Simulation Model Used As Design Improvement Decision Tool for Warehouse Material Flow

by

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B.S. Mechanical Engineering, Georgia Institute of Technology1994

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

Master of Business Administration
and
Master of Science in Mechanical Engineering

In conjunction with the Leaders for Manufacturing Program at the Massachusetts Institute of Technology June, 2005

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ABSTRACT

The basis for this thesis involved a six and a half month LFM internship at Efficient Storage, Shipping, and Selection.

ES3, Efficient Storage, Shipping, and Selection, is a third party logistics firm that specializes in a vendor-neutral consolidation model for the food distribution industry. ES3 receives, stores, and ships multi-vendor products through a distribution center (DC) in York, Pennsylvania. The product is moved and stored by an Automated Storage and Retrieval System (ASRS) which consists of a network of conveyors, vertical lifts, and Selection and Retrieval Machines (SRMs). The ASRS system is not performing to the designed put-away and shipping rates, thus limiting the DC's overall performance during peak operations.

The warehouse operations and warehouse design teams had numerous design suggestions for improving the ASRS operations, but it was difficult to predict the enhancement or impact on performance. A simulation model for the inbound system was created to analyze the impact, prioritize, and develop new ideas for improving the system.

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CHAPTER 1: Company Background

1.1 Business Background

ES3, Efficient Storage, Shipping, and Selection, is a third party logistics firm revolutionizing the grocery distribution business. The firm specializes in offering dry goods manufacturers a vendor-neutral storage and consolidation point for just-in-time distribution to retailers. This innovative approach varies significantly from the traditional business model in different ways.

The traditional grocery distribution supply chain consists of a manufacturer, the manufacturer's distribution center for consolidating products, a wholesaler's distribution center or retail distribution center for consolidating products from different vendors, and the final retailer. Figure 1 depicts the traditional grocery distribution supply chain.[1]

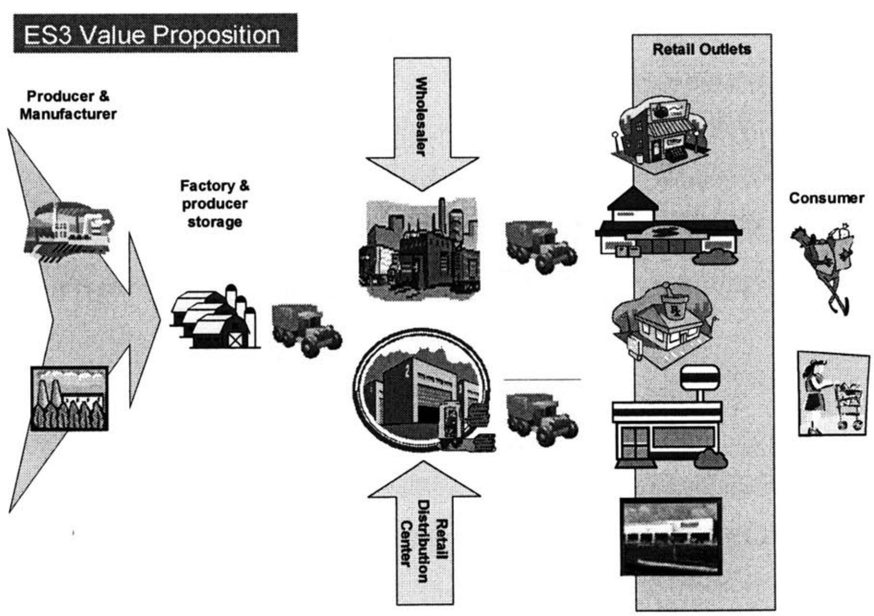

Figure 1 Traditional Grocery Supply Chain Model

[1] Adapted from Daniel Park, *Design and Development of Customer Priority Decision Aid Tool*, page 14

The traditional chain consists of numerous storage locations and excessive double handling and transporting the groceries. ES3 updates the distribution chain by eliminating the manufacturer's own distribution center and the retailer's distribution center and replacing with a multi-vendor mixing facility. The updated distribution supply chain consists of manufacturers shipping their product directly to ES3's distribution center for storage and consolidation. The consolidated product is then shipped to the end retailer. The new distribution supply chain eliminates unnecessary storage space, unnecessary product handling, and shorter order lead time.

Figure 2 depicts the updated distribution supply chain.[2] Additional savings is established by leveraging the ability to ship mixed-product pallets specific to end retailer needs. Traditionally, the end retailer has always balanced transportation cost from shipping full Truck Load (TL) vice Less Than Truckloads (LTL) with inventory costs. The end retailer would sacrifice inventory costs to save in transportation costs or vise-versa. ES3 eliminates this by shipping mixed-product pallets, across numerous vendors, to avoid the LTL cost, thus avoiding the excess inventory caused by one-product type pallets.

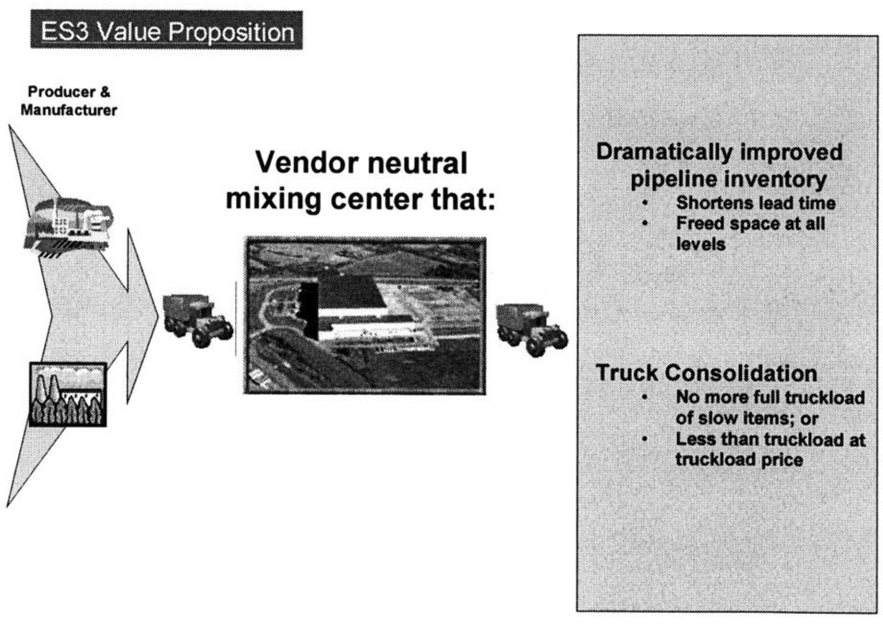

Figure 2 ES3 Value Proposition

[2] Adapted from Daniel Park, *Design and Development of Customer Priority Decision Aid Tool*, page 14

1.2 Mixing Facility

The mixing facility is the heart of ES3's operations. The facility is located in York, PA, a strategic receiving and shipping point servicing the eastern seaboard from New England to Northern Virginia. The manufacturer coordinates delivery of product to the facility from their finished goods inventory warehouse and ES3 coordinates the outbound shipping through a third party. The facility resembles a manufacturing plant and in fact, the operators use terminology from the manufacturing industry to describe the flow of product laden pallet through the warehouse. For example, meeting "production" is used to describe the facilities ability to keep up with the inbound trucking offload rate or outbound trucking shipping schedule. Forklifts offload the product laden pallets from the trucks and transfer the pallets to an Automated Storage and Retrieval System (ASRS). The ASRS consists of a complex network of roller conveyors, vertical lifts, Selection and Retrieval Machines (SRMs), and a large racking system consisting of approximately 140,000 pallet positions.

The Equipment Management System (EMS), the software portion of the ASRS, uses an algorithm to assign pallets to the best storage location based on covering like-product, meeting "First-in-First-Out" (FIFO) windows across same products, meeting the physical limitations for a rack position, meeting sprinkler requirements for the product, and potentially a "home aisle" assignment. The "home aisle" assignment is a requirement because of the value-added service it provides – mixing product on manually constructed pallets. ES3's ability to construct mixed-vendor pallets at the case level provides potential savings for the end retailer. The pallets are constructed manually by hourly workers referred to as "case selectors". In the facility, rack slots at the ground level have been set aside to store pallets from which "case selectors" will pick product. An important consideration for storing pallets is the assignment to a predetermined aisle that corresponds to the right pick slots. This predetermined aisle is the pallet's "home aisle".

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CHAPTER 2: Warehouse Material Flow – The Process

2.1 Overview

Chapter 2 is a detailed discussion of the Material Flow Process reviewed during the internship. The flow of material is reviewed at a macro level of the York Warehouse operations and a micro level. The macro level review consists of the tractor-trailer process as it travels from the Gate House to the Unloading Dock within the York Warehouse Compound. The micro level is the flow of the material within the warehouse. Specifically of interest is the material handling system, Automated Storage and Retrieval System (ASRS), and the lack of performance at peak operations.

2.2 Macro Level Overview of Warehouse Operations

The flow of tractor-trailers (trucks) in and out of the ES3 York compound is worth discussing. The overview will increase the understanding of how the pallets are received and shipped, and will help set the stage for understanding the impact of the bottleneck – the ASRS inbound operations. In general, cases of product are shipped to York on wooden pallets with cases of product shrink wrapped together. The cases vary in size, but the pallets tend to weigh within a range between 1,500 to 3,000 pounds.

Material Flow Direction

ES3's operations are very similar to a factory, and in fact, the terminology will be familiar for those with manufacturing plant experience. "Inbound" is the terminology used for delivery trucks and for the flow of material within the warehouse up to the point of storage. "Outbound" is the terminology used for material flow from the point of rack retrieval to truck loaded for shipment to end customer.

Types of Deliveries

ES3 has various forms of processing deliveries. In general, the driver of deliveries can stay with the trailer or drop the trailer off and leave with a staged outbound trailer (or leave empty). The deliveries may or may not be scheduled in advance and most inbound trailers are Truck Loads (TL). The types of deliveries are:

Live Unloads – The driver stays with the trailer and is processed as quickly as possible.

Drop Unload – The driver leaves the trailer and the trailer is unloaded when the workload permits.

Types of Shipments

Less Than Truckload (LTL) – The trailer is released for shipment without being full and creates a more expensive transportation cost, on a cost-per-product basis.

Truck Load (TL) – The trailer is released for shipment full.

Customer Pick-up (CPU) – The outbound trailer has a scheduled pick-up and the driver will pick-up at the loading dock. Potentially the driver could be waiting for fulfillment because this is scheduled on a tight timeline.

Drop Pick-ups – The outbound trailer is being loaded ahead of schedule and will be staged in the Yard.

Transparency of Orders

The Inbound material delivery can be scheduled or unscheduled. Approximately 80% of the Inbound trucks are unscheduled.[3] As a service provider, ES3 is not in the business position to mandate the scheduling of materials. The scheduling would require some level of inventory management and most likely production management. ES3's business model is not to provide inventory management. The vendor must determine the appropriate product to store, the appropriate inventory level, and the appropriate deployment timeframe. Next we will discuss the physical flow of material. Figure 3 is a diagram of the York Facility Compound.

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[3] Interview with Dave Badten, ES3 Analytics Director

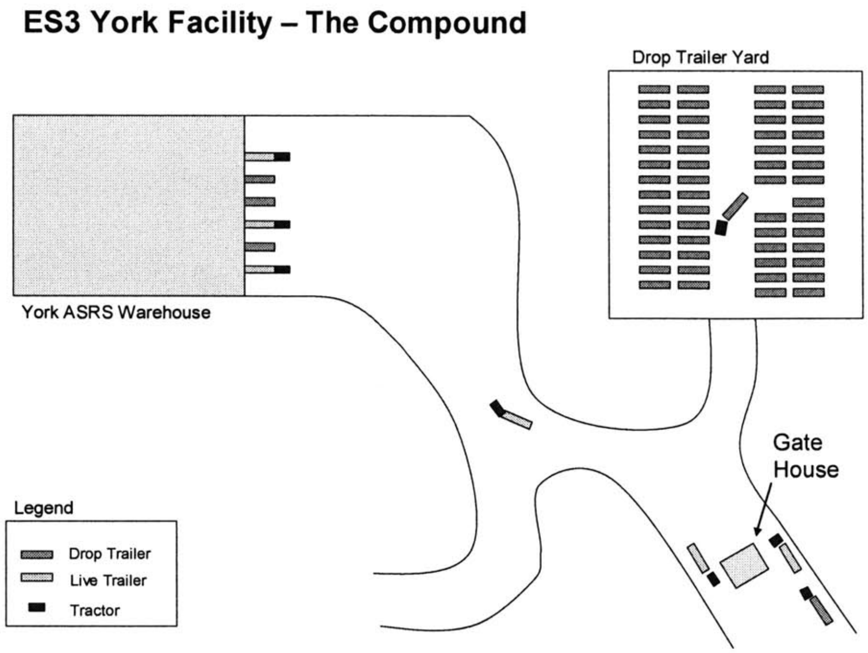

Figure 3 ES3 York Facility - The Compound

Gate House

The trailers arrive at the Gate House with an arrival rate of approximately 10 tractor-trailers an hour. The gate house personnel double check the trailer's paperwork and a radio-transmitter is applied for tracking and verifying trailer location within the compound.

Drop Trailer Yard

Drop Unload trailers are taken to the "Drop Trailer Yard". The trailers will be called for when unloading doors become available at the warehouse. "Yard Jockies" manage the flow of trailers throughout the compound. They stay in radio contact with the external drivers of Live Unloads and with the ES3 drivers of Drops.

Warehouse Trailer Doors

There are 38 total trailer rollup doors. The number of doors is actively managed by the warehouse operators and can vary significantly. The doors are a shared resource across the

Outbound and Inbound operations. Currently, the type of delivery and shipment utilizes the doors in the following manner (average):

Drop Unloads	6 doors
Live Unloads	6 doors
CPU	6 doors
Drop Pick-ups	8 doors

2.3 Internal Warehouse Process Overview

The flow of pallets in and out of the Warehouse is handled by forklifts and a network of conveyors, vertical lifts, and SRMs. The Inbound ASRS operations are the bottleneck for the product flow and the focus of the recommended improvements. Please refer to Chapter 3 for a full capacity analysis of the facility operations. A discussion of the Outbound Operations is also included because the two operations share resources, the SRMs and the warehouse doors. Also, the internal transfer of product from the Outbound to the Inbound wreaks havoc on the Inbound processing capability. Figure 4, Product Flow through York Facility, is a high-level block diagram of the product flow through the warehouse.

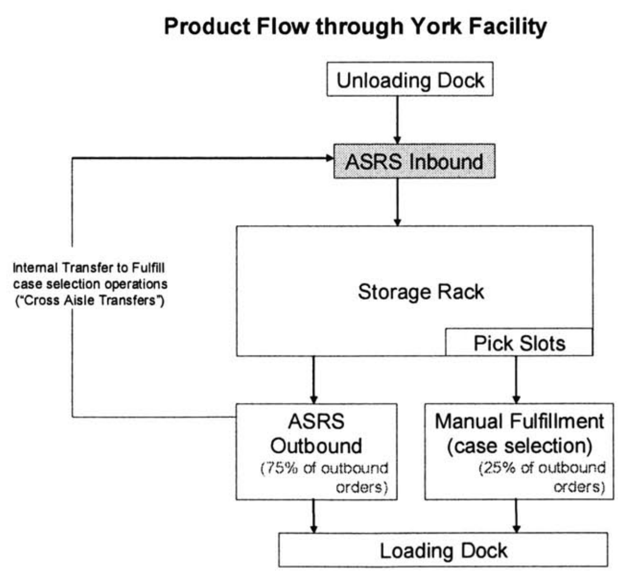

Figure 4 Product Flow through York Facility

In general terms, the product is offloaded on the Unloading Dock and the ASRS puts the pallets away in the Storage Rack. Once an order is placed, the ASRS retrieves the pallets and transfers the product to the Loading Dock for shipment. Fulfillment of mixed product pallets is conducted in a manual manner. The case selectors stack the individual cases on the pallets and then transport the pallet to the Loading Dock. Sometimes the Pick Slots, the slots set aside for the case selectors to manually pick product, empties and the ASRS must transfer product from one storage aisle to the aisle with the assigned pick slot. This procedure is called a Cross Aisle Transfer (CAT).

The following sections communicate the flow of the pallets via; a block diagram, written description of the material handling equipment and processes, and physical plant diagrams. The diagrams will be included with the written description where the researcher feels most appropriate.

2.4 Inbound Process Overview

The pallets flow from the unloading dock to four different receiving points (called spurs) of the ASRS and collect on a Main Conveyor on the third level before being put away by the SRMs. Figure 5 is a process block diagram of the inbound flow.

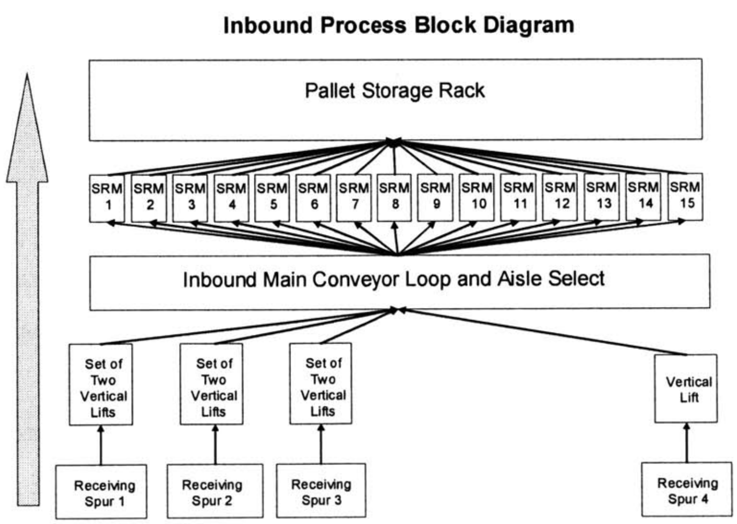

Figure 5 Inbound Process Block Diagram

The following sections describe the operations and equipment in Figure 5.

Unloading Dock

The trailers are positioned at the unloading dock doors for emptying. Forklift operators unload the truck and place the product laden pallets onto an "induction spur". The spur is also the transfer point between human and machine, the starting point of the ASRS and the beginning of the conveyor on the ground floor. The ASRS was constructed to handle cases of product loaded on wooden pallets.

Photo 1 Receiving Doors

Photograph of forklift operators unloading product laden pallets from trucks at receiving doors.

Conveyor system

The conveyor throughout the building consists of steel rollers and located at approximately 30 inches high. The conveyor is supported by tubular steel and allows one pallet to be loaded at a time at each induction spur. The conveyor is divided into 5 foot stages, referred to as zones, and the conveyor speed is 60 feet per minute.

The conveyor has pneumatically operated air-bags and chain-driven transfer stations at points where the pallets change direction. The air-bags are located on the concrete slab and when inflated they lift a table connected to chain drives. The chain drives lift the pallet vertically off the steel rollers while the chains become activated; pulling the pallet onto the right-angle oriented next set of steel rollers. The transfer stations speed is approximately 37.5 feet per minute.

Photo 2 Main Conveyor Loop

Photograph of main conveyor loop and a transfer station.

2.5 Receiving Spur

The Inbound receiving area is referred to as the Receiving Spur. There are four total receiving spurs at ES3. The spurs consist of an electronic information exchange location, pallet verification equipment, and a network of conveyors and vertical lifts.

Induction

At the induction spur, the pallet's electronic information is inputted for the ASRS to manage pallet flow and storage. Each pallet has a placard, called a License Plate Number (LPN), with the product's pertinent information; including product Store Keepers Unit (SKU), size, weight, height, and heat sensitivity. The forklift operator scans the LPN with a hand-held bar-code scanner to collect the electronic data and then the data is transmitted to the system reader at the Induction spur. The reader is the physical location where the information is received into the Warehouse Management System (WMS). WMS manages the inventory for ES3. WMS transfers the data to the Equipment Management System (EMS). EMS manages the flow of pallets through the warehouse and at a later stage selects the rack storage position for the pallet. The information is "attached" to the pallet as it travels through the ASRS.

Induction Spurs 1 through 3 are located at one end of the building while Induction Spur 4 is located at the other. Induction Spur 4 can handle special product – product loaded on "slip sheets" vice wooden pallets. Slip sheets are sheets of cardboard that the cases of product rest upon. At Spur 4, the product is transferred to a wooden pallet and an automatic shrink wrap machine attaches wrap.

Photo 3 Receiving Spur

Photograph of forklift operator waiting to induct pallet at Spur 1 as a result of bottleneck operations further downstream the operations.

Verification Equipment

The receiving spur uses specialized equipment to verify the weight of the pallets, to align the cases properly on the pallet, and to detect for loose nails. Each pallet traverses the check points before full acceptance into the building's storage system.

Rejection Stage

Pallets fail to be inducted properly for various reasons, such as poor quality pallet, poor quality shrink wrap, product not aligned properly, or failed reading of the LPN. If the pallet fails, the pallet is transferred to a rejection point. The warehouse operators at the dock monitor and task forklift operators to fix the problem. In most cases, the product is transferred to a new pallet, because the majority of failures are created by poor quality pallets.

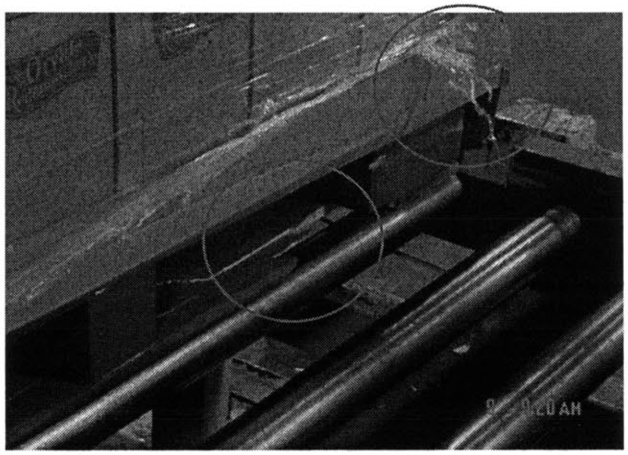

Photo 4 Common Causes for Pallet Rejections

Photograph of two main causes of pallet rejections; defective pallet stringer and poor shrink wrap application.

The quality of the pallets and the quality of the shrink wrap attachment are the two primary causes for rejections. ES3 has focused time and energy on improving their rejection rate, but the primary responsibility on high quality pallets falls upon the third party provider. The third party provider has very low incentive on pulling poor quality pallets out of circulation and repairing them. This creates a lot of rework for ES3 and required management attention. The time to repair a pallet or swap product from a poor pallet to a good pallet is lengthy and because the employees are paid on incentive, they would prefer someone else attend to poor quality pallets.

