Optimizing In-Line Vehicle Sequencing Systems: Applications to Ford Component Manufacturing

by

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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 Science in Management
and
Master of Science in Mechanical Engineering
at the
Massachusetts Institute of Technology
June 1997

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JUL 21 1997
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Abstract

Recent studies of In-Line-Vehicle-Sequencing (ILVS) at assembly plants have revealed the potential for tens of millions of dollars of cost savings to the Ford Motor Company. However, ILVS cannot be confined to the assembly plants, since this scheduling concept can require suppliers to provide components that match the forecasted sequence imposed by ILVS on the assembly plant. Additionally, not all production systems as easily meet the ILVS requirements, since Ford developed and installed much of its component manufacturing system before the conception of ILVS.

This thesis examines the implications for component plants of implementing an ILVS environment. The thesis bases its results upon application of discrete event simulation, design of experiments, fault tree analysis, and probability modeling. A study of door trim panel production at one of Ford’s component plants serves as the foundation of the thesis.

This thesis attempts to lay the groundwork for more cost-effective ILVS implementation within Ford by identifying those critical characteristics of a manufacturing system and product design that strongly influence the ILVS environment within component plants. In particular, it:

1) proposes a framework for evaluating a production system for the ILVS environment;
2) presents a systems perspective of ILVS to show the impact on system performance of scheduling, process design, and product design;
3) proposes metrics for characterizing a production system, which include not only the output of the process, but also the material flow, machine flexibility, information systems, and other features of the production process;
4) characterizes several operational control strategies for managing a production system in the ILVS environment; and
5) proposes design rules for future production systems and product designs to improve their compatibility with ILVS.

Our study of door trim panel production has shown that the concepts presented in this thesis can significantly lower the cost for installing and operating systems in an ILVS environment. For one of the product lines studied, the potential of annual cost savings relative to current practice is over one million dollars.

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ACKNOWLEDGMENT

The author gratefully acknowledges the support and resources made available to him through the MIT Leaders For Manufacturing program, a partnership between MIT and major US manufacturing companies.

I am indebted to my family for their support over the years. I truly would not be in the position I am today without your encouragement, support, and love. Thank you Mom, Dad, Ed, Sharon, and Nick.

The thesis advisors Tom Magnanti and David Staelin. The quality of this document greatly benefited from their guidance. The thesis reader David Cochran.

Ford Motor Company for providing such a challenging topic of research. In particular, I would like to thank the two company advisors Zig Lipka and Steve Meszaros for their insights and encouragement. I also want to thank the team members of the project upon which the case study is based. Hossien Nivi his work with the LFM program.

I want to thank the 1997 LFM class for a great two years of learning, friendship, and fun. In particular, I want to thank the group whose internship was located in Detroit, Elizabeth Kao, Eunmee Park, Melanie Dever, Denise Johnson, Jeremy Cram, Kevin Florey, Tony Kramer, and Brian Sullivan.
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1. **Thesis Introduction**

1.1 **Introduction to In-Line Vehicle Sequencing**

The Ford Motor Company has developed In-Line Vehicle Sequencing (ILVS) to improve scheduling of its vehicle assembly operations. The objective is to stabilize the actual sequence of vehicle leaving the end of the assembly line against a fixed five day forecast for the sequence. Originally, the concept was intended to allow an assembly plant to better balance the work force requirements on the assembly line and reduce material handling. However, the ILVS environment also removes uncertainty in demand to component suppliers within the five day forecast window. Therefore, the concept evolved to capture cost savings through better supply chain management and reduced assembly plant material handling. Ford’s vehicle assembly operations worldwide are in the process of adopting the ILVS environment.

![Component Plant Sequence Stream](image)

**Assembly Plant Production Line**

![Diagram](image)

**Figure 1-1: ILVS Component Delivery Format**

Recent studies of assembly plants indicate the potential of tens of millions of dollars per year of cost savings ([1],[2]). However, the ILVS environment reaches beyond the vehicle assembly operations. For those components requiring delivery in the ILVS
format, component plants provide a matched sequence of components to the forecasted sequence of vehicles at the assembly plant, as shown in Figure 1-1. ILVS effectively synchronizes the output of two production systems down to the individual component end item style. This approach could conceivably shift the cost of sequencing from vehicle operations to component supplies and, therefore, provide no company level savings. The component supplier cost of meeting the sequence requirements depends upon the characteristics of the component production system. As will be shown, not all production systems as easily meet the requirements of the ILVS environment. Chapter 14 presents an Executive Summary of this thesis.

