Analyzing and Improving Throughput of Automated Storage and Retrieval Systems in Personal Computer Manufacturing

by

G. Thomas Heaps-Nelson

B.S. General Engineering, Harvey Mudd College, 1995
B.S. Chemical Engineering, Iowa State University, 1997

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

Master of Business Administration
and
Master of Science in Chemical Engineering

In conjunction with the Leaders for Manufacturing Program at the
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Signature of Author ________________________
Sloan School of Management
Department of Chemical Engineering
May 6, 2005

Certified by ________________________
Professor Stephen C. Graves
Sloan School of Management
Thesis Supervisor

Certified by ________________________
Professor David Simchi-Levi
Department of Civil and Environmental Engineering
Thesis Supervisor

Certified by ________________________
Professor Gregory J. McRae
Department of Chemical Engineering
Thesis Reader

Accepted by ________________________
Margaret C. Andrews
Sloan School of Management
Executive Director of Master's Program

Accepted by ________________________
Daniel D. Blankschtein
Department of Chemical Engineering
Graduate Committee Chairman

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ABSTRACT

The content of this thesis draws heavily on work completed during a 6.5 month MIT Leaders for Manufacturing (LFM) internship at Dell Corporation's personal computer manufacturing facility in Lebanon, Tennessee (EG1) from June 2004 to December 2004. This work relates primarily to efforts to analyze and improve the throughput of the Automated Storage and Retrieval System (ASRS) in that factory. Wherever possible, the thesis abstracts from the EG1 factory case study to provide lessons for improving the throughput of ASRSs and accumulative manufacturing systems in general.

In addition to this core of the thesis, specific implementation challenges encountered during the EG1 case study are addressed. Finally, general cultural observations about Dell's manufacturing environment are discussed.

The author believes the two most unique aspects of this work are the Crane Frontier framework developed for analyzing ASRS throughput (Section 2.6) and the range and taxonomy of ASRS throughput improvement solutions (Chapter 3).

Thesis Supervisors:

Stephen C. Graves
Abraham J. Siegel Professor of Management,
MIT Sloan School of Management

David Simchi-Levi
Professor, MIT Department of Civil and Environmental Engineering

Thesis Reader:

Gregory McRae
Professor, MIT Department of Chemical Engineering

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Chapter 1: Background Information about Dell and this Project

1.1 Dell's Business Model

Dell has been wildly successfully since its founding a little over 20 years ago (1984). It has been a Wall Street darling for much of that time as well. The success of the PC itself can largely be seen as a testament to Clayton Christiansen's insight provided in The Innovator's Dilemma that new technologies often come into business prominence from the "low-end" of the market.[1] Dell's success can be viewed as an extension of the same sort of "bottom-up" market penetration strategy *within* the PC business. Now that Dell has firmly established itself as the market leader in low-end "commodity" PCs, it is quickly becoming a force to reckon with in higher margin products such as high-end PCs, servers, workstations, and printers (which provide their high profitability through the ongoing revenue stream from ink sales.)

Another seminal business thinker, Michael Porter, makes the claim that the three general dimensions on which businesses compete are cost leadership, differentiation, and focus.[2] Using this competitive framework, it is clear to outsiders and insiders alike that Dell's success has been due to its remarkable cost competitiveness. Clearly, in this strategic framework Porter means not that a company can focus only on one of these three pillars while ignoring the other two. He means that a successful company is usually "good enough" (compared to customers' alternatives) on two of the three criteria and that it

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[1] Christensen, Clayton M. The Innovator's Dilemma. New York: HarperBusiness, 2000.

[2] Porter, Michael E. Competitive Strategy: Techniques for Analyzing Industries and Competitors. New York: The Free Press, 1980.

shines by standing out from the crowd on a third criterion. The company usually highlights the pillar that they differentiate themselves with prominently in their mission statements so that employees, investors, customers, and suppliers know "what that company is all about." There are many benefits which accrue from having an articulated and streamlined corporate strategy. Dell has been wildly successful using this kind of corporate philosophy. They have been able to use their cost consciousness to drive large improvements in customer service, quality, and safety. It has been much easier for Dell to leverage its cost focus (which has a high level of cultural buy-in already) in the service of improving other metrics of interest, than it would have been to attempt to push those metrics only for their own sake. Blaine Paxton has done a wonderful study of the culture at Dell which has enabled this remarkable business success.[3]

Dell has not been secretive about its business model – everyone knows what it is. Other companies have tried to emulate this model in PCs to little avail. Smaller players simply do not have the scale to compete with Dell at its own game. Larger players have pre-existing interests and rigidities[4] that make it virtually impossible to transition over to a Dell-like model in a very graceful way (i.e., without suffering in profitability and market share during the transition period.)

The commoditization of the PC has played itself out in a large consolidation in the PC business recently. Hewlett Packard completed its merged with Compaq in 2002. Also,

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[3] Paxton, Blaine. The Dell Operating Model. S.M. Thesis, Massachusetts Institute of Technology, 2004.

[4] For an example of the difficulties encountered in copying Dell's model see: Schrage, Michael. "The Dell Curve." Wired July 2002. 2 Apr. 2005 <http://www.wired.com/wired/archive/10.07/dell.html>.

Lenovo announced its intention to buy IBM's PC division in 2004.[5] While the other large players in the PC business were struggling, Dell announced its intention in 2004 to build a new manufacturing plant on US soil in North Carolina.[6] In the midst of the vigorous debates in the United States about the effect of manufacturing off-shoring, Dell is uniquely poised to expand its US manufacturing operations because localized production suits its make-to-order business model. (More discussion of Dell's incentives toward keeping and expanding US manufacturing is in sections 1.3 and 1.4.)

The main focus of this thesis is not Dell's business strategy or Dell's culture. However, this context is useful when thinking about the motivation for this project and thesis which revolve around improving throughput in certain types of manufacturing bottlenecks (using the Dell PC manufacturing environment as a case study.)

1.2 The Context of Dell's Manufacturing Improvements

The departure point for discussing Dell's operations is the fact that Dell is a "make-to-order" enterprise; this fact has been at the center of Dell's success in the marketplace. The primary benefits conferred by using the make-to-order model are elimination of a whole layer of the distribution supply chain (e.g., retailers), reduction in the overall amount of inventory in the supply chain, and closeness to the "pulse" of the customer by having more direct information about customer preferences. The popular press often discusses the supply chain aspects of Dell's operations, but much less attention is focused on Dell's actual manufacturing processes "within the 4 walls."

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[5] John G. Spooner and Kanellos, Michael, and. CNET. 8 Dec. 2004. CNET News.com. 2 Apr. 2005 <http://http://news.com.com/IBM+sells+PC+group+to+Lenovo/2100-1042_3-5482284.html>.
[6] For example, see http://www.industryweek.com/ReadArticle.aspx?ArticleID=10007.

Final PC assembly is a very modular, low-skill labor process. Dell is the only large PC maker who still assembles any PCs in the United States, and then even only desktops and enterprise products bound for North America. Laptops destined for North America are built in Dell's manufacturing facilities in either Malaysia or Ireland, then air freighted to Dell distribution sites in the United States.

The fraction of the overall PC assembly process for Dell desktops which is happening in the United States is diminishing. Dell is moving to higher and higher levels of "chassis integration" with its Asian component suppliers. This means that if a part can be assembled into the chassis in Asia (prior to receiving the order specification for that PC) it should be. The integrated chassis are then shipped by barge to the United States and transported to one of Dell's two North American PC assembly campuses (Austin, TX or Nashville, TN). This still allows for the final customization of the PC after the North American customer places his or her order. Essentially this is an optimal implementation of a "postponement" strategy which has many other benefits, including inventory reduction.

The following quote illustrates Dell management's perspective about keeping inventory low:

> "That's why inventory is a four-letter word at Dell. To Kevin Rollins, who succeeded Michael Dell as CEO this past July (Dell continues as chairman), inventory is like fish. 'The longer you keep it the faster it deteriorates -- you can literally see the stuff rot,' he says. 'Because of their short product lifecycles, computer components depreciate anywhere from a half to a full point a week. Cutting inventory is not just a nice thing to do. It's a financial imperative.' "[7]

This same sort of management drive for cost-containment results can be seen in the following quote from the same article:

> "Dell, which hit $45 billion in annual revenue this past July and is growing at a nearly 20% yearly clip, seems well on its way toward surpassing its goal of $60 billion within the next few years. And it's not letting up. Still relentlessly striving to get better faster, Dell intends to slash $2 billion in costs. CFO Jim Schneider has indicated that much of the cuts will come from manufacturing operations and the supply chain."[8]

It is in the context of this overall corporate imperative to continue to drive costs out of the manufacturing process and supply chain that this internship project and thesis arose.

1.3 What is GeoManufacturing?

Because Dell has been so successful at driving cost out of its supply chain and manufacturing processes, outbound logistics costs have become a very significant fraction of the overall "transformational cost" (referred to internally at Dell as Cost Per Box or CPB) of getting PCs into the hands of customers. Dell is hard-driving on itself and its suppliers to continually drive out cost.

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[7] Bill Breen, "Living in Dell Time," Fast Company Nov. 2004, 5 Nov. 2004.<http://www.fastcompany.com/magazine/88/dell.html>.

[8] ibid

Several years ago a corporate imperative was made explicit to "build PCs close to our customers." This imperative was dubbed "GeoManufacturing" or GeoMan for short. As the name implies Dell intends to continue manufacturing in all the major geographies that it serves – to the extent that it is economically sensible, Dell will manufacture PCs for customers in a given region in factories in that region.

Five major benefits that flow from GeoManufacturing are:

- Reduced outbound logistics costs
- Reduced customer lead times (improving sales and customer satisfaction)
- Increased variability pooling over different customer categories (reducing capital expenditure)
- Goodwill based on creating employment in each of the geographies
- Increased visibility to customers and resulting word of mouth advertising

The first two benefits are rather straightforward (and important). It is clear that the closer PC manufacturing is to the customers, the less costly and the timelier it will be to ship finished product to the customer.

The third benefit noted above is a bit more subtle. If the full Dell product portfolio of PCs (or any products for that matter) is to be built closer to customers, flexible factories must replace product-dedicated factories to accommodate seasonal variability which takes place across the year. A prime example of seasonal variability in PC manufacturing is that the peak of home desktop PC demand is during the Christmas buying season while the peak of business desktop PC demand is during the summer when many corporate and governmental PC budget cycles are ending. Implementing factory flexibility means that less overall capital equipment will be needed (assuming relative flexibility of most types of factory equipment, which is generally characteristic of Dell's manufacturing processes) to satisfy the demand across the year. This benefit ties in quite nicely with Dell's cultural virtue of frugality.

The fourth and fifth benefits are "bonus" benefits one receives from geographical diversity in manufacturing if one is perceived as a good employer and as a producer of quality products.

All five of these benefits of GeoManufacturing fit in extremely well with Dell's strategic implementation of make-to-order and cost control.

1.4 How GeoManufacturing Gives Rise to this Project

This project directly pertains to GeoManufacturing in the North American PC market. Dell's two existing PC assembly sites in the United States are in Austin, TX and Nashville, TN; it has recently announced a third plant in Winston-Salem, NC (expected in September 2005). Prior to the GeoMan initiative, the Austin, TX facility had specialized in corporate desktop PCs (OptiPlex desktops and Precision workstations), and the Nashville, TN facility has specialized in home desktop PCs (Dimension desktops). OptiPlex desktops are the desktop PCs targeted mainly at corporate and government customers, while Dimension desktops are the desktop PCs targeted mainly at home and small business customers. The differences in sales characteristics (specifically in order size) between OptiPlex and Dimension will play an important role in subsequent chapters.

Given that the vast majority of Dell's North American customers are still near the east coast of the United States, it has become very attractive for the reasons discussed in the previous section to be able to flex Dell's factories to make Dimension desktops in Austin and to make OptiPlex desktops in Nashville, enabling production closer to customers on average.

Clearly there are many factors to trade off when deciding where to locate new factories, but being close to customers was one of the key factors in Dell's decision to locate its newly announced manufacturing facility in North Carolina (even closer to the bulk of its customers):

> " 'The education system, commitment to businesses and proximity to a large and growing base of Dell customers were important in our decision to expand into North Carolina,' said Kevin Rollins, Dell's chief executive officer."[9]

In order to create this product flexibility in Nashville to manufacture both Dimension desktops and OptiPlex desktops, significant changes were required in the Nashville factory layout. The reason for this is illustrated in Figure 1, a simple schematic of Dell's manufacturing process. While most of the factory processes (such as kit, build, burn, and box) "behave" in a similar manner whether the PC being assembled/packaged is a

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[9] CarolinaNewswire.com, 9 Nov. 2004, 2 Apr. 2005 <http://carolinanewswire.com/news/News.cgi?database=topstories.db&command=viewone&id=2222&op=t>.

Dimension or an OptiPlex, for one area of the factory these two categories of products behave very differently. That area is the Automated Storage and Retrieval System (ASRS), the storage area where partially completed orders of more than one PC are stored until all PCs in an order are ready to be released to a truck for the first leg of transportation. The need for an ASRS follows directly from Dell's commitment to ship all systems in an order together and the complication and lack of space associated with storing PCs on the factory floor. Since single PC orders do not have any other PCs to which they are "tied," they can typically bypass the ASRS entirely, as shown in Figure 1. Occasionally, individual PCs comprising small-sized orders (of perhaps 2 or 3 PCs) arrive close enough in time to allow the order to entirely bypass the ASRS also. Also, the last PC in an order often can bypass the ASRS entirely, as its arrival at the ASRS triggers the release of the other stored systems in the order. This assumes that the associated accessories (monitors, speakers, printers, etc.) are available and that the downstream operations and trucks are available for the release of the order. Many more details of the operation and behavior of the ASRS will be explored in Chapter 2.

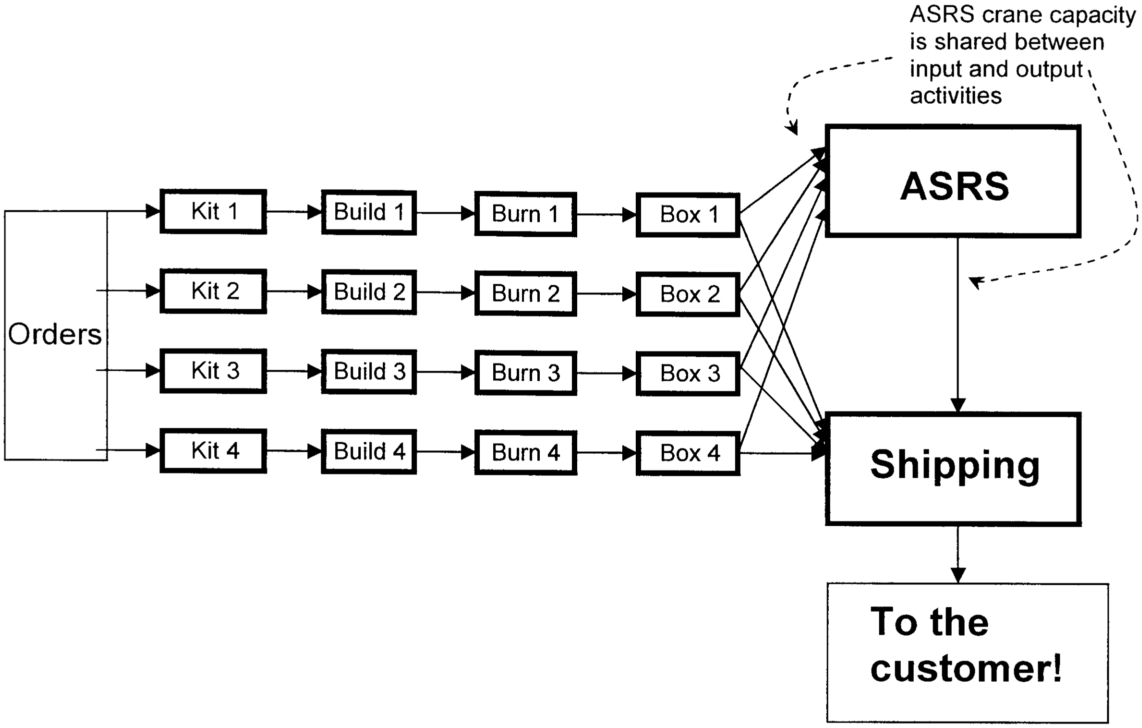

Figure 1: Schematic of Dell's PC Assembly and Shipping Processes

The reason that the load on the ASRS is much different for OptiPlex desktops than for Dimension desktops is that OptiPlex orders are on average much larger (i.e., a corporate customer is much more likely to place an order of 100 PCs than a transactional, home consumer is.) This basic fact, coupled with Dell's desire to make more corporate PCs (OptiPlex) in Nashville, shifted the bottleneck of that factory (named EG1) from an earlier stage of the manufacturing process to the ASRS.