Vertical Lift 1

Pallets are transferred one at a time to the second level by a vertical lift. The vertical lift cycle time is 40 seconds. The pallets are transferred to a short conveyor capable of holding three pallets and then transferred to another vertical lift.

Vertical Lift 2

Pallets are transferred one at a time to the third level by a vertical lift. The vertical lift cycle time is 40 seconds. Vertical Lift 2 and the short conveyor on the second level is not is not depicted in the diagrams.

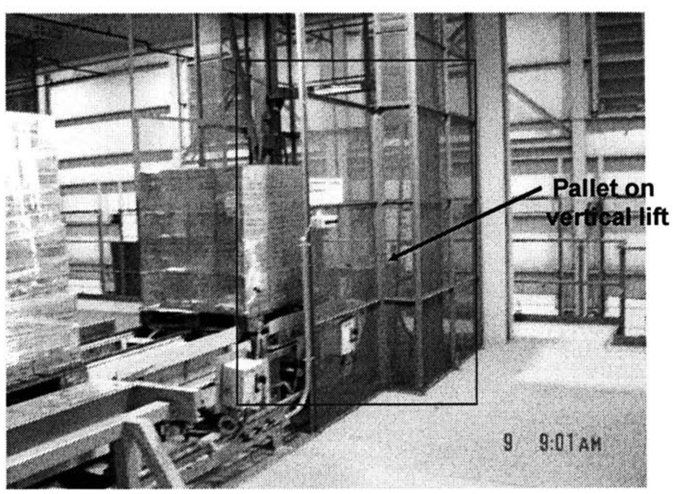

Photo 5 Vertical Lift

Photograph of vertical lift raising pallet to higher level in warehouse.

2.6 Inbound Main Conveyor Loop

The pallets are transferred to a main conveyor loop that has approximately 150 zones and is 725 feet long. The pallets are allowed to circulate on the loop if they are "bumped" by a build up of pallets behind them as they await transfer into their assigned SRM Buffer (refer to SRM Buffer for detailed discussion of "bumping"). The Inbound Main Conveyor Loop has an established spacing of pallets of approximately every 10 feet in certain sections, because the motors driving the steel rollers are rated for moving one pallet. This spacing is evident in Photo 2. Refer to Figure 6 for a diagram of the Inbound Main Conveyor Loop.

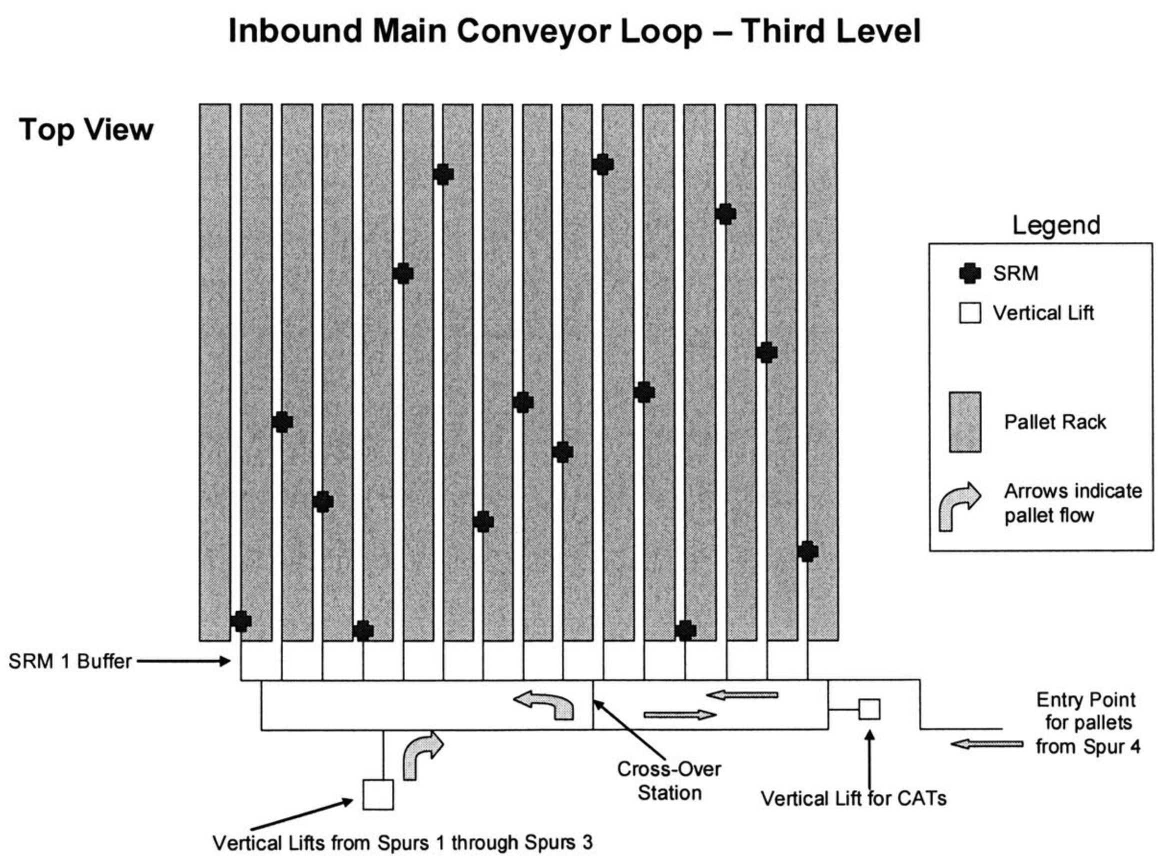

Figure 6 Inbound Main Conveyor Loop Diagram

Diagram shows the flow of pallets starting at the vertical lifts from the receiving spurs or starting at the vertical lift as a CAT. The pallets traverse the conveyor and head to the assigned SRM.

Aisle Select

Aisle Select is the decision point for which aisle to store the product. The EMS uses an algorithm to decide the best SRM Aisle. The algorithm determines the best Aisle by considering the following factors; SRM not in "maintenance mode", cover-like SKU that is uncovered, percentage of pallets in aisle is less than desired percentage, total number of pallets (like-SKU within FIFO window) in aisle is less than threshold, the aisle that contains most available triple deep bins of desired bin type, or contains the greatest number of usable triple deep bins available. The First-In First-Out (FIFO) window is important in grouping product and it is based on the date of manufacturer. The FIFO window is thirty days. Also considered is the "home aisle" for the product. Because of case picking operations, there exists a preferred aisle for all SKUs that can be shipped as a tier picked pallet. If a product is not assigned to its home aisle, the ASRS might have to transfer product internally to fulfill a pick slot replenishment. (Refer to section 2.10 Pick Replenishment Operations for thorough discussion of case picking operations.)

For inbound pallets, each SRM has an "en route counter" that counts the number of pallets assigned that are physically between Aisle Select and the SRM's inbound Pick up & Delivery (P&D) Station. Each SRM has a maximum en route allowed that is adjustable. Once this maximum en route is reached, Aisle Select looks for another aisle to store the product based on the algorithm. The maximum en route counters were established to help balance the loads across the aisles to enhance throughputs. This creates a certain percentage of future Cross Aisle Transfers, that can be better understood through the Casual Loop discussion in Chapter 6.

Cross-Over Transfer Station

Pallets from Spur 1 through Spur 3 bound for SRM 1 through SRM 9 are transferred to the far side of the loop immediately following Aisle Select by the Cross-Over Transfer Station. Photo 2 depicts the Cross-Over Transfer Station. The Cross-Over Transfer Station is chain-driven with a cycle time of 19 seconds. Thus, a pallet bound for SRM 4 is transferred via the cross over station and passes SRM 9 through SRM 5, than transfers to SRM 4's buffer. Pallets bound for SRM 10 through SRM 15 travel to the far corner of the Inbound Main Conveyor Loop and they are not transferred at the Cross-Over Transfer Station. The cycle time for pallet bound for SRM 10 and SRM 15 is the same as along any other stretch of the roller conveyor, 5 seconds.

Cross Aisle Transfer Entry Point

The Cross Aisle Transfer (CAT) Entry Point allows for an entry point of internally transferred product onto the Inbound Main Conveyor Loop. Product is transferred from one Aisle to another Aisle by coming out of the rack via Outbound operations and being vertically lifted upward to the third level and released onto the Main Conveyor Loop in the Inbound Operations. The EMS tracks the Aisle assignment of the pallet. Product is transferred for various reasons, the two primary being for a Quality Assurance Check and to replenish a Pick Slot. Refer to Outbound Operations for a full discussion on Pick Slot replenishments.

Spur 4 Entry Point

Spur 4 was added to handle "slip-sheeted" product. Some product does not arrive on wooden pallets but on cardboard sheets, or slip-sheets. The ASRS cannot handle such product, so the slip sheets are removed. The forklift operators place the product on a wooden pallet and "induct" at Spur 4. The pallet traverses through an automatic shrink-wrap and travels on a vertical lift to the third level. On the third level, the pallets travel 60 conveyor zones before being released onto the Inbound Main Conveyor Loop. The current release logic allows for one pallet from Spur 4 to be allowed onto the Main Conveyor Loop after two pallets pass. A pallet bound for SRM 1 has to travel pass all SRMs to reach SRM 1. This does not occur for pallets from Spur 1 through Spur 3 because of the Cross-Over Transfer Station.

SRM Buffer

Each SRM has a collection point for pallets, termed a SRM Buffer, which allows for an accumulation of pallets waiting for put away. SRM 1 has a SRM Buffer of X+3 pallets while the remaining SRMs have a Buffer of X pallets positions.

Pallets bound for a particular SRM are allowed to wait along the Main Conveyor Loop, if the SRM Buffer is full. A maximum allowable number of pallets is allowed to "stack-up" upstream of the pallet waiting for the SRM Buffer. The maximum number is based on the number of zones upstream that are allowed to fill with pallets called maximum hold zones. Each

SRM has an adjustable maximum hold zones. Once the maximum number is reached, the next pallet to stack-up downstream will trigger the pallet waiting on the SRM Buffer to release and travel the loop of the conveyor. Thus the pallet is re-circulated around, back to aisle select for another aisle assignment. The re-circulation of pallets occurs fairly often, approximately 29 pallets an hour during peak operations.

The pallets that are allowed to stack-up on the main conveyor are not all destined for the SRM creating the back up. The potential problem created by the stack-up is that downstream SRMs may be starved for work because an upstream's SRM Buffer is full with the X+1 pallet awaiting on access to the Buffer on the Main Conveyor Loop. The stacking of pallets on the Main Conveyor Loop occurs often enough that SRM utilization is impacted, thus creating one of the causes for the less than designed performance for the inbound system.

Inbound Pick-up and Delivery (P&D) Station

Each SRM has an Inbound P&D Station and it is the last zone on the conveyor. When a pallet arrives at the Inbound P&D Station, a pneumatic operated scissor lift table lifts two plates vertically. The plates lift the pallet upward and allow the SRM shuttle to pick-up the pallet. EMS selects the appropriate storage bin at the P&D Station. EMS selects the bin according to; cover like SKU (cannot be scheduled for retrieval), select an appropriate deep location based on physical attributes (weight and height), and select an appropriate near location.

There is another P&D Station on the second level used for Outbound operations.

Photo 6 SRM **Photo 7 SRM with pallet**

Two photographs depicting SRM shuttle telescoping to pick-up pallet from the P&D Station. The pallet storage rack is shown in the background.

Selection and Retrieval Machines (SRMs)

The SRM consists of a vertical mast that rides on two rails, one ground rail and one ceiling rail and a telescopic shuttle for picking up (or delivering) pallets. The shuttle pulls a pallet back into an enclosed cage, where the pallet "rides" when the vertical mast travels along the rails. There are a total of 15 SRMs with triple deep shuttles that have a carrying capacity of 3,000 pounds. The triple deep shuttle capability means the shuttle can telescope out into a three pallet deep rack.

SRM specifications:

- Horizontal velocity: 700 fpm
- Horizontal acceleration: 1.5 f/s^2
- Vertical velocity: 150 fpm loaded and 210 fpm unloaded (2,500 lbs)
  125 fpm loaded and 138 fpm unloaded (3,000 lbs)

SRMs have three major types of pallet movements; put-away of Inbound, retrieval of Outbound, and replenishment of Pick Locations (Refer to section in Outbound Process). All other pallet movements are conducted in order to complete one of these movements. Currently, the SRMs operate in either two modes – dual cycle of pallet storage and pallet retrieval or single cycle of just pallet storage (or just pallet retrievals).

Rack Storage Positions

There are 146,952 physical pallet storage locations (or bins) in the 15 Aisles. The rack is a three deep storage location. The steel rack is ten stories high (approximately 110 feet). As shown in the photograph, the rack was erected first and then the sheet metal skin exterior of the building was added. Certain products, such as cooking oils, have to be stored in specific racks that have tighter sprinkler-head spacing, specifically Aisles 1 through 3.

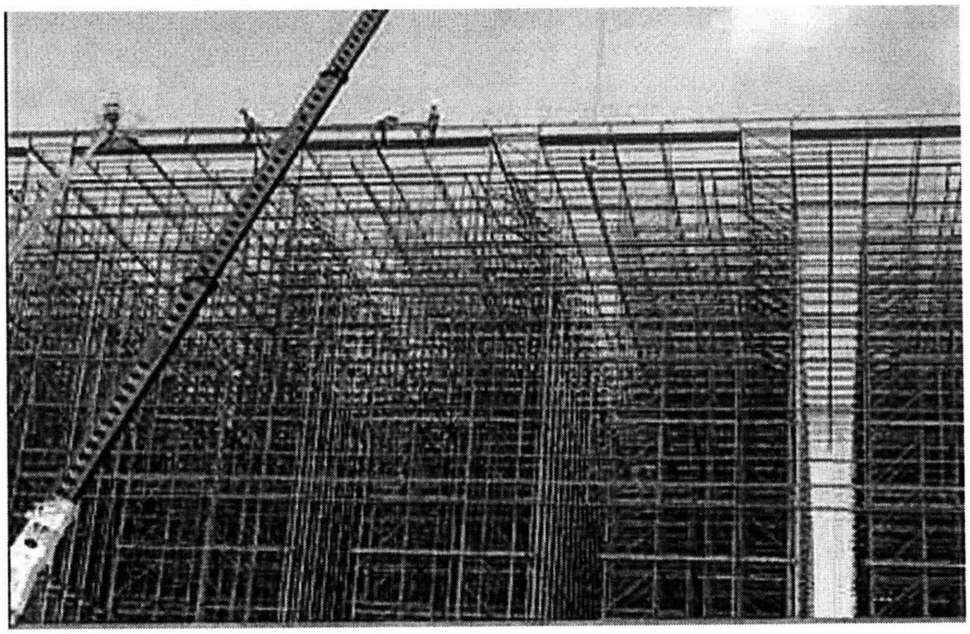

Photo 8 Racking System

Photograph of storage rack being erected during the initial construction of the York Facility.

2.7 Outbound Process Flow Overview

The Outbound ASRS operations are the retrieval and shipping of the product at the York Facility. The flow of material for the Outbound Process occurs in the reverse order as Inbound. The pallets are retrieved from the pallet storage rack by the SRMs and placed onto an Outbound Main Conveyor on the second level. Four vertical lifts drop the pallets to the ground level and onto the Shipping Spurs (Stations). There they wait to be loaded onto a truck by a forklift operator. Presented is a process block diagram of the outbound flow as Figure 7. A more detailed understanding of the process (or material handling equipment) is provided in the written descriptions.

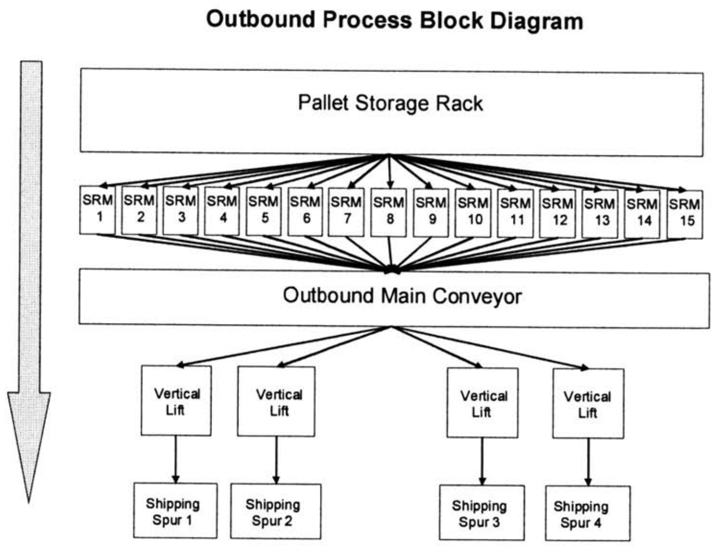

Figure 7 Outbound Material Flow Block Diagram

Figure 8 is provided to highlight the outbound pallet flow.

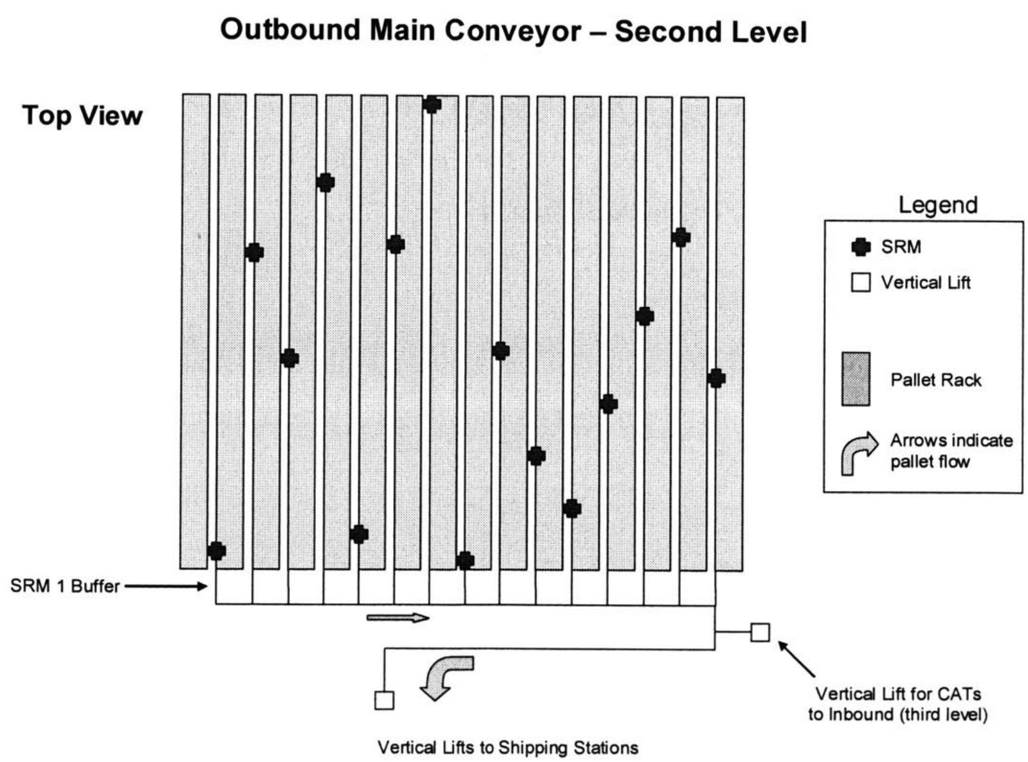

Figure 8 Outbound Main Conveyor

The following sections describe the order fulfillment process.

Allocation of Orders

The pallet (SKU type and amount) required to fulfill orders are known in advance, typically 24 hours before shipment on CPUs. EMS receives orders from WMS with case quantity, SKU, owner, dock door assigned, and date/time (to indicate processing order). Currently, the manufactures still handle the receipt of orders from the end customers and update WMS. The orders are transmitted to ES3 and the order is allocated through EMS. Allocation is the assignment of product (pallet or cases) to fulfill the order. The warehouse operators schedule the shipments based on manpower, door availability, and tractor-trailer availability. Once a door is activated, WMS notifies EMS that the pallets can be assigned into a database of outbound SRM moves as first come, first served. EMS verifies that there is only one order allocated per dock door.

2.8 Outbound Main Conveyor

Rack Retrieval

The rack is a three deep storage system. The pallets are stored one behind another, similar to products stored on a grocery shelf. Thus to retrieve the third deep pallet, the front two pallets have to be removed to gain access to the third pallet. The SRM shuttle retrieves the pallet and the SRM travels to the Outbound P&D Station.

Outbound P&D Station

The Outbound P&D Station is the delivery point, thus the entry point for pallets onto the Outbound Conveyor system. The Outbound P&D operates in similar manner as the Inbound P&D.

Outbound Main Conveyor Buffer

An Outbound Main Conveyor Buffer allows for an accumulation of 2 zones, immediately following the Outbound P&D Station. The pallets are released onto the Outbound Main Conveyor when an opening in the stream of pallets is available. A build-up of pallets rarely exists because an opening is almost always available.

Outbound Main Conveyor

The Outbound Main Conveyor is a series of conveyor zones that transports the pallets to the 4 vertical lifts. Refer to Photo 9 for a picture of the Outbound Main Conveyor.

Photo 9 Outbound Main Conveyor

Photograph of pallets traveling on the Outbound Main Conveyor.

Outbound Vertical Lifts

The Outbound Vertical Lifts move the product from the second level to ground level. The pallets are assigned to vertical lifts based on which Shipping Spur they are assigned. EMS assigns a Shipping Spur based on the proximity to the Loading Door the pallet is assigned.

<u>2.9 Shipping Spur</u>

Shipping Spurs (Stations)

There are 4 Shipping Spurs and they allow 12 pallets to accumulate. A forklift operator scans the pallet's LPN with the hand held bar-code scanner and the assigned Loading Door is displayed. The forklift operator than picks-up the pallet and moves to the specified Door. EMS keeps an en route counter for each Shipping Spur to control the number of pallets going to the stations.

Loading Doors (Dock Door or Shipping Door)

There are 24 Loading Doors typically, but this changes depending on the type of operations (Inbound verse Outbound) operations being conducted. The doors assigned to Outbound Operations are actively managed by the operations staff. The staff has to balance the Inbound demand.