1.2 Logical Commodities for Delivery in Sequence

By delivering a sequence of components matching the sequence of vehicles in an assembly plant, a company can reduce the amount of inventory and material handling required at the assembly plant. However, not all commodities require delivery in sequence. The justification for this approach is a function of the:

- size and shape of the commodity;
- complexity (number of unique end items) of the commodity;
- space available for the commodity within the assembly plant;
- economic value of the commodity; and
- amount of handling required at the assembly plant for the commodity.

Deliveries in sequence for small, inexpensive, low complexity commodities requiring little material handling does not make economic sense. These types of commodities present little cost savings due to reduced inventory (holding cost) or reduced non-value added activity (handling cost). Examples are bolts, push pins, etc. However, deliver in sequence for large, expensive, high complexity commodities requiring considerable material handling does make economic sense. These types of commodities present potential cost savings through reduced inventory (holding cost) and/or reduced non-value added activity (handling cost). Examples are fascia, seats, door trim panels, etc.
1.3 **ILVS Environment Versus Broadcast Environment**

1.3.1 **ILVS Environment**

As already mentioned, an ILVS environment provides a five day fixed sequence of orders to component suppliers. For components delivered in the ILVS format, the sequence delivered exactly corresponds to the forecasted sequence. The component suppliers utilize the five days forecast to optimize their production systems. It is projected that the assembly plants maintain 98% accuracy of the forecast to actual production. The assembly plant internally handles the two percent deviation from the forecast.

1.3.2 **Broadcast Environment**

The broadcast environment provides component suppliers in real time with the actual sequence of vehicles at a point in the assembly operations. Component suppliers then deliver components sequenced to the broadcast order before the associated vehicle reaches the component installation point. Since most sequence distortion occur in the body shop and paint system, the assembly plant normally provides the broadcast of vehicles leaving the paint system and entering the chassis assembly operations. The component supplier's order-to-delivery window is measured in hours and minutes.

1.3.3 **Implication on Choice of Commodities to Deliver in Sequence**

As noted in Section 1.2, theoretically it makes economic sense to deliver only some commodities in sequence. The main difference between ILVS and broadcast is the more restrictive order-to-delivery timing associated with broadcast. For broadcast to be practical:

- the component plant must be physically close to the assembly plant, and
- the process of sequencing components must be quick. This implies:
  - pulling from finished goods inventory,
  - commodities with very short production times, or
  - products where the end item complexity is added late in the production process.
Theoretically the ILVS environment:

- optimizes more of the production system by removing uncertainty in demand for five days – creating less inventory,
- permits more distant plants to deliver the sequence – creating a larger potential supply base, and
- for a given production system can provide more protection for failures in the system – creating less disruptions in supply to the assembly plant.

1.4 Expected Advantages of the ILVS Environment

The ILVS environment has many potential advantages. The primary advantages include:

- **Reduced Inventory**: ILVS removes uncertainty in demand from the component production scheduling. The reduction in uncertainty of demand allows a lower level of inventory. However, the uncertainty due to supply still exists.

- **Reduced Non-Value Added Activities**: A stable production schedule allows a reduction of non-value added activities in the production process. Examples include reduced double handling, reduced premium freight, increased paint block size, and improved work load balance.

- **Reduced Assembly Plant In-Coming Material Complexity**: The matched sequence of components to the vehicle forecast reduces assembly plant complexity. Ideally, an operator at the assembly line uses the next component in the sequence for each operation. This reduction in complexity allows for increased subassembly by component suppliers.

- **Improved Order-to-Delivery Cycle**: ILVS places incentives in the production system to provide what is required when ordered. It enforces a pull versus push philosophy in production operations.

The secondary advantages include:

- **Increased Manufacturing Discipline**: ILVS imposes increased discipline in the manufacturing operations. For example, ILVS requires high levels of machine uptime and reduced errors in component plant scheduling.
• **Increased Quality**: More discipline in the production system and reduced inventories should increase vehicle quality. For example, it reduces the use of the wrong component caused by in engineering revisions.

