Kelton 1991). In addition to trace, two other techniques were used to debug the model. Firstly, the model was run under a variety of input parameter settings and checked to asses whether output was reasonable. Secondly, the model was run under simplified conditions for which its true characteristics were easily calculated as well as divided into components that could be debugged separately.

The most definitive test of a simulation model's validity is assessing whether its output data closely resembles the output data from the actual system. If the two sets of data are similar, the model of the actual system is considered valid. However, it should be noted that there is no completely definitive method to validate a simulation model and it is important to determine when the model is "close enough" to produce reliable and meaningful results. In this study, three main validation measures were used to compare the simulation output data to the existing system: work-in-progress (WIP) levels as well as cycle time averages and probability distribution functions. In addition, the order size profiles of the simulation model were compared to the actual order size probability distribution.

WIP levels were validated by comparing the minimum WIP, maximum WIP and average WIP levels to the actual data. This was not an easy task as there was no historical data on WIP levels available. Thus, I saved several snapshots of the WIP levels and compared them to the simulation WIP levels. Figure 22 compares the average WIP levels of the simulation model to the existing system. This comparison shows that the simulation model closely approximates the real system. The deviation between simulation WIP and existing WIP levels was approximately 10%.

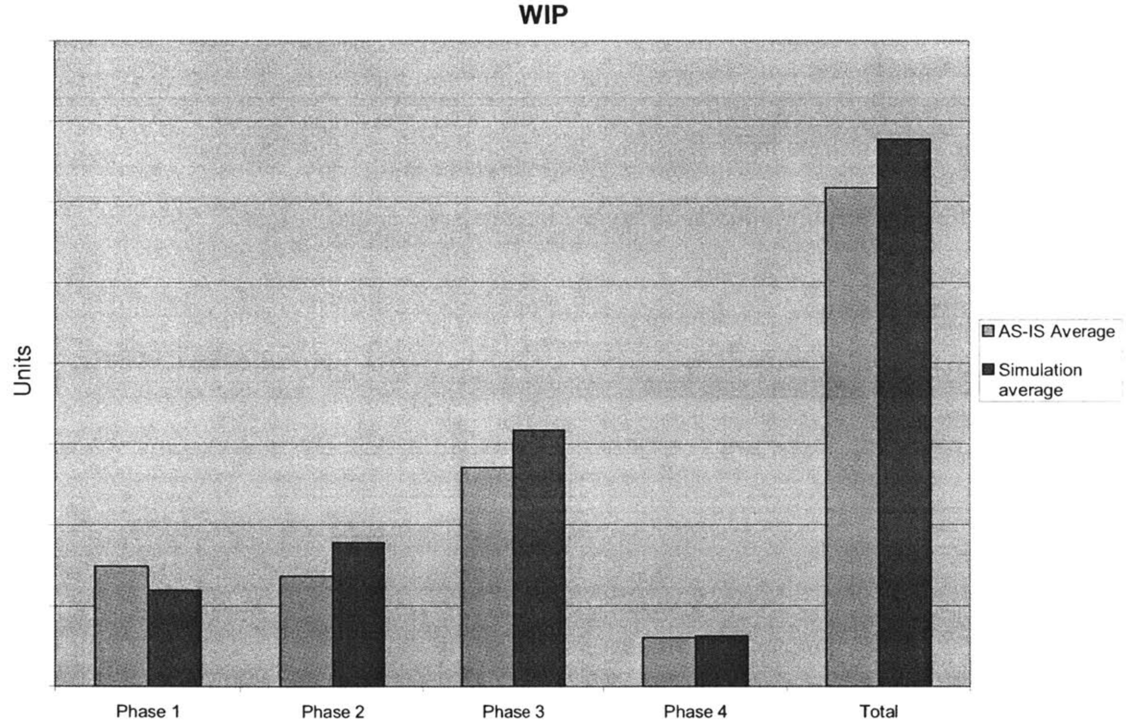

*Figure 22: WIP levels of the simulation model compared to the existing system*

The next step was to validate the cycle time probability distributions for the

1. Individual phases (kitting, build, burn and box) for order size 1
2. Total cycle time for order size 1
3. Individual phases for order sizes 2 though 8

4. Total cycle time for order sizes 2 though 8.

The first task was to compare the cycle time distributions of individual phases for order size 1 with the actual values. Averages and standard deviations of the individual phases were very close to the actual data as they were within 95% of the actual values. The comparison showed that both the averages and standard deviation of the cycle times in each individual manufacturing phase in the simulation model were similar to the actual values (within 95% of the actual values). In addition, the shape of the cycle time distributions of each phase was modeled using the Bestfit software and compared to the actual distribution. The comparison indicated that the simulation model was accurate as shown in Figure 23. Figure 23 compares the kitting cycle time distributions from the simulation model with the distribution of the actual data and shows that the simulation model accurately represents the actual values.