2.10 Pick Replenishment Operations

That would be the full extent of the Outbound Operations if ES3 did not provide Case Selection or Tier Pick service. Case Selection is the loading (or building) of pallets case-by-case. The end retailer could receive a pallet with different products and a different quantity of cases. For example, the end retailer may only want 10 cases of tomato sauce and 25 rolls of paper-towels vice two full pallets of both products. Thus, the advantage is holding less inventory at the retail store. Tier Pick is similar, but instead of constructing on a case-by-case, the order is fulfilled on a tier level. By tier level, enough same-product cases are stacked to allow for a level surface, upon which a different product case could be placed. This activity is completed by workers called case selectors. Refer to Photo 10 for a picture of a case selector constructing the bottom tier of a mixed case pallet. This is easier to execute because of the various case shapes and sizes across the different SKUs. In practice, the terms Tier Pick and Case Pick are used interchangeably.

Photo 10 Case Selector & Pick Tunnel

Photograph of case selector building a Tier Picked pallet.

Pick Locations (Slots) or Pick Face

Pick Locations are rack positions on the ground level that have been set aside for case selectors to pull product. The pick locations are classified in the manner in which they are replenished, Static or Dynamic Replenished Slots. EMS creates a replenishment order for all slots by the removal of a pallet from the pick face queue position (pick slot). EMS processes replenishment orders as a priority.

- Static Replenished Pick Slots always hold pallets with a specific SKU and physically are two pallet positions deep. Static Slotted pallets are always picked clean.
- Dynamic Replenished Slots can hold various SKUs over time and physically only allow one pallet. Once the case selectors have picked the cases required for order fulfillment, a slot manager re-wraps the pallet with shrink wrap. The pallet is than returned to the storage position by the SRM. The Dynamic Replenished Slots are constructed differently than the Static, which allows for this return. The replenishment of a dynamic is demand driven. A case selector has to wait as the product is being pulled from another SRM Aisle and is transferred to the correct SRM Aisle (Cross Aisle Transfer). Currently, managing Dynamic slots is a full time job for an ES3 employee.

Pick Tunnels

There are 14 Pick Tunnels and they run parallel to the SRM Aisles at ground level (beneath the racking vertical rack positions). Pick Tunnels are located between SRM Aisles. For example, Pick Tunnel 1 is located between SRM 1 Aisle and SRM 2 Aisle. The case selectors traverse the Pick Tunnels to gain access to the Pick Slots. A wire cage protects the case selectors from falling debris, thus creating the appearance of a tunnel. Figure 9, a cut away view of the storage rack and SRM aisles, shows the physical relationship between SRM Aisles and Pick Tunnels.

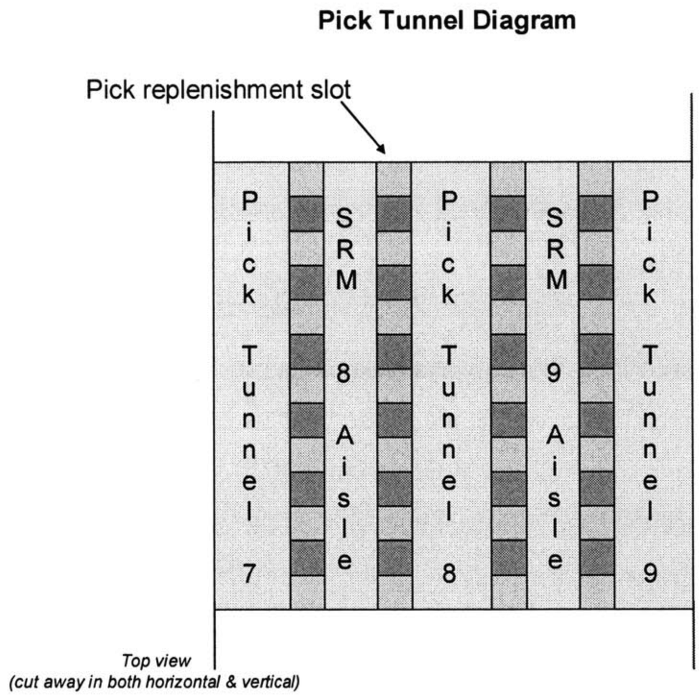

Figure 9 Pick Tunnel Diagram

Cross Aisle Transfer

Pallets are sometimes required to be transferred internally from one SRM Aisle to another so that Pick Slots can be replenished. This internal transfer causes the SRMs to double handle the pallet at a minimum and creates wait time for the case selector.

3.1 Performance Design Overview

The ASRS system was designed specifically for ES3 with the following system handling rates.

Conveyor Capacity

The conveyor was designed as the bottleneck operation at a maximum rate of 240 pallets in and 240 pallets out, as displayed below for the inbound operations.

- Conveyor capacity: 240 pallets per hour
- Vertical Lifts: 150% of conveyor capacity
- Truck receiving capacity: 120% to 130% of conveyor capacity (depending on door turn time assumptions)
- SRM capacity: 125% of conveyor capacity

The conveyor specifications indicate a rating calculated in the following manner:

- Conveyor speed is 60 feet per minute
- Pallet spacing is every 12 feet due to motor spacing
- Standard conveyor design capacity is 80%

$$(60fpm) * (1pallet / 12feet) = 5pallet / \min$$

$$(5pallets / \min ute) * (60 \min utes / hour) = 300pallets / hour$$

$$(300pallets / hour) * (80\%) = 240pallets / hour$$

The researcher believes a more accurate conveyor capacity estimate would be calculated using the cycle time of the Cross-Over Station, in the following manner:

- The Cross-Over Station transfers two-thirds of total inbound pallets to Aisle 1 through Aisle 9 at a cycle time of approximately 19 seconds.

- One-third total pallets are transferred along the Inbound Main Conveyor Loop at a cycle time of approximately 8 seconds.

$$(1\,palletmove/19\,\sec onds)*(60\,\sec onds/1\min ute)*(60\min utes/1hour) = 190\,palletmoves$$

$$(1\,palletmove/8\,\sec onds)*(60\,\sec onds/1\min ute)*(60\min utes/1hour) = 450\,palletmoves$$

$$190\,palletmoves*(2/3) + 450\,palletmoves*(1/3) = 276\,palletmoves$$

If the actual cycle times are used, the inbound conveyor is rated for 276 pallet moves. The manufacturer rated the conveyor for 240 pallets per hour with a conservative 80% standard design factor. The origination of this design factor is unclear. Let's assume the conveyor can operate at 300 pallets moves per minute when factoring speed and pallet spacing. Then the conveyor could operate at a higher rate than 240 pallets per hour – potentially 276 pallets per hour, if the SRMs can operate at their designed peak rate. Also mentioned is that the overall system handling rates will also be affected by:

- Pick slot replenishment or the number of manually picked pallets
- Pallet shuffling within same aisle
- Strictness of FIFO enforcement
- Aisle-to-aisle pallet moves

SRM Capacity

The SRMs are rated to handle 300 pallet moves per hour, based on a dual cycle operation. Dual cycle is defined as; the SRM alternates between pallet storage and pallet retrieval. Variability in the length of time required for the movements does not appear to be part of the design. The specification documents includes a statement that the extra SRM capacity, (600 – 480 = 120 pallet moves per hours), would help meet the required pick slot replenishment and aisle-to-aisle transfers. But the corrupting influence of variability impacts the SRMs more than anticipated:

- Variation in the process time means that the SRM Buffer may be unable to handle the queuing of pallets. Pallets will be bumped and re-circulated on the Main Conveyor Loop.

- Lack of variation in the product-type (SKU) arrival (i.e. batches) and the requirement to store in a home aisle means one SRM is heavily utilized for each truckload.
- Lack of aisle storing options for heavy pallets (pallets greater than 2,500 pounds), heat sensitive, or oils.

The actual performance of the system is a good indicator of how variation or lack of variation has impacted the operation.

3.2 Actual Performance

ES3 reports daily production numbers on new pallet put-aways, replenishment of tier picked slots, and pallet shipments. Figure 10 is a graph of the SRM throughput as a percentage of the designed facility capacity from June through early December 2004.

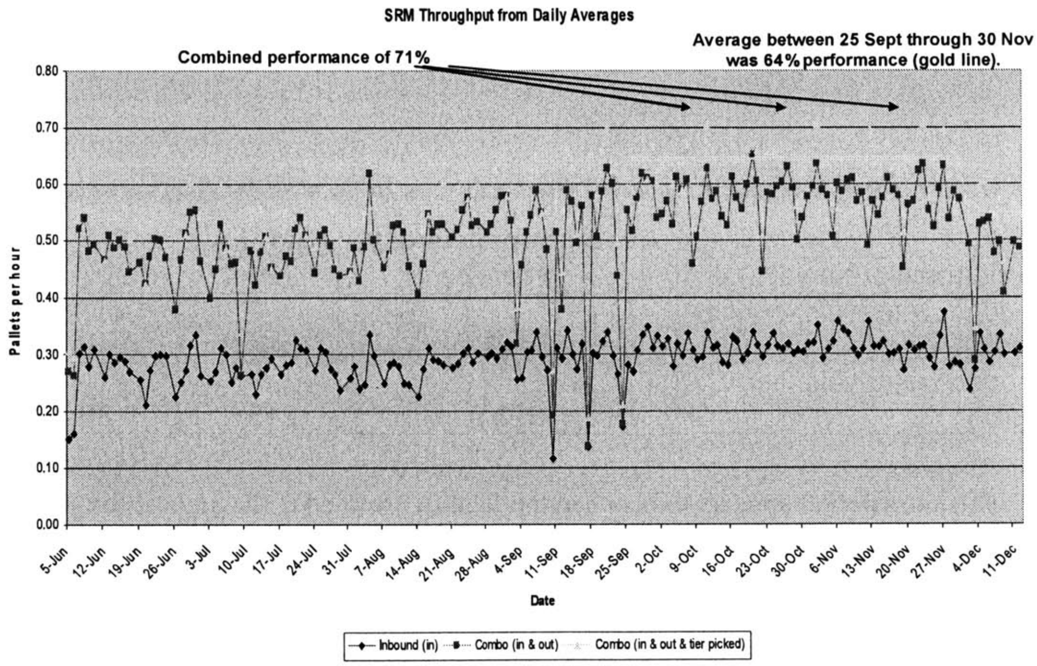

Figure 10 SRM Throughput Daily Averages

The graph presents the number of pallets per hour from a daily report. For example, the hourly pallet number was calculated from the daily total number put-away divided by 22 hours (the assumed operation day length). The hourly rates are used for this discussion because this is a common metric discussed within the company. The percentage numbers are actually optimistic, because often ES3 works 24 hour days to maintain this throughput.

The throughput requires a SRM movement for each new put-away, each replenishment, and each retrieval. Included in the analysis is an hourly average for tier picked pallets because SRM movements would be required to replenish the pick slots. Notice the best operating day for combined put-away and retrieval was 71% of the designed capacity. This occurred on three separate dates, 11 October, 2 November, and 23 November. The average inbound and outbound throughput rate was 63% of the designed SRM capacity for the entire period. The ideal would be to have an hourly reporting period to determine the best hours of operations and a true variance could be calculated.

The horizontal yellow line on Figure 10 represents one of the busiest seasons in the food industry – the Thanksgiving rush. The daily numbers are presented below for this period between 25 September and 30 November:

	Average (pallets/day)	Std Dev	CV
Inbound (new put-aways)	4114.2	291.4	0.07
Outbound (retrievals, not tier picked)	3449.8	504.2	0.15
Outbound (retrievals, tier picked)	823.9	215.9	0.26

This time period appears to be when the facility operated at the highest throughput with consistency, at a daily level, as evidenced by the low Coefficient of Variations. Also during this time, inbound trucks were backed-up and being stored within the yard because the system could not handle the number of trucks arriving. Even during this time period, the ASRS operated at only 64% of the designed performance level.

The SRMs are operating well below the inbound conveyor capacity of 240 pallets per hour; in fact the average at best was approximately 190 pallets per hour. So why is the conveyor operating below the 240 pallets per hour capacity? I hypothesize that the inbound operations are the bottleneck because of the delivery truck build-up in the yard and the system's ability to meet the outbound operation requirements. For determining the bottleneck within a warehouse operation, Mark Kosfeld[4] recommends graphing the equipment utilizations over time and the piece of equipment that reaches 80% utilization first is the system bottleneck. ES3's ASRS system is too complex for using this analysis because of the internally transferred product, the build-up pallets within the SRM buffers, the SRM process time variations, the different number of allowable hold zones on the main conveyor loop, and the possibility of re-circulated pallets. The complexity of the system will be explored in detail in Chapter 6 by using a Causal Loop Diagram.

3.3 Storage Capacity to Warehouse Operations

The ASRS capacity analysis assumes the warehouse has adequate storage positions available for the product received. Once the warehouse begins to reach storage capacity, new system dynamics delay the Inbound operations of the ASRS. A discussion of the storage capacity is discussed in Chapter 6.

[4] Kosfeld, "*Warehouse Design Through Dynamic Simulation*", page 1051 of Winter Simulation Conference Proceedings

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4.1 Suggested Design Improvements

The operations team developed a list of suggested design improvements to be incorporated in Tower II, with the potential to be added into Tower I. The two ideas the team felt would significantly improve operations were:

- Increase SRM buffer size from 3 to 6
- Decrease cycle time of Cross-Over Station

The team also wanted to increase their system intuition. The belief was as the system was modeled and studied; new ideas for improvements would materialize. The new ideas could be tested with the same model or a derivation of the model. This created an extra level of tension between the model complexity and the utility. See section 4.10 for a more detailed discussion.

The operations team developed the suggested improvements believing there would be a significant impact gain in throughput. The operations team had a very thorough knowledge of the ASRS and the feedback interactions. Their insight was critical in the development of the Inbound Production Shortfall Casual Loop Diagram, a detailed cause and effect diagram that highlights the why the production is short. The Casual Loop Diagram (CLD) is discussed in Chapter 6. The CLD is classified as a Descriptive Model and is an effective way to communicate the real world system. Despite the deep understanding, the operations team could not state an actual improvement gain or even guarantee an increase in throughput. The operations team wanted a thorough way to flush their ideas and that's when simulation modeling was suggested.

4.2 Why Discrete-Event Simulation Models

Simulation is a modeling and analysis technique commonly used for evaluating improvements or developing new insights for dynamic systems. Simulation is not the only solution for solving dynamic systems and the following general guidelines for selecting simulations have been suggested[5];

[5] Harrell, Simulation Using Promodel, page 12

- An operational decision is being made.
- Process is well defined and repetitive.
- Activities and events exhibit some interdependency and variability.
- Cost impact of decision is greater than cost of building and running simulation.
- Cost to experiment on the actual system is greater than cost to build and run simulation.

The ES3 operations team believed that the requirements presented by Harrell had been satisfied.

Several types of simulations exist, but a discrete event simulation seemed the most appropriate type of modeling application because it could incorporate the numerous feedback loops required to ensure appropriate modeling. Discrete event modeling is time based, and takes into account all the resources and constraints involved, and the way these things interact with each other as time passes.[6] This is important, because the complexities of the feedback made it difficult to determine the true impact of suggestions. Figure 11 is a logic diagram of a typical discrete-event simulation.[7]

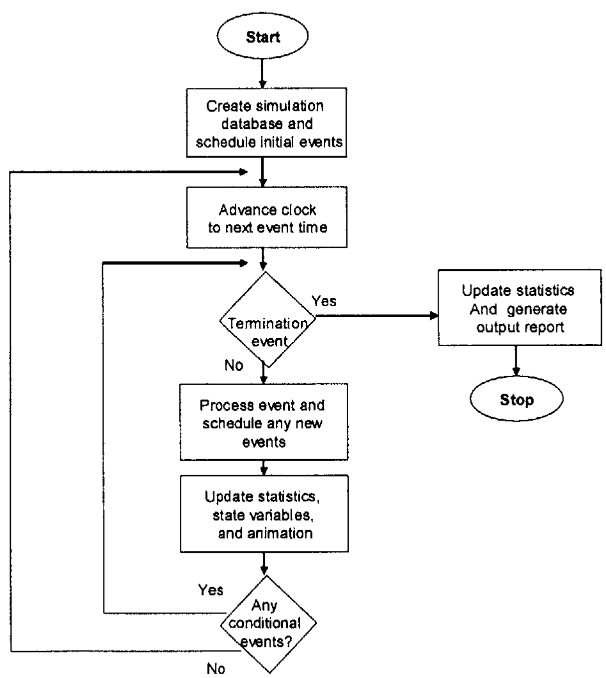

Figure 11 Block Diagram of Discrete-Event Simulation Logic

[6] Harrell, Simulation Using Promodel, page 57
[7] Harrell, Simulation Using Promodel, page 57

A discrete-event calculation could be completed by hand calculations, but the amount of data that would be stored and manipulated dictates a computer should be used.[8] Law and Kelton offer the following explanations on the widespread popularity of discrete-event simulation[9]:

- Most complex, real-world systems cannot be described by a mathematical model which can be evaluated analytically.
- Simulation allows one to estimate performance under some projected operating conditions.
- Alternative designs can be compared.
- Maintain better control over experimental conditions, as compared to experimenting with actual system.
- Simulation can be used to observe a system over a long time frame.

The ES3 operations team selected discrete-event simulations as the appropriated modeling technique. Several things the team wanted to capture included; the re-circulation created by exceeding the maximum hold zones, the maximum number of pallets allowed to be en route to a SRM, the impact of Cross Aisle Transfers, the impact of Spur 4, and the ability to adjust the number of SRM Buffer Zones and cycle times on equipment. The specific simulation software, SIMUL8, was chosen because of my working knowledge and the academic version appeared to be less limited than other packages. Also, SIMUL8 provided the ability to quickly change parameters and run numerous trials, which was extremely attractive.

4.3 Generic Modeling Process

The roadmap for modeling at a high level is presented by Figure 12. The iterative nature of modeling is important to note. Pritsker and Pegden (1979) describe the iterative nature[10]:

"The stages of simulation are rarely performed in a structured sequence beginning with problem definition and ending with documentation. A simulation project may

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[8] Law, Kelton, Simulation Modeling and Analysis, page 4
[9] Law, Kelton, Simulation Modeling and Analysis, page 8
[10] Pritzer, Pegden Introduction to Simulation and SLAM

involve false starts, erroneous assumptions which must later be abandoned, reformulation of the problem objectives, and repeated evaluation and redesign of the model. If properly done, however, this iterative process should result in a simulation model which properly assesses alternatives and enhances the design making process."

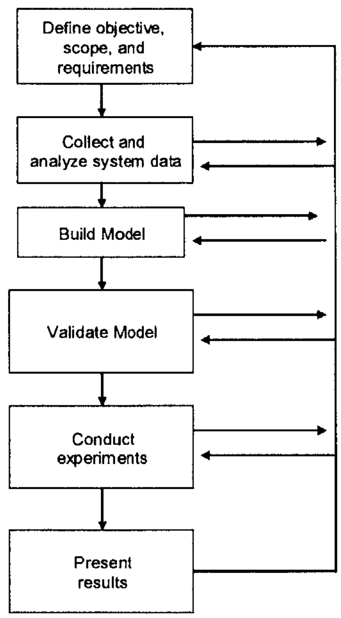

Figure 12 Block Diagram of Simulation Process[11]

The iterative nature of the modeling process cannot be emphasized enough. The importance of establishing the scope and defining the objective is extremely important. It has been suggested by some modelers to set this in writing and review it often during the building and validation stages. In actual application, returning between the validation stage and the data collection stage occurred more often than expected. For example, I initially assumed the inter-arrival rate of the Cross Aisle Transfers was somewhat consistent from hour to hour. I found that the model throughput performance was extremely sensitive to the inter-arrival rate and I had to filter my data to determine the inter-arrival rates of the CATs for each hour I examined. There exists a trade-off between tightening the prediction error of the model and the time required to improve

[11] Harrell, Ghosh, Bowden, Simulation Using Promodel, page 82

the model. During my simulation modeling experience, I recorded the approximate percentage of time required for each stage. Please refer to Section 4.10 for a thorough discussion.

4.4 ASRS Models

ASRS is commonly modeled using simulation. The system designer for ES3 used a software package, AutoMod. This software package provides three-dimensional graphics that represent the actual operations in a nice visual manner. But any specific modeling application requires countless hours and dedication to model the specific operation accurately.

Common modeling inputs for ASRS systems include[12]:

- Number of Aisles
- Number of SRM
- Rack configuration
- Bay or column width
- Tier or row height
- Input point
- Output point
- Zone boundaries based on activity
- SRM machine speed and acceleration/deceleration
- Pickup and deposit times
- Downtime and repair time

Common modeling performance measures for an ASRS system[12]:

- SRM utilization
- Response time
- Throughput capability

Common decision variables[12]:

- Rack configuration
- Storage and retrieval sequence and priorities

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[12] Harrell, Ghosh, Bowden, Simulation Using Promodel, page 310-311

- First-in, first-out or closets item retrieval
- Empty SRM positioning
- Aisle selection (i.e., random, round robin, etc)

Typical questions in a simulation ASRS[12]:

- What is the required number of aisles to handle the load?
- Should storage activity be performed at separate times from retrieval activity?
- How can dual cycle be maximized?
- What is the best stationing of empty SRM to minimize response time?
- How can activity zoning improve throughput?
- How is response time affected by peak periods?

Two important aspects of ES3's system not captured in the common modeling techniques is the arrival of batched material and the picking slot replenishment activity. Material arrives from one manufacturer at a time, and usually only one product type (or SKU) per truck. The picking slot replenishment is the primary driver for transferring the pallets internally. ES3 was primarily focused on increasing throughput. The following are our model inputs, measurements, controls, and questions:

ES3 Inputs (all based on actual data):

- Equipment cycle time
- Equipment Mean-Time-to-Failure and Mean-Time-to-Repairs
- Equipment Speed
- Aisle Selection distribution (based on actual data)
- Cross-Aisle Transfer (CAT) arrival rate
- Entry decision for CAT and Spur 4 pallets onto Main Conveyor Loop

ES3 measurements on performance and validation (Objective):

- Throughput
- Number of re-circulated pallets
- SRM utilization

ES3 decision variables:

- Maximum en route counter
- Maximum hold zone
- SRM Buffer size
- Cycle time for cross over station
- Aisle Select decision (see Section 4.9)

ES3 questions:

- What is the impact to throughput for the suggested design improvements?
- How can we improve operations?
- What new insights are gained from modeling?

4.5 Important Distinction between New Design and Existing Operations

ES3 is a company that collects and filters a lot of data. Their decision making processes are data intensive and focus on what the numbers tell them. When designing the York Facility, several operational assumptions were made as a starting point. The modeling provided a great opportunity to increase the team's understanding of the system to help verify or change the operational assumptions. The team was sensitive not to criticize the original project management team who coordinated the construction and layout. Criticizing now would not be appropriate because everyone has hindsight vision of 20-20 vision. Since the building has an established operational history; we have a lot of data to assist in validating our assumptions. This should be celebrated because ES3 should be able to proceed with even more confidence on the recommendations uncovered.