1.4.1 **Different Theories for Improved Order-to-Delivery Cycle**

Ford’s stated goal is a 15 day order-to-delivery cycle. The company is working at achieving a pull system from the dealer showroom to the component plant production floor. In the ILVS environment, long delays in the production system are unacceptable. ILVS imposes pressure on the production system to reduce production process constraints and delivery constraints. Consequently, the production system becomes more nimble at meeting “customer” orders.

Other companies use different philosophies to improve their order-to-delivery cycle. General Motors Corporation is moving toward the use of central inventories of finished vehicles ([3],[4]). The assembly plant pushes the high take rate vehicles into the central inventories. Dealers pull customer orders from the central inventories within twenty-four hours of a customer order. The assembly plant expedites customer orders not supplied by the central inventory for delivery within fourteen days. The disadvantage of this approach is that it is sensitive to variability in orders and so requires large levels of inventory for the variety of buildable combinations. The cost of holding this inventory places pressure to reduce its size. One means is reducing buildable combinations, thus lowering the inventory required.

The number of buildable combinations is directly related to the level of available customization. Reducing customization might induce customer dissatisfaction if that level of customization is a customer requirement. ILVS does not artificially limit the level of customization.

1.5 **Thesis Project Statement**

A useful mental model to consider is a continuum of production systems.
• At one end are production systems so quick, reliable, and flexible they provide what is ordered immediately. These systems present little difficulty in meeting the ILVS requirements.
• At the other end of the spectrum are production systems so slow, unreliable, and inflexible they effectively can provide only one end item style. These systems experience more difficulty in meeting the ILVS requirements.

A production system’s location along this continuum greatly influences the cost associated with meeting the ILVS requirements.

This thesis attempts to lay the groundwork for more cost-effective ILVS implementation within the component supply base. The manufacturing system’s and product design’s characteristics impact the cost of meeting the ILVS environment. The operational strategy for the ILVS environment should recognize those characteristics that strongly influence this environment and should make cost justifiable changes to the production system or product design to achieve the best overall production delivery system.

1.6 Thesis Goals

The thesis goals are to identify a production system’s location along the continuum of production systems and to propose methods to improve the production system’s positioning within this continuum. This thesis:

1) proposes a framework for evaluating a production system for the ILVS environment;
2) presents a systems perspective of ILVS to show the impact on system performance of scheduling, process design, and product design;
3) proposes metrics for characterizing a production system, which include not only the output of the process, but also the material flow, machine flexibility, information systems, and other features of the production process;
4) characterizes several operational control strategies for managing a production process in the ILVS environment; and
5) proposes design rules for future production systems and product designs to improve their compatibility with ILVS.
The thesis bases its results on the application of discrete event simulation, design of experiments, fault tree analysis, and probability modeling of door trim panel production at one of Ford’s component plants.

1.7 Overview of Remaining Chapters

SECTION A, which contains a single chapter, presents a framework for developing an ILVS system.

Chapter 2 presents a framework for developing an ILVS production system. The framework presents a method to characterize, model, analyze, and evaluate the production system for the ILVS environment.

- **Characterize:** We first present a system-level view of the ILVS environment. The properties of the system elements characterize the production system. **Section B** discusses each element in detail.

- **Model:** We examine methods for developing models to predict system performance of the production system: probability models, discrete event simulation models, and a design of experiments approach. **Section C** discusses several simplified models.

- **Analyze:** Through the use of increasingly detailed models, we develop an iterative approach to “optimize” the system performance. Early in the analysis we use process screening models to quickly evaluate different alternatives. We then further analyze those alternatives with the greatest promise using more detailed models that can give greater accuracy in the analysis.

- **Evaluate:** We choose the alternative with the best combination of system performance and total system cost for the production system.

**SECTION B** presents in detail each system element of the ILVS environment. The properties of the system elements characterizes the production system.
Chapter 3 describes the current approaches for vehicle scheduling at assembly plants. The chapter briefly explains the procedure used to develop the five day fixed forecast.