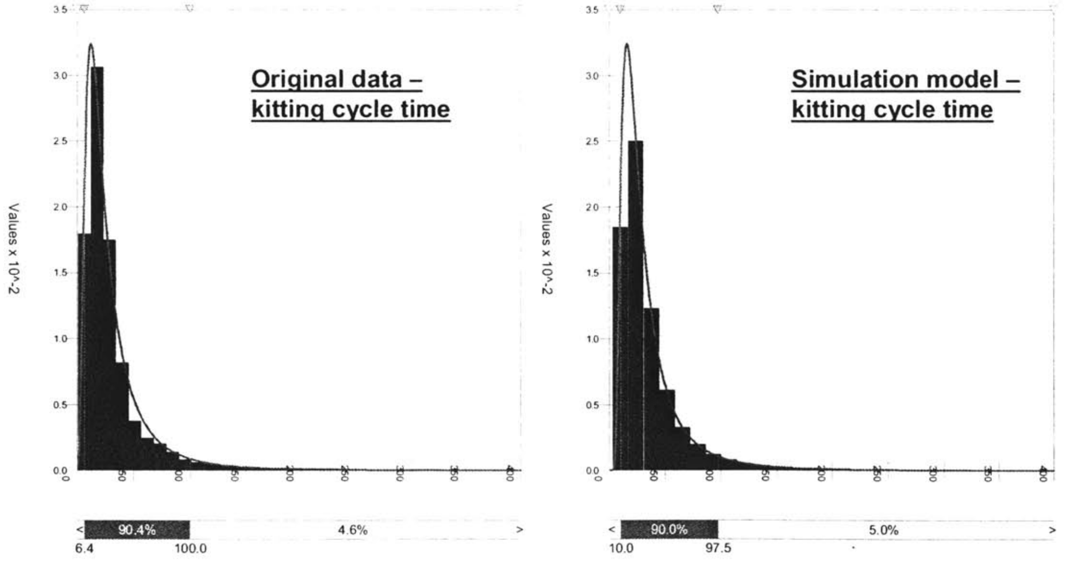

*Figure 23: Comparison of the cycle time distribution in the kitting phase*

The next step was to compare the total cycle time probability distributions between the simulation model and the existing system. Figure 24 illustrates the total cycle time probability distributions for both the simulation model and existing data. They appear to be very close to each other. The primary source for deviation was the truncated tail of the original data which excluded the most extreme exceptions (e.g., EMR failures). Based on the above analysis, the validation for order size 1 was completed.

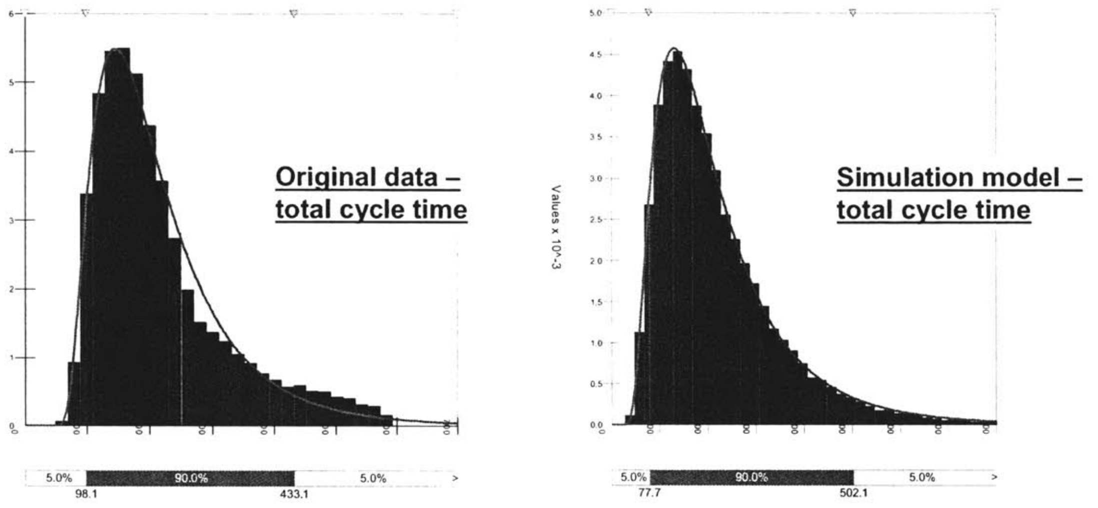

*Figure 24: Probability distribution for total cycle times*

The next step was the validation for order sizes from 2 to 8. As mentioned above the cycle time distributions used for individual manufacturing phases were the same for each order size because the computer systems travel independently though the manufacturing process.

When validating the total cycle time for order sizes from 2 to 8 one interesting problem arose. At first the cycle times for order sizes greater than 3 appeared higher than the real values. The difference seemed to grow as the order sizes grew (deviation was largest for order size 8). In addition, the biggest difference seemed to appear in the build and burn phases. To identify the cause of this deviation, it was critical to understand the underlying process that was modeled. This proved how valuable a thorough understanding of the actual manufacturing process is. With the knowledge of the process, I was then able to determine that the primary cause of the deviation was the fact that the model did not include the existing expediting process. Dell uses expediters who expedite all the old orders using the "out-of-lead" report. Orders older than 4 hours appear in this report. This clearly has an effect on the order cycle times and had to be included in the model. After the expediting process was included in the simulation model, the cycle times seemed to reflect the actual process at appropriate level. As an example, Figure 25 illustrates both the original data and simulation model cycle time distribution for order size 5.