4.6 Critique of Simulations

Although simulation is a widely used operations research technique and despite its growing popularity, there are impediments to why it is not more widely accepted. Law and Kelton express impediments for why the modeling technique is not even more widely accepted.

- Models used to study large-scale systems tend to be very complex time consuming to build, and are often expensive.[13]
- Models used for complex systems require an extensive amount of computer time.[14]
- Models are used to obtain "the answer" and neglect the inferences that can be drawn about the system from a properly coded model.[15]
- A greater confidence is placed in the model than is justified because of the large volume of numbers produced by a simulation study.[15]

4.7 ES3's System: Inbound Operations to be modeled (third level)

A simulation model was developed that focused on the Inbound operations on the third level. Actual data from the York Facility was used as much as possible for the process times and distributions of aisle assignments for the pallets. The data collected was during a 4 hour period of time on 15 September. A detailed discussion of the data collection and the validation of the model is presented at the end of this Chapter in section 4.10. Presented as Figure 13 is the conveyor portion of the "Inbound Main Conveyor Loop" reviewed in Chapter 2.

Exert from "Inbound Main Conveyor Loop – Figure 6"

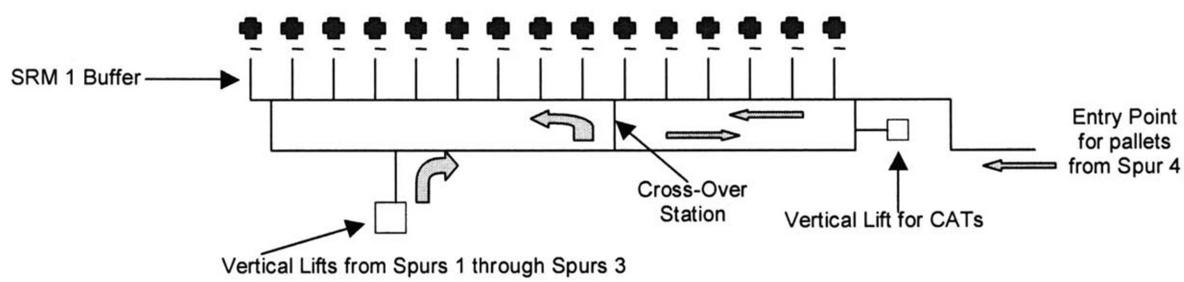

Figure 13 Inbound Main Conveyor Loop (partial)

The team decided to focus on the inbound operations conducted on the third level because a build-up of pallets appears at the Cross Over Station and by the SRM buffers (on the

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[13] Law, Kelton, Simulation Modeling and Analysis, page 2, 8
[14] Law, Kelton, Simulation Modeling and Analysis, page 2
[15] Law, Kelton, Simulation Modeling and Analysis, page 2

main conveyor). Also, the ASRS complexities, such as the en route counters and maximum hold zones, are focused within this portion of the ASRS. The operations team was confident they could manage the upstream forklift operations to ensure that the third level always had consistent arrival of pallets.

4.8 Review SIMUL8 Modeling Techniques

Unique properties of SIMUL8 provided challenges. SIMUL8 is an object based modeling program. The objects are organized as; work entry point, work center, storage queue, conveyor, or work exit point. They are shown here as Figure 14, SIMUL8 Objects.

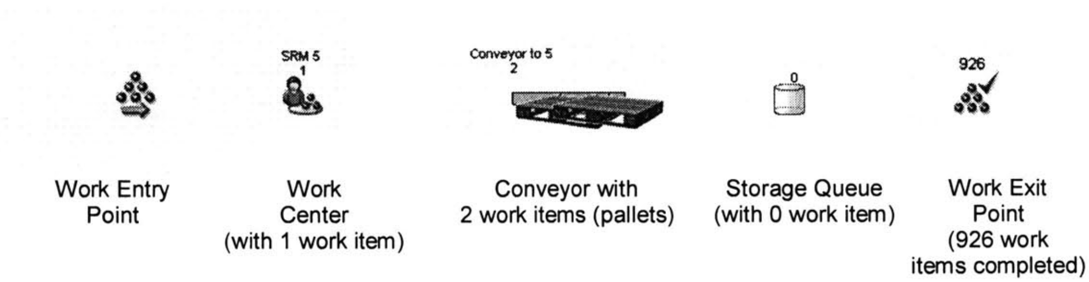

Figure 14 SIMUL8 Modeling Objects

The physical appearance of the model is similar to the actual York Facility layout, but several programming options could only be accomplished with particular objects. For example, Visual Logic commands cannot be attached to the conveyor object. Therefore, the simulation model has to use other objects, such as work centers, in order to use Visual Logic. The simulation model will appear very similar to the actual layout, but at some critical junctions, another modeling object will be used instead of a standard modeling choice. SIMUL8 is a powerful modeling tool, but this limitation can hinder effective communication. People not forewarned may be quite confused when reviewing the model.

4.9 The Inbound Model for York and Data Discussion

The Inbound Operations Model built with SIMUL8 is shown below as Figure 15. The image is copied from the monitor screen.

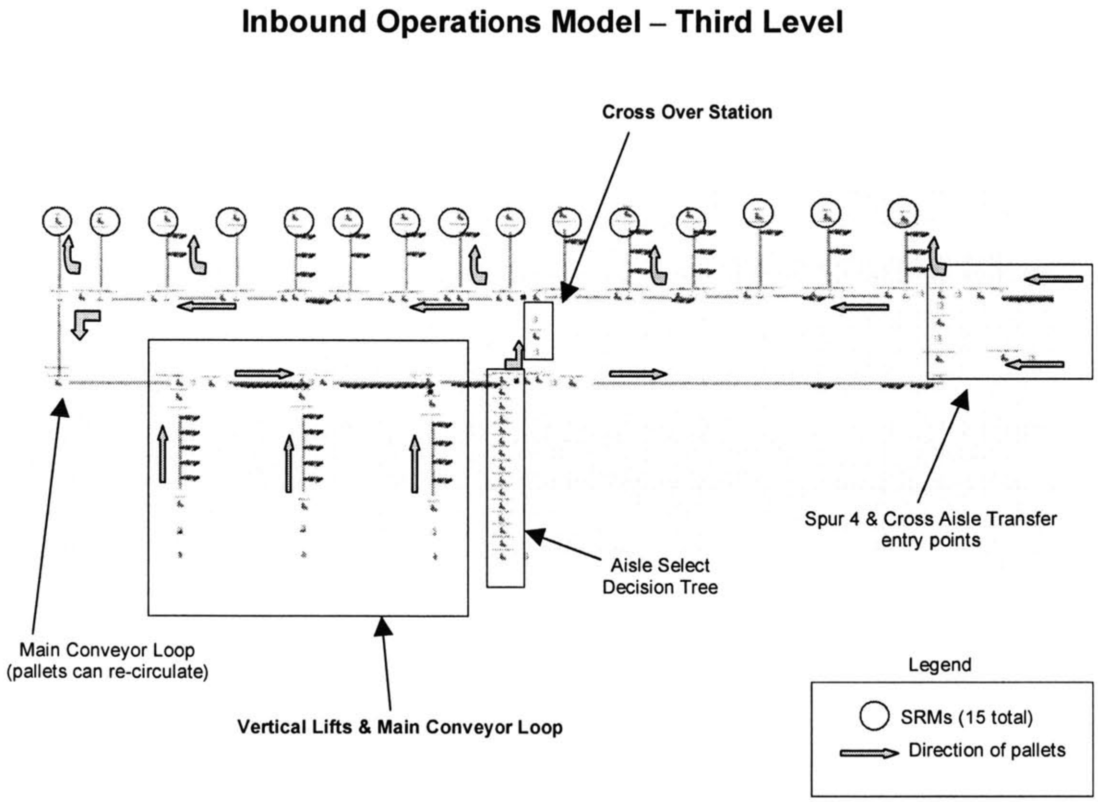

Figure 15 Inbound Operations Model from SIMUL8

Notice the similarity in appearance between Figure 13 and Figure 15. Highlighted in the model are the following key elements: the vertical lifts from the second level (from Spurs 1 through Spur 3), the aisle select decision point, the cross-over station, work entry point from Spur 4 and work entry point for Cross Aisle Transfers, and the Main Conveyor Loop. The following sections are blow-ups of the boxed sections in Figure 15.

Vertical Lifts and Main Conveyor Loop

Figure 16 is an image pulled from SIMUL8 of the 3 vertical lifts from Spurs 1 through Spur 3 and the Inbound Main Conveyor Loop.

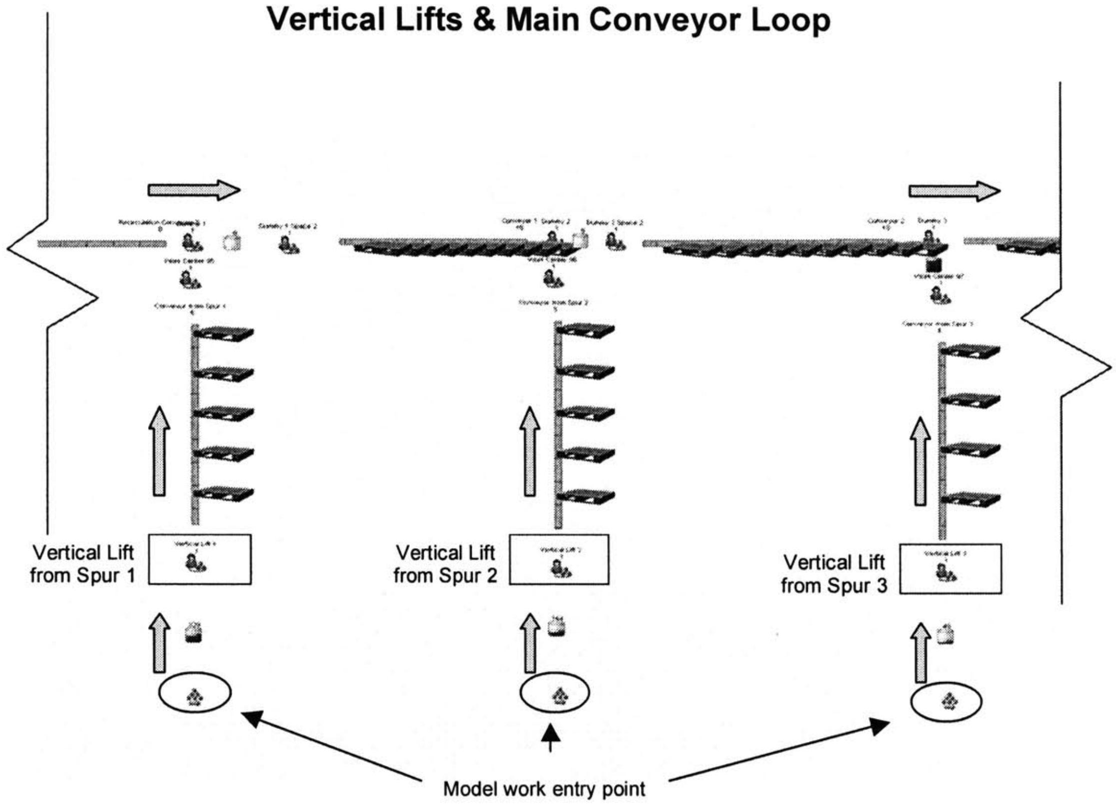

Figure 16 Vertical Lifts & Main Conveyor Loop from SIMUL8

The model has 3 work entry points that represent the 3 induction spurs. The work item for the model is shown as pallets. The arrival process was assumed to be Poisson and the work was set to enter at an exponential inter-arrival rate of 0.8 minutes, or an average of 75 pallets an hour. The vertical lifts were set to cycle at 40 seconds as observed and the conveyor speed throughout the model was set at 60 feet per minute. The build-up of pallets along the three main feeder conveyors was typical.

Cross Over Station & Aisle Select

Figure 17 is a blow-up image pulled from the simulation model, Figure 15.

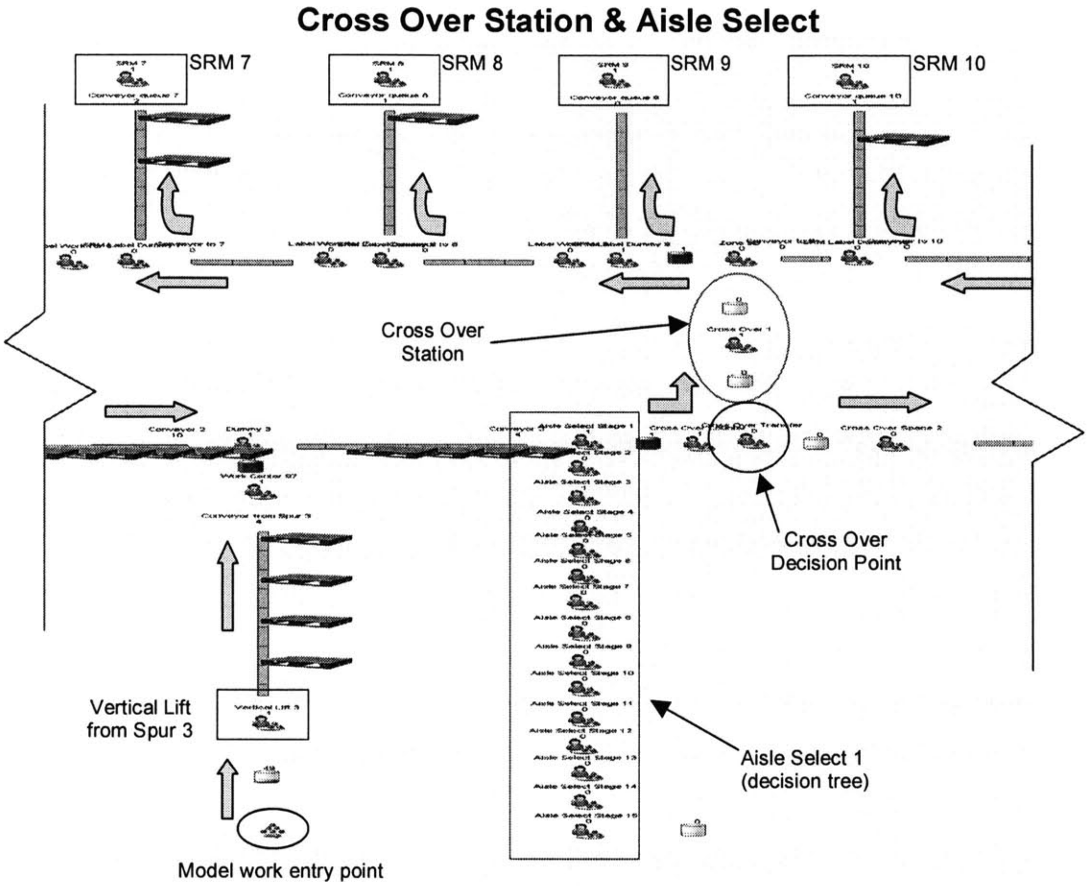

Figure 17 Cross Over Station & Aisle Select from SIMUL8

It is provided to highlight the Cross Over Station and Aisle Select. The Aisle Select is the location where EMS decides on the aisle assignment for each pallet. EMS first attempts to assign a pallet to the home aisle or preferred aisle because of the pick-slot replenishment requirement. The aisle is assigned to the pallet by attaching a "label" that will be used for routing throughout the model. The Aisle Select 1 Decision Tree is an attempt to model the number of decisions the EMS cycles through before deciding upon an aisle assignment. The Visual Logic looks at the maximum en route counter to determine if another aisle should be assigned. If the maximum en route occurs, the pallet travels to the next lower work center for another aisle assignment (by attaching a different label). Currently, ES3's operations team does not know the number of pallets assigned to their non-home aisle. The modeling is an attempt to determine this parameter. Figures 18, 19, 20, and 21 are the final Aisle Selected percentages actually experienced at York between 0700 and 1100 AM on 15 September 2004. The low percentage of pallets assigned to Aisles 1 through Aisles 3 is interesting. One manager noticed this on a daily basis and summarized it as, "The York Facility behaves as two buildings, when a large shipment of heavy pallets is delivered, Aisle 1 through Aisle 3 is very busy and the others not so. While during normal deliveries, Aisle 4 through Aisle 15 is very busy and Aisles 1 through Aisle 3 are not busy."

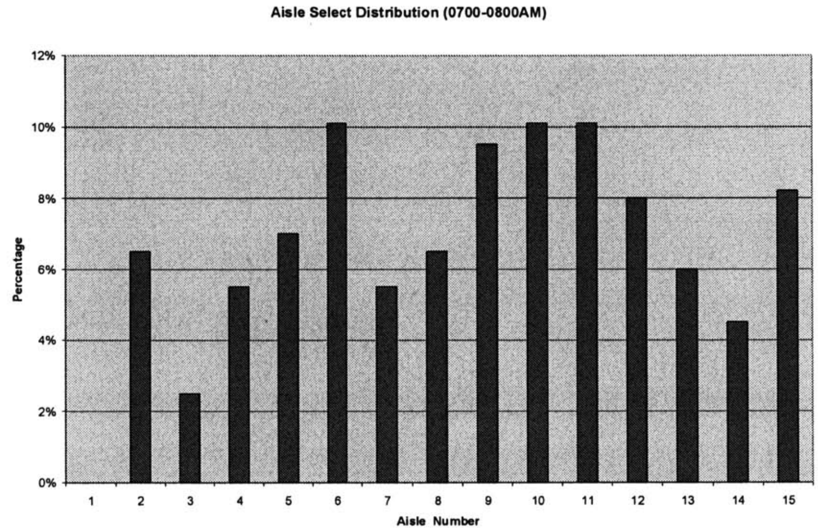

Figure 18 Aisle Select Distribution 0700-0800AM

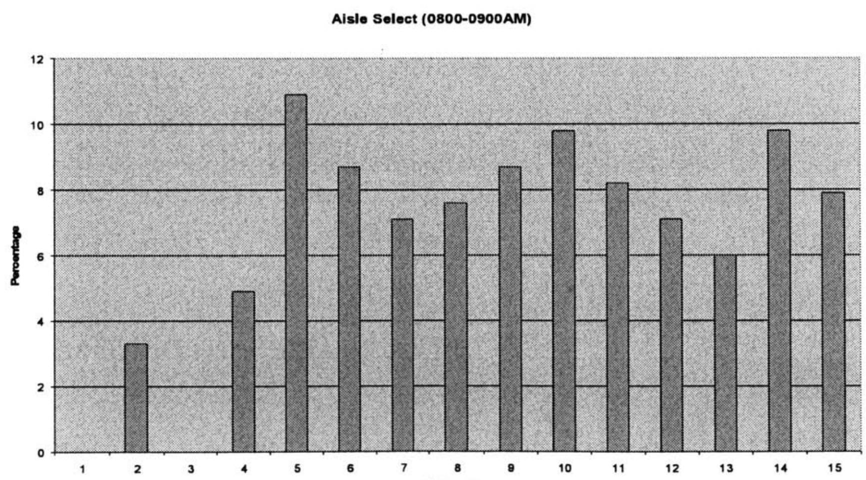

Figure 19 Aisle Select Distribution 0800-0900AM

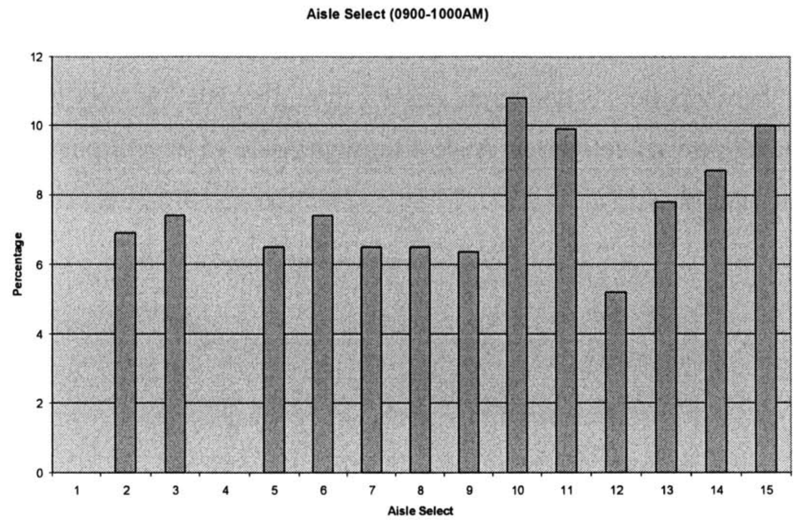

Figure 20 Aisle Select Distribution 0900-1000AM

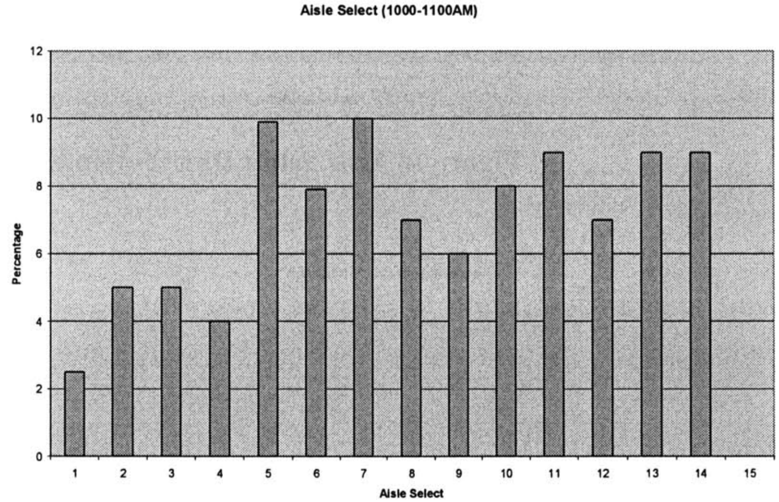

Figure 21 Aisle Select Distribution 1000-1100AM

In real life, the Cross-Over Decision Point is where EMS routes the pallet based on the aisle assignment. In the model, the Cross-Over Decision Point reads a routing label for directing the pallet across the conveyor via the Cross Over Station or along the Main Conveyor Loop.

The Cross-Over Station is modeled to cycle at 19 seconds. Also built into the model is a delay for pallets traveling the far side of the Main Conveyor Loop. This was added because the chain-driven cross-over station cannot allow pallets to travel along the far-side as another pallet is being transferred. Thus the far pallets have to wait the entire cycle.

Spur 4 and Cross Aisle Transfer Entry Points

Figure 22 is blow-up image pulled from the simulation model, Figure 15. It is provided to highlight Spur 4 and Cross Aisle Transfer entry points.