1.5 Problem Statement

The shift of the factory bottleneck to the ASRS is at the heart of the internship project and this thesis.

A more formal definition of the problem statement consists of two parts:

1. Perform a factory flow analysis (at an appropriately chosen level of sophistication and detail) to understand and characterize the throughput workload and throughput capacity of EG1's ASRS.
2. Develop and implement cost-effective ways to increase the throughput of large orders of PCs in EG1.

The first phase of the project task was to perform the analysis of EG1's new ASRS bottleneck (the subject of Chapter 2.) Only on the basis of solid analysis could the second phase of the project be initiated – brainstorming possible solutions, prioritizing the feasible options, and implementing changes to alleviate the ASRS bottleneck and thus allow greater volume of OptiPlex (and PCs overall) through the factory (the subject of Chapter 3).

Chapter 2: Data Collection and Problem Analysis

2.1 Introduction to Data Collection and Problem Analysis

As stated in Chapter 1, the purpose of the first phase of this internship project was to understand and characterize the throughput workload and capacity of EG1's ASRS. The initial data collection efforts focused on that purpose. In Section 2.2 some details of the design and operations of ASRSs in general and EG1's ASRS in particular will be discussed. Section 2.3 will be a qualitative discussion of the important issues pertaining to ASRS throughput and ASRS storage capacity. Sections 2.4 and 2.5 will present hourly crane workload data and crane timing study data, respectively. Section 2.6 will present "The Crane Frontier," an analytical framework used in this thesis to analyze the crane workload and timing study data. Finally, Section 2.7 will summarize what has been presented in this chapter.

2.2 What is an Automated Storage and Retrieval System and How Does it Work?

Automated Storage and Retrieval Systems (ASRSs) are generally large, 3-dimensional racks of storage space and the associated automation and control systems used to store and subsequently retrieve boxed products (see Figure 2). Notice that the ASRS comprises a rectangular "solid" of space which often almost reaches the factory ceiling. This geometrical configuration is efficient in its use of factory floor space.

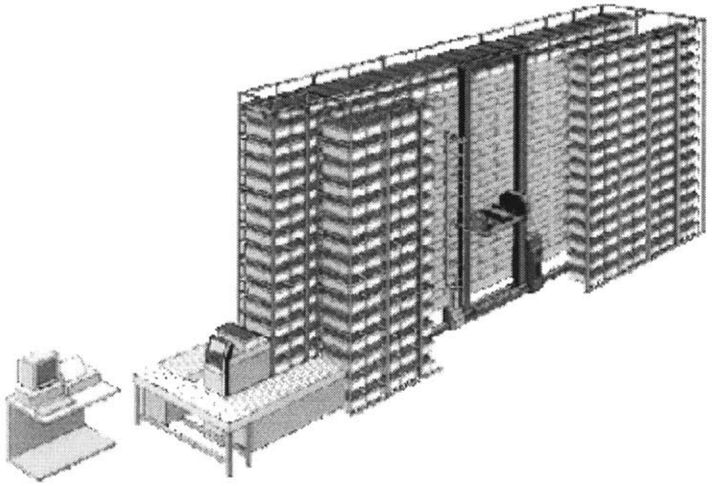

Figure 2: Diagram of Typical ASRS (Similar to that Used in EG1)[10]

Automated cranes are used to move the products into and out of storage locations as required by upstream and downstream factory processes. Often, in practice, multiple-shuttle cranes (i.e., cranes which can hold more than one box at once) are used because they increase the throughput of the ASRS system.[11] Figure 3 shows a diagram of a twin-shuttle ASRS crane similar to those used in EG1 and elsewhere.

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[10] Diagram from daifukuamerica.com. 2004. Daifuku America Corporation. 27 Jan. 2004 <http://http://www.daifukuamerica.com/daifuku/dac/fada/f_mlab_2.asp>.

[11] Russell D. Meller, and Anan Mungwattana, Multi-Shuttle Automated Storage/Retrieval Systems, 3 July 1996, Auburn University, 2 Apr. 2005 <http://filebox.vt.edu/users/rmeller/ms-asrs.pdf>.

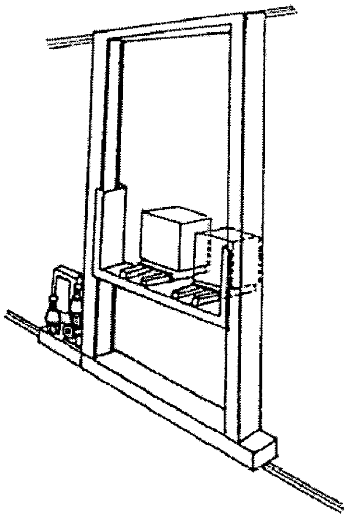

Figure 3: Diagram of Typical Twin-Shuttle Crane[12]

Most ASRSs use a number of (often multi-shuttle) cranes to store and retrieve boxes although typically only one crane serves a given storage location (bin). In the case of EG1, there are five (essentially identical) cranes, each of which serves an aisle of storage space. Each rack is composed of two opposing sides of storage bins. A row of bins is termed a tier, and a column of bins is termed a bay. A side view of one of the opposing sides of a storage rack (partially filled with loads) is shown in Figure 4. Note that the input and output locations are on the same end of the storage rack and relatively close to one another.

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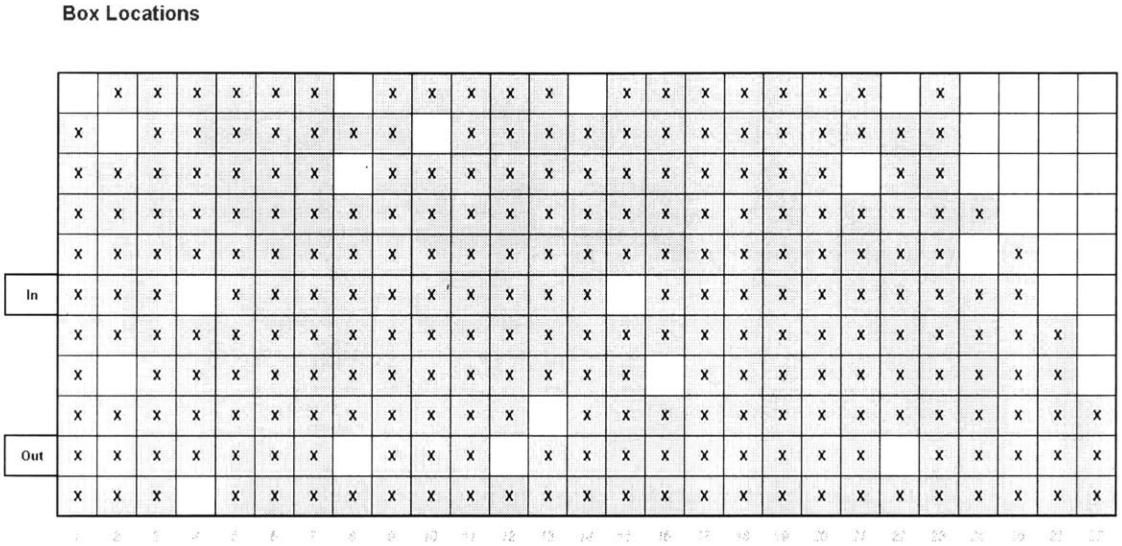
[12] ibid



Box Locations

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
		x	x	x	x	x	x		x	x	x	x	x		x	x	x	x	x	x	x		x				
	x		x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x				
	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x		x	x				
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x		
In	x	x	x		x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x		
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
	x		x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	
	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x
Out	x	x	x	x	x	x	x		x	x	x		x	x	x	x	x	x	x	x	x		x	x	x	x	x
	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

[Diagram courtesy of Michael Hoag, Dell Corporation]

Figure 4: Side View of Half of One of EG1's Storage Racks

Each crane traverses the length and height of the vertical storage racks and is able to service both sides of a storage rack. One set of motors transports the crane along the length and height of the ASRS. Another motor is used to extend and retract the crane shuttles into and out of the storage locations once the whole crane body has been positioned adjacent to the appropriate storage location. Because the shuttles can be extended in either direction, each crane can serve the storage rack which resides on either side of the plane of motion of the crane body.

An important aspect of EG1's ASRS is that each crane has two shuttle arms (i.e., is twin-shuttle) and thus can store or retrieve two boxes at a time (of course, only from the storage rack "within its reach," as discussed above.) This crane characteristic will be critical to some of the bottleneck alleviation solutions described in Chapter 3.

Another important point to recognize is that EG1's cranes perform dual duty–they both move PCs from the input to storage locations and move PCs from storage locations to the output (en route to shipping). Thus a twin-shuttle crane can perform two storage actions and two retrieval actions in one cycle, sometimes referred to as a quadruple-command (QC) cycle.[13] A QC cycle for a twin-shuttle crane can be schematically depicted as shown in Figure 5 below. The outer rectangle represents the storage rack area, and I/O represents the area where loads are input and output from the system. The arrow points designated as s1 and s2 represent where the first and second storage actions occur, and the arrow points designated as r1 and r2 represent where the first and second retrieval actions occur.

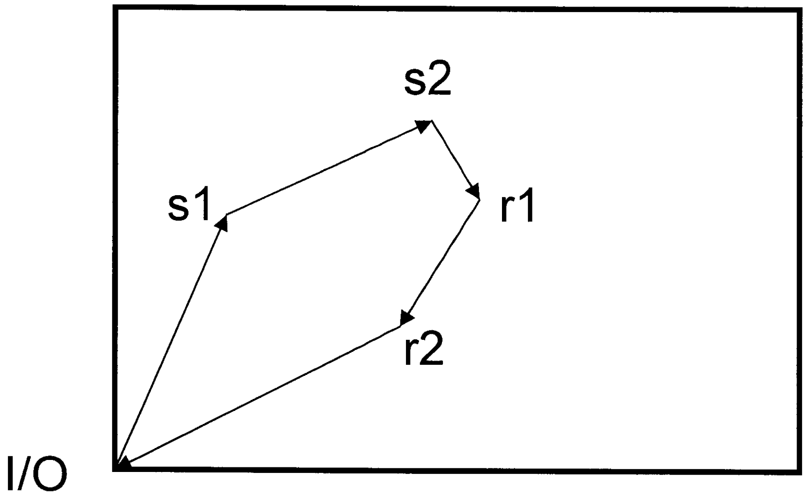


Figure 5: A Quadruple-Command Cycle Tour[14]

During steady-state operation of the ASRS (when many inputs and many outputs are occurring) the crane logic of EG1's cranes is geared toward performing many repeated QC cycles – that is, two stores, followed by two retrieves, followed by two stores, etc.

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[13] ibid

[14] adapted from ibid

Indeed, it will be demonstrated later with EG1 timing studies that this is the most throughput-efficient move cycle for twin-shuttle cranes. In one QC cycle a crane executes the following steps:

- Travel to its own dedicated input conveyor
- I/O: Extend both of its crane forks to pick up two boxes (one box per fork) and retract its crane forks (with the boxes now on the forks)
- Move the crane body so that the box on fork #1 is adjacent to the assigned (empty) storage location for the box on fork #1
- s1: Extend fork #1 to store that box and then retract fork #1 (now empty)
- Move the crane body so that the box on fork #2 is adjacent to the assigned (empty) storage location for the box on fork #2
- s2: Extend fork #2 to store that box and then retract fork #2 (now empty)
- Move the crane body so that the box on fork #1 is adjacent to the first stored box which is to be retrieved
- r1: Extend fork #1 to get that box and then retract fork #1 (with the box on it)
- Move the crane body so that the box on fork #2 is adjacent to the second stored box which is to be retrieved
- r2: Extend fork #2 to get that box and then retract fork #2 (now the crane body has two boxes on it.)
- Move the crane body so that it is adjacent to its own dedicated output conveyor
- I/O: Extend the forks to deliver the two boxes (one box on each fork) to the output conveyor

Applying some thought to the input/output interleaving process just described, one realizes that ASRS throughput and ASRS storage utilization are not independent of one another. Said another way, if the vertical storage racks are very full, it will take the cranes more time to input and output boxes because the cranes will have to travel longer distances to perform the operations.

It is also worth noting at this point that both ASRS throughput and ASRS storage capacity were, at times, bottlenecks for EG1. Each of these events on the factory floor could easily be visually observed. Occasionally, EG1 introduced a large amount of OptiPlex orders into the start of the manufacturing process and subsequently one could see the effects of the ASRS bottlenecks. It was not uncommon to see the ASRS storage racks get very full. Then the operation managers would reduce the amount of OptiPlex orders started in the factory. In fact, a system of guidelines called the "Rules of Engagement" had been established, expressly to avoid the scenario of filling up the storage locations in the ASRS. Many associates (hourly manufacturing line employees) and operations managers recounted vivid stories of how factory operations had been extremely hampered or stopped all together when the ASRS vertical storage racks became full. Sometimes the majority of associates would be sent home early from their shifts as a result.

Somewhat less dramatic, but much more common at EG1, was having ASRS throughput be the bottleneck. Even if the ASRS storage bins were only half occupied, the cranes were sometimes incapable of storing the arriving boxes fast enough to keep up with the arrivals. In this case, the boxes arriving at the ASRS input conveyors would back up all the way to the boxing lines (and sometimes further) causing manufacturing personnel to stop production for extended periods of time (sometimes also causing a large number of associates to be sent home early from their shifts.)

Given the observation that both ASRS throughput and ASRS storage capacity were at times bottlenecks for the factory, let us proceed to discuss some frameworks for thinking more deeply about these problems.

EG1's ASRS seems to be a fairly "standard" ASRS (provided by a large, established vendor of such equipment). Thus, many of the lessons learned in the course of this internship should be applicable to other ASRSs.

2.3 Thinking about ASRS Throughput and ASRS Storage Capacity

Normally, ASRSs are sized with some (relatively large) safety factor built in to ensure that enough throughput and storage capacity exists in the factory. Reasons for the large safety factor built into the size of ASRS construction include:

- High cost of throughput or storage capacity shortage. A shortage often leads to shutting down the factory and/or inefficient labor usage.
- Imprecision and difficulty of factory modeling (conventional or simulation), leading to uncertainty in ASRS need
- Highly variable box input rate

- Medium to highly variable shipping rates (a direct determinant of ASRS box output rates)
- Potential for high growth rate of factory throughput required in the future
- Potential for shift to product mix which requires more ASRS resources
- Higher fixed cost to expand the existing system. (The cost of adding one additional crane and rack of storage during initial construction is much less than retrofitting the system to add the additional crane and rack later.) This is because a large fraction of ASRS cost is due to the control system and supporting conveyors. It also stems from the fact that retrofitting often entails moving or dismantling other factory equipment to make room.

Despite these important reasons for making the ASRS large, one cannot make it infinitely large. That is, one must accept at least *some* risk of the ASRS storage racks being too small (insufficient storage capacity) and/or the input and output rates of the ASRS being too small (insufficient throughput).