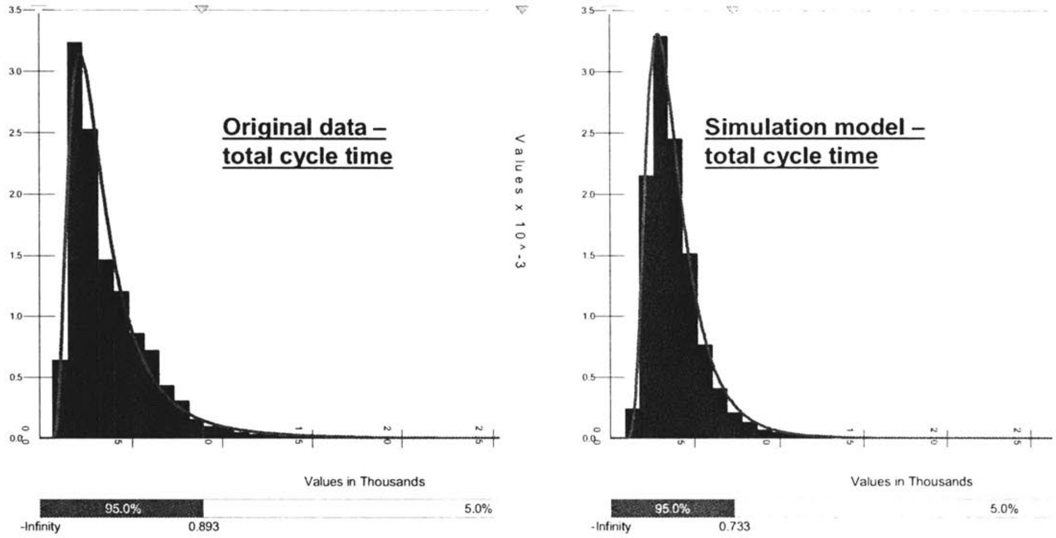

*Figure 25: Total cycle times for order size 5*

In addition to the probability distribution of the cycle times, the averages and standard deviations of the cycle times were compared between the simulation model and existing data. After the simulation model values accurately represented the existing system the validation of the cycle times was completed.

Additionally, I wanted to ensure that the model correctly assigned the order sizes using the correct order size distribution. As demonstrated in Figure 26, the model correctly assigned different order sizes.

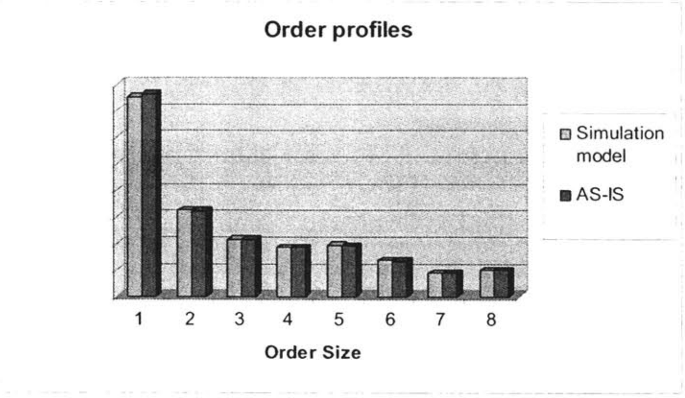

*Figure 26: Order profiles*

Lastly, a qualitative verification and validation of the simulation was performed at the factory by interviewing several employees involved in the order-fulfillment process. It was critical to get their feedback to increase the model credibility and the likelihood that the model will be used in the decision making.

After the model debugging and data comparison validation was completed, the next simulation step, analysis, was started.

## *4.4. Simulation Experiments and Results*

The simulation experiments were run with actual TOD volumes for order sizes 1 though 8 for a three-month cycle. The first simulation experiment studied the expected TOD success without any changes to the existing order fulfillment process (i.e., scheduling rules, manufacturing variability or release criteria). In addition, the effect of the current expediting process was studied. In the next experiment, the appropriate scheduling rules that allow TOD orders to be started at optimum times were added. Different start times were studied for different order sizes. Again, the effect of the expediting process on TOD success was determined.

In the third model, the release rules were added to examine the effect of the release rules on the accumulation WIP levels (in the ASRS). In addition, the additional WIP was compared to the actual WIP within that time period in order to determine how many times the capacity of the ASRS would be exceeded. Lastly, I investigated the impact of the cycle time variation on the process performance and TOD success rate.

### *4.4.1. Expected TOD Success Rate with Current System*

Currently, if no scheduling or release rules are used, less than 25% of orders are manufactured and shipped within the appropriate time window as shown in Figure 27. The current expediting process used for old orders does not appear to be important for order sizes between 1 and 6 but becomes important for order sizes 7 and 8. This highlights how changes in the current order fulfillment process can produce higher success rates for the TOD routing.

| SUCCESS | OS 1 | OS 2 | OS 3 | OS 4 | OS 5 | OS 6 | OS 7 | OS 8 |
|---|---|---|---|---|---|---|---|---|
| NO EXPEDITING | 23% | 20% | 22% | 24% | 23% | 20% | 12% | 16% |
| WITH EXPEDITING | 23% | 20% | 22% | 25% | 23% | 22% | 23% | 21% |

*Figure 27: Expected TOD success rate with the current system*

In addition, it should be noted that high variation in the distribution cycle times, i.e., the cycle time from the order accumulation area (ASRS) to the truck, could further lower the TOD success rate for orders going to hubs with carrier cut-off times close to the end of the business day. For example, if a carrier cut-off time is within 1 hour of the end of the business day, then an order that is released within the last half an hour might not make it to the truck on time. This is true not only for this particular experiment but also for the following experiments with specific scheduling and release rules.

### *4.4.2. TOD Success Rate with Appropriate Scheduling Rules*

The next step was to examine the effect of appropriate scheduling rules on the TOD success rates. As mentioned in chapter two, the Factory Planner makes the schedules based on a set of criteria. To ensure the appropriate start times for each order size, a new priority level is needed in the Factory Planner scheduling algorithm. The new priority level will be assigned to orders with certain destinations and service levels (e.g. hub A and next-day or hub B and second-day service level) that determine whether an order is a TOD candidate. The results indicate that in addition to the destination and service level, the order size must be taken into account when determining the optimum start time for TOD candidate orders.