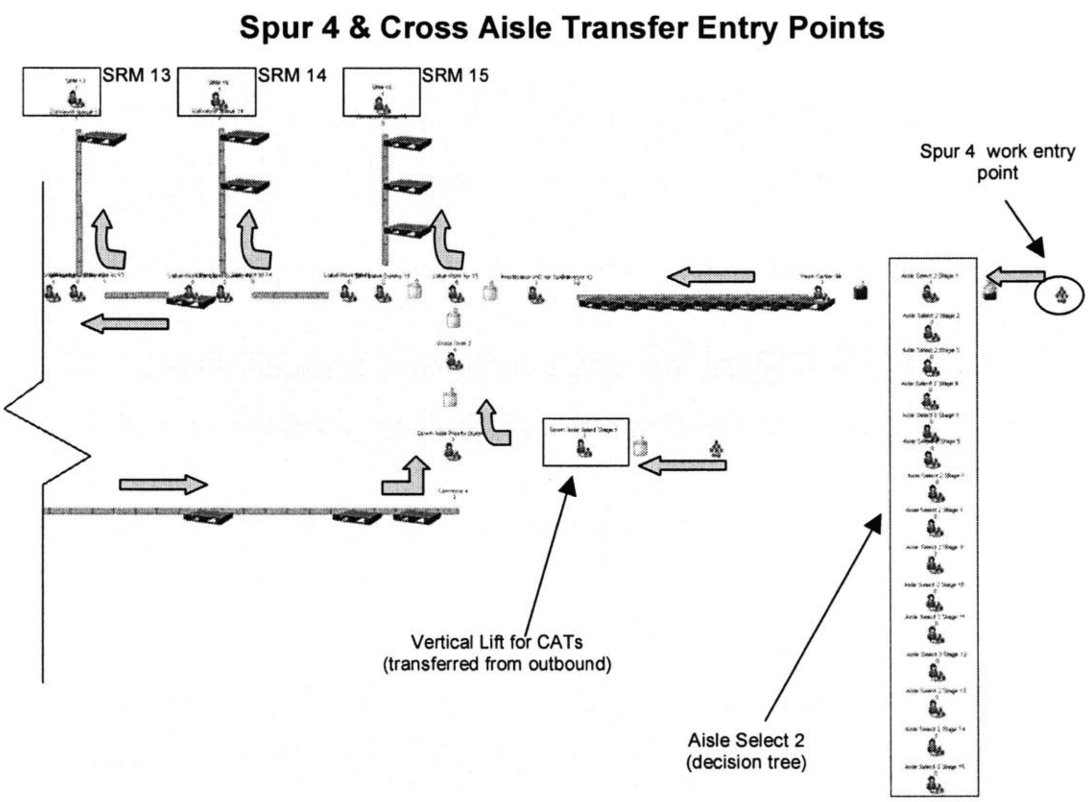

Figure 22 Spur 4 & Cross Aisle Transfer Entry from SIMUL8

Work items from Spur 4 are modeled with an exponential inter-arrival rate of one minute, thus averaging 60 pallets per hour. The Aisle Select 2 Decision Tree uses the same logic and aisle assignment distributions described for Aisle Select 1. The pallets arriving from Spur 4 are allowed to enter the Inbound Main Conveyor Loop after two pallets from Spur 1 through Spur 3 have passed.

Real data was downloaded to model the arrival rate of Cross Aisle Transfers (CATs) within the actual system. The system experienced an average of 28 CATs during the 4 hour period modeled. The real inter-arrival time distribution between 0700 and 0800 AM is presented as Figure 23. The distributions for the other three hours follow a similar pattern.

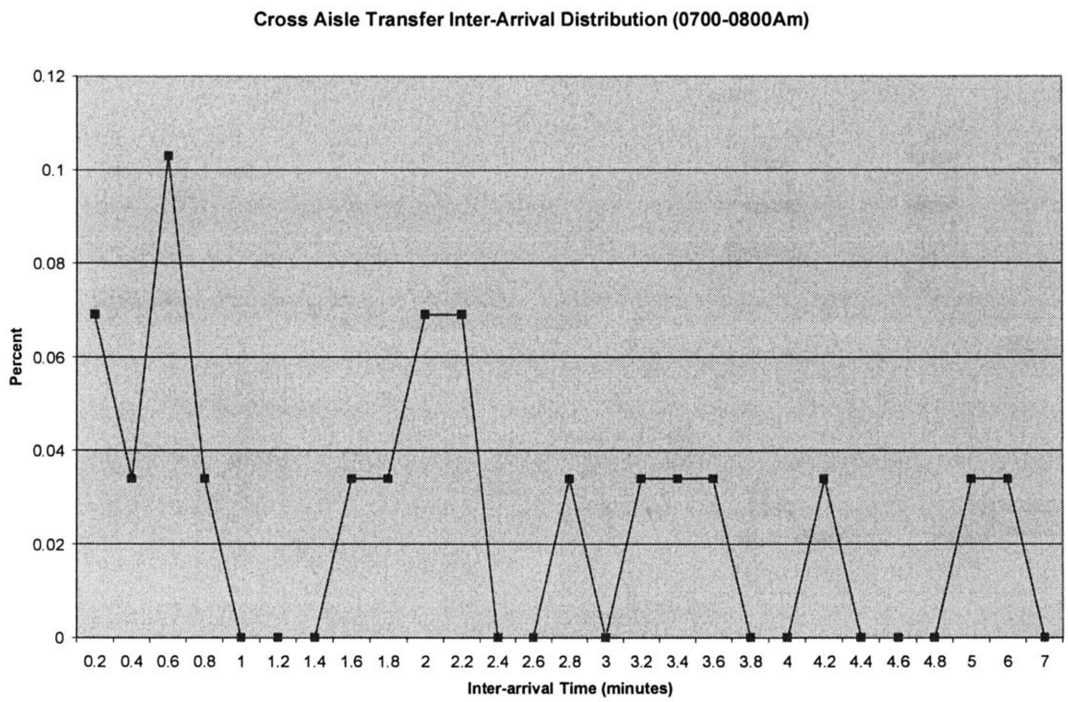

Figure 23 Cross Aisle Transfer Inter-Arrival Distribution

SRMs

Modeling the SRMs' performance was a critical issue because they were considered the bottleneck for the operation. ES3 tracked the SRMs on a weekly basis with a SRM Utilization Report. This provided a great source of data on their performance. The ASRS would experience a significant number of false breakdown errors. The false errors would be triggered by poorly attached shrink wrap and cause the SRM to trip into error mode. The SRM would not operate until a maintenance person, known as a fault chaser, would reset the machine. This could take several minutes. The maintenance personnel made significant improvements to several SRM detection settings so they would not be as sensitive to false errors like this. Presented below, as Table 1, is a table of actual performance data at an aggregate level for the period between 28 March and 19 June 2004.

28 March - 19 June 2004

	Average
UTILIZATION - Util minutes/total minutes	67.6%
TOTAL ERRORS	94.6
MTTFwc (minutes & running workclock)	119.6
MTTFop (minutes & based on util time)	82.9
MTTR (minutes)	9.95

Table 1 SRM Report

The $MTTF_{wc}$ is the mean-time-to-failure[16] based on a continuous running clock (or workclock). This is important to calculating SRM efficiency, which is a more common modeling input. The $MTTF_{op}$ is the mean-time-to-failure based on the time the SRM is actually in use. This would be more important to understanding the scheduling of maintenance when based on hours running. MTTR is the mean-time-to-repair[16] or reset in case of false errors. Because the maintenance crew made significant strides on decreasing the false errors, the SRM performance improved and the following SRM efficiency and MTTR was used as inputs into the simulation model.

MTTFwc (minutes & running workclock)	128.1
MTTR (minutes)	7.3
SRM efficiency	94.3%

The data used to determine the 15 SRMs process times was not readily available. Mixed into the data for each SRM was their idle time and breakdown time. The best data for determining the SRM process time was the inter-arrival rate of pallets to the Inbound P&D Station. This also presented a problem of corrupting data with the inclusion of pallet arrivals not waiting in a queue (SRM was idle). It was decided to discard any arrival data higher than six

[16] Hopp, Spearman, Factory Physics, pages 255-258

minutes. This was chosen because there appeared to be a natural break in the data. This potentially jeopardizes the integrity of the analysis, so this was considered during the validation test. The inter-arrival rate ranged from 0.8 minutes to approximately 4.5 minutes for the 15 SRMs. Figures 24 through 27 are several graphs of the inter-arrival rates or what were decided to be good indicators of the SRM process time.

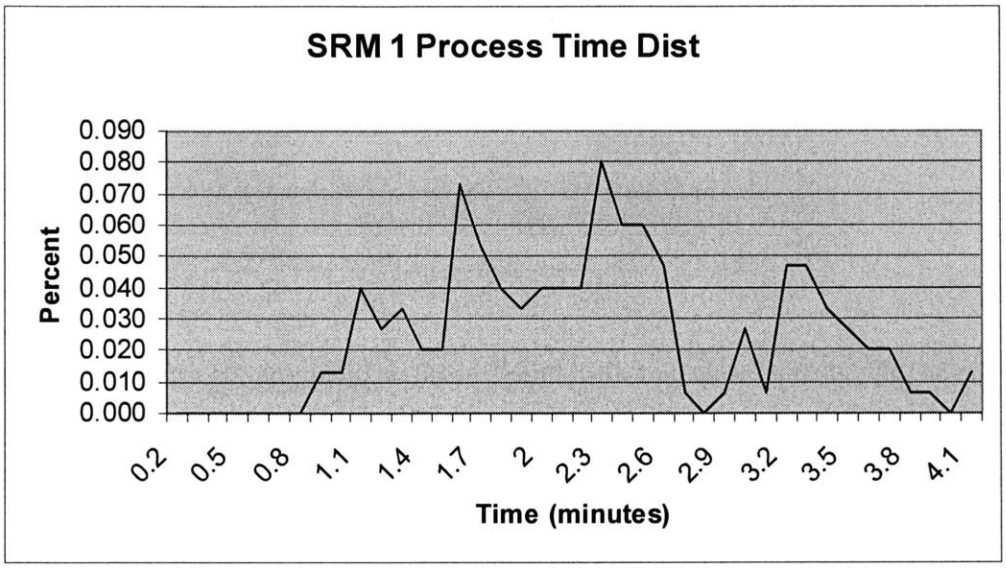

Figure 24 SRM 1 Process Time Distribution

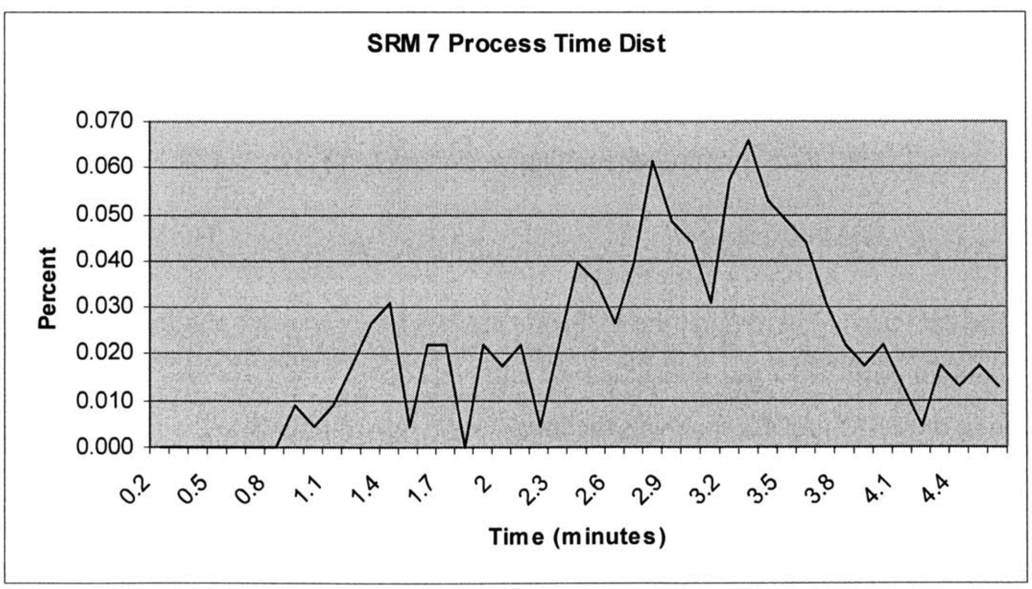

Figure 25 SRM 7 Process Time Distribution

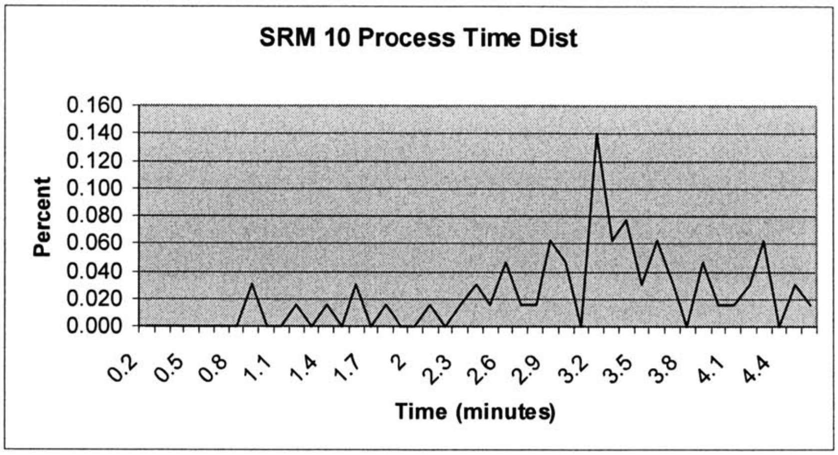

Figure 26 SRM 10 Process Time Distribution

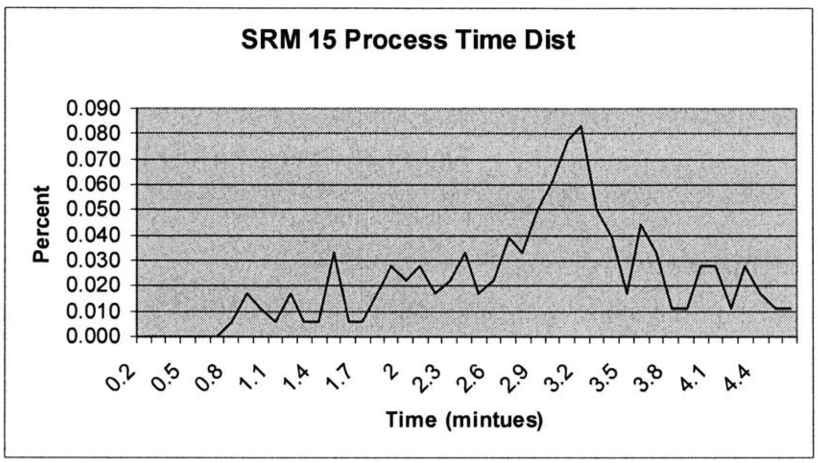

Figure 27 SRM 15 Process Time Distribution

The majority of the SRM process distribution times were similar in shape, with an average of 3.3 minutes, as presented with SRM 7 and SRM 15. SRM 1's process distribution time was the only one with a dissimilar shape, with an average of 2.6 minutes. SRM 10 had the highest average of 3.8 minutes.

A blended SRM process time was decided upon and was used for all 15 SRMs in the model. Figure 28 is a graph of the Average SRM Process Time Distribution.

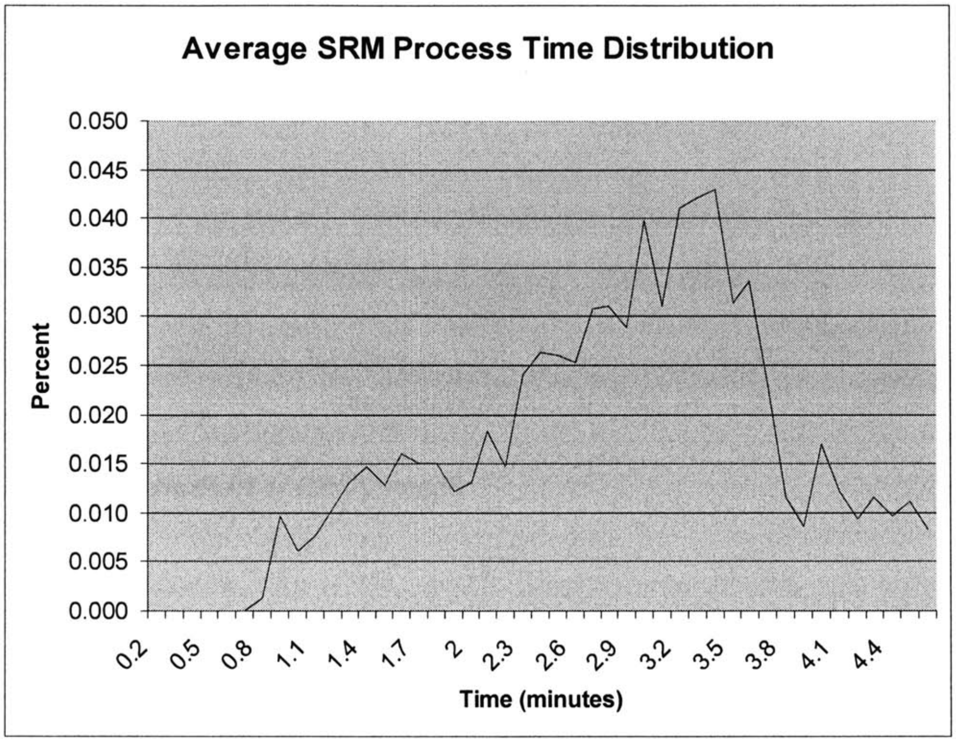

Figure 28 Average SRM Process Time Distribution

4.10 Validation Discussion

The validation of the model was time consuming but critical for getting buy-in from the different parties. Determining whether the model accurately represented the system was the most time consuming stage of the modeling process. During literature research some confusion of terminology was discovered between verification and validation. Law and Kelton suggest the following definitions[17];

- Verification – Determining whether a model performs as intended (i.e. debugging the computer program).
- Validation – Determining whether a model accurately represents the real-world system.

In general, the verification technique was completed in stages. First a simple model was constructed with basic assumptions, than run to verify that it worked. When introducing a new

[17] Law, Kelton, Simulation Modeling and Analysis, page 333-334

code for routing or work process distribution, the model would be re-run to ensure the code worked appropriately. This explanation of code verification matches well with Figure 16, the iterative nature of modeling processes.

The validation process was straight-forward in concept but difficult in execution. Figure 29 shows the "calibration" steps during validation.

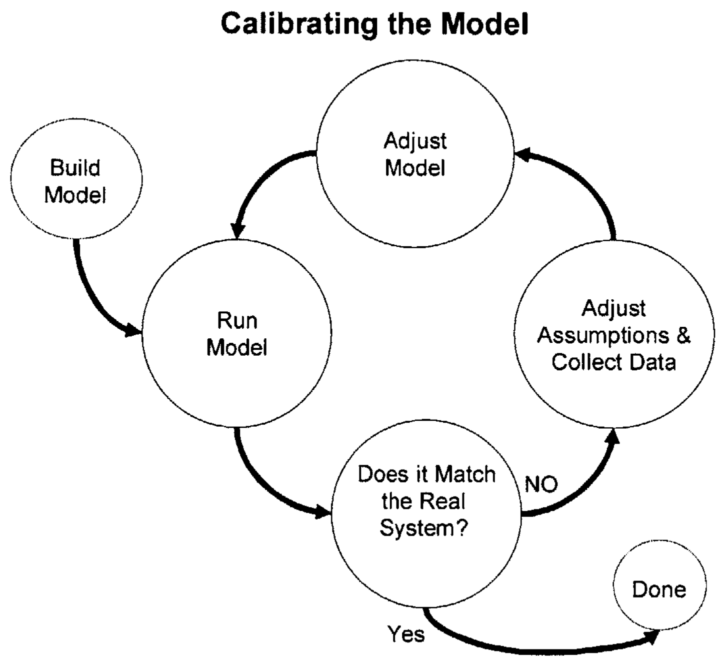

Figure 29 Calibrating the Model

Again, the diagram shows the iterative nature of modeling. Law and Kelton suggest "calibrating" a model with one set of historical data. The modeler will continually adjust assumptions and adjust the model to match the historical data. Another set of historical data is recommended to be used for the validation.[18] The "Does it Match?" step might look simple but it is very important. The modeler has to determine how close to matching the observed system – within 30%? 20%? 10%? 'What we are seeking is not certainty but rather a comfort level in the results.'[19] I followed this process when building and validating the ES3 simulation model.

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[18] Law, Kelton, Simulation Modeling and Analysis, page 343
[19] Harrell, Ghosh, Bowden, Simulation Using Promodel, page 182

The two primary measurements agreed upon during the initial phase of the modeling process were throughput and recirculation. The model was developed for examining how the system performed during peak operations. As discussed in Chapter 3, mid-September was a time when the ASRS throughput was consistently high. Although the system averages 189 pallets per hour new put-away, the team felt the appropriate timeframe to measure the impact of design improvements would be during peak operations. The belief was this time period would be easier to model because conveyor downtime, vertical lift downtime, and shift changes would not have to be factored. Also, the team felt this level of throughput could be obtained through efficient change over at shifts and through efficient forklift operators.

The two sets of historical data, one used to calibrate and one used to validate, downloaded from ES3's EMS system had similar throughputs and re-circulation results but very different Aisle Assignment Distributions. The different Aisle Assignment Distributions displayed the dependence of SRM use by which type of product was being received or shipped in that particular time period.

The following table is a comparison between the actual and modeled objectives.

	Actual Data (09/15/05)	**Model Prediction (w/C.I.)**	**Relative error**
Throughput	867	911.8 (+_0.1%)	5.3%
Recirculation	116	110.5 (+_0.8%)	5.5%

Table 2 Baseline Simulation Results

The real question is how to compare the simulation model results with the real system results. The two types of error concerned with;

- Error associated with the model's estimated throughput mean matching the model's true mean. In my model, this error was within 1% for both throughput and recirculation.
- Error associated with the model's estimated throughput mean matching the real system mean.

The model produces a 95% confidence interval for the model's true mean. The model built could run individual runs per trial very quickly, approximately 30 seconds per run. A high number of runs, 800, were set to tighten the confidence interval for the trial. The fact that a model can run very quickly is an advantage. The advantage helps during both the "calibration" and the validation stages.