Chapter 4 presents the requirements that ILVS imposes on the sequence stream released from the component plant to the assembly plant. One section details the different requirements between the component plant sequence stream and the assembly plant actual and forecasted production stream.

Chapter 5 discusses scheduling at the component plant. This is the process of integrating the ILVS forecast and the state of the production system into the component plant schedule. This chapter discusses four methods of scheduling: the ILVS sequence method, the batch sequence method, time period requirements, and the blend method. The chapter examines how the production processes characteristics impact the component plant schedule.

Chapter 6 presents a method for choosing a location in production process to begin using the forecasted information to control the production system. The location is based on the ability of the component plant to meet the sequence stream requirements. A section is devoted to decoupling segments of the production system to improve its performance.

Chapter 7 considers the production process. It discusses various properties of the production process and their importance in the ILVS environment. Including the production process flow, the process flexibility, the process reliability, the end item differences, and the process operating pattern.

Chapter 8 examines methods for controlling the sequence within the production system. The chapter discusses why a production system requires a control mechanism. The chapter presents three sequence control strategies a replication strategy, a dynamic resequencing strategy, and a sequence safety stock strategy.
Chapter 9 considers the sort and hold process in the production system, namely the process controls the quality of the sequence stream released to the assembly plant. A comparison of the sequence quality metrics at the component plant and the assembly plant is given. One section identifies potential sources of error within the sort and hold process.

SECTION C presents methods for developing analytic models: probability models, discrete event simulation models generic to a set of production systems, and a design of experiment approach. It uses these models to evaluate production systems for the ILVS environment. It also characterizes different operational control strategies through the application of these models.

Chapter 10 presents probability models for the three different sequence control strategies introduced in Chapter 8. The probability models apply to simple production processes. One section of the chapter is devoted to understanding the constraining condition for the performance of the production system. The chapter is intended to give insight to the mechanisms of control.

Chapter 11 develops discrete event simulation models to assess different operational control strategies. These models apply to the production of door trim panels at the Utica Plant and are generic to those production systems.

Chapter 12 proposes a method for characterizing different operational control strategies. It uses design of experiments to develop empirical equations for the performance of the generic models developed in Chapter 10.

SECTION D is a case study illustrating the use of the concepts presented in the previous chapters.
Chapter 13 presents a case study illustrating the use of the concepts presented in the previous chapters. The evaluation presented is complete through the first level of simplified models. The case study is based on the analysis of a future door trim production system at the Utica Plant.

SECTION E presents the recommendations and conclusion of this thesis and proposes areas for future work. The desire is to improve the overall supply chain by making the production system and product design more compatible with ILVS.

Chapter 14 presents the thesis recommendations and conclusions. In brief, some of the recommendations are:

- decrease set-up times through product/process design;
- eliminate the need for set-up through product/process design;
- remove non-value added work-in-process;
- increase production system reliability;
- institute systems to reduce errors in the sort and hold process;
- schedule using the ILVS forecast as far into the production process as possible;
- institute production process flow control based on the forecast sequence; and
- do not go with the high technology solution for technology’s sake.

Chapter 15 suggests future areas of research for ILVS based upon the results in this thesis. We suggest additional basic research into methods to speed development of analytic models for evaluating production systems.
SECTION A

SECTION A presents a framework for developing an ILVS system.
2. Framework for Developing an ILVS System

The framework presents a method to characterize, model, analyze, and evaluate the production system for the ILVS environment.

- **Characterize**: We first present a system-level view of the ILVS environment. The properties of the system elements characterize the production system. Section B discusses each element in detail.

- **Model**: We next examine methods for developing models to predict the performance of the production system: probability models, discrete event simulation models, and a design of experiments. Section C discusses several simplified models.

- **Analyze**: Through the use of increasingly detailed models, we develop an iterative approach to “optimize” the system performance. Early in the analysis we use process screening models to quickly evaluate different alternatives. We then further analyze those alternatives with the greatest promise using more detailed models that can give greater accuracy in the analysis.

- **Evaluate**: We choose the alternative with the best combination of system performance and total system cost for the production system.