In EG1 the size of the ASRS was quite sufficient for the first four years of the factory's operation (1999-2003). However, a product mix shift in 2004 (toward the production of more OptiPlex) increased the throughput and storage capacity demands on the ASRS tremendously. In fact, although the ASRS historically had never been considered the bottleneck, it had become the bottleneck with the implementation of the GeoMan project. The amount of product mix shift toward OptiPlex which Dell could enable in EG1 was limited by the size and speed of its ASRS.

Refer again to Figure 1 (in Chapter 1), a simple schematic of the manufacturing process at Dell. This figure suggests that for most of the categories of manufacturing steps at Dell (such as kit, build, burn, and box), the capacity scales with the throughput – that is to say, their throughput capacities can be adequately measured by a single number, measured in units per hour (UPH). This is indeed the case, and EG1 manufacturing personnel routinely use this methodology. It is very convenient when such a manufacturing step is the true bottleneck of the factory because then it is apparent what that "bottleneck throughput" is. However, Figure 1 also suggests that the ASRS step is not a linear process in the sense just described. Because the ASRS input and output processes are both competing for the same shared resource (i.e., a crane's processing time), the throughput capacity of the ASRS is not well characterized by a single numerical throughput rate. In Section 2.6 a new way of characterizing the throughput capacity of the ASRS, "The Crane Frontier," will be presented.

There is a very rough analogy between the operation of an ASRS and that of a bathtub (see Figure 6). The level of water in the bathtub is analogous to how many boxes are stored in the ASRS. In both cases, filling up the storage vessel completely or even almost completely greatly reduces the usefulness of the storage vessel to the operator.

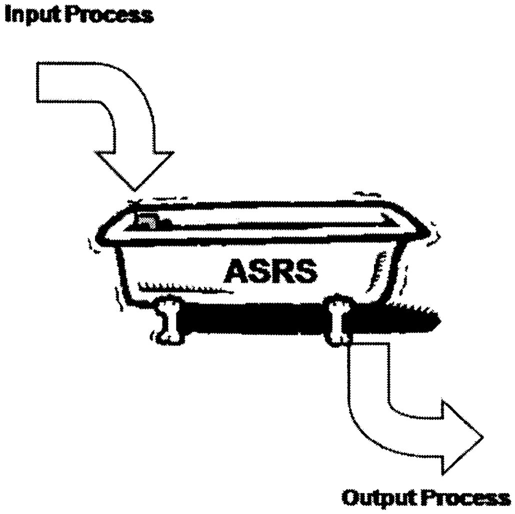

Figure 6: A Rough ASRS Analogy to Operation of a Bathtub

The faucet represents how quickly water enters the tub, and the drain represents how quickly water exits the tub. At this point, the analogy breaks down somewhat. In the case of the ASRS the maximum input rate is linked to the output rate (because cranes are shared resources.) This is clearly not true in the case of the bathtub. Also, in the case of the bathtub, the water level has an effect on the material output rate–that is, the higher the level, the higher the output rate. In the case of the ASRS, the fullness affects both the input rate and the output rate, and it is negatively correlated with them (as was described in Section 2.2.)

These complexities of design/operation are reasons that factories with designs similar to that shown in Figure 1 are purposefully planned to avoid having the ASRS be the bottleneck. Given this general context for thinking about the ASRS as a bottleneck, the rest of this chapter will address how to analyze the throughput workload and the throughput capacity requirements for the ASRS in greater detail[15]. Chapter 3 will proceed to address solutions for increasing throughput in EG1's ASRS when it has become the bottleneck. Where possible, generalizations of these EG1 results and solutions will be made to accumulative manufacturing processes in general.

2.4 Variability of Hourly EG1 Crane Usage Data

The first steps in the data collection process were to create a database which captured the hourly crane usage and to investigate how the usage varied across different time scales. Independent of this data, simply spending a small amount of time on the factory floor revealed that there was high variability of ASRS crane usage across the day and from day-to-day. Interviews with Dell manufacturing employees made it clear that they were aware of this high variability of ASRS crane utilization across the day but that they had not quantified the variability. Figure 7 and Table 1 contain over a month of (Monday through Thursday) hourly data for the EG1 facility. In Figure 7, the y-axis scale has been left out to protect the confidentiality of factory throughput values. The x-axis starts at 4 am on the left and finishes at 4 am of the following day on the right.

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[15] As a result of the commercial importance of ASRSs, the theoretical mathematical framework for analyzing their operation is quite advanced. For example, see ibid for an extensive mathematical treatment of this theory.

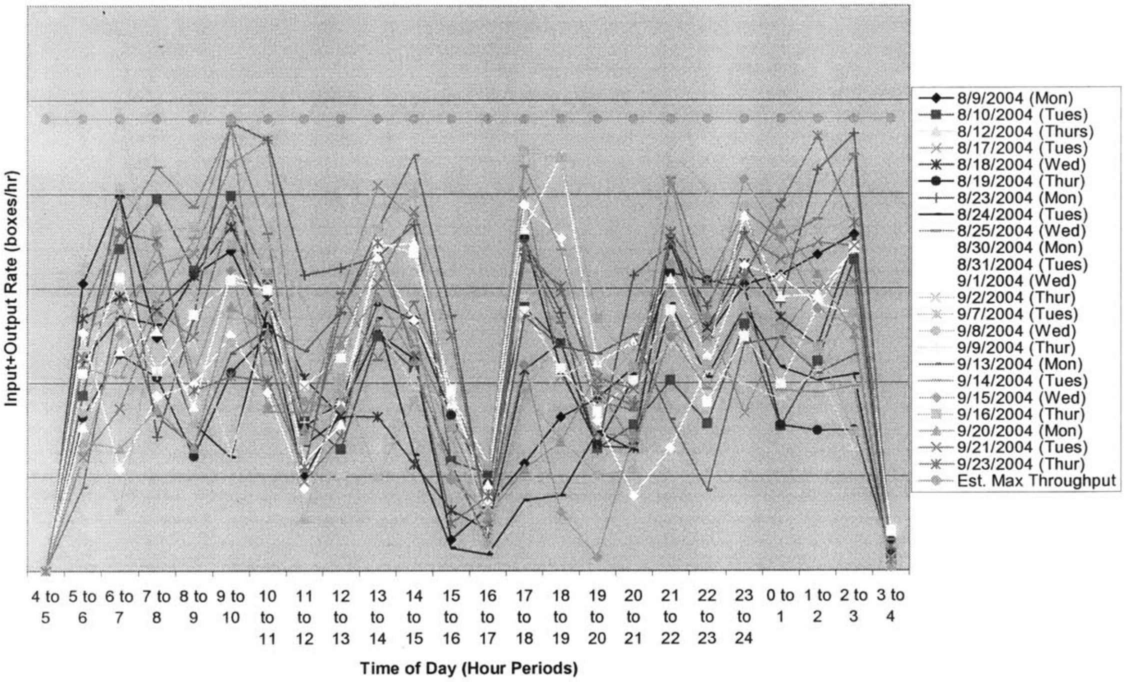

Figure 7: EG1 Total Hourly Crane Flow Rate (Weekdays Only), 8/9/04 - 9/23/04

Table 1: Summary Statistics of EG1 ASRS Total Load, Weekdays, 8/9/04 - 9/23/04

Hour of the Day	**Average Total Load, Input + Output (Boxes/hour, scaled so 100 is maximum)**	**Coefficient of Variation of Total Load, Input + Output**
4 am to 5 am	0	2.36
5 am to 6 am	65	0.33
6 am to 7 am	88	0.41
7 am to 8 am	80	0.39
8 am to 9 am	77	0.40
9 am to 10 am	97	0.39
10 am to 11 am	89	0.33
11 am to 12 pm	48	0.46
12 pm to 1 pm	65	0.35
1 pm to 2 pm	90	0.35
2 pm to 3 pm	86	0.40
3 pm to 4 pm	44	0.51
4 pm to 5 pm	21	0.50
5 pm to 6 pm	85	0.47
6 pm to 7 pm	77	0.45
7 pm to 8 pm	56	0.42
8 pm to 9 pm	59	0.30
9 pm to 10 pm	100	0.25
10 pm to 11 pm	78	0.26
11 pm to 12 am	99	0.19
12 am to 1 am	90	0.25
1 am to 2 am	93	0.28
2 am to 3 am	94	0.31
3 am to 4 am	6	0.67

One can see a few key patterns from this data:

- Even though ASRS throughput often is the bottleneck of EG1 factory flows, total usage across the day is roughly 50% of the theoretical maximum of throughput through the ASRS. (The derivation of the value of theoretical maximum throughput will be shown in Section 2.6. As one might hope, this value approximately corresponds to the largest hourly output measured at EG1 during the data collection period of Figure 7.) This data suggests that there are likely opportunities to reclaim some of the unused ASRS capacity across the day.

- Within a given hour of the day, there is high variability of utilization from day to day.
- There is a pattern of clear peaks and valleys of utilization throughout the day. The valleys correspond to shift changes, lunches, and breaks when much of the equipment in the entire factory is idle. (The weekend shifts have different standard hours and thus were not included in the data in Figure 7 and Table 1 above.)

Now, looking at ASRS input rate and ASRS output rate separately, the mean and standard deviation of the same data set is shown in Figure 8 and Figure 9.

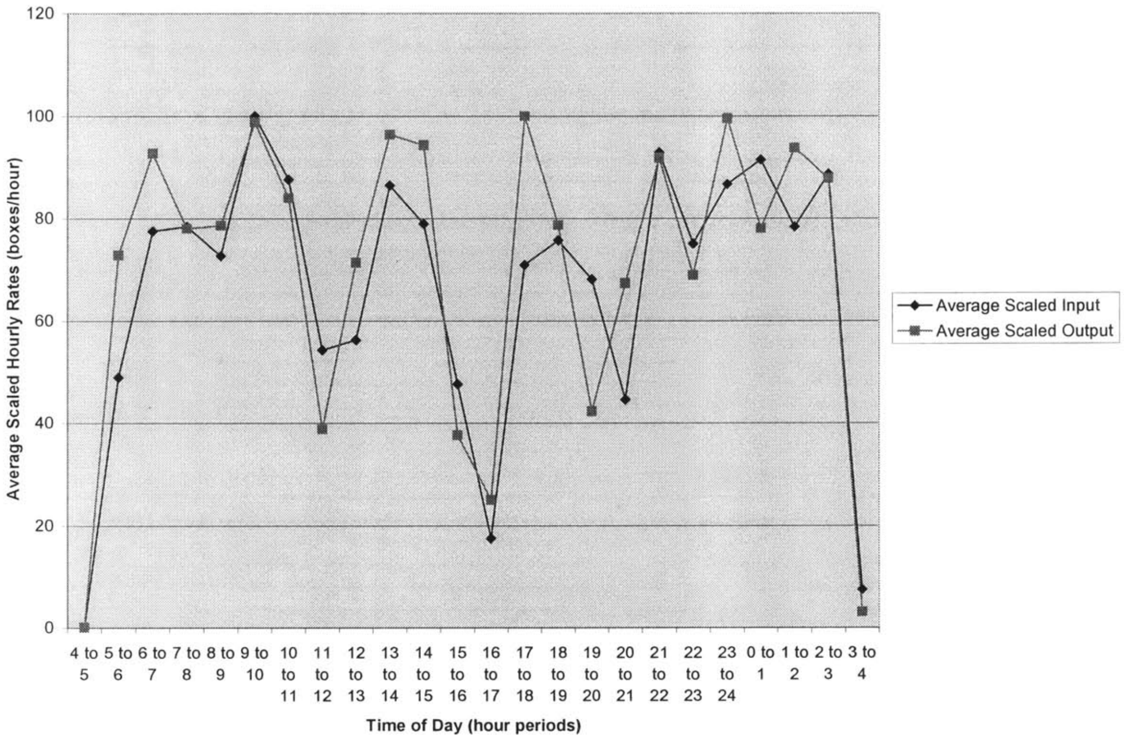

Figure 8: Average Scaled EG1 Input and Output Rates, Weekdays, 8/9/04-9/23/04

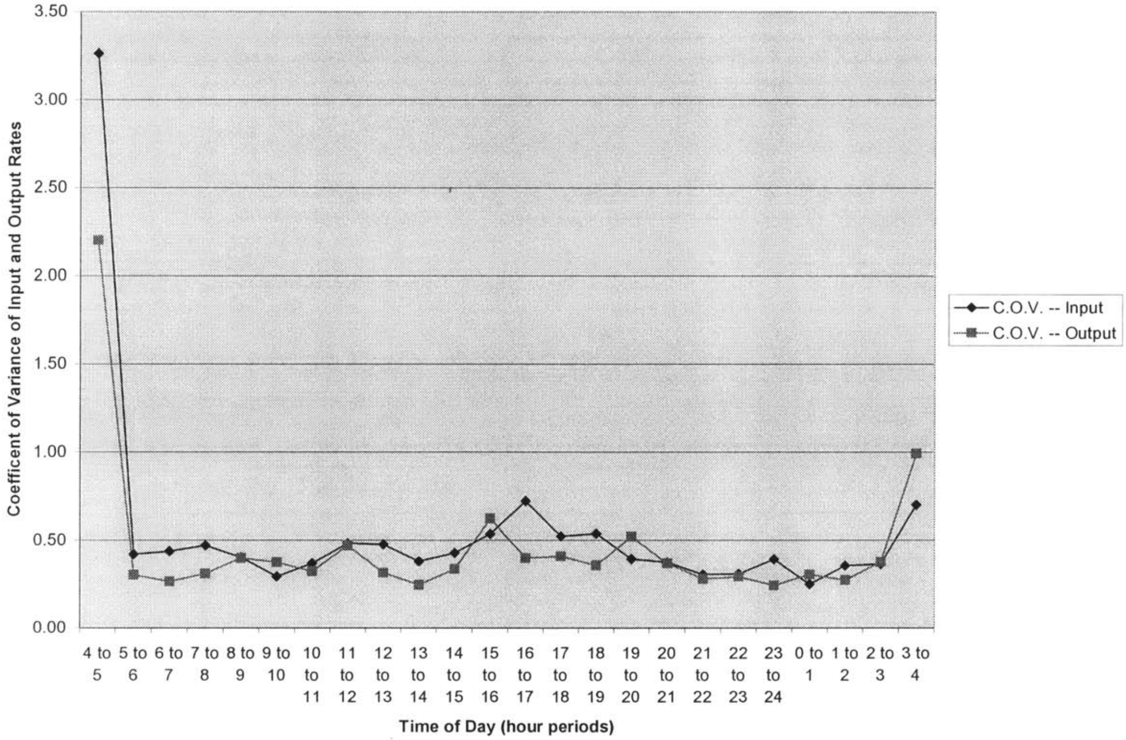

Figure 9: Coefficient of Variation of EG1 Input and Output Rates, Weekdays, 8/9/04-9/23/04

It is apparent from these graphs that there is room for improvement. Details of the improvements recommended and implemented will be given in Chapter 3.

Even the process of showing these graphs to various groups in EG1 manufacturing was a powerful cultural influencer. Dell aspires to (and largely succeeds at) making decisions primarily on the basis of data. A number of manufacturing personnel understood that high variability and sub-optimal utilization of the ASRS cranes existed. However, many of them initially believed that there was little that could be done to really help increase utilization (and thus overall factory throughput). The quantification of and the creation of visual representations of the data constituted an instrumental starting point for motivating a collaborative effort to find ways that equipment and operations could be changed to gain back some of the currently unused ASRS throughput capacity (across the day).

In addition to the within-day and day-to-day variability discussed above, there are often important week-to-week, and quarter-to-quarter variabilities also. Variations across these time scales will not be addressed in this thesis, but the practitioner should be aware of them when performing ASRS analysis and planning.

With this understanding of EG1's ASRS utilization, a more detailed investigation of the details of the crane operation is warranted. The initial data collection effort on this front involved performing timing studies of the crane operation.

2.5 Timing Studies of the Cranes

Because of the recognition that the ASRS cranes were the bottleneck to the whole factory, several improvements to crane performance such as removal of unnecessary waiting time had already been completed prior to the arrival of the author. There was also a general recognition that improvements to the reliability of the cranes (and efficient responses to mechanical crane downtime) would result in more throughput for the ASRS and thus for the factory.