A prediction error for the simulation model was estimated by a comparing the real system mean with the furthest confidence interval limit divided by the real system mean.
The prediction error in the model was 6% for both throughput and re-circulation. Presented here is the formula I used for calculating my prediction error:

$$(ActualThroughput - ModeledThroughputHigh) / ActualThroughput = (867 - 912.9/867) = 5.3\%$$

$$(Actual\mathrm{Re}circ - Modeled\mathrm{Re}circLow) / Actual\mathrm{Re}cird = (116 - 109.6/116) = 5.5\%$$

A more reliable approach would be to use a confidence interval approach as described by Law and Kelton.[20] But this approach potentially requires a large amount of data from the real system and the model. Collecting data from ES3's EMS was difficult. Downloading the data interfered with actual operations, for the database system accessed is the system tracking the pallet movements through the facility.

Because data collection is often difficult and creates limitations, Law and Kelton discuss a common approach used by most simulation practitioners, an inspection approach. The approach directly compares the model statistics with the real world system statistics, without the use of a formal statistical procedure (t-test, two-sample chi-square, Mann-Whitney, etc.) [20]

The ES3 team was satisfied that the model represented the Inbound system with the simple validation approach. Significant model development time may have been saved with an upfront discussion of how closely the model should match the system. I estimate that trying to improve the model from matching within 9% to within 6% took an additional 40 hours of work. The throughput performance gap of the actual system, as compared to the designed system, is

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[20] Law, Kelton, Simulation and Modeling Analysis, 343-345

21%. The team wanted to uncover improvements that would close the performance gap significantly, by at least 10%. The low 6% prediction error increased our confidence of the model's ability to predict performance improvements of that magnitude.

Overall I spent approximately fourteen weeks defining and building the simulation model for ES3. I believe this time would have been approximately 35% shorter, if I had been fully trained on the simulation software package. The different stages of building a model as percentages of time expended are estimated to be:

- Define scope and Process Mapping 7%
- Data Collection 14%
- Build Model 43%
- Verify Model 14%
- Validate Model 21%

The percentages are an approximation because I did repeat steps and constantly verify the model as updates were made. I did find that it was important to verify the model after every intermediate update. It was easier to track down programming errors when a minimum of updates had been inputted. Also, it did seem worthwhile to attempt to validate the model once a crude model had been built. The validation step helped confirm that at least I was on track with the magnitude of the results, even though the initial results had approximately 30% predictive error.

Another important aspect already discussed is trying to find the right balance between time required to build the model and accuracy. I constantly had to decide whether the model was good enough for understanding the system and for measuring our recommendations. For example, I built one model that was within 8% error of the system before I realized that the pallets from Spur 4 allow two pallets on the Main Conveyor Loop. After I adjusted for this indexing, the model was only within 14% error. Because pallets bound for all SRMs enter from Spur 4, it did seem important that the model accurately reflect the true indexing behavior of the system. But the time required to update the model can be quite extensive, so I believe it is important to have clear expectations on the confidence of a model.

4.11 Modeling; Complexity and Utility

Complexity with simulation models and the time required to build a detailed model is worth discussing. The power of a model is a function of its simplicity rather than its complexity. Lou Kelton at Promodel has expressed the relationship between the complexity of a model and the utility of a model with the Laffer curve, borrowed from economics.[21]

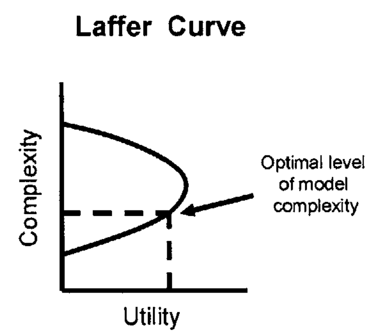

Figure 30 Laffer Curve[21]

The curve describes the balance between the two, and the fact that some complexity is required to capture the cause and effect relationship within a system. The optimal level of model complexity is when the model utility is "good enough". After a certain complexity point, the model's utility starts to diminish. I found this to be true because the model becomes too rigid and it cannot be easily converted to measure a new parameter. As the team developed new ideas for improvements, the simulation model built had to be altered to measure the impact based on what was altered. Sometimes, the model took a completely different direction, but once again the baseline model had to be complex enough to capture the important interactions. For example, management requested the team explore decreasing the cycle time of the P&D Stations. The model was not built with this as a parameter, but the team could quickly alter the model to include the P&D Stations. This is discussed in detail in Chapter 7. If the model had been too

[21] Harrell, Ghosh, Bowden, Simulation Using Promodel, page 182

complex, we would have been better to start over with a new simpler model to measure the impact of decreasing the P&D Station cycle time. But, I also would warn a team to remember the first step of defining a clear objective. The modeler should try to develop a thorough understanding of the potential parameters that may be altered during modeling explorations. This would help guide the modeler on balancing the Utility with the Complexity.

5.1 Suggested Design Improvements

The design improvements suggested by the operations team were measured using the simulation model. The improvements are presented as:

- SRM buffer to 6 total positions 5% throughput increase
- Cross over cycle time 5.5% throughput increase

The original belief was the first two design improvements would increase throughput significantly. The team originally thought increasing the buffer size from 3 positions to 6 positions and decreasing the cross over cycle time from 19 seconds to 12 seconds would significantly increase the throughput. The prediction error calculation was 6% and the first two design improvements estimate an increase of 5% throughput. If both improvements were to be implemented, the combined increase in throughput was modeled as 6%. The performance gap was 21%. The team's confidence about the improvements actually increasing throughput by 5% to 6% was low, because the increase was the same as our prediction error percentage. The team was also looking for improvements that would have a more significant impact in closing the 21% performance gap. With the model results, the team began to rethink and refocus. The team discounted the original recommendations and began to think differently about how to increase throughput.

The team began to experiment with different system parameters to gain a greater intuition of the facilities operations. The parameters we examined include the following:

- Resetting of the en route counter immediately after a pallet had been bumped from entering its current assigned SRM's buffer. Currently, the pallet is still counted as en route to the SRM even though it has been tripped and will re-circulate back to Aisle Select for another SRM assignment. A re-circulated pallet on average takes 30 minutes to return to Aisle Select. We believed the system would perform better if the en route counter was updated sooner instead of having a pallet that was no longer en route count against the limit. As shown in Table 3 below, resetting the en route counter actually decreased the throughput by 3.6%. Our initial intuition was incorrect; the additional time the en route counter is assigned to the pallet actually helps the SRM clear the queue before more pallets can be assigned.

- Next, we assumed we could eliminate all Cross Aisle Transfers. This increased the throughput by 11.8%. Because of the picking operations, eliminating all CATs may not be realistic.
- We ran several experiments adjusting the SRM buffer size and the maximum en route counters. Adjusting the SRM buffer size was one of our suggested design improvements that we wanted to measure. We adjusted the maximum en route counter, because increasing the buffer should allow more pallets to be sent en route. In Table 3, design changes 3 through 9 are variations of this concept.
- We ran an experiment with each pallet having the same likely hood of being assigned any one of the 15 SRMs (or Aisles), at 6.67%. We thought this would balance the load across the SRMs. This increased throughput by 1.6%. The chance of evenly distributing pallets at any given period is not likely because ES3 receives same type SKU pallets from vendors within each truckload.
- Lastly, we ran two experiments with the pallets being assigned in a cascading SRM patter, i.e. with the first pallet being assigned to SRM 1, the second pallet assigned to SRM 2, etc. The first experiment resulted in 11.6% increase in throughput. The second experiment with the cascading pattern also included the elimination of CATs and this resulted in a throughput increase of 26.7%.

	DESIGN CHANGE DESCRIPTION	THROUGHPUT INCREASE
1)	Reset "en route" counter after re-circulated pallet has been tripped (100 trials)	-3.6%
2)	No "Cross Aisle Transfers" (100 Trials)	11.8%
3)	SRM buffer increased to 6 total (100 trials) (max en route counter +3,)	2.4%
4)	SRM buffer increased to 6 total (100 trials) (max en route counter +2)	5.0%
5)	SRM buffer increased to 6 total (100 trials) (max en route counter +1)	5.6%
6)	SRM buffer increased to 6 total with no CATs (100 trials) (max en route counter +2)	0.7%
7)	SRM buffer increased to 5 total (100 trials) (max en route counter +2)	2.2%
8)	SRM buffer increased to 5 total (100 trials) (max en route counter +1)	4.5%

9)	SRM buffer increased to 4 total (100 trials) (max en route counter +1)	1.8%
10)	Aisle Select assignment with "Even Aisle Distribution"	1.6%
11)	Aisle Select assignment with Cascading Distribution	11.80%
12)	No "Cross Aisle Transfers" & Aisle Select with Cascading Distribution	26.7%

Table 3 Design Change Descriptions

5.2 The Real Advantage of Simulation Modeling

The real advantage to simulation modeling is the knowledge gained by gathering actual data to build the model and the intuition gained from observing the model. Watching the model performing with the accelerated timeline allowed the team to observe the dynamic nature of the system and the impact of Cross Aisle Transfers. The team brainstormed several ideas and tested the ideas to measure the impact. At the end of the day, the team began to shift the focus from physical changes, such as increasing the SRM buffers, to more fundamental process changes and potential software changes.

The advantages described in Chapter 4 for simulating are valid.

- Most complex, real-world systems cannot be described by a mathematical model which can be evaluated analytically.
- Simulation allows one to estimate performance under some projected operating conditions.
- Alternative designs can be compared.
- Maintain better control over experimental conditions, as compared to experimenting with actual system.
- Simulation can be used to observe a system over a long time frame.

But I would caution against using the model as a definitive way to quantify performance with different designs. It is extremely difficult to capture all feedback loops in a real world system. The real advantage is the ability to observe the system with the accelerated timeline and increase one's intuition. After a model is built, the ability to quickly test alternatives and formulate new solutions is another advantage. I highly recommend developing a Causal Loop Diagram in conjunction with a Simulation Model. The Causal Loop Diagram helps crystallize and communicate what portions of the real-world system are captured in the simulation model. From my experience, senior management is more concerned with ensuring the simulation model is a true representation of the real world system. The Causal Loop Diagram is a good way to ease this concern.

Chapter 6: Causal Loop Diagram of System

6.1: Causal Loop Diagram Results

In Chapter 2, the receiving and shipping processes at the York Warehouse were discussed in detail. The discussion of the receiving process, in particular the maximum hold zones and the en route counter highlight a peculiar phenomenon for the ASRS. The inbound pallets are not always put-away in the most desirable aisle. This occurs for numerous reasons, mostly because of the feedback controls that were designed to enhance the performance of the ASRS.

This Chapter will focus on the development of the Inbound Operations Shortfall Casual Loop Diagram and the importance it played in increasing our understanding of the ASRS and the importance it played in communicating the final recommendations. Causal Loop Diagrams are one of the system diagnostic tools that have been developed. The tool is useful for diagramming the feedback structures, showing causal links between variables with an arrow from the cause to an effect.[22] The simulation model was important on assessing the suggested design improvements with a realistic expected gain on throughput, but the key model in effectively communicating the interactions and feedback was the Casual Loop Diagram (CLD). The team that developed the final CLD includes; the researcher, the Director of Process Engineering, the Operations Planner at York, Vice President of Process Economics and Engineering, Executive Vice President of ES3, the Senior Vice President of Construction for C&S, and the Vice Chairman of C&S. At different times, the Director of Process Engineering and the researcher pitched the CLD and the final simulation model results with the recommendations. During each session, the CLD was refined and critiqued by the audience. This was critical, the active listening and open channel of communication by both sides of the dialogue helped ensure the CLD was a shared mental model of the ASRS. This shared mental model helped in two ways; it quickly brought everyone up to the same learning point and it created buy-in on the part of the audience. The audience took great care to ensure the system feedback loops were accurately represented. The shared mental model also helped create a level of trust which impacted the decision cycle speed.

[22] Sterman, Business Dynamics, page 102

6.2 Inbound Production Shortfall CLD; Root Cause

The Casual Loop Diagram will be presented here as a series of five diagrams, each slide followed by a short discussion and expansion of the ideas. Figure 31 is the first of the five diagrams.

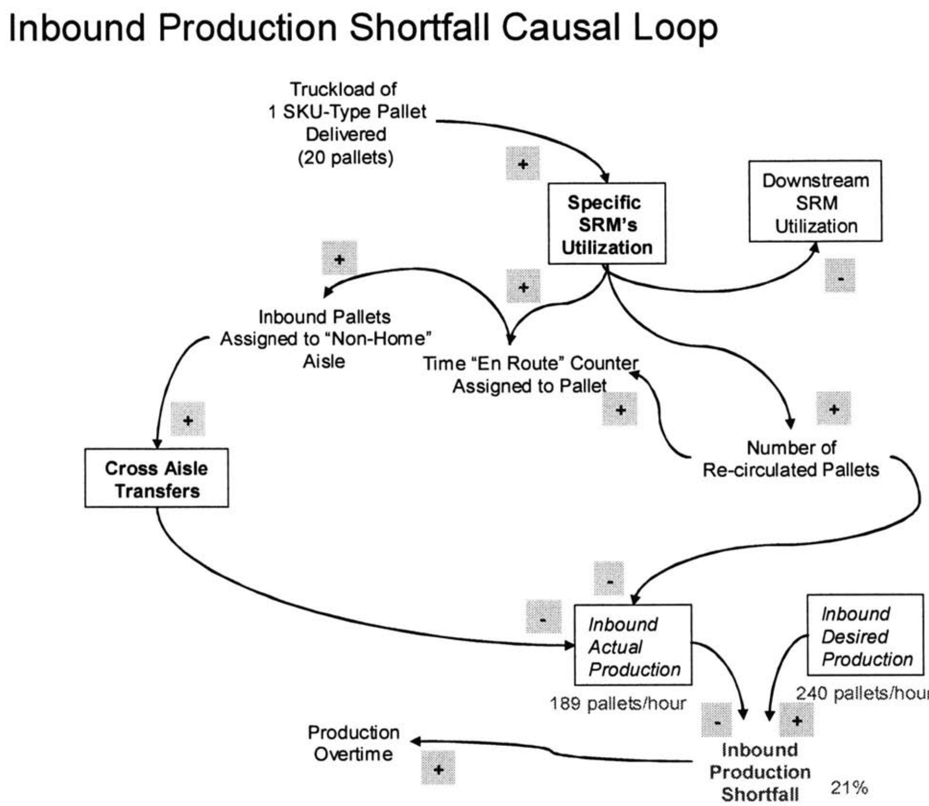

Figure 31 Inbound Production Shortfall Causal Loop (Root Cause)

One underlying cause of the inbound production shortfall was traced to how ES3 receives shipments from the manufacturers. The trucks arrive with 1 SKU-type of pallets, on average 20 pallets with a truckload. The Aisle Select algorithm attempts to assign the 20 pallets to the same aisle, thus driving up the specific SRM's utilization. As pallets wait to be served by a heavy utilized SRM, other pallets assigned to downstream SRMs may build up on the conveyor and be blocked from traveling to the assigned SRM. Thus downstream SRMs may be starved for pallets to put-away. The Aisle Select algorithm is limited on the number of pallets it can assign because of the maximum en route counter limitation. As a SRM's utilization is increased, the time a pallet is counted against that SRM's en route counter is increased. As the length of time a pallet is counted against the SRM's en route counter increases, the likelihood the maximum en route counter limitation has been reached, thus driving up Aisle Select's assignment of pallets to a "non-home aisle". Pallets being assigned to a non-home aisle increases future Cross Aisle Transfers (CATs) because the internal transferring of products is required for the pick slot replenishments. The CATs decrease the ASRS actual inbound performance, thus creating a shortfall from the desired production (or designed performance).

Also creating a production shortfall is the number of re-circulated pallets. Re-circulated pallets are created by one reason, an SRM is unable to keep up with the inbound demand and a build-up of pallets occurs on the Inbound Main Conveyor Loop. Once the number of pallets in the build-up reaches the maximum hold zone limit for that SRM, the pallet creating the bottleneck is released from its hold zone and sent around the loop as a re-circulated pallet. The other pallets are allowed to resume to their assigned aisles. As the re-circulated pallet travels the loop to return to Aisle Select, the en route counter is still attached to the pallet, thus decreasing the likelihood that other pallets could be assigned to that aisle (SRM).

The production shortfall of 21%, as compared with the designed performance, is counteracted with production overtime. Depending on the season, production overtime may not be enough to meet all the inbound demand.

6.3 Inbound Production Shortfall CLD; CATs and Re-circulated Pallets Interaction

The interaction between CATs and re-circulated pallets can compound the problem. Figure 32 highlights the interaction.

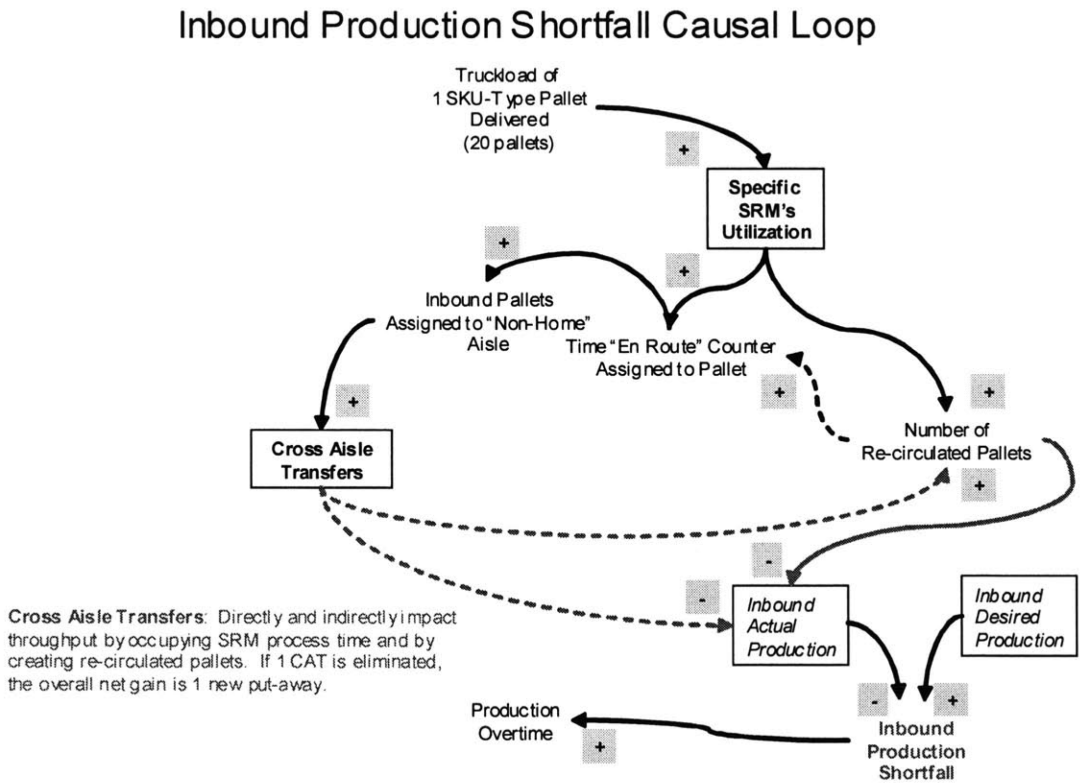

Figure 32 Inbound Production Shortfall Causal Loop (CATs and Re-circs)

As a CAT travels the Inbound Main Conveyor Loop, it counts against the number of pallets in the maximum hold zones, thus an opportunity to create re-circulated pallets exists. Just as in Figure 31, the re-circulated pallets travels the loop to return to Aisle Select, the en route counter is still attached to the pallet, thus decreasing the likelihood that other pallets could be assigned to that aisle (SRM). Through the simulation modeling, the team determined the CATs directly and indirectly impact throughput on a one-to-one ratio.

6.4 Inbound Production Shortfall CLD; Maintenance Feedback

The production overtime will have a long-term impact on the ASRS. The inability to provide preventive maintenance will increase the likelihood of future breakdowns, as shown in Figure 33. Currently, the main equipment not being serviced is the conveyor network. The SRMs preventive maintenance is being provided, by close coordination with the operations staff and review of the scheduled inbounds and allocated orders.

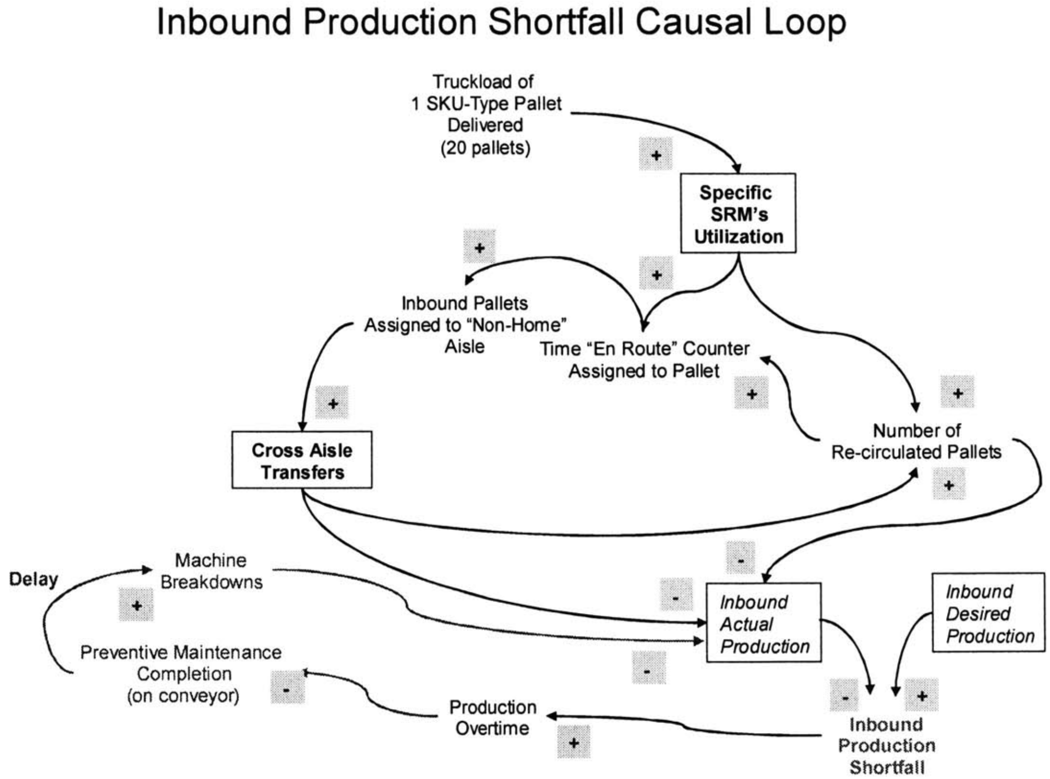

Figure 33 Inbound Production Shortfall Causal Loop (Maintenance Feedback)

6.5 Inbound Production Shortfall CLD; Shuffle Manager Impact

The production overtime also impacts the ability to run Shuffle Manager, as depicted in Figure 34. Shuffle Manager is an SRM setting that allows the ASRS to "clean" up sub-optimal put-away options, such as mixing product within the rack's three-deep slots or storing product in non-home aisles. The Shuffle Manager can correct these sub-optimal storage options, but it requires a significant amount of SRM operation time. The production overtime also has limited the amount of ASRS down-time. The Shuffle Manager is best run when the ASRS is not in receiving mode, because a significant number of CATs can be created. The Shuffle Manager has operated only a few hours in the past six months, June to December 2004.