2.1 Characterizing the Production System

Figure 2-1 presents at a high level the interaction between the assembly plant and the component plant for delivery of components in the ILVS format. The assembly plant provides the component plant with a five day fixed forecast of the sequence of vehicles leaving the end of the assembly line. The component plant then provides components in the forecasted sequence to the assembly plant to meet the five day forecast. The component plant includes all operations on-site and off-site that are controlled by the component plant.
Figure 2-1: Interaction Between Assembly Plant and Component Plant

The component plant requires a process to ensure delivery of components in the proper sequence. This process sorts and holds the output of the production process until the production sequence meets the ILVS forecast sequence requirements. The number of components components within this sort and hold process depends on the component plant’s ability to manage the production process output relative to the ILVS forecast. The important elements in determining the number of components are:

- component plant scheduling,
- characteristics of the production process, and
- methods for controlling the sequence within the production system.

The process of developing a plan for releasing components into the production process is **component plant scheduling**. The location where the sequence requirement (forecast) information is first used to control the release of components to the next production station is the **sequence control location**. The sequence control location releases a component which is a platform upon which the rest of the production system is controlled. We refer to this component as the **platform component**. The characteristics of the production system might require modifying the sequence of orders released to the sequence control location relative to the forecasted sequence. This modified sequence is a **modified ILVS sequence command**.
The production process converts raw materials into finished goods. Metrics such as process flow, down time, scrap rates, cycle times, etc. characteristic the operation of the process.

The strategy used to control the output sequence of the production system is the sequence control strategy. The sequence control strategy is concerned with providing commands within the production system based on the state of the production system to optimize the output of the production process relative to the forecast.

Figure 2-2 presents a process diagram of the production system as just described. The framework uses the element properties to characterize the production system.

Figure 2-2: Production System Process Diagram
Component Plant Production System Input and Output:

- **Component Plant Input: Assembly Plant Vehicle Schedule**: An assembly plant vehicle schedule is a five day fixed forecast of the sequence of vehicles leaving the end of the assembly line. This information allows component plants to increase their operational efficiency. For more information, see Chapter 3.

- **Component Plant Output: Assembly Plant Material Input**: The material input to the assembly plant are components from the component plant sequenced in the ILVS forecast sequence. The assembly plant installs these components at the component installation point. For more information, see Chapter 4.

Component Plant Production System:

- **Component Plant Scheduling**: Scheduling is a process of developing a plan for operating a production process. The component plant converts the ILVS sequence forecast and plant operating conditions into a production schedule or modified sequence command. For more information, see Chapter 5.

- **Sequence Control Location**: The sequence control location releases the platform components into the production process. For more information, see Chapter 6.

- **Production Process**: The production process converts raw materials into finished goods. In control theory language, it is a transformation function. The characteristics of the production process determine the form of the transformation function. For more information, see Chapter 7.
  
  - **Rework**: The production process places components with correctable quality defects off-line. The rework operation increases the quality to acceptable levels and then releases the component back into the production process.
  
  - **Scrap**: Components with uncorrectable quality levels are removed from the production process and discarded.

- **Sequence Control Strategies**: A sequence control strategy is the mechanism for providing control commands in the production system. For more information, see Chapter 8.
• *Sort and Hold Process*: The sort and hold process is the element ensuring the component plant releases components to the assembly plant meeting the ILVS sequence requirements. For more information, see Chapter 9.

2.2 Modeling the Production System

We desire to use models of the production system in the most efficient manner possible. In the past, no quick analytical method existed for evaluating the production system. When a plant wished to analyze a new production system, it developed a detailed simulation model. The problem with a detailed model is the amount of time required to develop it. This time investment limits the amount iterations an analyst can perform. The use of simplified models reduces the analysis cycle time. The reduced cycle time permits additional iterations on the production system. These iterations should enable a higher quality, lower cost alternative.

This thesis presents three methods of simplified model development.

• **Probability Models**: Probability models use probability equations to investigate mechanisms for affecting the production system performance in the ILVS environment. For more information, see Chapter 10.

• **Generic Models**: When a component plant uses a similar production system for more than one product line, it might be useful to create a generic model for that type of system. Using the generic model for future analysis of these product lines can reduce the development time required for modeling. For more information, see Chapter 11.