The existing ASRS crane logic rules were not fully documented, so the best method to characterize them was careful observation of crane operation combined with timing studies. (Ongoing work at EG1 includes parsing large data logs from which it is possible to obtain much larger amounts of crane timing data.) As background information for the crane control logic, a few features of EG1's ASRS need to be explained first. These salient features include:

- The input and output areas for each crane are on the same side of the ASRS, one directly above the other (see Figure 4).
- In order to effectively perform the stopwatch timing studies, one needs to be able to simultaneously view the input and output of each crane.
- In order to maintain macroscopic balance between inputs and outputs, each crane tended to alternate between performing store and retrieve operations.
- Because of this interleaving of inputs and outputs, there are only 8 basic crane logic "moves" (cycles) which are possible for each trip of the ASRS crane, namely (2,2), (2,1), (1,2), (2,0), (0,2), (1,1), (1,0), and (0,1). Where the first number in the pair stands for the number of boxes input, and the second number in the pair stands for the number of boxes output. Therefore, a (2,2) means that two boxes were input followed by two boxes being output. In Section 2.2, the (2,2) interleaving move was termed a Quadruple-Command (QC) cycle; its component mechanical operations were listed, and it was diagrammed schematically in Figure 5.
- The queues (input and output) waiting for each of the cranes can be much larger than two boxes. Because of physical limitations on the incoming conveyors, the

input queue is limited to five boxes for each crane, but the output queue is virtual and thus not constrained.

To obtain a complete picture of crane operation, the cranes were observed during busy times (both during times with biases toward heavy input and times with biases toward heavy output) and during slow times. A disguised (but representative) set of times and other derivative variables for each of the 8 types of moves is shown in Table 2 below. This data set comes from the aggregation of a busy period biased toward inputs, a busy period biased toward outputs, and a number of separately collected (2,2) cycle observations.

Table 2: Summary of EG1 Crane Timing Study Data

Move Seq.	# of Crane Stops	Total # of Box Moves	Crane Stops Per Box Move	# of Box Inputs	# of Box Outputs	Mean Time (sec.)	St. Dev. Time (sec.)	# of Data Points	Mean Time/Box Move (seconds)	Mean Time Per Crane Stop (sec.)
(2,2)	6	4	1.50	2	2	85.3	3.24	83	21.3	14.2
(2,1)	5	3	1.67	2	1	73.1	1.36	8	24.4	14.6
(1,2)	5	3	1.67	1	2	72.4	5.44	4	24.1	14.5
(2,0)	3	2	1.50	2	0	48.4	2.15	21	24.2	16.1
(0,2)	3	2	1.50	0	2	52.8	2.5	9	26.4	17.6
(1,1)	4	2	2.00	1	1	*	*	*	*	*
(1,0)	2	1	2.00	1	0	*	*	*	*	*
(0,1)	2	1	2.00	0	1	*	*	*	*	*

* Each data field indicated with an asterisk corresponds to move sequences for which the sample size was too small to calculate summary statistics.

It can be seen from this table that the most overall efficient move sequence is (2,2) because it has the lowest mean time per box move (21.3 seconds). This is partially a result of the fact that crane stops are very time consuming (compared to actual crane traverse time) and that (2,2) is tied for the smallest crane stop/box move ratio (1.5). As mentioned above, this data is an aggregation that included one time period where inputs were greater than outputs (accumulation) and another time period where outputs were greater than inputs (dis-accumulation). To look at the relative stability of crane moves, it is important to note the relative frequency of the moves in each of these episodes. For the time period where the inputs were greater than the outputs, the frequencies are given in Table 3.

Table 3: Frequencies of Crane Moves During an "Accumulation" Period

Move Sequence	Frequency
(2,2)	47
(2,1)	8
(1,2)	0
(2,0)	21
(0,2)	0
(1,1)	0
(1,0)	0
(0,1)	0
(0,0)	N/A

For the time period where the outputs were greater than the inputs, the frequencies are given in Table 4.

Table 4: Frequencies of Crane Moves During a "Disaccumulation" Period

Move Sequence	Frequency
(2,2)	13
(2,1)	0
(1,2)	4
(2,0)	0
(0,2)	9
(1,1)	0
(1,0)	0
(0,1)	0
(0,0)	N/A

These data indicate that (2,2) is the most common move for the crane. In fact, the ASRS software is written to perform a (2,2) move whenever the input queue and output queue are each two or greater (which is often the case during busy factory times).

The somewhat limited data in Tables 3 and 4 also indicate that (2,0) is more common (i.e., occurs more frequently) than (2,1) and that (0,2) is more common than (1,2). In fact, the ASRS software is written to prefer carrying two boxes instead of just one. (2,0) occurs more frequently than (2,1) because the software system prefers a (2,0) followed by another (2,0) even if a single box is staged to be output.

So, the general observation is that the ASRS software is set up to "prefer" various moves over others. The three dominant moves for the ASRS in the EG1 factory are (2,2), (2,0), and (0,2). This observation gave rise to a framework for analyzing the throughput of EG1's ASRS, which will be referred to as "The Crane Frontier" in the rest of this thesis.

2.6 The Crane Frontier

The Crane Frontier is a way to describe what the *maximum possible* throughput capability of the ASRS is based on the observation that the cranes are shared resources used to both input and output boxes from the ASRS. Given a certain number of input boxes achieved in an hour, one can deduce (from the timing studies described in the previous section) what the maximum possible outputs achievable are. This pairing of input and output rates will create a "frontier" of maximally possible outcomes.

The three dominant moves described in the previous section will give rise to three points along the Crane Frontier–one corresponding to all inputs (2,0), one corresponding to all outputs (0,2), and one corresponding to an equal matching of inputs and outputs (2,2). What follows is a derivation of these three maximal throughput rate points on the Crane Frontier. From Table 2 it can be seen that the (disguised) length of time it takes to complete one (2,2) cycle is 85.3 seconds. If (2,2) cycles are repeated for an entire hour, then the total throughput for that hour is:

$$\left(\frac{4\text{ boxes moved}}{1\text{ crane} * 1\text{ min } 25.3\text{ sec}}\right)(60\text{ min})(5\text{ cranes}) = 844\frac{\text{boxes moved}}{\text{hour}} \tag{1}$$

Remember that the 4 boxes moved in this equation consists of the 2 inputs and 2 outputs in a (2,2) move. Thus, 422 inputs and 422 outputs can be performed in an hour of repeated (2,2) cycles. Process engineers at the EG1 facility had an estimate close to the actual equivalent for this disguised number as the maximum possible throughput of the ASRS.

Similarly, one can calculate the hourly equivalent of the timing study data shown in Table 2 for the (2,0) and (0,2) moves. For the (2,0) move:

$$\left(\frac{2\text{ boxes moved}}{1\text{ crane} * 48.4\text{ sec}}\right)(60\text{ min})\left(\frac{60\text{ sec}}{1\text{ min}}\right)(5\text{ cranes}) = 744\frac{\text{boxes moved}}{\text{hour}} \tag{2}$$

For the (0,2) move:

$$\left(\frac{2\text{ boxes moved}}{1\text{ crane} * 52.8\text{ sec}}\right)(60\text{ min})\left(\frac{60\text{ sec}}{1\text{ min}}\right)(5\text{ cranes}) = 682\frac{\text{boxes moved}}{\text{hour}} \tag{3}$$

Thus, the total box throughput for the (2,0) and (0,2) moves are somewhat different. An hour of continuous (2,0) moves would result in 744 inputs and 0 outputs, while an hour of continuous (0,2) moves would result in 0 inputs and 682 outputs.

Figure 10 below shows these three points of theoretically possible crane behavior over an hour long period of time.

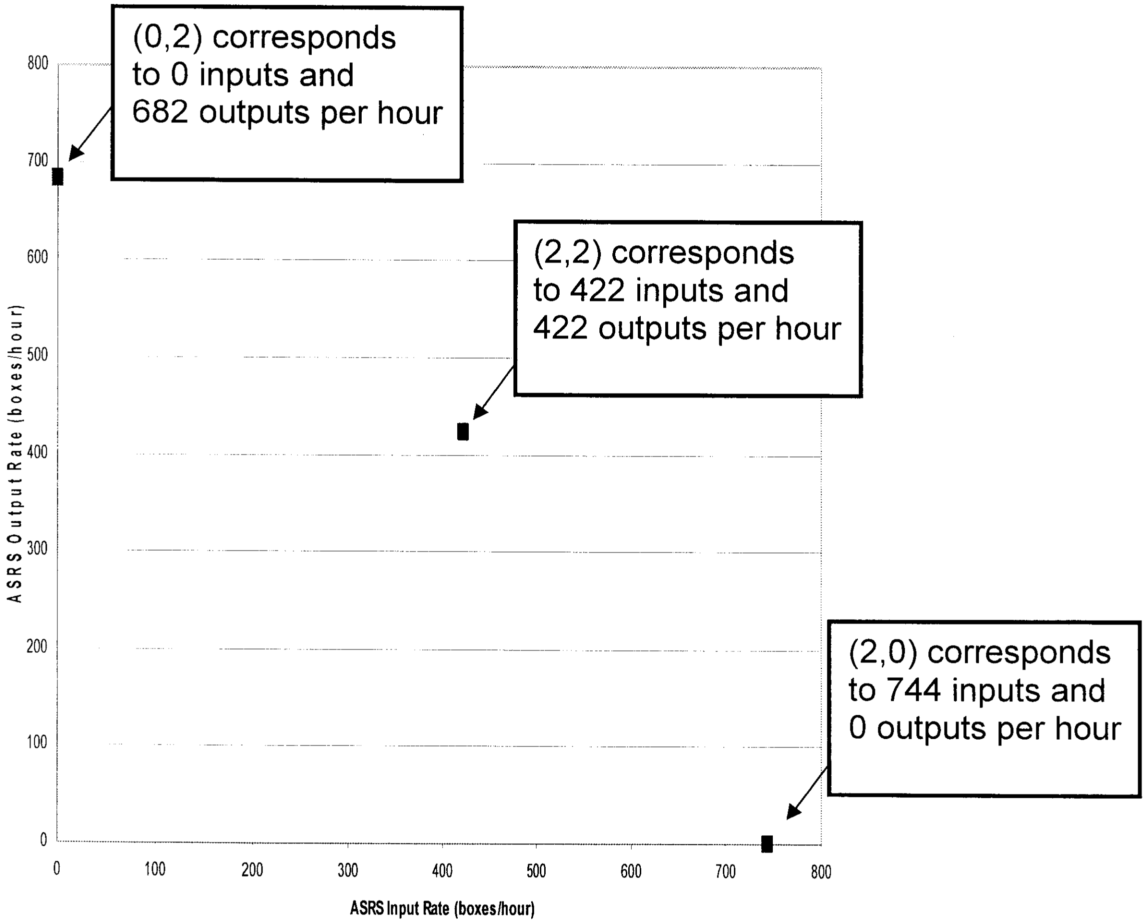

Figure 10: Three Feasible Vertex Points Corresponding to (2,2), (0,2), and (2,0) Moves

Of course, the EG1 factory operation (or any factory with a similar type of flow into an ASRS) is virtually always in an intermediate state between perfect balancing of ASRS input/outputs and either only input or only output. So, the question remains of how to create a continuous "curve" to connect the three feasible points shown in Figure 10 and thus to define a feasible region of possible hourly throughput for the ASRS.

To address this question, remember that a description of the *maximum possible* ASRS crane throughput is desired. Consider a frontier of points consisting of an input rate and an output rate, designated as a data pair (input rate = X_i, output rate = X_o) which are possible to achieve given the crane timing studies discussed above. First of all, it is known that this frontier must contain the points (0, 682), (422, 422) and (744, 0) since it has been demonstrated that they are possible (and maximal) with Equations 1, 2, and 3 above. Now let us address the intermediate regimes. Let us make the assumption that for the range where the input rate is less than 422 boxes per hour and greater than 0 boxes/hour, that the first portion of the hour is spent in "perfect interleave mode" continuously performing (2,2) moves (ignoring the complications introduced by fractional cycles, which were also ignored in Equations 1, 2, and 3 above). Then, when all of the input boxes required for the hour are "used up," so to speak, the crane finishes up the remaining outputs for the portion of the hour which is left. Under this assumption the following Crane Frontier line segment derivation applies.

<u>Crane Frontier valid for Range 0 < X_i < 422:</u>

Phase 1: $2X_i$ @ 844 boxes/hour

Phase 2: X_o-X_i @ 682 boxes/hour

But, it is also known that Phase 1 and Phase 2 can only take 1 hour to complete in total:

$$\left(\frac{2Xi}{844\,\frac{\text{boxes}}{\text{hour}}}\right)+\left(\frac{Xo-Xi}{682\,\frac{\text{boxes}}{\text{hour}}}\right)=1\,\text{hour} \qquad (4)$$

This is the equation of a line segment which has ends of (0, 682) and (422, 422). See Figure 11 for a graphical representation of this line segment.

Using exactly analogous logic it is possible to determine the Crane Frontier line segment corresponding to values of ASRS input greater than 422 boxes per hour.

<u>Crane Frontier valid for Range 422< X_i < 744:</u>

Phase 1: $2X_o$ @ 844 boxes/hour

Phase 2: X_i-X_o @ 744 boxes/hour

But, it known that Phase 1 and Phase 2 can only take 1 hour to complete in total:

$$\left(\frac{2Xo}{844\,\frac{\text{boxes}}{\text{hour}}}\right)+\left(\frac{Xi-Xo}{744\,\frac{\text{boxes}}{\text{hour}}}\right)=1\,\text{hour} \qquad (5)$$

This is the equation of a line segment which has ends of (422, 422) and (744, 0). See Figure 11 also for a visual representation of this. The "scatter plot" data shown in Figure 11 are actual data points (using the disguised time scale) of individual hours of factory operation at EG1. As expected, all of the EG1 actual ASRS throughput data points fall inside the feasible region defined by the Crane Frontier.

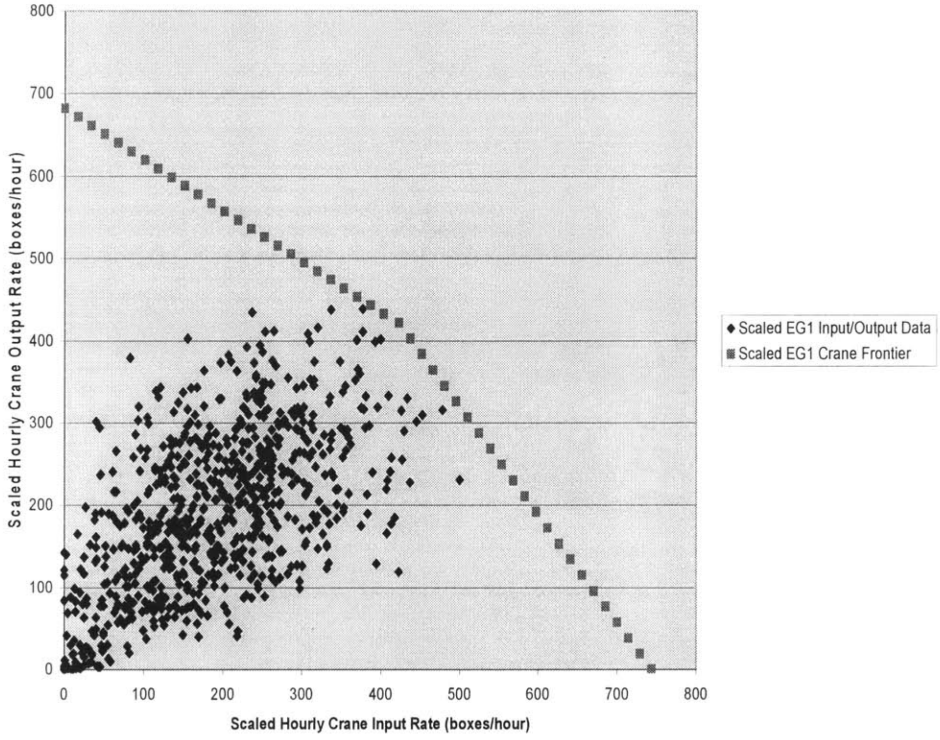

Figure 11: Scatter Plot of EG1 ASRS Hourly Crane Data with Crane Frontier

2.7 Chapter Summary

This chapter first gave an overview of the operations of ASRSs and the qualitative issues related to ASRS throughput and storage capacity. Next, EG1 data of ASRS hourly crane workload and ASRS crane timing studies were presented. Finally, the ASRS Crane

Frontier concept for analytically bounding ASRS throughput capabilities was derived. The Crane Frontier will be revisited several times again in the next chapter in the context of understanding possible ASRS throughput improvements both qualitatively and quantitatively.