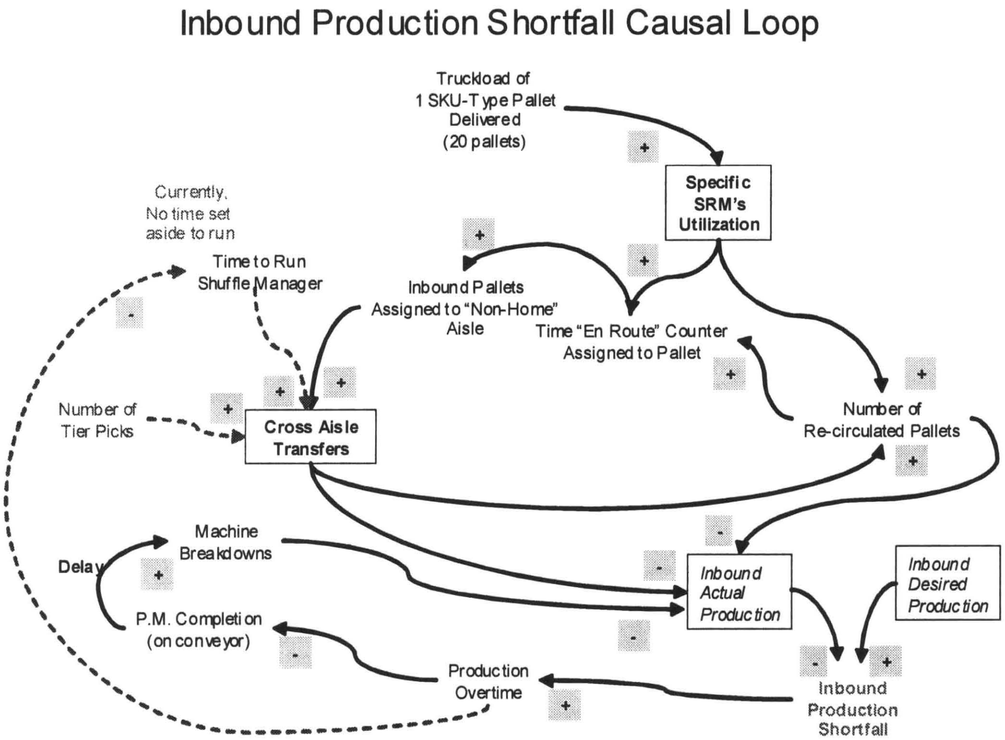

Figure 34 Inbound Production Shortfall Causal Loop (Shuffle Manager)

Another factor that drives up CATs is the number of tier pick operations undertaken by ES3. There is a strong likelihood that the number of tier picks will increase, at least ES3 strives for this because additional revenue is generated from tier pick operations.

6.6 Inbound Production Shortfall CLD; Reaching Storage Capacity

The York Facility has reached its storage capacity, which has impacted the ASRS operations in two ways. First, the correct storage bins (height, weight requirements, etc.) for the products is limited, thus increasing the likelihood of a pallets being stored in non-home aisles. From actual data, CATs accounted for approximately 54% of the pick replenishments. This equates to only 46% of the "pickable pallets" being assigned to their home aisle.

Second, reaching storage capacity decreases the likelihood of covering like product. This drives up SRM utilization, because pallets have to be shuffled to reach the desired (ordered) pallet.

CATs also increase the opportunity for Late Shipments. Late shipment is defined as missing a door turn time, which is approximately 2 hours. The door may be held open as a case selector waits for a few cases to fill a tier picked pallet - the average wait time for a CAT to make its transit is approximately 30 minutes. For any non-CAT pallet, the case selector does not have to wait. Figure 35 is a diagram reflecting the impact of reaching storage capacity on the system.

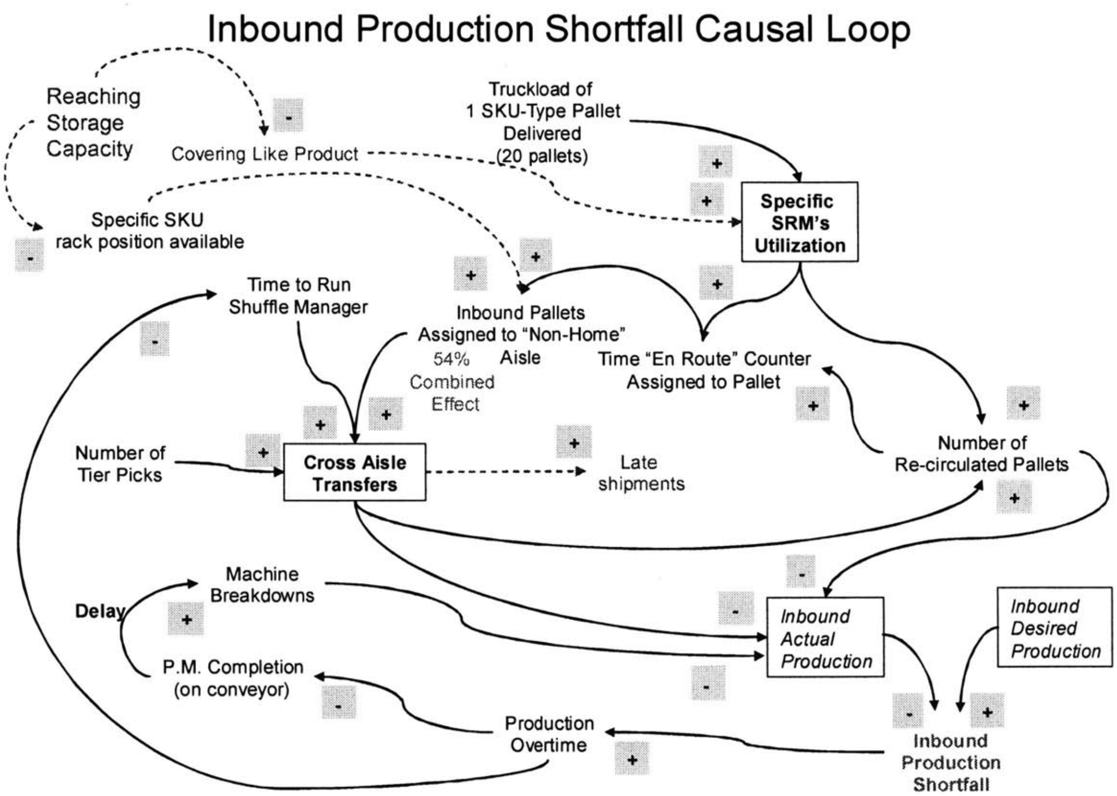

Figure 35 Inbound Production Shortfall Causal Loop (Reaching Storage Capacity)

6.7 Conclusion for Causal Loop Diagrams

"Feedback is such an all-pervasive and fundamental aspect of behavior that it is as invisible as the air that we breathe. Quite literally it is behavior – we know nothing of our own behavior but the feedback effects of our own outputs." (Psychologist W. Powers).[23]

[23] Sterman, Business Dynamics, page 15

Modeling feedback with the Casual Loop Diagram served as a useful communication tool and for establishing trust. The researcher found an inverse-proportional relationship between the level of interest in the simulation model and the level of management. The higher the management level the model was reviewed, the less interest and the more interest in the Causal Loop Diagram. This is understandable, because the model could be viewed as a "black box". They do not know the Visual Logic commands and the assumptions made to build it. But with that said, management did seem to trust the results of the simulation model. This trust seems to be rooted in their comfort level of the modeler fully understanding their process, as displayed by developing the Causal Loop Diagram.

7.1 Tactical Recommendations Overview

The recommendations provided were gained after hours of discussion with the process engineering team. The two main insights gained from modeling are the need for a more sophisticated put-away and retrieve logic and the need to minimize the internal transfer of product (the CATs). The insights were gained from two four-hour meetings in which the team played with many different variations of the model as describe in section 5.2. It was also during this meeting that the team also began to develop the Causal Loop Diagram.

Establishing a shorter SRM process time during heavy inbound or outbound periods will have a significant impact on throughput capability. A shorter process time cannot be accomplished without sacrificing time with the opposite operation (inbound or outbound) or by reducing the idle time for the SRM. This will be discussed in detail in section 7.2.

The facility at York will not perform as designed unless Cross Aisle Transfers (CATs) are reduced or eliminated. Actual data and the use of simulation modeling helped determine the following insights:

- CATs limit throughput on a 1 to 1 ratio during peak operational periods. CATs are created to backfill a pick slot on the ground level. During the CATs lifetime within the facility, the pallet is moved twice for put-aways and one retrieval SRM movements. Thus the CAT eliminates the possibility of a new put-away when it is being transferred.
- In mid-September, York averaged 20 CATs per hour with 25 CATs per hour during peak times.
- CATs create less opportunity for “new put-aways” thus starting an inbound production shortfall and generating re-circulated pallets. CATs initiate a negative feedback loop or death spiral that only worsens as the facility reaches storage capacity, as discussed in Chapter 6.
- Actual data downloaded from EMS was used to determine that only 46% of the pickable pallets are being assigned to their home aisle.

7.2 SRM Inbound/Outbound Balancing Logic

The York Facility has 15 Selection and Retrieval Machines (SRMs) as part of the Automated Storage and Retrieval System (ASRS). Currently, the SRMs operate in either two modes; dual cycle of pallet storage and pallet retrieval or single cycle of just pallet storage (or just pallet retrievals). There are circumstances where the ASRS would perform better if SRMs were allowed to deviate from one of these modes. For example, during heavy receiving periods, a SRM should be able to switch from dual cycle to single cycle until the receiving period demands are met. ES3's Process Engineering group has developed the following specifications for a SRM Inbound/Outbound Balancing Logic.

General Concept 1

The first Concept is controlling the release of the retrieval orders to the SRMs so that there is opportunity for a work queue of activity to develop. Currently, the warehouse operators wait on releasing retrieval orders based on door availability and anticipated workload of the SRM. The SRMs sometimes are idle because there are no inbound pallets and the retrieval orders have not been released. Figure 36 is an Inter-Arrival Time (or release time from the warehouse operators) for SRM Outbound Orders.

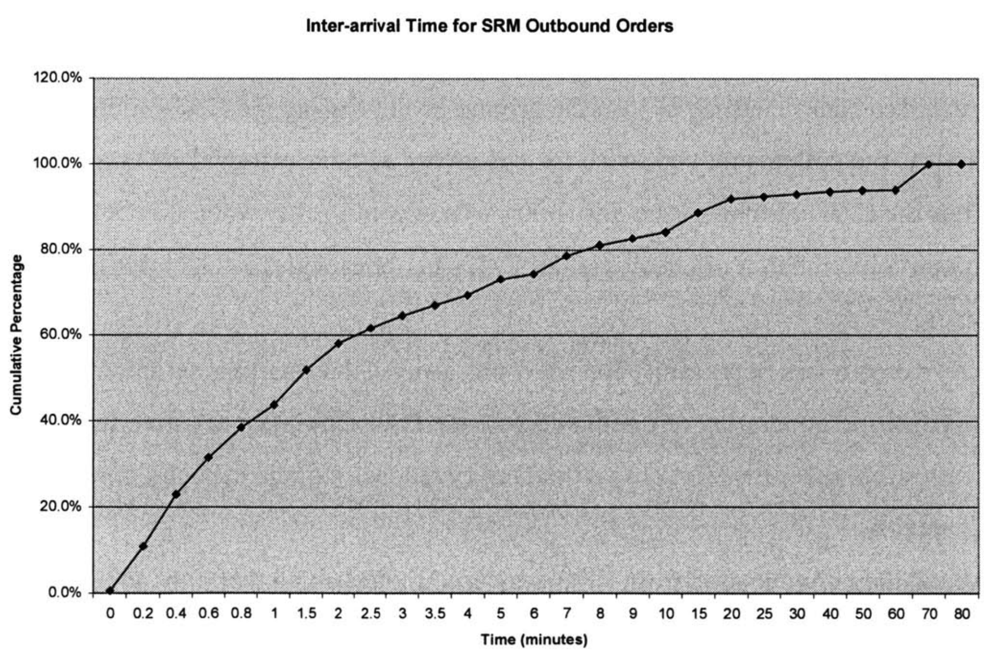

Figure 36 Inter-Arrival Time for SRM Outbound Orders

The graph highlights that approximately 80% of the orders (for all SRMs) are released (arrive) within 7 minutes. The concerning part is that approximately 5% are not released within 60 minutes. This indicates that one hour passes before the fifteen SRMs are assigned any retrieval orders. This occurs because the releasing of orders is a manual process and it appears to be a human lapse in monitoring the workload or not enough doors have been activated for outbound shipments.

The team recommends that every 10 minutes all new orders be released automatically. A new model was created to test this recommendation. The new model was an expansion of the older model, but several new options were added. First, the SRM process time was segregated to include a process time for put-aways and for retrievals. The process times were modeled by normal distributions. Second, the release of orders to trigger an outbound "work queue" of outbound movements was created. The SRM would continue to process inbound pallets if the outbound work queue was empty. The new model measured inbound throughput and outbound throughput and a prediction error of 2% was established. The outbound throughput increased by 10%. This was significant enough to pursue and matches intuition. This concept of releasing retrieval orders automatically would be relatively easy to implement, while General Concept 2 would not.

General Concept 2

Every SRM will have an algorithm running to determine the appropriate mode of operation: dual cycle (pallet storage and retrieval), single cycle pallet storage, or single cycle pallet retrieval. The algorithm will determine the appropriate mode in advance of the SRM completing the current operation. This should ensure the SRM pallet movements are not delayed as the algorithm updates.

The default setting for normal operations would be dual cycle. The SRM would switch to a single cycle mode depending either on the en route counter for storing pallets or on a countdown for retrieving pallets. The SRM should immediately switch back to the default setting, or dual cycle, as soon as practical.

Examples

The following highlights the switching between dual and single cycle modes of operation:

<u>Single Cycle Pallet Storage (Inbound)</u>

For inbound pallets, each SRM has an "en route counter" that counts the number of pallets assigned to it that are physically between Aisle Select and the SRM's inbound Pick up & Deliver (P&D) positions. The SRM will switch to single cycle pallet storage when the en route counter meets an "Upper Inbound Threshold" and return to dual cycle mode when the en route counter meets the "Lower Inbound Threshold". The two thresholds should be reconfigurable, with each SRM having its own settings.

This is how it works; SRM 10 has the following settings:

a. Maximum en route – 7 pallets (as defined by current operations)
b. Upper Inbound Threshold – 5 pallets en route
c. Lower Inbound Threshold – 2 pallets en route

SRM 10 operates in the dual cycle pallet storage and retrieval mode until the en route counter is 5 pallets (Upper Inbound Threshold). SRM 10 completes its current operation and then switches to single cycle pallet storage. SRM 10 remains in single cycle pallet storage until the en route counter is 2 pallets (Lower Inbound Threshold). SRM 10 completes its current operation and then returns to the default setting of dual cycle, starting with the opposite cycle (in this case, retrieve).

<u>Single Cycle Pallet Retrieve (Outbound)</u>

For outbound pallets, not being late is a critical issue. Being late for the logic will be defined as missing the Door Time. Each SRM will have a "work queue of retrieval moves". The size of the "work queue" should be populated with enough pallet moves to capitalize on the SRM's idle time. Operational changes may need to be implemented to ensure an appropriate work queue level. A buffer of "non-critical" pallet moves may need to be established to ensure the SRM always has work to be accomplished. For example, additional dock doors may need to be open with Drop trailers positioned to be filled. This example in particular will have two possible improvements – the idle time will decrease and the Inbound/Outbound Balancing Logic can be programmed to look for the next best move based on distance from the current pallet move (put-away). Thus, the order of SRM pallet moves will be adjusted to optimize the SRM travel time. The algorithm is updated when orders are allocated and every three minutes (the average dual cycle completion time).

The outbound pallet moves will be prioritized by type of move and by time. Attachment 2 is the preferred SRM completion order of pallet moves by type, referred to as the Rule Set. The Rule Set is the prioritized pecking order for outbound moves and should be reconfigurable for each SRM. Each pallet move in the work queue will have two time stamps; a dynamic time stamp for when calculated (current EST) and a constant time stamp for when considered late (threshold time). Each algorithm update will compare the two time stamps (Threshold time – dynamic time) and calculate a "Countdown to Late Move" (CLM). The CLM will be used to prioritize moves within certain types of move. And if the CLM becomes zero or negative, the pallet move will become a higher priority. The algorithm should calculate the next move by CLM and by the Rule Set. For example, a Live late shipment, with a CLM of -2 minutes, would still have a higher priority than a Drop late shipment, with a CLM of -40 minutes.

This is how it works; the algorithm for SRM 10 populates the work queue with 47 pallet moves. The pallet moves will be prioritized by type of move and time. Currently no moves are considered late (all 47 moves have a positive CLM). SRM 10 operates in the dual cycle mode.

ES3 allocates an order for 20 pallets, 12 of which are stored within aisle 10 (SRM 10). SRM 10's work queue increases to 59 pallet moves. The algorithm assigns two time stamps; one for the current time and one for when the order is late. The order was allocated only 4 hours before the Door needs to be turned. Initially the 12 pallets are not considered late, but they are high on the priority because of their CLM. SRM 10 continues to operate for the next 4 hours in the dual cycle mode, completing 40 of the pallet moves. SRM 10 has 3 out of the 12 moves remaining to complete when their CLM becomes 0. SRM 10 switches to single retrieve mode and pulls the 3 remaining pallets from the rack for outbound. Once complete, SRM 10 switches back to dual cycle mode.

Resolution Rules for Conflicting Priorities

The potential for a SRM to have a priority storage (inbound) move and a priority retrieval (outbound) move exists. Below highlights the order in which the moves should be completed: Late Live outbound created by static/dynamic replenishment, Late Live outbound, Prioritized inbound (Upper Threshold met), Late Drop outbound created by static/dynamic replenishment, and lastly Late Drop outbound.

Next Optimal Outbound

If possible, the software could calculate the "closest" outbound move to the new put-away from among the outbound work queue of activity. This should provide for the best next retrieval move and will allow for the shortest possible cycle time for the SRM.

Conclusion for SRM Inbound/Outbound Balancing Logic

The SRM Inbound/Outbound Balancing Logic will enhance the ASRS performance. The logic will use simple calculations to determine the next best move and will be based on the en route counter, a general Rule Set, and a countdown. The SRM Inbound/Outbound Balancing Logic should be as reconfigurable for each SRM as possible. Access to alter the setting should be limited and with personnel who fully understand the complexities of the system interactions. The guidelines highlighted are general and may need to be updated as the vetting process continues.

7.3 Same Aisle Drop for Dynamics

Recommend establishing "Same-Aisle" drops for dynamic pick replenishment operations. This means transferring dynamic pick replenishments from stored rack positions to a dynamic slot in the current aisle vice transferring to the preferred aisle (home-aisle). Approximately 10-20% of CATs are dynamic slot replenishments. The recommendation to drop all dynamics in current aisle would increase new put-aways on average 3.75/hour or between 2 to 5 pallets an hour. Calculations presented below (with sensitivity analysis):

Average CATs			25	pallets/hr
Percent dynamic	10%	15%	20%	
	2.5	3.75	5	Decrease in CATs

Table 4 Dynamic CAT

7.4 Aisle Assignment Based on Pick Zones

Recommend establishing "Pick Zones" as the preferred assignment for pallets versus using home aisle. Currently, pickable pallets are assigned to a SRM aisle as the home-aisle. The suggested improvement would be to assign a pickable pallet a Pick Zone vice a SRM Aisle. The Pick Zone would be assigned per Pick Tunnel and thus consist of two SRMs, at a minimum. The available rack storage options and pick storage options will double for pickable pallets. The gain for the York facility would be in lowering CATs and thus increasing throughput. Figure 37 is cut-away diagram showing the layout of the Pick Tunnels in comparison with SRM Aisles.

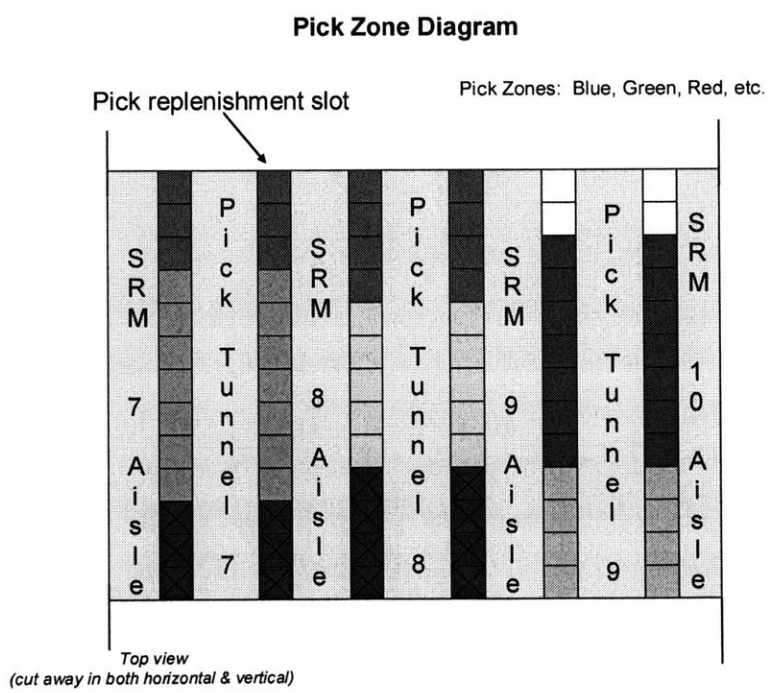

Figure 37 Pick Zone Diagram

Figure 37 shows how diverse the Pick Zone idea can be. The Zones can be spread throughout the aisles, not limited to two aisles. For example, the red pick replenishment slots (also marked with X) represent one Zone. A SKU can be stored in the rack on either side of SRM 7, SRM 8, or SRM 9 aisles. This zone in particular opens the number of preferred aisles and increases the available preferred slots from 7% to 21% of the facility.