Three different start times were investigated. In addition, the effect of the expediting process on TOD success was investigated. The results are depicted in Figure 28.

**START TIME A**

| **ORDERS ON TIME** | **OS 1** | **OS 2** | **OS 3** | **OS 4** | **OS 5** | **OS 6** | **OS 7** | **OS 8** |
|---|---|---|---|---|---|---|---|---|
| WITH EXPEDITING | 87.6% | 77.7% | 80.7% | 74.8% | 71.4% | 65.6% | 56.5% | 56.2% |
| WITHOUT EXPEDITING | 87.6% | 77.7% | 69.2% | 59.3% | 54.6% | 44.4% | 38.8% | 31.9% |

**START TIME B**

| **ORDERS ON TIME** | **OS 1** | **OS 2** | **OS 3** | **OS 4** | **OS 5** | **OS 6** | **OS 7** | **OS 8** |
|---|---|---|---|---|---|---|---|---|
| WITH EXPEDITING | 44% | 65% | 73% | 81% | 84% | 87% | 86% | 89% |
| WITHOUT EXPEDITING | 44% | 65% | 75% | 78% | 78% | 75% | 74% | 69% |

**START TIME C**

| **ORDERS ON TIME** | **OS 1** | **OS 2** | **OS 3** | **OS 4** | **OS 5** | **OS 6** | **OS 7** | **OS 8** |
|---|---|---|---|---|---|---|---|---|
| WITH EXPEDITING | 17% | 31% | 31% | 38% | 45% | 53% | 57% | 63% |
| WITHOUT EXPEDITING | 17% | 31% | 40% | 50% | 56% | 58% | 63% | 72% |

*Figure 28: TOD success with appropriate scheduling rules*

The results demonstrate that the ability to schedule different order sizes at different times is a key driver of TOD success. In addition, the current expediting process for old orders has a significant impact on the TOD success because of the high variability in manufacturing cycle times.

Adding new priority rules to the Factory Planner can be implemented relatively easily. Thus, Dell is looking forward to piloting this feature in its Nashville desktop manufacturing plant as soon as possible. In comparing the implementation requirements and the expected impact of this feature it will certainly provide the "biggest bang for the buck" at least in the short term.

### *4.4.3. TOD Rules with the Intelligent Release*

Even if the correct start times for each order size are implemented and the current expediting process is used, a certain percentage of orders that are completed and released for shipping will still miss the preferred window as shown in Figure 29. Every shipment that does not meet the optimum window must be shipped via air instead of ground. This would more than double the shipments costs.

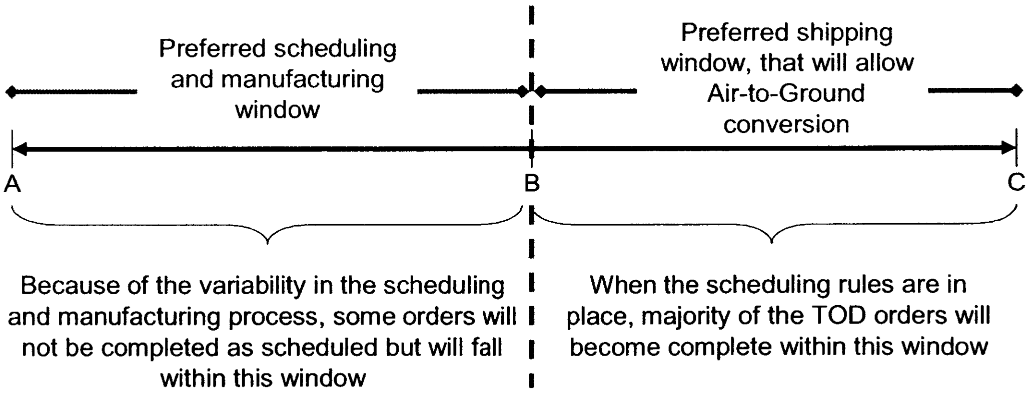

*Figure 29: Optimum shipping and manufacturing windows*

As a result, the maximum air-to-ground conversion requires combined scheduling and release rules. The release rules ensure that orders that are completed outside the optimum window are not released until the next optimum shipping window. The prerequisite is that enough lead time remains so that the shipment is not delayed and customer experience is not endangered. The proposed approach for intelligent release is:

1. Add a new release logic that will make the decision as to whether orders are released from the accumulation area based on current release conditions (SPAMs available, carrier available, etc.) *and* time-of-day, so that air-to-ground candidates will be released only within the preferred time frame.
2. Release rules must take into account the customer due date in order to ensure that possible holds will not affect customer satisfaction.
3. Because adding new release rules will require significant IT changes in the current Speedway shipping system, this feature should be implemented with the new integrated WMS/TMS system rather than changing the existing system.

The proposed release rules are:

1. ***If due date – current date > 1 AND current ≠ time of day window AND order = TOD candidate***; do not release until the TOD window (i.e. optimum shipping window) is open again.
2. ***If due date – current date*** ≤ 1: Release regardless of the time. This will ensure that a possible hold will not negatively impact the customer experience.
3. In order to ensure a minimum background release process, the system should not attempt to the release an order again until the TOD window re-opens.