Chapter 3: ASRS Improvement Recommendations and Implementation

3.1 Context of ASRS Throughput Improvement Decisions

Clearly managers must take a balanced scorecard approach to running manufacturing enterprises because there are a number of competing measures of success which all contribute to bottom-line success. Hopp and Spearman posit a list of the main competing manufacturing measures of performance as: Quality, FGI, WIP, Customer Service, Utilization, Throughput, Cycle Time, Capacity, Order Acceptance, Product Mix, and Product Releases.[16]

Much of Chapter 2 focused around analysis of the throughput of ASRSs. In the case of EG1, it is theoretically possible to optimize ASRS throughput completely. This would require modifying upstream and downstream processes to allow the operation of the ASRS at the vertex at the "bend" of the Crane Frontier (shown in Figure 11) 24 hours a day, 7 day a week. It is useful to know that this is the upper bound of what is possible given the current ASRS functioning, but this clearly does not globally optimize Dell's business because operating at that vertex necessitates the sub-optimization of other very important operating variables, conspicuously cost. Dell quantifies the cost effectiveness of its manufacturing operation (within the four walls of its factories) in terms of units per labor hour (ULH) and at the macro-scale of its operations (including manufacturing and inbound/outbound logistics) in terms of cost per box (CPB).

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[16] The author would agree with their list and append to it one or more measures of safety. From Hopp, Wallace J., and Mark L. Spearman. Factory Physics. New York: McGraw-Hill, 2000. 289-290.

Dell's central measure of "four walls" manufacturing cost, ULH, is still a very high level control variable. In the case of EG1, the following factory variables needed to be balanced against ASRS throughput when considering possible solutions:

- *Factory* throughput/output
- Mean and variability of order completion time
- Robustness of proposed solution to variety of manufacturing situations
- Synergy with newly created "control center" (a centralized information center at EG1 to enable more real-time and better coordinated manufacturing decisions)
- ASRS storage capacity
- Risk of having to send employees home early due to lack of work
- Product mix entering the ASRS
- Overtime of employees (and thus indirectly employee morale)
- Ease/clarity of manufacturing operations (including shift-to-shift transitions)

Happily, many (but not all) of these other operational variables tend to also be improved by the proposed ASRS throughput improvement projects described later in this chapter. It was critically important to have a clear view of the necessary tradeoffs in mind during the solution generation process. Initially, the brainstorming process was focused on generating ideas for increasing ASRS throughput without much consideration of the effect on other factory metrics. Later in the brainstorming process, these other factors were applied as filters to the ideas generated initially to arrive at a possible solution list.

As a result of the brainstorming sessions a number of possible improvements were generated which fit into three main categories:

- Improvements to the cranes' physical capabilities
- Operational changes which improve "use" of the region inside the Crane Frontier
- Process modifications which reduce the need for ASRS accumulation

The improvement ideas in each of these categories will be described in detail in the next three sections. In each section the pros and cons of the possible solutions will be explored for EG1 and for ASRSs in general. Finally, Section 3.6 will describe lessons learned during the implementation of some of these solutions in EG1.

The Crane Frontier concept (presented in Section 2.6) is useful for framing the three categories of improvements listed above. Generally, physical improvements to the ASRS hardware and software capabilities correspond to movements of the Crane Frontier outward (one exception to this is the software improvement termed "Intelligent Input Buffering" – see Section 3.2.3 for an explanation of this.) Operational improvements of sections of the factory other than the ASRS correspond to movements of more points (and thus the average of the points) closer to the Crane Frontier, thus increasing the overall ASRS throughput rate. These two effects are shown graphically in Figure 12 below. The third category of improvements, the reduction of systems which need to go to the ASRS, simply reduces the need for ASRS capacity, thus alleviating it as a bottleneck.

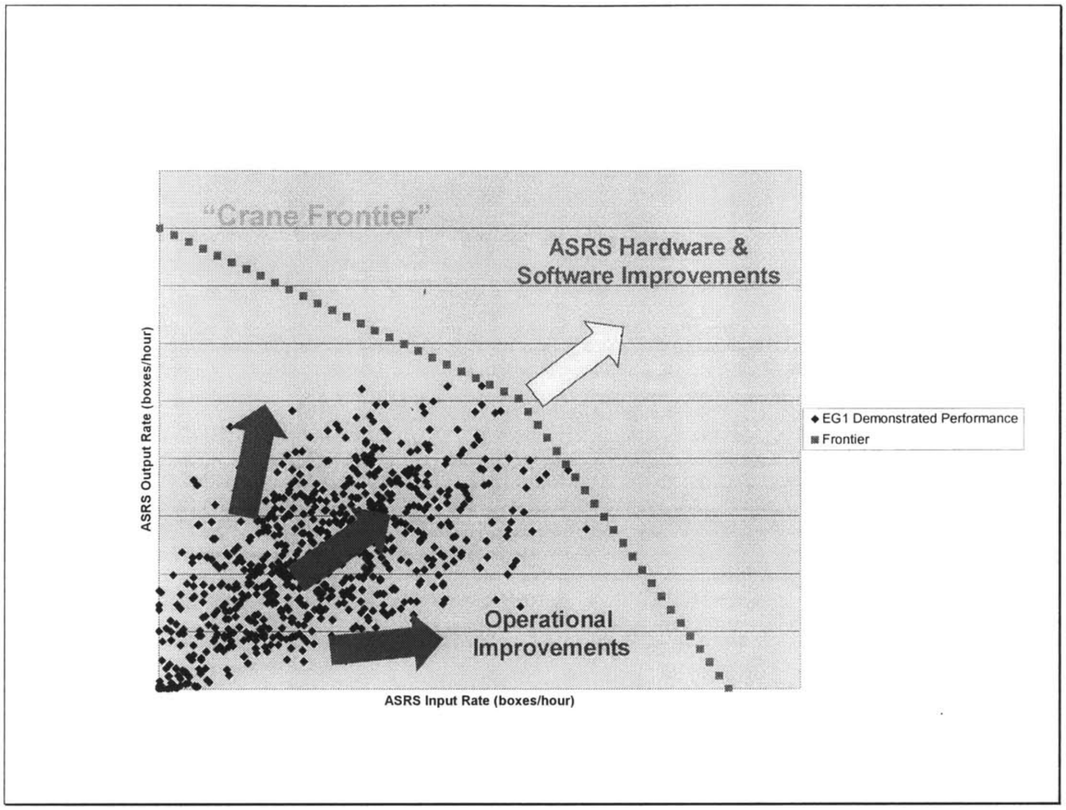


Figure 12: Graphical Representation of Categories of ASRS Throughput Improvements

3.2 Solution Category 1: Improvements to the Cranes' Physical Capabilities

Included in this category are improvements to both crane hardware and crane software which can be made without significant modification of upstream or downstream factory operations. The best improvement ideas generated and developed in this sphere were:

- Dual Box Placement
- Bin Optimization
- Intelligent Input Buffering
- Expansion of the Existing ASRS (no improvement in operating mechanism)

3.2.1 Dual Box Placement

Apart from reducing crane distance (and thus crane travel time), another way to reduce the crane cycle time at the most basic level is to reduce the number and duration of stops that the crane has to make in order to store and retrieve a certain number of boxes. As discussed in Section 2.5, in EG1 the crane stops (including the deceleration and acceleration phases) consisted of a significant fraction of the total crane cycle time for (2,2) moves (a.k.a. QC cycles) as defined in Chapter 2. Given this observation, significant benefits would accrue from reducing the amount of "stop time" within a QC cycle. One possibility for this type of reduction is to decrease the acceleration and deceleration times associated with each crane stop. However, there are clearly mechanical limits on the ability to do this.

Another possibility is to reduce the number of stops required of the crane. If the movable crane body could transport only one box at a time, this would be impossible. However, the fact that the movable crane body can transport two boxes at once (and that it generally only places one box at a time) gives rise to the possibility of "dual box placement." The most straightforward application of this concept would be "dual box storage"—the idea of storing two incoming boxes in adjacent empty bays of the storage rack concurrently. This would save time by eliminating one of the crane stops and by reducing the amount of crane travel time in (2,2) and (2,0) crane moves. Also, this line of thinking also raises the theoretical possibility of *retrieving* two adjacent boxes using the crane at the same time – i.e., a "dual box retrieve." Depending of the factory in question, the dual box retrieve can be much more complicated to implement than a dual box store because it requires a mechanism for ensuring that the two neighboring boxes belong to the same order (and thus would need to be retrieved at the same time). In EG1, the physical hardware of the crane was already set up to allow dual box placement without any modification. In fact, on the rare occasion that the best "storage move" (based on considering each of the two boxes independently) was to store the two boxes in adjacent locations, the crane did indeed perform the dual box storage. So, the only changes required to implement dual box storage were software changes that created and used adjacent empty bay locations.

The Crane Frontier can not give a precise answer to how much throughput benefit is derived from dual box placement but it can at least frame the question. Because the Crane Frontier is the maximum possible performance attainable from the ASRS, it does not take into account the inefficiencies introduced into actual ASRS operation by input and output process variability. The only way to rigorously address performance enhancement due to dual box placement is simulation modeling.

Figure 13 below shows a qualitative example (from EG1) of how one can estimate and visualize the improvement of dual box storage. In this example, only dual box storage (not dual box retrieval) is assumed. Best case and a worst case Crane Frontiers after the implementation of dual box storage were estimated by making educated guesses about how the length of (2,2), (2,0), and (0,2) cycles would change with the implementation of dual box storage (recall that the three vertices of the original Crane Frontier were derived in Section 2.6 solely based on the results of the timing studies of the cranes.)

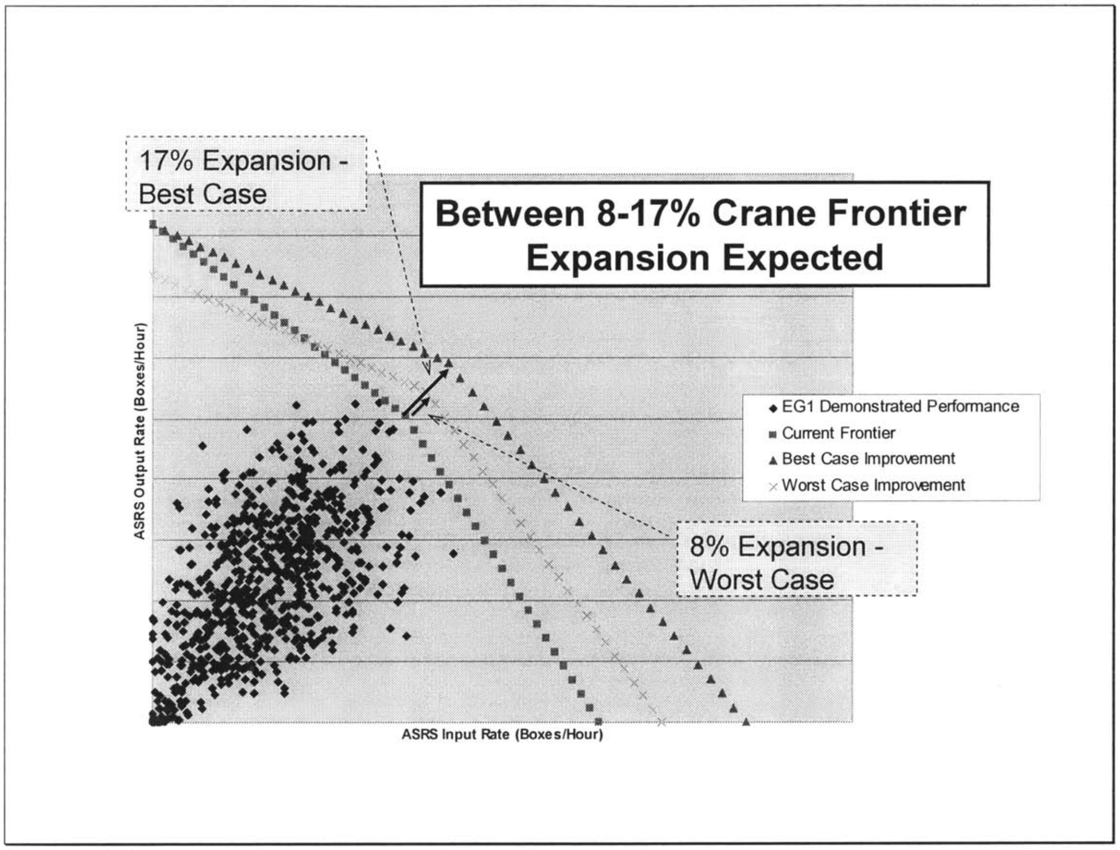


Figure 13: Estimate of Crane Frontier Expansion due to Dual Box Storage in EG1

The best case and worst case scenarios were derived by making different assumptions about how the increased bin porosity resulting from dual box storage would affect the Crane Frontier. The average porosity of the storage racks will increase because dual box placement requires that the crane travel to pairs of adjacent empty bins which are significantly rarer than single empty bin locations. Thus the crane will have to, on average, travel "deeper" into the storage racks to successfully complete dual box stores. The net result will be a more porous storage rack. For a given number of stored boxes, a more porous storage rack means that the average box is further away from the Input/Output side of the ASRS.

The assumption underlying the best case scenario was that there would be a negligible increase in crane travel time due to this increased storage rack porosity. Thus, the best case scenario assumed that the crane cycle times (analogous to the disguised numbers shown in Table 2) would be reduced by the average duration of the traverse from one storage location to the next storage location; this reduction in travel time consists almost entirely of the "stop time." Using the disguised time scale presented in Table 2's data, this reduction was estimated to be 12 seconds for each (2,0) move and for each (2,2) move (i.e., for each cycle which would "take advantage" of dual box storage.) Thus, we assumed that the mean (2,0) cycle time decreases from 48.4 seconds (Current Frontier) to 36.4 seconds (best case Crane Frontier). Similarly, we assume the mean (2,2) cycle time decreases from 85.3 to 73.3 seconds. The (0,2) cycle time was unaffected because such moves do not benefit from dual box *storage*. We applied these assumptions to replicate the analysis of Section 2.6 to produce the best case Crane Frontier.

We modified these assumptions about the effect of storage rack porosity on crane cycle times to derive the worst case Crane Frontier. Specifically, we observed that most of the crane traverses ranged from 12 seconds to 15 seconds and that the longest crane traverse (from a location farthest away from the I/O of the ASRS crane) lasted about 20 seconds long. Thus, a very short crane traverse time (including stop) was about 12 seconds. Certainly, it is clear that increased storage rack porosity will not transmute every short crane traverse (12 seconds) into a long traverse (20 seconds). Thus we made a rough assumption that the increase in storage rack porosity would increase the crane cycle time of each of the (0,2), (2,0) and (2,2) cycles by at most 6 seconds (2 x [15 seconds-12 seconds]). Thus, we assume for (2,0) and (2,2) cycles that half of the dual box placement benefit (a 12 second reduction) would be negated by the porosity effect (a 6 second increase). For (0,2) cycles there is no benefit of dual box storage, but these cycles are still subject to the (6 second) penalty due to increased storage rack porosity. Combining these very conservative assumptions with data from Table 2, one estimates that the (2,0) cycle time should decrease by 6 seconds from 48.4 seconds (Current Frontier) to 42.4 seconds (worst case Crane Frontier.) Similarly, the (2,2) cycle time should decrease from 85.3 seconds to 79.3 seconds, and the (0,2) cycle time should increase from 52.8 seconds to 58.8 seconds. We used these assumptions to replicate the analysis of Section 2.6 to produce the worst case Crane Frontier. Note that due to this "storage rack porosity penalty," the worst case Crane Frontier crosses over the Current Frontier at high output rates in Figure 13.