• **Design of Experiments (DOE) Characterization**: When applied to a production system model a DOE can quantify how changes in design variables effect the system performance. The DOE process develops an empirical equation to explain the production system’s response to changes in the design variable(s) within the operating range investigated. This quantification can provide insight for further model-based evaluations. For more information, see Chapter 12.
Each of these modeling alternatives presents a different loss of accuracy. Which model is best suited to a situation depends on the previous analysis performed and the level of accuracy required from the analysis.

2.3 **Analyzing the Production System**

To analyze a production system, it is important to understand what is and is not variable. What is variable has a time dimension associated with it. The farther from the start of production, the greater the number of variables. Listed below are the variables to consider. See Figure 2-3 for a graphical representation of the discussion directly below.

![Figure 2-3: Framework for Developing an ILVS System](image)

- **Product Design**: A product design is the description of the desired output of the production system. The product design is an input into the development of the production system, but is not a one direction flow of information. To improve company performance might require modifications of the product design.

- **Assembly Plant Requirements**: For this thesis, we will limit customers needs: to the assembly plant requirements placed on the sequence stream provided by the component plant. Like product design, there should be a two way flow of information to optimize corporate costs. For more information, see Chapter 4.
• **Production System Characteristics:** A production system utilizes resources to convert inputs into a product that meets its design specifications and intent. The production system is developed based upon the requirements of product design and customer needs. Associated with the production system are characteristics that specify how resources are utilized. This is based upon the production process characteristics and the operational strategy of the production system. For more information, see Section B.

• **Production Process:** A production process converts raw materials into a finished product. Its design and operation is based upon the product design, assembly plant requirements, and operational strategy. In order of decreasing scope, this thesis uses the terms production process, production segment, and production station.

  • **Production Segment:** A production segment is a subset of a production process. An example of a production segment is the paint system at an assembly plant.

  • **Production Station:** A production station is an individual production unit. An example of a production station is an injection molding machine at a component plant.

• For more information, see Chapter 7.

• **Operational Strategy:** An operational strategy is a method for running a production process. It includes such items as a scheduling method, a sequence control strategy, a sequence control location, and decoupled production segments. A production segment is a subset of a production system. Each of these choices influences the cost structure and performance of the component plant. The production process might be influenced by the choice of an operating strategy. Again, development of the operating strategy and production process is a two way flow of information.

  • **Scheduling Method:** This is the method for developing a production plan to release orders into the production system. For more information, see Chapter 5.
• **Sequence Control Strategy:** A sequence control strategy is the mechanism for feeding control commands within the production system. For more information, see Chapter 8.

• **Sequence Control Location:** A sequence control location releases platform components into the production process in response to the component plant schedule. For more information, see Chapter 6.

• **Decoupled Production Segments:** Decoupling removes the short term operational influence between production segments. By removing these influences, it might be possible to reduce the cost structure of the component plant. A production segment is a subset of the production process. For more information, see Section 6.5.

We believe that by iteratively evaluating alternatives, we should be able to reduce overall corporate costs. Therefore, our proposal for evaluating production systems for the ILVS environment is a multiple step process, as shown in Figure 2-4.

![Figure 2-4: Multiple Step Evaluation Process](image-url)
Early in the evaluation process, we use a simplified model to evaluate the performance of the production system. Considering the results of the previous alternative, we modify the production system and product design where possible to create new alternatives. We quickly screen new alternatives using the simplified predictive models and iterate until satisfied with the performance. We then develop more detailed models to analysis those alternatives showing the greatest promise. Section D (Chapter 13) presents an application of this analysis process up to the use of simplified predictive models.

There is a loss of accuracy when using a simplified model. The development of simplified model requires simplifying assumptions of the production system. With simplified models, we trade accuracy for speed of analysis. We do not propose to evaluate the production process using only these simplified models. Rather, they screen options and help determine those with potential for further investigation.