Based on the simulation results (Figure 28), approximately 16% of all the TOD orders are completed and shipped outside the optimum shipping window even if the new scheduling rules ensuring optimum start times are implemented and the current expediting process is maintained. The percentages of computer systems that become available outside the optimum shipping window for each order size are summarized in Figure 30. In order to achieve maximum TOD success, these orders need to be held in the ASRS until the appropriate shipping window opens again.

| ORDERS | OS 1 | OS 2 | OS 3 | OS 4 | OS 5 | OS 6 | OS 7 | OS 8 |
|---|---|---|---|---|---|---|---|---|
| Shipped inside TOD window | 87.6% | 77.7% | 80.7% | 81.0% | 84.0% | 86.7% | 86.2% | 89.2% |
| Shipped outside TOD window | 12.4% | 22.3% | 19.3% | 19.0% | 16.0% | 13.3% | 13.8% | 10.8% |
| Orders requiring delayed release (i.e. release rules) | 12.4% | 22.3% | 19.3% | 19.0% | 16.0% | 13.3% | 13.8% | 10.8% |

*Figure 30: The impact of intelligent order release criteria on TOD success.*

The results demonstrate the need for intelligent order release. The next step aimed to determine the impact of the additional release criteria on the ASRS WIP levels. Figure 31 shows the increase in ASRS capacity resulting from the intelligent order release.

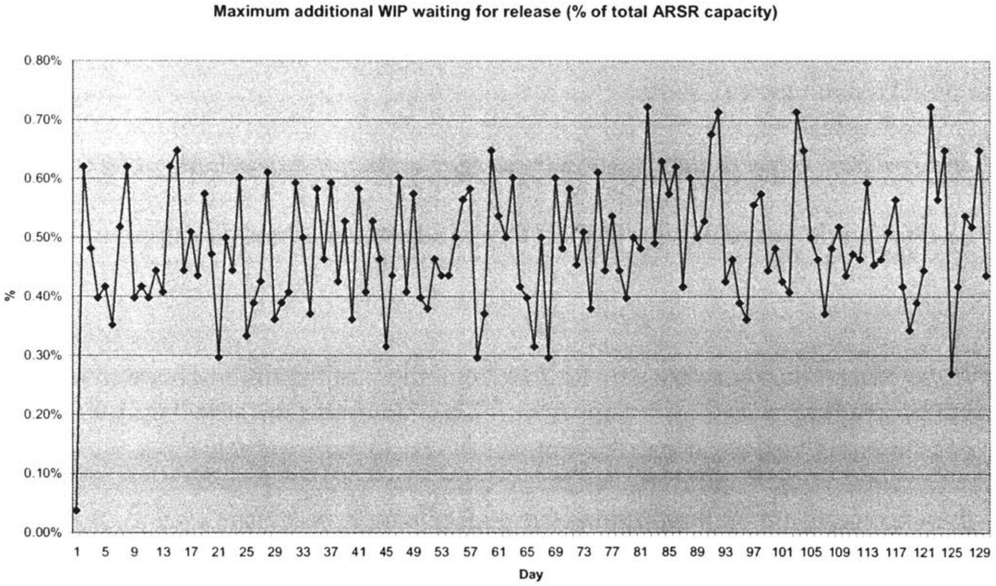

*Figure 31: Maximum additional WIP waiting for release*

It can be concluded that the impact of new release rules on the ASRS is minimum. However, this also needs to be analyzed in the context of actual utilization rates of the ASRS. If the actual ASRS utilization rates are high even smaller additions to WIP levels may affect production performance. Figure 32 depicts the actual WIP levels for the simulated period together with the new WIP levels due to the additional release criteria. These two curves in Figure 32 are so close that one can barely distinguish one from another. It seems that the addition in the WIP level had a minimal effect on ASRS fill rate. However, the graph also shows that currently in about 8% of the cases, the preferred maximum fill rate/utilization of the ASRS in exceeded. In these situations, every additional computer system in the ASRS endangers the production flow by causing the ASRS to create a bottleneck in the production system. Thus, the impact of the additional release criteria on the ASRS utilization rate can not be neglected.