In practice, this porosity effect is only of high significance to EG1's actual throughput by virtue of its effect on the Crane Frontier near the (2,2) vertex since the distribution of actual EG1 hourly performance is much closer to this vertex than to the (0,2) vertex (see Figure 13.) Thus, under the assumptions just outlined, the (2,2) Crane Frontier vertex was estimated to expand outward between 8% (worst case scenario) and 17% (best case scenario). The percentage improvement range just derived only directly applies to the Crane Frontier itself. In the absence of good simulation modeling or actual testing of dual box storage, an estimate of how this will impact overall EG1 ASRS throughput can be found using the linear assumption, i.e., by assuming that actual EG1 ASRS throughput would increase from between 8% and 17%. Conceptually, this means that the rest of EG1's operations will "extend" to fill in the additional feasible region created by the expanded Crane Frontier. Accurate simulation modeling paired with experienced operations manager review will give more accurate estimates of the throughput improvements possible through dual box placement.

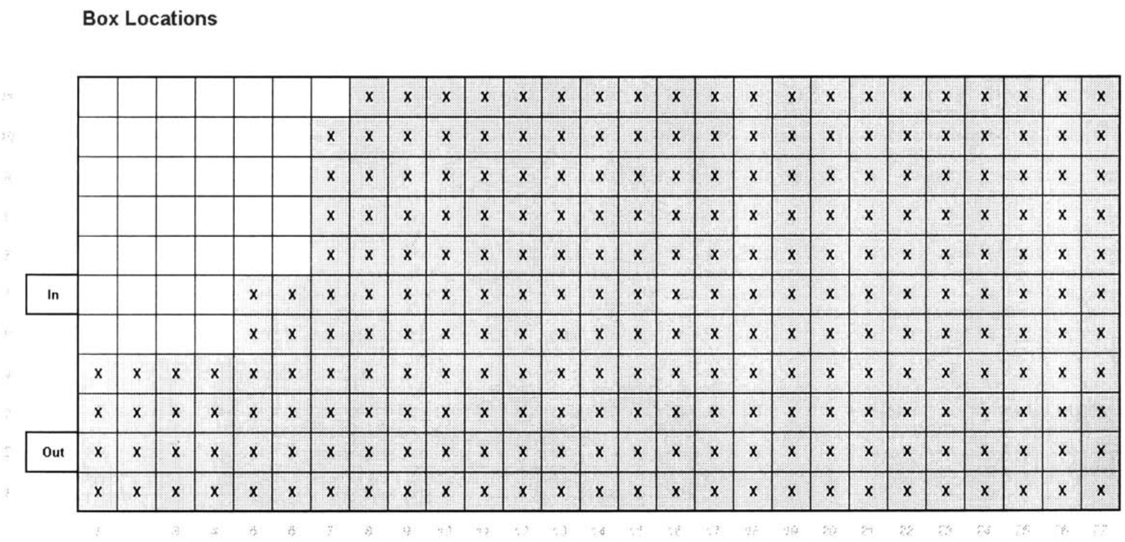
This discussion of the detrimental effect of storage rack porosity gives rise to the question of whether anything can be done to counteract it. This question is addressed in the next section which raises another ASRS throughput improvement possibility call "Bin Optimization."

3.2.2 Bin Optimization

Figure 4 shows half of an ASRS storage rack (consisting of numerous storage bin locations) with a "swiss cheese" appearance due to the vagaries of when boxes from particular orders are stored and retrieved. In the last section, dual box placement's increase of ASRS throughput was discussed. However, the countervailing worsening of the "swiss cheese" effect (termed the storage rack porosity effect in the last section) was also raised.

Recall also that there are many times during the day when the ASRS cranes are not being utilized (Figure 8). This suggests that there might be some benefit to be gleaned from reducing the porosity effect by consolidating stored boxes into larger contiguous sections of stored boxes within the ASRS storage racks in a manner analogous to the hard-disk de-fragmentation process which occurs in personal computers.[17] Obviously, the larger crane traverse time is as a fraction of total crane cycle time, the larger the potential time savings possible from this type of consolidation.

In the case of de-fragmentation of a hard drive, data which tends to be accessed together is stored together. This minimizes the time spent moving hard-drive heads from one track of data to another during typical PC operation (thus speeding up the computer's operation). In the case of ASRS consolidation, the traverse time of the cranes is minimized by reducing how far the cranes have to travel (on average) to store and retrieve boxes. An example of what a consolidated half of an ASRS storage rack would look like is shown in Figure 14.



[Diagram courtesy of Michael Hoag, Dell Corporation]

Figure 14: Diagram of a Consolidated ASRS Storage Rack

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[17] The author was exposed to this insight through discussions with Michael Hoag of Dell Corporation in the fall of 2004.

In EG1 where the ASRS input and ASRS output locations are close to one another the benefit of this bin consolidation is a bit muted. That is because keeping boxes away from the bins near the ASRS input location will also necessitate (to an extent directly related to how close the input and output locations are to one another) keeping boxes away from the ASRS output location. However, as you can see from Figure 14, the likely optimal result will have at least a pocket of empty locations right next to the input to allow inputs to be quickly stored. Apart from that input pocket, the rest of the boxes will be stored as close to the output as possible. However, there is an over-riding incentive to have the input and output locations close to one another because it reduces the average total distance of travel required for the storage and retrieval of a given box. (This can be seen most easily if one thinks about the scenario where the ASRS storage rack is not very full. In this case, the box can be placed in a location very close to the input and output, leading to a very small total travel distance for that box.)

There are many variables which would need to go into the creation of an optimal bin consolidation strategy. In addition to the distance trade-offs discussed above, a full optimization scheme would also need to incorporate quantitative information about when the cranes have "excess time" to accommodate rearrangement of the boxes within the storage racks. Depending on the particulars of the manufacturing situation, bin consolidation could occur continuously throughout the day (whenever it is determined that the crane is or will be idle) or at specified times of the day which are known to have low crane utilization. Clearly, simulation modeling would a very useful tool in performing this optimization analysis.

Several important mechanical considerations must be taken into account when devising a bin consolidation strategy also. One possible drawback to this solution is "placement error build-up" from the mechanical placement of boxes multiple times within the storage bins. The significance of this drawback depends on the "calibration" procedures the ASRS in question uses (i.e., if the system calibrates during each one of the box placements, the errors would not "build up"). Another potentially important drawback of bin consolidation is increased mechanical wear and tear on the ASRS cranes. If one were concerned with optimizing an ASRS because it is a bottleneck, increased planned and unplanned downtime due to increase wear and tear are counterproductive. The magnitude of this effect is difficult to quantify though since the wear mechanisms generally are not fully understood. Under the proposed solution, the number of crane stops will increase, but the effect on the total crane distance traveled is unclear. Also, the average amount of idle time between crane movements will go down. The total effect on downtime will depend on the particular nature of the wear mechanisms involved.

It is important to note also that there are significant opportunities for positive synergies between bin optimization and the dual box placement solution concept which was introduced in the last section. For instance, if bin consolidation is implemented, more "side-by-side two bin voids" which can be used for dual box storage will exist, and they will be closer to the ASRS input location.

3.2.3 Intelligent ASRS Input Buffering

The improvement options discussed in the previous two sections focused on wringing time out of the ASRS crane travel cycle, thus pushing the crane frontier further outward (illustrated in Figure 12). Intelligent Input Buffering focuses on improving the process for getting boxes efficiently to the ASRS cranes prior to being picked up by the cranes. In any ASRS with multiple cranes there must be some process for assigning boxes to a given crane and for diverting boxes from the incoming conveyance to the appropriate crane. Depending on the factory layout and operation, this ASRS input process can sometimes become the bottleneck – not the ASRS crane throughput itself. If this is the case, there are various methods to buffer against incoming box variability. The solutions to this problem will be highly specific to the manufacturing environment in question. The specifics of EG1's ASRS input process will not be discussed in detail here, but it is interesting to note that this input buffering process was sometimes the factory bottleneck. A software solution to reduce the impact of the ASRS "pre-input" process on the overall ASRS throughput was successfully implemented. This sort of solution does not technically move the crane frontier outward—it technically, moves the "center of mass" of points of ASRS operations closer to the Crane Frontier (see Figure 12) because it reduces the fraction of time when the input buffering process limits the cranes' ability to receive boxes.

3.2.4 Expansion of the Existing ASRS

This improvement option consists of simply increasing the number of cranes (and associated storage racks) of the ASRS without necessarily changing any of the underlying

ASRS operating processes. The ASRS expansion solution idea generally allows for the easiest estimation of throughput improvement because one is simply scaling up the existing ASRS, for which throughput data and operating experience already exist.

Of course, in deciding between various bottleneck improvement options (or a combination of options) one should perform Net Present Value (NPV) analyses to decide on the future course of action. Usually (as in the EG1 case), this "simple" expansion of the ASRS is the financial basis of comparison for more creative improvement options. Sometimes, however, "simple" expansion requires considerable real estate in the factory and has some undesirable secondary consequences. The secondary consequences must be accounted for in the NPV and any other analyses when deciding how to proceed.

3.3 Solution Category 2: Operational Changes which Improve "Use" of the Region Inside the Crane Frontier

Now that physical improvements to the ASRS cranes and ASRS input conveyances have been examined, this section will raise the next large category of improvement ideas–operational improvements which improve the use of the feasible region within the Crane Frontier. The three examples of this type of improvement discussed here are:

- Split-Shift Team
- Almost-Ready-To-Ship WIP Staging
- Pulling WIP Differently from Upstream Operations

3.3.1 Split-Shift Team

Figures 7 and 8 shows us that there is high variability of ASRS usage across the day. Specifically, there are dominant peaks and valleys of usage that correspond to the working schedules of the factory employees. The biggest valleys correspond to shift changes, lunch breaks, and other worker breaks. Utilization drops during these events because too few upstream box inputs continue feeding the ASRS and too few ASRS output requests are generated. One well-explored way of improving throughput in such time periods is to modify the employee schedules or add supplemental employee schedules to fully utilize the bottleneck operations. In the case of EG1, one operational improvement which was considered was the addition of a supplemental set of employees who worked a shift from 10 am to 9 pm each weekday (see cross-hatched time segment in Figure 15). Notice that this so-called "split-shift" (since it overlaps both the standard day shift hours and the standard night shift hours), covers three of the largest dips (i.e., valleys) in the hourly ASRS input and output rates throughout the day (from 11 am - 1 pm, 3pm – 5 pm, and 7 pm – 9 pm).

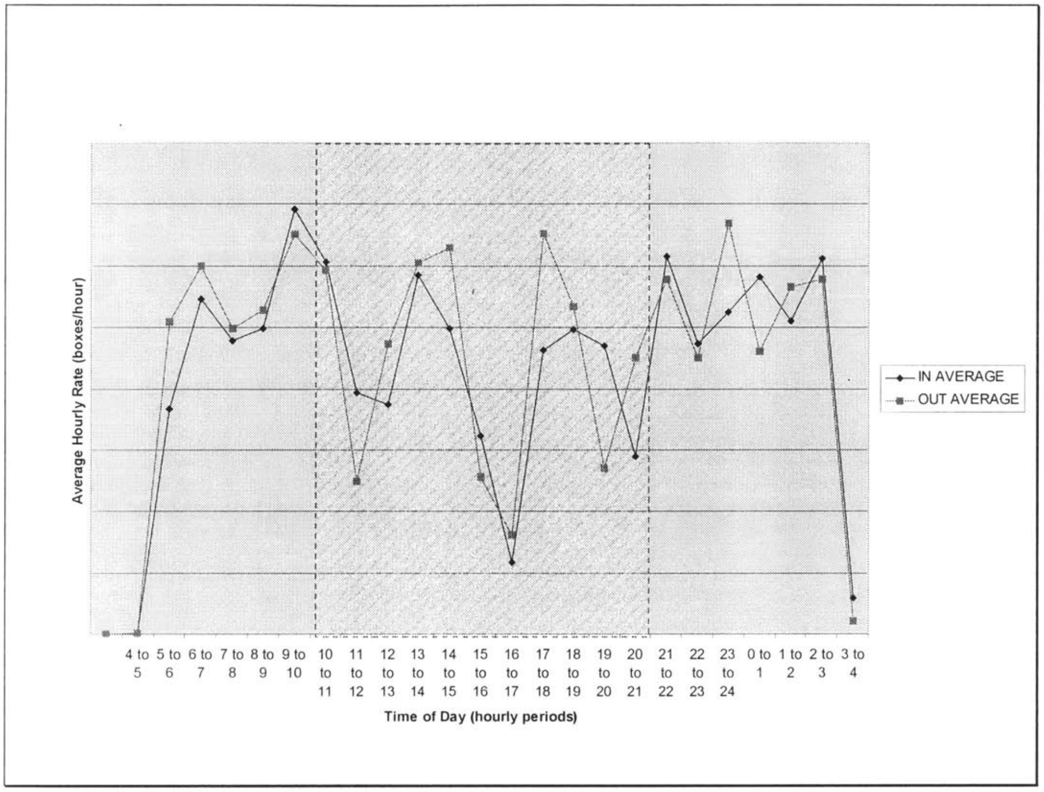

Figure 15: How Split-Shift Hours Overlap Valleys in ASRS Utilization

In EG1, the operational strategy to be employed during split-shift was to focus on increasing the number of ASRS *outputs* produced during the ASRS utilization valleys. This would free up more ASRS crane time to perform inputs during historically busy input times of the day (the so-called “peaks” such as 9 am – 10 am and 9 pm – 10 pm). This output-focused approach to split-shift is economically attractive because less additional employees are required to staff the factory areas needed to accommodate outputs (compared to inputs). The reason this is true is that the split-shift can focus on completing and shipping large orders (for example, orders of 50 PCs) which requires less labor hours than producing 50 boxed PCs to be input to the ASRS.

One way to visualize this output-focused approach is using the Crane Frontier concept. Figure 16 below illustrates this strategy of focusing predominantly on outputs during the historical "valleys" and focusing more on inputs during the historical "peaks." Said another way, if EG1 gets its outputs out of the way when the ASRS is typically quite idle (i.e., the valleys), the factory will be able to perform more inputs during the time frames when it is historically ASRS throughput-limited (i.e., the peaks). This can all be done with relatively little additional labor cost.