Quantifying the Throughput Gain

Let's review only the possibility of using two SRMs as a Pick Zone assignment. Table 7.1 shows the Summary of Pick Replenishment activity for 15 September and 8 November 2004. The pick replenishment can either be from a CAT or a drop in the aisle.

Summary of Pick Replenishment Data

15-Sep-04

Hour	Picks from CATs	Picks from Drop in Aisle	TOTAL
0700-0800 AM	35	17	52
0800-0900 AM	29	36	65
0900-1000 AM	37	35	72
1000-1100 AM	30	25	55
4 hour total	131	113	244
hourly average	32.75	28.25	61
percentage	54%	46%	

8-Nov-04

Hour	Picks from CATs	Picks from Drop in Aisle	TOTAL
0400-0500 AM	6	7	13
0500-0600 AM	11	10	21
0600-0700 AM	5	11	16
0700-0800 AM	25	12	37
0800-0900 AM	19	7	26
0900-1000 AM	14	15	29
1000-1100 AM	21	20	41
1100-1200 PM	10	11	21
1200-1300 PM	22	21	43
1300-1400 PM	31	26	57
1400-1500 PM	33	29	62
1500-1600 PM	35	37	72

12 hour total	232	206	438
hourly average	19.33	17.17	36.5
percentage	53%	47%	

Table 5 Pallets Picked per Hour

As shown in Table 2, 46% of the pickable pallets are assigned to their 1st Choice SRM Aisle Assignment. Assuming the 2nd Choice SRM Aisle Assignment has the same 46% probability of occurring, the combined chance that a pallet is assigned to its 1st or 2nd Choice becomes 71%. The following equation was used to calculate the percentage:

$$[46\% + (54\%) * (46\%)] = 71\%$$

The assumption of 71% for combined 1st and 2nd Choice seems reasonable. Below highlights the expected gains:

*1st Choice SRM Aisle Assignment	2nd Choice SRM Aisle Assignment	Combined 1st & 2nd Choice
46%	25%	71%

* real data

Average CATs = 25 pallets/hour
Expected Decrease in CATs/hour = 11 pallets

Table 6 Pick Zone Impact on CATs

If the Pick Zone is expanded to more than two SRMs, than the gain would even be greater. Eliminating 11 pallets per hour would increase throughput by 5.8%.

Physical Changes

The Pick Zone recommendation does not require any physical changes. The changes would occur within the EMS aisle assignment decision algorithm. ES3's process team is developing the software specifications for this change. An important change to the current slot classification is that the slots will now all be dynamic slots. The distinction will be between two-deep dynamics (old static slots) and one-deep dynamics (old dynamic slots). The decision to fill the one-deep dynamic will be based upon demand while the decision to fill two-deep dynamics can be completed within the SRM idle time.

7.5 Strategic Recommendation – Use of Modeling to Accelerate Decisions

Developing a simulation model increased the team's understanding of ASRS feedback effects but it also accelerated the decision making process. One particular example that stands out occurred after a group of senior management toured the York Facility and recommended an operational improvement. The group thought by reducing the P&D cycle time, an incremental gain of throughput could be obtained that was worth the effort. The group referred to the Inbound Simulation Model to estimate the expected gain. The model was run within four days and a probability plot of "Time before Pallets forced to Re-circulate" was determined for one SRM. "Time before Pallets forced to Re-circulate" is the period of time a pallet waits on the Main Conveyor Loop for an opening within the SRM's buffer. Figure 38 is a plot of the Time versus the cumulative percentage. One can read the figure as follows, 40% of the pallets wait on the conveyor loop for approximately 0.7 minutes before they are bumped and sent around as a re-circulated pallet to Aisle Select.

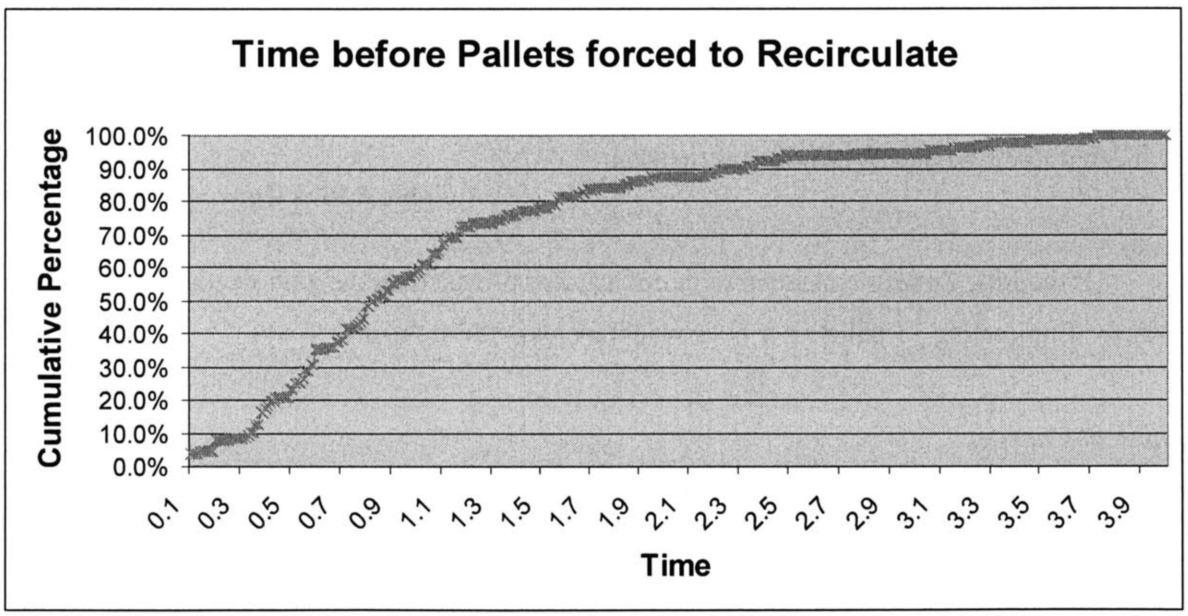

Figure 38 Time before Pallets Re-circulated

The graph depicts how if the cycle time could be reduced by 0.1 minutes (six seconds) than we should expect a throughput increase of approximately 4% of the pallets re-circulated. The timeframe we reviewed had an average of 29 pallets re-circulated per hour. The gain would be one pallet per hour, if we assume all SRMs re-circulation wait pattern is similar. The cycle time of the P&D could not be reduced by six seconds; the cycle time was less than six seconds. It is not the analysis that is important, but the speed at which the analysis was conducted and the results agreed upon that is of interest. The delay of four days only occurred due to the unfamiliarity with the software package, theoretically, this could have been produced in less than two hours.

This accelerated decision cycle could not have occurred without trust and agreement on the appropriate shared Mental Model for the ASRS. The significance of the two factors, trust and agreement, should not be discounted or assumed easily won. Before delving into the importance, presented here is John Boyd's OODA Loop, a "new" approach to decision making. John Boyd was a little understood and under-appreciated United States Air Force Colonel and military tactician. He is credited with establishing Maneuver Warfare and a novel approach to decision making he termed OODA Loop. OODA is a four letter acronym for Boyd's four steps to adapting to uncertainty.[24] Figure 39 is a diagram of the OODA Loop and the feedback loops. I will not expand upon the four steps because the diagram conveys the key concepts in a concise and clear manner.

[24] Hammond, The Mind of War, page 155-174

OODA Loop

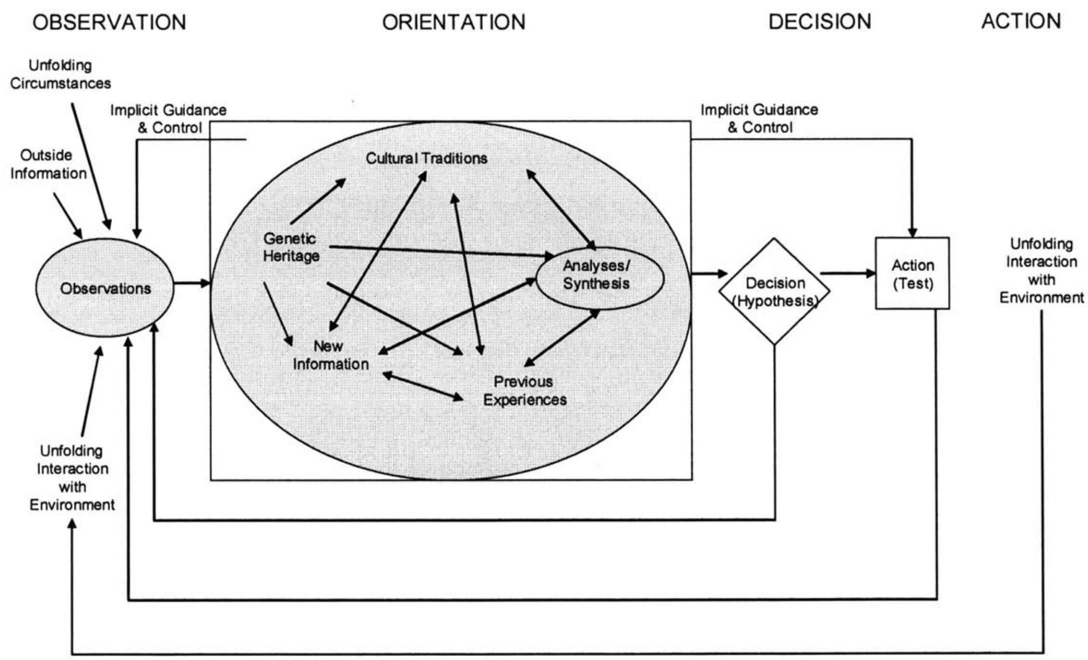

Figure 39 OODA Loop

Notice the similarity to the scientific method; observe, form hypothesis, test hypothesis, and adjust from observation. The scientific method tests theory with experimentation and uses experimentation to get insights about possible new or improved theories.[25] John Boyd's OODA loop is the scientific method restated. However, he expands the scientific method and addresses the importance in accelerating the cycle. I believe two important concepts illuminated by the OODA Loop can also be applied to continuous improvement programs;

- The importance of accelerating the decision-cycle between Observation and Action.
- Understanding the competitor's cycle (or adversary) and developing ways to react quicker or exploit their orientation.

[25] Shiba, Four Practical Revolutions in Management, page 93

The acceleration of the decision-cycle is intuitive enough. A company has to react faster to change. Tom Peters, author of Thriving on Chaos, explains that companies must challenge everything, change everything, and improve everything. The cycle time must be cut by 75 to 90 percent, become orders-of-magnitude more responsive, implement thousands of individual and team suggestion each just to keep up with the competitors.[26] But in the business setting how should one exploit the competitor's decision-cycle process? First, a company must understand the competitor's orientation – the cultural traditions, the firm's ability to analyze and synthesize new concepts, the firm's ability to adjust to new information, and how quickly can a firm react to external forces.[27] Second, a company must be faster to exploit changes. Many examples exist where firms did not react quickly enough to exploit new technologies or new markets.

Modeling techniques, such as Causal Loop Diagrams and simulations, make great decision tools to re-orient and test hypothesis. Because modeling occurs in a virtual world and not the real world, the business is not penalized for testing risky alternatives or innovative approaches.

Boyd stressed the development of trust among team members. According to Boyd, trust and open communication developed from sharing the same orientation or mental model is the key factor in accelerating decisions. If trust exists, a team could cycle through this four-step process at faster cycle speeds than competitors (or adversaries). An important corollary to consider is the bigger the mission or the bigger the operational change, the more important the trust. As discussed in Chapter 6, the shared mental model of the key feedback loops expressed in the Causal Loop Diagram established this trust. This trust most likely would not have occurred with just the simulation model. By watching the model, the team members could never be confident that the feedback loops were incorporated, let alone understood. The importance of the trust cannot be overstated. The recommendations developed are not insignificant and will require personnel and financial resources. It is estimated that both recommendations will require approximately 180 man-days of effort to develop and implement.

[26] Peters, Thriving on Chaos, pages 269-275
[27] Saloner, Strategic Management, page 275

Of course the application of a war-fighter's four step process to the business environment breaks down at some level, but it isn't a stretch to see analogies between an enemy and a competitor. Grant Hammond, a biographer of John Boyd, captures the advantage of the OODA Loop cycle succinctly with his observation:

> "Knowledge of the strategic environment is the first priority. Secondly, one must be able to interact with the environment and those within it appropriately. You must be able to observe and orient yourself in such a way that you can indeed survive and prosper by shaping the environment where possible to your own ends, by adapting to it where you must. Doing so requires a complex set of relationships that involve both isolation and interaction. Knowing when each is appropriate is critical to your success. In OODA Loop fashion, one must continually observe, orient, decide and act in order to achieve and maintain freedom of action and maximize the chances for survival and prosperity. One does so through a combination of rapidity, variety, harmony, and initiative. It is these that are the core of "Boyd's Way." Rapidity of action or reaction is required to maintain or regain initiative. Variety is required so one is not predictable, so there is no pattern recognition for a foe to allow him to know of your actions in advance and thus plan to defeat them. Harmony is the fit with the environment and others operating in it. Initiative—taking charge of your own destiny—is required if one is to master circumstances rather than be mastered by them. All of course would be focused on attaining the specified Objective that is implicit in this discussion."[28]

Modeling Team Recommendation

Recommend the formation of a process mapping and modeling team. The team would work on developing process maps, causal loop diagrams, and simulation models as an approach to continuous improvement. The mental models would be used to test improvements before implementation, either at a conceptual level or more detailed as through the use of simulation modeling. The shared mental models would create a level of trust between the team and the

[28] Hammond, *The Essential Boyd*

organization impacted. The modeling would also accelerate the decision making cycle and help fast-forward to failure or success.[29] This accelerated decision cycle can actual become a competitive advantage by creating an even faster ability to respond to change or fail without consequence.

[29] Peters, Thriving on Chaos, pages 315-326

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CHAPTER 8: Conclusions

8.1 Conclusions

The warehouse operations and warehouse design teams had numerous design suggestions for improving the ASRS operations at ES3, but it was difficult to predict the enhancement or impact on performance. A simulation model for the inbound system was created to analyze the impact, prioritize, and develop new ideas for improving the system. A discrete-event simulation modeling package was used because of the system's complexity and numerous interactions. Several things the team wanted to capture included; the re-circulation created by exceeding the maximum hold zones, the maximum number of pallets allowed to be en route to a SRM, the impact of Cross Aisle Transfers, the impact of Spur 4, and the ability to adjust the number of SRM Buffer Zones and cycle times on equipment.

Prediction Error

A model's ability to represent the real system is measured by a prediction error. Our prediction error was calculated from comparing real data and the model's output for throughput and recirculation. One limitation discussed to developing an accurate prediction error is the difficulty in collecting real system data. Often the modeler has to work with the data on-hand. Our prediction error was compared with the real system's performance gap (as compared to the designed performance). The team's confidence in using the model to measure and develop improvements was high because our prediction error of 6% was well below the performance gap of 21%.

Complexity and Utility

Another important aspect of modeling is the trade-off between the model's complexity and utility. The Laffer curve describes nicely the balance between the two, and the fact that some complexity is required to capture the cause and effect relationship within a system. The optimal level of model complexity is when the model utility is "good enough" because after a certain complexity point, the model's utility starts to diminish. I found this to be true because the model becomes too rigid and it cannot be easily converted to measure a new parameter.

Accelerated Decision Cycle

The speed at which new ideas can be tested is a great advantage. Once a model has been built, the ability to watch a representation of the system under an accelerated timeframe significantly increased the team's understanding of ASRS feedback effects. The team tested over ten design suggestions and was able to quickly dismiss ideas that did not improve the performance significantly.

Marriage of Simulation Models and Causal Loop Diagram

I highly recommend developing a Causal Loop Diagram in conjunction with a simulation model. The Causal Loop Diagram helps crystallize and communicate what portions of the real-world system are captured in the simulation model, while the simulation model quantifies the system improvements. From my experience, senior management wants to know a reasonable estimate on the performance improvement but feel confident that the simulation model is a true representation of the real world system.

ATTACHMENT 1 - ES3 Definitions

Aisle Select – A physical location on the inbound conveyor where pallets are assigned their preferred aisle. Also, aisle select may be the process of assigning the pallet a preferred aisle.

Automated Storage and Retrieval System (ASRS) – Network of conveyors, vertical lifts, SRMs, and programmable logic used to move product (pallets) through a warehouse and that stores and retrieves product from a storage rack.

Customer Pick-up (CPU) – The outbound trailer has a scheduled pick-up and the driver will pick-up at the loading dock. Potentially the driver could be waiting for fulfillment because this is scheduled on a tight timeline.

Drop Pick-ups – The outbound trailer is being loaded ahead of schedule and will be staged in the Yard.

Drop Unloads - The driver leaves the trailer and the trailer is unloaded when the workload permits

Dual Cycle Mode – SRM completes one pallet storage move for every one pallet retrieval move, alternating between the two types. Proposed default setting for SRM operation.

En route counter – The number of pallets physically located between Aisle Select and the inbound Pick up & Delivery. Each SRM has an en route counter that monitors the number of pallets to be serviced by the SRM.

Inbound – ES3's product receivable process or specifically the movement of pallets from delivery trucks to their rack storage position.

Induction Spur – The location where the pallet's electronic information is inputted for the ASRS to manage pallet flow and storage.

Late Shipment (two possible definitions):

A. "Dispatch Time" – A shipment may be considered late if the truck is not released before the prescribed dispatch time. Dispatch time may be inappropriate for setting SRM move priorities because the truck may be late in showing to the door (shipper problem and not an ES3 problem).

B. "Door Time" – A shipment may be considered late if the truck is not turned (or filled) and released within the prescribed "door time". The door time is 2 hours for most vendors. Door Time would be more appropriate for setting SRM move priorities because it would be more likely an ES3 caused event. The rare occurrence of missing a door time when a CPU driver disappears will have to be managed by York Facility employees.

License Plate Number (LPN) – Each pallet has a placard with a specific alpha-numeric assigned. The LPN is used to track pallets within the supply chain.

Live Unloads – The driver stays with the trailer and is processed as quickly as possible.

Less Than Truckload (LTL) – The trailer is released for shipment without being full and creates a more expensive transportation cost, on a cost-per-product basis.

Lower Inbound Threshold - Proposed lower limit for pallets en route that trips a SRM to switch from single cycle pallet retrieval mode to dual cycle mode.

Maximum En Route – Each SRM has an en route counter that monitors the number of pallets to be serviced by the SRM. The maximum en route is the highest number of pallets allowed to be physically located between Aisle Select and the SRM. Once the maximum en route has been reached, Aisle Select will re-assign the pallet to another SRM. Maximum en route serves as a relief valve to protect against inundating a SRM with too many pallets at one time.

Mode of Operation – Type of cycle the SRM is operating - dual cycle, single cycle pallet retrieval, or single cycle pallet storage.

Outbound – ES3's order fulfillment operation or specifically the movement of pallets from their stored rack position to loading the pallet in the truck.

Rule Set - The prioritized pecking order for the outbound pallet moves.

Selection and Retrieval Machine (SRM) – Automated crane used to store and retrieve product (pallets) from a storage rack.

Single Cycle Pallet Retrieval Mode - SRM completes only pallet retrieval moves.

Single Cycle Pallet Storage Mode – SRM completes only pallet storage moves.

Store Keeper's Unit (SKU) – Every product is assigned an alpha-numeric for tracking and record keeping purposes.

Truck Load (TL) – The trailer is released for shipment full.

Upper Inbound Threshold – Proposed upper limit for pallets en route that trips a SRM to switch from dual cycle mode to single cycle pallet storage mode.

Warehouse Management System (WMS) – Computer software package that is used to maintain accurate inventory counts of pallets within the warehouse.

Yard Jockies – At the York facility, yard jockies control the flow of trucks to the loading and unloading doors.

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ATTACHMENT 2

RULE SET: The Rule Set is the prioritized pecking order for the outbound pallet moves. Altering the order of a pallet move within the Rule Set should be an option within the software, but access should be limited to minimum number of employees. The following is a proposed Rule Set:

RULE SET (SRM Move Priorities)

*1. pallet move to meet late shipment based on "door time"
2. shuffle move required for late shipment
3. pallet move to fill a static replenishment slot to meet a late shipment
4. shuffle move required for static replenishment to meet late shipment
5. pallet move to fill a dynamic replenishment slot to meet a late shipment
6. shuffle move required for dynamic replenishment to meet late shipment
7. pallet move to satisfy Live CPU order (prioritized by time)
8. OPTIONAL: pallet move to satisfy Live CPU order (prioritized by vendor)
9. shuffle move required for CPU shipment
10. pallet move to satisfy Drop order (prioritized by time)
11. OPTIONAL: pallet move to satisfy Drop order (prioritized by vendor)
12. shuffle move required for Drop shipment
13. pallet move to fill a static replenishment slot to replenish empty slot (not late)
14. pallet move to fill a dynamic replenishment slot to replenish empty slot (not late)
15. pallet move to satisfy QA check (vendor requested)
16. pallet move to satisfy QA check (ES3 requested)
17. shuffle move required for static replenishment (not late)

* An outbound shipment, either CPU or Drop, that has become "late" based on door time requirement. Each outbound pallet move activity TYPE will have a pre-defined (alterable) time threshold. See NOTE 5.

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REFERENCES

Hammond, G. (2001), The Mind of War – John Boyd and American Security, Smithsonian Books Washington

Hammond, G., *The Essential Boyd,* War Business and Chaos Publication

Harrell, Ghosh, Bowden (2000), Simulation using ProModel, McGraw-Hill

Hopp, W.J. and Spearman, M.L. (2000), Factory Physics, 2nd edition, McGraw-Hill

Kosfeld, Mark (1998), *Warehouse Design Through Dynamic Simulation,* Winter Simulation Conference Proceedings 1998

Law, A. and Kelton, W.D. (1982), Simulation Modeling and Analysis, McGraw-Hill

Park, Daniel (2003), *Design and Development of Customer Priority Decision Aid Tool*, MIT Thesis

Peters, T. (1987), Thriving on Chaos, Harper and Row Publishers

Pritzer, Alan B, and Claude Dennis Pegden (1979), Introduction to Simulation and SLAM, John Wiley & Sons, Inc.

Saloner, G., and Shepard, A. and Podolny, J. (2001), Strategic Management, John Wiley & Sons, Inc.

Shiba, S. and Walden, D. (2001), Four Practical Revolutions in Management – Systems for Creating Unique Organizational Capability, Productivity Press

Spall, J.C. (September 2003), *Simulation and Monte Carlo; General Principles*; Lecture Notes from John Hopkins University

Sterman, J. (2000), Business Dynamics – System Thinking and Modeling for a Complex World, McGraw-Hill