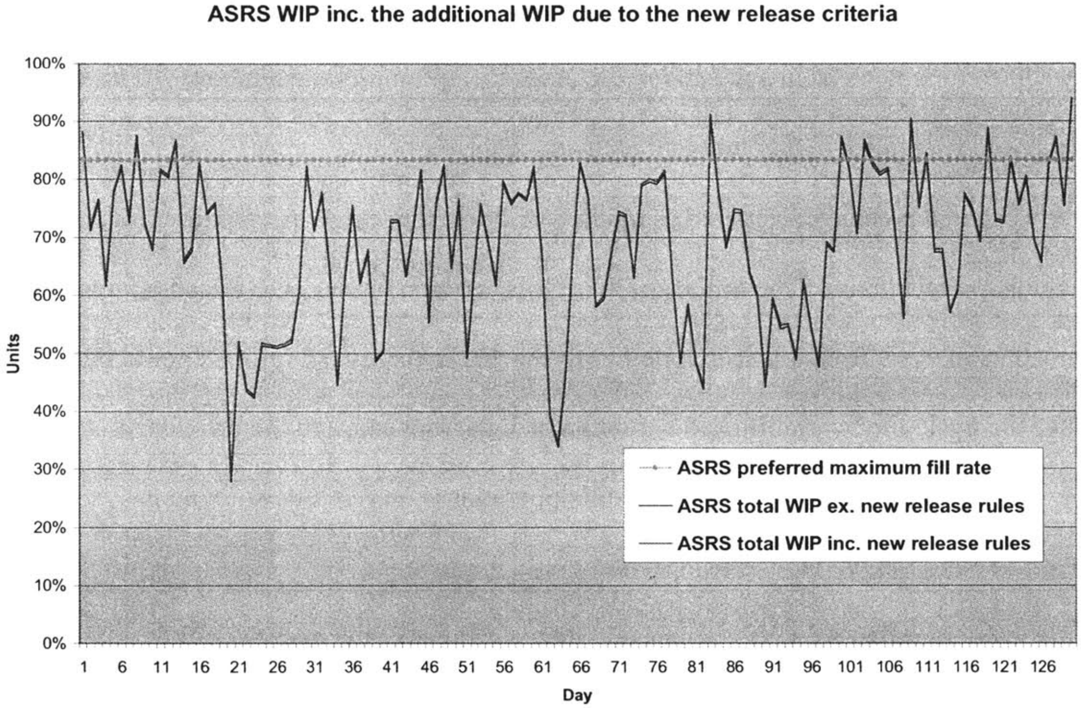

*Figure 32: ASRS Analysis*

The high current ASRS fill rates emphasize a possible need for a manual override of the new release criteria so that TOD orders may be released from the ASRS in the following cases:

1. If a spike occurs in the ASRS fill rate. This can be caused by unexpected problems in production that hinder order completion.

2. If there is no other shippable WIP and stop shipping is not an option. Number of shipped units is a major metrics used to measure production personnel and the new release criteria should not conflict with this measure.

The implementation of the release criteria is not part of the specifications for the new integrated TMS and WMS. Adding this new requirement for intelligent order release appeared to be a big change in the software code. Thus, the projected implementation time frame is within the next two years rather than within the upcoming quarters.

However, it should be noted that adding the release criteria will not solve the root cause why some computer systems are shipped outside the optimum time window. Thus, a more appropriate way to solve this problem is to attack the root cause, process variability. The release criteria can not even be considered as quick win due to the long expected time frame for software change implementation. The impact of the release criteria on the TOD success rates was an interesting analysis from a research point of view but in reality, all efforts should be geared to reduce the cycle time variability. That will attack the root cause of the problem and thus, will have a significantly greater impact on Dell's operations. Variability is not an easy task that can be carried out quickly. However, it will not only improve the TOD success significantly but also dramatically improve the performance and manageability of the manufacturing process.

### *4.4.4. The Impact of Cycle Time Variation to the TOD Success*

In order to quantify the impact of cycle time variation on the TOD success and process performance I conducted a separate simulation experiment that focused on reducing the cycle variation in manufacturing. Variability was reduced in every manufacturing phase (kitting, build, burn and box) by cutting the tail of the cycle time probability distribution. This was accomplished by taking away 10% of the tail, i.e., the most extreme values of the cycle times.

Then the model was run again with the correct start time for each order size. Additional release criteria and expediting processes were not included in this model because the purpose was to determine the impact of variability. Figure 33 illustrates the impact of variability reduction on TOD success.

| **TOD Success** | **OS 1** | **OS 2** | **OS 3** | **OS 4** | **OS 5** | **OS 6** | **OS 7** | **OS 8** |
|---|---|---|---|---|---|---|---|---|
| TOD success with scheduling rules and expediting | 87.6% | 78.0% | 80.7% | 81.0% | 84.0% | 86.7% | 86.2% | 89.2% |
| TOD success after cycle time variability reduction | 99.7% | 99.4% | 99.1% | 98.7% | 98.6% | 97.3% | 97.0% | 97.0% |
| TOD success Improvement | 12.1% | 21.4% | 18.4% | 17.7% | 14.6% | 10.6% | 10.8% | 7.8% |

*Figure 33: TOD success after variability reduction*

The results indicate tremendous improvement in the TOD success rate. Additionally, it is important to notice that additional release criteria or current expediting processes become obsolete as variability decreases.

Additionally, reducing the variability not only improves TOD success but also improves the manageability of the order-fulfillment process. The results demonstrate that reducing variation also had the following effects:

- 50% reduction in total manufacturing cycle time (average for each order size).
- 69% reduction in variation, i.e., standard deviation of the total manufacturing cycle time (average for each order size)

The results for every order size are shown in Figure 34.

| Metric | **OS 1** | **OS 2** | **OS 3** | **OS 4** | **OS 5** | **OS 6** | **OS 7** | **OS 8** |
|---|---|---|---|---|---|---|---|---|
| Reduction in the average manufacturing cycle time | 41% | 61% | 41% | 49% | 49% | 52% | 50% | 56% |
| Reduction in st. dev of the manufacturing cycle time | 72% | 80% | 62% | 63% | 63% | 63% | 66% | 63% |

*Figure 34: Effects of variability reduction in production process performance*

Lastly, as was also suggested in the literature review, the cycle time variation has a direct relationship with WIP levels. I investigated how the reduction in the cycle time variability affected WIP levels. The results are shown in Figure 35. The total WIP was reduced by 27% so the effect on the WIP levels could be determined to be significant. The WIP level reduction at individual phases varied from 19% to 42%.