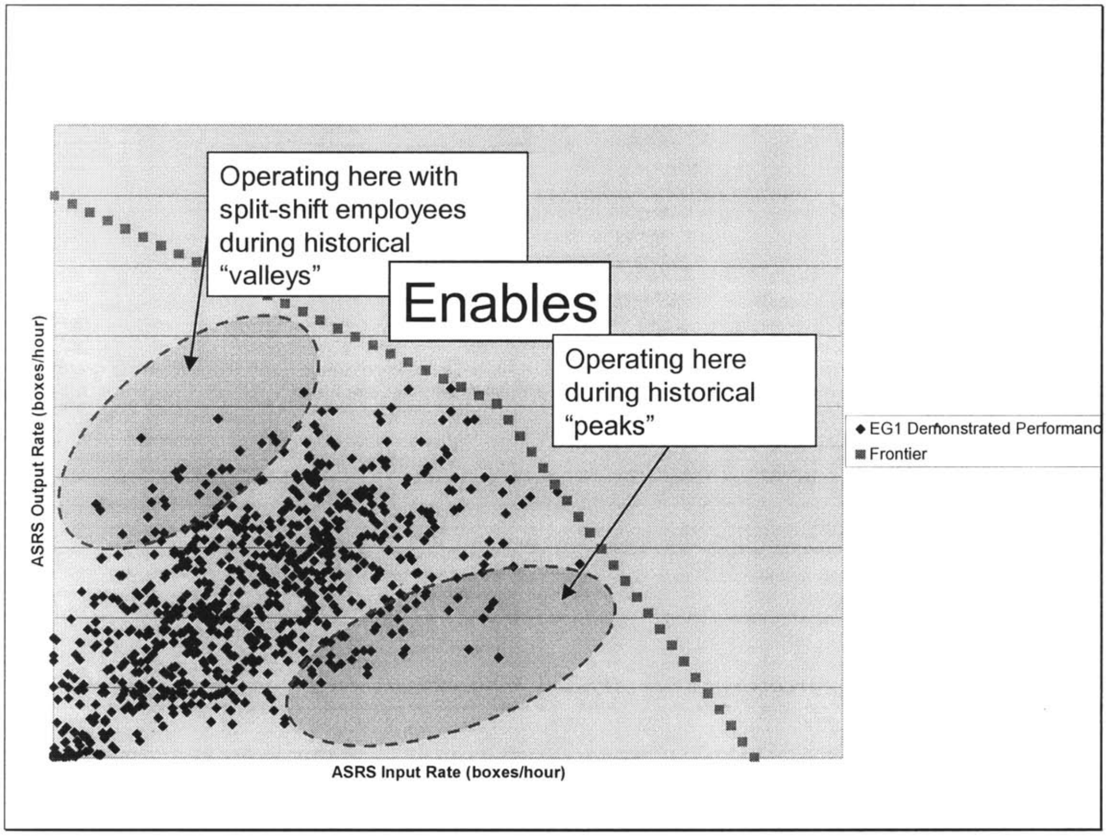

Figure 16: Illustration of Split-Shift's Output-Focused Strategy

3.3.2 Almost Ready-To-Ship WIP Staging

Instead of staffing the valleys of ASRS crane utilization to take advantage of unused throughput capacity, one can also use the valleys of utilization to populate extra storage areas outside the ASRS with boxes from orders which are almost ready-to-ship. To make this scheme work, one needs additional hardware and software to accurately control the release of boxes which are ready to be shipped. For example, consider an order of 20 PCs, of which 19 have already been successfully built and boxed. Suppose in times of low crane utilization one could retrieve these 19 boxes from the ASRS and stage them elsewhere (e.g., on a conveyor or another type of storage area external to the ASRS.) This would eliminate the need for the ASRS to output 19 boxes from the ASRS once the 20th box arrived (which under current operation could very well occur during a period of already high crane utilization). As the ASRS does now, this external storage system would need to recognize when the 20th box had completed processing and be able to release the other 19 staged PCs to the shipping area.

One also needs to intelligently size and design the additional storage area and choose appropriate criteria for what constitutes "almost ready-to-ship" partial orders. The additional storage area could be essentially a conveyor with a modest set of controls which means that it could be significantly less expensive to create than the option of simply expanding the ASRS (section 3.2.4).

3.3.3 Pulling WIP Differently from Operations Upstream of the ASRS

Very often peaks and valleys of bottleneck throughput are a direct result of high incoming variability. If that incoming variability can be reduced, then the demand that the bottleneck sees will be more "level-loaded" across the day. To effect this incoming variability reduction, one first needs to identify the "buffer" where WIP builds up prior to the ASRS (or any operation which is the bottleneck for that matter). In EG1 the most significant buffer prior to the ASRS is the burn area (see Figure 1). To the extent possible, one needs to pull WIP from this buffer in order to level-load the ASRS input. Clearly, level-loading is easier to do in some situations than others for both technical and cultural reasons. Often, a change in the measurement and incentives system for the operations upstream of the ASRS is needed to facilitate effective level-loading. Despite these challenges, an effective implementation of level-loading can have high payoffs in terms of overall throughput increases.

3.4 Solution Category 3: Improvements Which Reduce the Need for ASRS Accumulation

As the ASRS currently operates at EG1, the final PC of an order generally bypasses the ASRS and proceeds directly to the shipping area. This event acts as the trigger for the ASRS to release all of the other boxed PCs in that order which are stored in the ASRS. Currently, based on the timing of the triggers, almost all orders have one (and only one) PC which is allowed to bypass the ASRS.

The ASRS throughput improvement options discussed in Sections 3.2 and 3.3, for the most part, have assumed that boxes currently destined for the ASRS had no alternative other than being stored there for some amount of time. What if we challenged that assumption? One fundamental reason it is tough to relax this assumption is that limited box storage space exists on the factory floor. After all, ASRS stands for Automated *Storage* and Retrieval System. If significant storage space existed, it would be possible to be very aggressive about storing boxes pre or post the ASRS in order to optimize ASRS throughput. However, given that storage space is at a premium, perhaps it is possible to reduce the fraction of boxes which are required to enter the ASRS at all. Each box which is not placed in the ASRS will eliminate one crane storage action and one crane retrieval action.

A variant of the "Almost Ready-To-Ship WIP Staging" option discussed in Section 3.3.2 could achieve this partially. Some boxes could be preemptively diverted to the new WIP staging area (before the box even entered the ASRS). However, the new WIP staging area will likely be most effective for large orders, and thus the ability to do this is probably limited because large orders reside for long times in the WIP staging area (see Figure 17). Even so, this germ of an idea provides a few clues about finding a viable solution. Another direct way to allow boxes to bypass the ASRS is to send the most ideal "bypass candidates" into a recirculation loop where they can wait for the remainder of their order to become complete.

This raises the question of how one picks which boxes are the most attractive bypass candidates. Day-to-day floor manufacturing experience at EG1 suggested that order size is one of the most important determining factors for desirability. Two factory variables related to order size are especially pertinent:

- Order size profile of the factory (including any relevant seasonal variability)
- Dwell time as a function of order size

For EG1, samples of data for these two variables are shown in Figures 17 and 18 below.

Figure 17 shows (y-axis scale hidden for confidentiality) EG1's order size profile. In that figure, "system quantity" indicates the number of PCs of a given order size processed through EG1 within a one week period of operation. Notice the very steep drop off of PC frequency with order size. This suggests that from a purely volume standpoint (i.e., how many systems are available to bypass the ASRS) smaller orders may be a more desirable pool to choose from to find "bypass candidates."

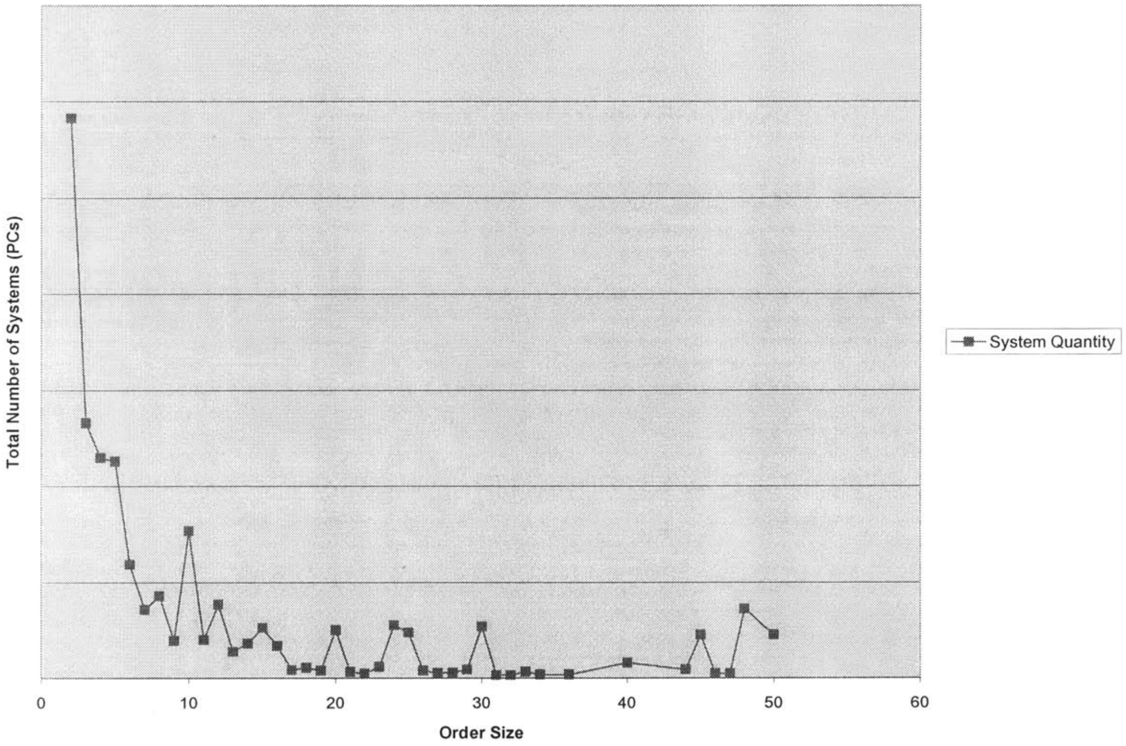

Figure 17: EG1 System Quantities as a Function of Order Size

Figure 18 below shows (y-axis scale hidden) EG1's dwell time mean and standard deviation. The dwell time is defined as the time between the first PC of an order being stored in the ASRS and the last system completing, thus causing the stored PCs to enter the output queue for the ASRS. The graph only displays the dwell times up to order sizes of 15, since the small sample sizes for orders larger than 15 give high uncertainty to values of the summary statistics and makes them quite noisy. However, in this data there is a clear trend that the larger the order size, the larger the dwell time. From the ASRS throughput perspective (taken throughout most of this thesis), this data also suggests the desirability of bypassing small orders because more time and space will be needed to deal with bypassed systems from larger order sizes (than small order sizes) before they are released to shipping.

However, if one is operating an ASRS in a regime where it is limited by ASRS *storage capacity* instead of by ASRS throughput, then one would interpret the trend in Figure 18 as supportive of the attractiveness of bypassing PCs from large order sizes.

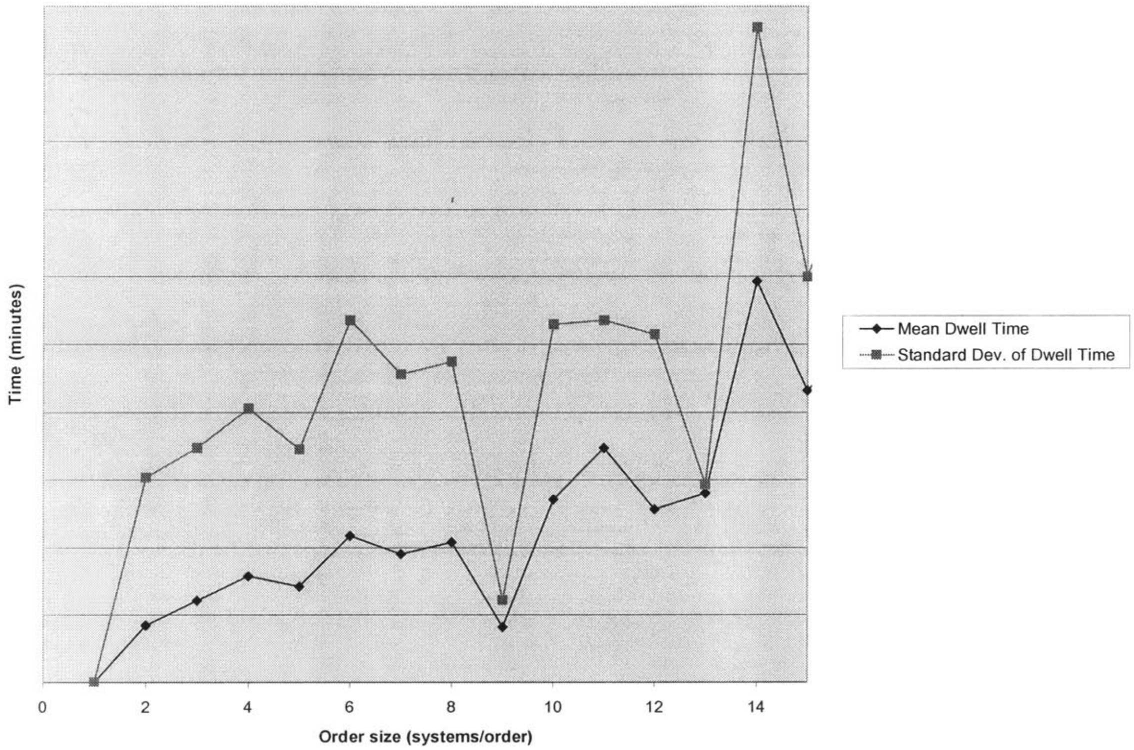

Figure 18: Trends of the ASRS Dwell Time Versus Order Size

Based on the high number of PCs in orders sizes of 2 through 5 (Figure 17) and smaller dwell times (Figure 18) for these order sizes, boxes in this order size range were considered attractive for bypassing ASRS storage in EG1.

In EG1, a small recirculation loop was piloted which allowed boxes from orders of size 2 and 3 to recirculate on a new conveyance loop until their straggling "brother and sister" boxes arrive and "released" the recirculating boxes directly to shipping.

Using this process, one has reduced the demand placed on the ASRS. Clearly, the practitioner should collect and use data similar to Figures 17 and 18 to help choose attractive bypass candidates and to appropriately size a recirculation loop.

3.5 Other Solution Ideas

The solution ideas presented in this chapter so far are not an exhaustive set of ways to improve ASRS throughput, but they do represent several of the major categories of ASRS throughput improvements. The ideas described so far were the ideas that were either implemented at or discussed seriously at Dell's EG1 manufacturing facility over the period from July 2004 to December 2004. During the brainstorming process a number of other solution ideas were raised. A list of these ideas is given here since it may spark useful concepts for ASRS throughput improvement efforts in other manufacturing contexts:

- Build further intelligence into the ASRS and greater connectivity to other factory data
    - Enables further crane optimization by allowing quick throughput orders to be close to the ASRS output[18]
    - Enables selective output of systems based on overall factory priorities instead of a blanket policy such as a first-in-first-out (FIFO) queue for box outputs

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[18] The author was introduced to this idea through e-mail exchanges with Professor Stephen Graves of MIT during the fall of 2004.

- Manual accumulation on empty floor space of the factory or offsite
    - An ASRS is an *Automated* Storage and Retrieval System. However, if the ASRS is the bottleneck, manual accumulation can still be a productive *short-term* solution.
- Implementation of Kanban limits on processes before the ASRS to reduce the incoming variability
- Implementation of other ways of getting boxes out of the ASRS (beside the cranes)
    - A gravity-driven output system can be build against outwardly-facing ASRS storage racks (boxes would "drain" out the side of the ASRS in a gravity-fed manner when the ASRS was given the appropriate signal).

3.6 EG1 Implementation Lessons

The focus of this chapter so far has been primarily on examining the various solution options for increasing ASRS throughout. This general approach has been maintained in order to make the solution discussion of most use to the practitioner trying to apply these concepts in his or her own factory. In this section, the lessons learned from solution implementation in the Dell EG1 case study will be explored. General cultural observations about Dell and EG1 will be discussed in Chapter 4.

In Sections 3.2, 3.3, and 3.4 eight solution ideas were explored in three general solution categories. Of these eight solution ideas, one was fully implemented, one was piloted, and one was being actively planned at the end of the author's internship in EG1. The remaining ideas (many of them longer-term, capital-intensive modifications of the factory) were integrated into the normal annual capital improvement planning and budgeting process for EG1. To the extent possible, this "mainstreaming" of ASRS improvement ideas should be encouraged because it creates greater visibility for the ideas and leverages the broader organization to make the implementation happen more quickly and more effectively.

The solution idea which was fully implemented was Intelligent Input Buffering (Section 3.2.3). The solution idea which was piloted was the recirculation loop (Section 3.4). The solution which was being actively planned was the split-shift team (Section 3.3.2). These three implementation efforts will be discussed briefly, not with the intention of providing exhaustive detail but with the intention of providing some more context about practical challenges to the implementation of these solution ideas.