2.4 Evaluating the Production System

To evaluate the performance of alternatives, we consider both monetary and non-monetary costs. We wish to choose the alternative with the best combination of system performance and total system cost. Generally it is difficult to place a dollar value on non-monetary cost such as the operational similarity of the alternative to the current practices. The monetary costs of installing and operating the production system include the following items:

- **Labor Expense**: The number of the people and their associated salary required to run the production system.
- **Facility and Tooling Investment**: ILVS specific capital required for the production system.
- **Floor Space Requirement**: The amount of floor space needed for the production system.
- **Inventory Cost**: The value of the inventory and its associate holding cost.
SECTION B

SECTION B presents in detail each system element of the ILVS environment. The properties of the system elements characterizes the production system.
3. Component Plant Input: Assembly Plant Vehicle Schedule

*Component Plant Input: Assembly Plant Vehicle Schedule:* An assembly plant vehicle schedule is a five day fixed forecast of the sequence of vehicles leaving the end of the assembly line. This information allows component plants to increase their operational efficiency.

3.1 Assembly Plant Vehicle Scheduling

Production scheduling is the process of developing a plan for operating a production process. There are two broad categories of scheduling: a pull system and a push system.

- **Pull System:** A pull system operates based on customer orders.
- **Push System:** A push system operates based on a projection (forecast) of demand.

3.1.1 Ford Assembly Plant Scheduling

At Ford, assembly plant scheduling uses a pull system of vehicle orders called the National Blend. The sales organization provides orders to the scheduling activity. Considering material availability, capacity limitations, work load balance, etc. at the assembly plant, the scheduling activity develops the assembly plant schedule.

The ILVS environment determines a rotation number (sequence number) associated with each vehicle order based on the attributes for a vehicle order and the production system’s priorities and constraints. Examples of vehicle attributes are exterior color, work content, interior color, body style, and order delivery date. Body shop and paint system priorities and constraints include capacity limitations, raw material availability, and work content balance. Body shop examples are limitations on releasing moonroof or export vehicle. A paint system example is the desire for increased paint block size [1]. Paint block size is the number of vehicle in a row painted with the same color. Increased paint block reduces cost incurred by purging of the paint system between different colors.
3.1.2 Other Automotive Companies Assembly Plant Scheduling

Some vehicle manufacturers use a push system of vehicle orders. The prediction of vehicle demand to varying degrees is the basis for their assembly plant’s schedule. Companies allocate assembly plant output to customer, dealers, or sales regions. By using predicted demand a firm can create a strict rotation of vehicle styles and large batches in the production process. Large batch sizes might have additional benefits, including increased paint block size. It might be possible to optimize some auxiliary items such as shipping racks, since the entire company production system becomes keyed off the batch size. The batch size, number of buildable combinations, and time frame for predicting orders determine the level of finished goods' inventory.
4. Component Plant Output: Assembly Plant Material Input

Component Plant Output: Assembly Plant Material Input: The material input to the assembly plant are components from the component plant sequenced in the ILVS forecasted sequence. The assembly plant installs these components at the component installation point.

4.1 Sequence Stream Complexity Requirement

To develop a production system, it is important to understand the complexity requirement placed on the sequence stream. The sequence stream complexity is the number of different end item(s) styles that the sequence stream can produce. The more complex a sequence stream, the more difficult the sequence stream is to produce. Consider two examples:

- a common production segment is required in the production of more than one sequence stream; and
- unique production segments' output must be merged into a single sequence stream.

Recall that a production segment is a subset of a production system.

4.1.1 Common Production Process Segments: Unique Streams

More than one unique sequence stream might require the use of a common production segment. Consider the example in Figure 4-1. A production segment produces front left hand, front right hand, rear left hand, and rear right hand components.

![Figure 4-1: Common Production Process Segments: Unique Streams](image-url)
The assembly plant can require all four products in a single sequence stream or require unique sequence streams for each of the four products. The lower sequence stream complexity, shown on the right in Figure 4-1, implies fewer components in the sort and hold process. Assume the production process introduces independent errors in the sequence streams. Recall from statistics, to obtain the system variance we add independent variances. The greater the variance the higher the maximum number of components in the sort and hold process, Equation 4-1.

\[
Var(A + B) = Var(A) + Var(B)
\]  \hspace{1cm} \textbf{Equation 4-1}

4.1.2 **Unique Production Segments: Common Streams**

Unique production segments might require integration to provide one common sequence stream. Consider the example in Figure 4-2. Assume a unique production segment produces front panels and rear panels. The assembly plant might require a sequence stream composed of a vehicle set (high complexity requirement) or unique sequence streams for the front right hand, the front left hand, the rear right hand, and the rear left hand components (low complexity requirement). The production of a vehicle set requires integration of the front panel and rear panel production segments. This integration complicates the operation of the component plant.