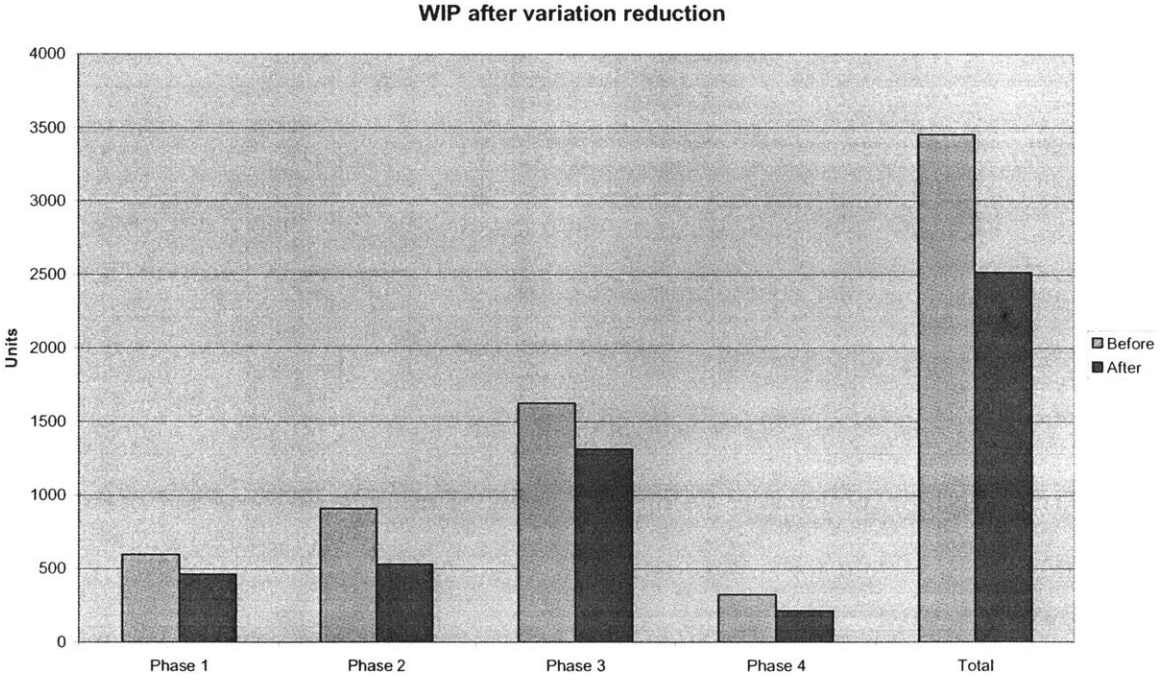

*Figure 35: WIP level after variability reduction*

In the past, Dell has mainly concentrated on reducing the average cycle time of individual manufacturing phases. The main metrics that are used today measure average cycle times of individual phases and individual computer systems. Order level cycle times are not measured. Based on both the literature review and my simulation results, it can be concluded that reducing the standard deviation instead of the mean would result in more significant improvements. Reductions in average cycle times can even have a negative impact on the process manageability and WIP levels if the standard deviations are not reduced at the same time. As a result of this analysis Dell, is now starting to realize the powerful effect that variability has on its process capabilities and manageability. Dell has subsequently instituted some changes that focus on reducing variability.

# 5. CONCLUSIONS AND RECOMMENDATIONS

This final chapter summarizes the key findings regarding how to achieve a maximum air-to-ground conversion ratio. In addition, the impact of implementing customer committed delivery on the suggested TOD routing principle is reviewed. Lastly, I make some recommendations how to manage the air-to-ground conversion process.

## *5.1. The Key Drivers for TOD Success*

The objective of this thesis was to maximize the probability of meeting or exceeding the customers' delivery time expectations at minimum logistics cost. The original project scope (intelligent order release) included only the release to carrier, i.e., how to control the accumulation release process to ensure maximum air-to-ground conversion/TOD success at Dell's Austin desktop manufacturing facility. After initial process analysis, however, the scope was broadened to include scheduling rules and managing the order-fulfillment process to meet the planned release window.

A discrete event simulation was built to aid in quantifying the key drivers for the air-to-ground conversion. The key drivers for TOD success are summarized in Figure 36.