3.6.1 Lessons from Implementation of Intelligent Input Buffering

One of the key issues related to the implementation of Intelligent Input Buffering was that the technical expertise for the ASRS and the related ASRS input hardware/software resided primarily with Dell EG1's ASRS vendor. There are plusses and minuses associated with this arrangement. On the positive side, the vendors are experts at this kind of systems and have a very large installed base of them across many industries. This was especially important because the Intelligent Input Buffering change required a seamless interface between the vendor IT systems pertaining to the ASRS and other EG1 factory IT systems. Even given this expertise, the implementation didn't work correctly the first time (which is more the rule than the exception with hardware/software installations of any complexity.) This first misstep reminds one that it is very important to choose when and how to implement in order to mitigate risk associated with ASRS hardware and software changes.

On the negative side of having this expertise reside primarily external to Dell, the ASRS had recently become the bottleneck for EG1. Thus, Dell was put in a position where something which was mission-critical for their factory throughput was not directly controlled by Dell. EG1 should at least consciously re-evaluate whether it is comfortable with the overall level of technical expertise which exists for their ASRS hardware and software systems and whether it is comfortable with the balance of that expertise internal and external to Dell.

3.6.2 Lessons from Piloting of the Recirculation Loop

Piloting is a strongly encouraged activity at Dell (more will be said about Dell's openness to change in Chapter 4). Specifically, piloting is very useful because it allows one to show proof of concept for an idea while at the same time allowing one to gather better data about the benefits and risks associated with the idea being testing. Because manufacturing accumulation systems/ASRSs can be particularly complex and capital intensive, these benefits of piloting improvement ideas are often critical to the ultimate implementation of the solution ideas. In broad outline, the attractive "bypass candidates" can be approximately determined from the factory order size data (as described in Section

3.4), but significant fine tuning is often done during the piloting stage (as was done in EG1).

3.6.3 Lessons from the Planning of the Split-Shift Team

Of the three solution ideas being discussed in this section, the split-shift team required, by a considerable margin, the most disruption of manufacturing employees' jobs. For this reason, it required the most gathering of inputs on its design, "over-communication" of the project plan, and gradual introduction.

Dell is a company which experiences significant increases in end-of-quarter demand (the so-called "hockey stick" demand effect). One practical lesson learned, was that it is usually very difficult to implement any changes during the high demand periods in such a company. The reason is simple enough; people are too busy, and they are naturally resistant to the introduction of new, untested operations during such busy times. This is as it should be, but the corollary is that one needs to push to make *sure* the new ideas are tested and debugged during the low-demand periods. Even though the benefit of many of the ASRS improvement ideas outlined in this chapter is greatest during high-demand periods, the only practical way to make the improvement ideas happen is often by getting them ready before the high-demand period comes.

3.7 Summary of ASRS Improvement Recommendations and Implementation

A practitioner should use the solution ideas presented in this chapter as only a jumping off point for application to a new situation. There are many specifics of ASRS design/operation and of how the ASRS fits into the overall factory which must be taken into account when deciding on appropriate ASRS throughput improvement strategies. That being said, there is some evidence supporting the broad applicability of the ASRS throughput improvement ideas presented in this EG1 case study. Representatives from other Dell manufacturing and distribution facilities, often with vastly different factory layouts, product mixes, levels of automation, and ASRS use-models were keenly interested in the solution ideas presented in this chapter. They discussed and seriously considered implementing some the ideas in their own factories.

Chapter 4: Cultural Observations and Lessons Learned

4.1 How Dell Embraces Speed

Now that the ASRS throughput analysis (Chapter 2) and the ASRS throughput improvement (Chapter 3) have been explored, this chapter will focus on some broader lessons learned and cultural observations from my internship.

Phrases often heard at Dell are "the speed of Dell" and "always happy, never satisfied." Dell has organizationally been set up to be ultra-flexible to meet the needs of changing market conditions. To instill this flexibility within Dell, it has consciously fostered a belief that change is good–that it should be embraced in fact. This premium on flexibility has served Dell well in many ways[19].

The GeoMan initiative described in Section 1.3 and its genesis of this project (Section 1.4) are good examples of Dell pursuing its flexibility strategy. GeoMan goes hand-in-hand with Dell's make-to-order model. It is useful to note however, that stresses naturally are created by Dell's hyper-flexibility. If decisions to change direction are made very quickly (i.e., the decision to make more OptiPlex in EG1 which was introduced in Section 1.4), then stresses are unavoidably introduced to the manufacturing and people systems which support Dell's business. The bulk of this thesis deals with how to alleviate some of the stresses introduced into the manufacturing system by a desire to make more OptiPlex in EG1 quickly.

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[19] A particularly poignant example of the power of Dell's flexibility during the 2002 West Coast dock workers strike is recounted by Bill Breen. See Bill Breen, "Living in Dell Time," Fast Company Nov. 2004, 5 Nov. 2004.<http://www.fastcompany.com/magazine/88/dell.html>.

I had prior work experience in semiconductor (microprocessor and flash memory) manufacturing, which is very conservative in its change management processes. Therefore, I was surprised to see how eagerly Dell embraced and adopted manufacturing change. Clearly, the PC and semiconductor industries have quite different business contexts which drive different decisions about manufacturing change management. The "cost of failure" at a particular manufacturing step is one of the largest distinguishing differences between PC manufacturing and semiconductor manufacturing. Compared to semiconductor manufacturing, PC manufacturing has many fewer process steps and a much greater fraction of errors at each process step which are "rework-able." If a mistake is made in PC assembly, the PC manufacturer is often able to rework the material into salable product. This is rarely the case with mistakes in semiconductor manufacturing. Clearly, keeping the relative costs in mind, a PC manufacturer (such as Dell) is required to have a much keener focus on speed relative to semiconductor manufacturing (which must have a higher relative focus on quality.)

Culturally, the corollary to the difference described in the previous paragraph is that PC manufacturing (on average) attracts employees who enjoy the freedom to make more frequent changes in their manufacturing processes. Conversely, semiconductor manufacturing (on average) attracts employees who like to change the manufacturing processes less frequently (i.e., they value permanence of the changes they make more than the ability to make changes more frequently.)

4.2 The Value of a "Fresh Set of Eyes"

I was reminded before the internship started not to forget the high utility of a "fresh set of eyes" in solving difficult problems. A newly-hired ASRS improvement team colleague and I both lacked experienced in Dell manufacturing systems. This introduced some problems for both of us, but it also presented considerable opportunities for us to look at the problem analysis and possible solutions in a new light. This phenomenon is equally true at fast-moving companies like Dell and at much slower-moving companies. Employees tend to develop a set of assumptions when they have been in an organization for a long time. Three ways Dell is effective at counteracting this ossification of assumptions is through a large and vibrant university internship program, frequent job rotation at various pay grades, and a mixture of promoting from within and external hiring for top management positions.

4.3 The Nature of Communications at Dell

Related to the organic conception of change discussed in Section 4.1, Dell also has a very spontaneous corporate communication protocol. The corporate culture is highly relationship-based, and informal communication plays an enormous role in building and maintaining these relationships. Thus, Dell tends to attract many gregarious employees who enjoy this aspect in their work lives.

However, I believe some strengthening of formal channels of communication could benefit Dell. More user-friendly and less time-intensive knowledge management software will soon lower the bar for these formal communications between people; with its tech-savvy workforce, Dell is poised to take advantage of this trend as it emerges. The less time and effort formal channels of communication require of employees, the more likely these systems are to "catch on" and thus become useful.

Dell is doing superlative job of using the bi-annual "Tell Dell" survey as a formal channel for employee feedback. Dell is leveraging its metrics-driven culture and meritocracy to get managers to really care about the concerns that employees raise in these surveys.

4.4 Relationship between Manufacturing and Engineering at Dell

At many (perhaps most) manufacturing organizations there are strong tensions between the manufacturing and engineering organizations. Dell is no exception to this rule. The reasons are pretty plain to see also – manufacturing is usually *fundamentally* measured on throughput while engineering is *fundamentally* measured on quality and process improvement. In healthy manufacturing organizations there is an alignment of incentives – manufacturing has some accountability for quality/process improvement, and engineering has some accountability for throughput. This natural tension had relevance to this project because some of the process improvements discussed in Chapter 3 have subtle throughput benefits which are difficult to quantify. In such situations there was a natural resistance on the part of the manufacturing organization to implement the change (an example of this was discussed in Section 3.6.3.) This is where Dell's openness to piloting new ideas (section 3.6.2) is critical to manufacturing process improvement. If simulation modeling can't validate that a change will likely succeed, then piloting new ideas on the factory floor is extremely beneficial because manufacturing and engineering can become “co-owners” of the change.

4.5 Relationship between Technology Development Site and Satellite Manufacturing Facility

Similar to the discussion in the previous section, there are usually natural tensions between the product/process development organization and “satellite” high-volume manufacturing sites. Again, Dell is no exception to this rule. Almost all of the product development and process technology development is performed in Austin, TX. As mentioned in Chapter 1, this project was focused on one of Dell’s satellite high-volume manufacturing facilities located in Nashville, TN. The typical tensions are as one might expect:

- The technology development facility believes the satellite manufacturing facility does not “pull” technology effectively enough from them.
- Conversely, the satellite facility believes the development facility has a “know it all” attitude and either believes that they are too authoritarian in transferring technology or that they neglect their duty to fully transfer the technology.

Although I spent a small part of my internship period in Austin (the technology development site), I was able to detect some of the attitudes described above at the two facilities. Simply becoming aware of these differences can go a long way toward mending them.

4.6 Tension between Functionally-Aligned and Geographically-Aligned Organizational Structure

I observed the highly-matrixed structure of Dell's operations in the US (a section of the company called Dell America Operations, or DAO, for short). A partial organization structure of DAO (focused on EG1) is shown in Figure 19. Notice that in this organizational structure many of the managers of functional groups aligned with EG1 have a direct reporting relationship with a higher-level manager located in Austin (note that the HR functional group is an exception to this). Thus some of the Nashville managers in these functional areas felt like they had divided attention between their Austin solid-line bosses and their strong dotted-line relationship to the director of manufacturing in Nashville. During my internship, I noticed a strengthening of the dotted line relationships shown in Figure 19 which I believe was a positive trend because it bolstered intra-plant coordination by tightening links between the functional groups directly responsible for EG1's day-to-day performance.

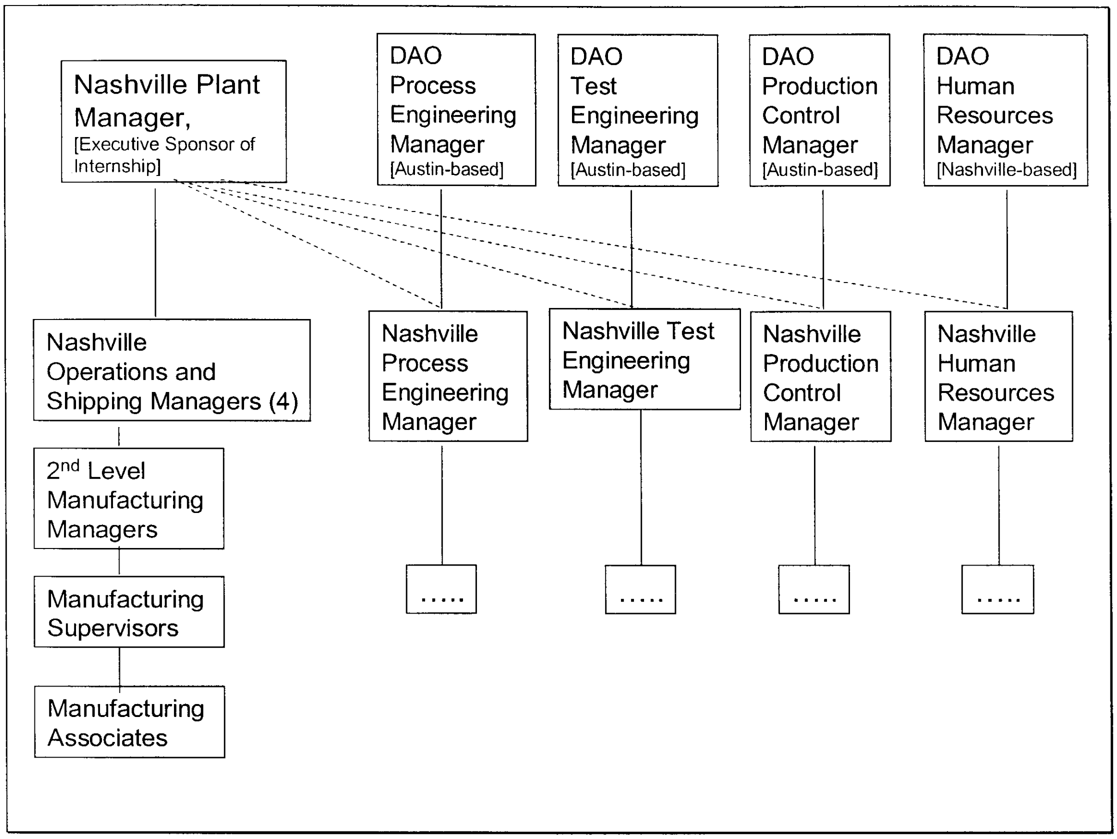

Figure 19: Partial Organization Structure of Dell America Operations

4.7 Observations about IT at Dell

One of the things that many Dell employees have voiced concern about is the quality of sales and manufacturing IT systems at Dell. "Tell Dell" survey results reported in DAO confirmed the anecdotal evidence on this subject that I heard during the internship. Part of the explanation of this can be traced to Dell's strong corporate focus on cost-containment. Dell likes to use a financial guideline that investment projects should have a payback period of less than 12 months. For most kinds of expenditures this rule is healthy in that it keeps discipline on costs. However, IT often requires a large expenditure up front (especially if one is making the IT system large enough and robust enough to accommodate Dell's fast growth rates) and has a payoff over a longer period of time than many other kinds of investments. Also, Dell's cost-containment biases Dell against building IT systems "ahead" of the growth in demand which necessitates more frequent expansion of IT systems. However, when market demand is overwhelming one's IT systems, it is often very difficult to schedule planned downtime to do the often very extensive software upgrades which are required to expand the capacity of the IT systems. I do not believe Dell should deviate from its strong cost focus but do think that Dell needs to think expansively about the costs and benefits of the IT strategy it has been pursing recently.

4.8 Opportunities for Future Work

At many places in this thesis so far, the usefulness of simulation modeling has been suggested. Dell Manufacturing used to have a larger group dedicated to simulation modeling than they had at the end of this project. Since the end of the internship, efforts have been increased to perform accurate simulation modeling of the EG1 facility. As described several times in the thesis, this modeling might enable much greater accuracy in determining the benefits of the solution options described in Chapter 3. Also, this modeling would allow for a much wider exploration of "what if" analyses and would likely give rise to additional ideas about how to improve ASRS throughput.

More future work on ASRS *storage capacity* and its interaction with ASRS throughput (the focus of this thesis) would be useful. Engineers at one of Dell's manufacturing facilities in Austin have already created an analytical ASRS storage capacity model which is more useful to that factory because it was fundamentally limited by its storage capacity, not by its ASRS throughput. (Being limited by storage capacity is analogous to the fullness of the bathtub described in the bathtub analogy given in Section 2.3.) In addition to illuminating a more fully developed analytical model, simulation modeling efforts might also be useful for understanding scenarios where ASRS storage capacity has become the factory bottleneck.

Future factory bottlenecks are often hard to predict. Historically, the main reason for historical bottleneck shifts in EG1 had been large productivity enhancements in the bottleneck areas of the factory. However, the reason the bottleneck shifted to the ASRS in EG1 (the case study presented in this thesis) was a shift in product mix being produced in the factory. Needless to say, estimating both future product demand (for the factory) and productivity enhancements are imprecise activities. At a minimum, these realities lead one to the conclusion that careful observation to discern bottleneck shifting is important. More ideally, accurate simulation modeling might enable better predictions about future factory bottlenecks.

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