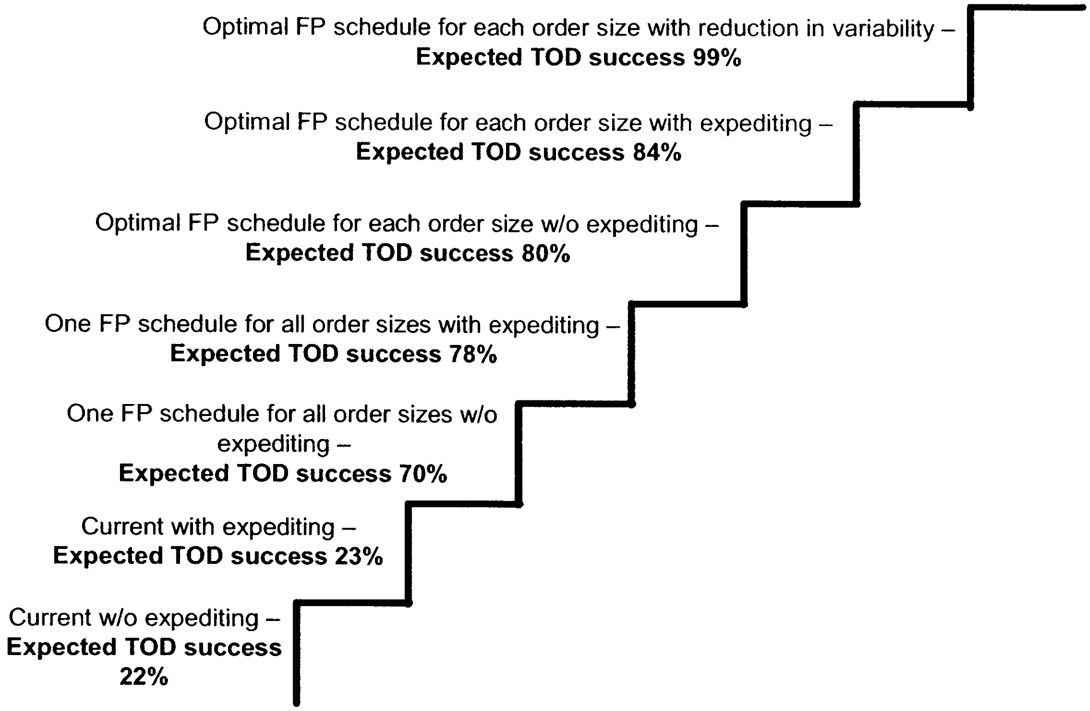

*Figure 36: Key drivers for the TOD Success*

The simulation model demonstrates that the correct Factory Planner schedule will have the most significant impact on TOD success. Another key driver for TOD success is variability in the cycle times. The shape of the probability distribution, i.e., the amount of variation, drives the results more than high/low average values. This is an important finding because currently manufacturing cycle times at the Austin desktop manufacturing facility have high standard deviations relative to the mean. This makes the manufacturing process unpredictable. In this environment, managing aged orders with the current expediting process is and will remain critical as long as variability remains high. While intelligent order release would minimize the number of orders that are shipped outside the optimum shipping window, it will not remove the root cause, process variability. Managing variability is discussed in the recommendations section.

Lastly, it is vital to understand that successful TOD execution can only be achieved by managing the end-to-end fulfillment process as TOD routing is not a mere scheduling problem: Optimizing only one part of the process (i.e., the Factory Planner or intelligent release) will not be enough.

## *5.2. Impact of Customer Committed Delivery Implementation*

My research also included how TOD routing changes after implementation of Customer Committed Delivery (CCD) and whether TOD touring will become obsolete after CCD. As explained in the first chapter, in the CCD environment, customers no longer choose the shipping service level but actual delivery date. Dell will then manufacture and ship orders based on customer's desired delivery date.

In the CCD environment, managing the process becomes even more critical as all orders have to be manufactured and shipped within appropriate time windows to avoid order expediting and expensive air shipments. Additionally, rather than one general window identical to all order like in the TOD environment each geographical area (i.e., each destination hub) will have its own optimum window that needs to be managed. Thus, TOD can be considered a first step towards successful CCD. Managing the shipping window, like the TOD process, is a fundamental enabler for optimized CCD implementation.

## *5.3. Recommendations*

This analysis has generated two general recommendations. First, focusing on reducing variability rather than reducing mean cycle times will deliver significantly more powerful results. In addition, order purity and order level cycle times should be considered a key metric in manufacturing.

### *5.3.1. Managing Variability*

Today, most of the focus in production is on average cycle times. Every manufacturing phase supervisor is required to report their average cycle time in daily meetings, and the consequent metrics are centered on the average times. This study shows that the problem is not the average cycle times but the variation. Focusing on the tail of the cycle time probability distribution will have significantly greater impact, not only on standard deviation but also on mean cycle times. In addition, reduction in variability will make the process more predictable and manageable. Thus, standard deviation of cycle times needs to be considered as important as average cycle times. This is vital not only now but especially after Dell's implementation of the CCD.

One of the most critical steps for managing variability is, at least in a metric driven organization like Dell, to choose as set of variation reduction metrics and targets, such a specific target levels of coefficient of variation. Additionally, the operators' and supervisors' incentive system should be reviewed to ensure that such variation reduction goals do not conflict with their existing goals and measures. Another critical step is to implement a user-friendly data collection scheme that provides meaningful and accurate insights into variability. In addition, this data should be compiled into daily reports that should be disseminated to all interested parties. Currently the average system-level cycle times are reported daily on an intranet page that is available production staff members. One possible solution could be to modify this intranet page to also include variability measures.

In the course of this study a number of high level root causes for the variation were identified. However, more thorough investigations are needed to identify the root causes in detail and to create a workable and successful implementation plan.

### *5.3.2. Order Purity*

Another recommendation is to use both computer system- and order-level measures to evaluate manufacturing process performance. Order purity/order completion should be monitored as closely as the number of units produced per hour. The current manufacturing metrics focus on units produced per hour which serves to sacrifice order purity over production rate.

An easily implemented metric is ASRS WIP, i.e., the number of systems waiting for order completion. This information is currently collected by IT systems and can be quickly pulled out and reviewed. As pointed out in chapter three, in 7.5% of the cases, the ASRS was more than 90% utilized. For the current normal production rate, this can equal about 35% of the daily production rate. This highlights the importance of order purity. Further, this problem will grow if production rates are increased according to Dell's growth goals, especially if variability is not reduced. Lastly, another good metric for order purity is order-level cycle times, which are currently not measured for any other order size than 1.

In summary, better ability to control and manage both variability and order purity would have a significant impact not only on TOD success but also on Dell's overall process performance and capabilities. However, currently operators and supervisors are encouraged to focus only on average cycle times and additionally, order level performance is not measured. Thus, new metrics are needed to ensure effective long-lasting changes to the order-fulfillment process.

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# Appendix A: Glossary of Acronyms

Automated Storage and Retrieval System (ASRS)

Co-efficient of Variation (CV)

Customer Committed Delivery (CCD)

Distribution Process (DC)

First In First Out (FIFO)

Electromechanical repair (EMR)

Goodness Of Fit (GOF)

In Production (IP)

Just In Time (JIT)

Less than Truck Load (LTL)

Order Pending Release (OPR)

Speakers, Monitors and other peripherals ordered with the system (SPAMs)

Supplier Logistics Center (SLC)

Time-of-Day (TOD)

Transportation Management System (TMS)

Value-Added Services (VAS)

Work In Progress (WIP)

Warehouse Management System (WMS)