**Figure 4-2: Unique Production Segments: Common Streams**

Consider an extreme example, the location of two production segments in different component plants supplying a common sequence stream (e.g., an assembly plant). It is
obviously not a desirable to merge different production processes together into a single sequence stream since the merger requires careful coordination between the component plants and/or integrating at the assembly plant.

4.2 Sequence Stream Release Requirement

The ILVS environment requires that component plants provide 100% accuracy to the ILVS forecast sequence. The component plant must hold all components in the sequence stream after a hole in the sequence. Stated another way, a component plant can release their sequence stream only up to the first hole in the sequence.

Consider the example in Figure 4-3. The sequence stream can release up to sequence number 9. This requirement is independent of the number of components correctly sequenced beyond sequence number 9. Once the plant has filled order 10, it can release sequence the sequence stream up to the next hole, sequence number 13.

![Sequence Stream Diagram]

**Figure 4-3: Sequence Stream Release Requirement**

4.3 Component Plant versus Assembly Plant Release Requirements

In the ILVS environment, the main difference between a component plant and an assembly plant is the release requirement. At the component plant, the sequence release requirement is 100% accuracy. However, the assembly the sequence requires only 98% accuracy for the sequence stream released from the paint system into chassis operation. Therefore, the release requirement for the assembly plant is less stringent than the requirement for a component plant.
5. Component Plant Scheduling

Component Plant Scheduling: Scheduling is a process of developing a plan for operating a production process. The component plant converts the ILVS sequence forecast and plant operating conditions into a production schedule or modified sequence command.

5.1 Modified ILVS Sequence

The desired schedule sequence at a component plant might not agree with the ILVS forecast sequence (includes a rotation number and end item style identification) required by the assembly plant for several reasons:

- The ILVS forecast is the sequence of vehicles. Each vehicle in the sequence might not require a component from the component plant sequence stream. The component plant must identify which vehicle orders require a component from their production system(s).
- Consider the situation where more than one assembly plant uses the same component production system. If the production system produces the sequence streams for the assembly plants concurrently then the ILVS forecasts for the assembly plants must be merged.
- The assembly plant might require the component plant to fills trucks or rail cars in reverse sequence series, with the highest sequence number first. Component plant scheduling must reverse the schedule sequence series in truck or rail car load size.
- The component plant might resequence the ILVS forecast sequence based on the flexibility and reliability of the production system. For example, if the scrap or rework rate for certain end item styles is high moving them earlier in the schedule might improve the performance of the system [1].

These decisions modify the schedule sequence at a component plant relative to the ILVS forecast sequence. Section 5.8 discusses modifying the sequence to correct errors in the production system.
5.2 Scheduling Viewed at an Individual Sequence Order Level

Table 5-1 shows an ILVS forecast which specifies a component by component piece flow at the component installation point. The component plant will supply its components in a shipping container. The assembly plant will then pull the orders from the container. If the components do not reach the end of the production process in the correct sequence, the sort and hold process must place them into the correct order. The more capable the component plant is at producing the exact ILVS sequence, the lower the number of components the plant must hold in the sort and hold process. The greater the number of components held in the sort and hold process, the greater the cost of installing and operating the sort and hold process. Scheduling goal is to minimize the number of components in the sort and hold process.

<table>
<thead>
<tr>
<th>Sequence Location</th>
<th>99</th>
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<th>101</th>
<th>102</th>
<th>103</th>
<th>104</th>
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<th>108</th>
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<td>Blue</td>
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<td>Red</td>
<td>Blue</td>
<td>Green</td>
<td>Red</td>
<td>Blue</td>
<td>Green</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-1: ILVS Sequence Forecast at Individual Sequence Location Definition

5.3 Schedule Distortions and Errors vs. ILVS Forecast

As described in Section 5.2, ILVS seeks a component by component piece flow to the assembly plant. The desired sequence of production into the sort and hold process might, however, be a modified ILVS sequence as discussed in Section 5.1. Schedule distortions and errors create deviations in the production schedule from the modified ILVS sequence. The greater the distortions and errors, the greater the number of components in the sort and hold process.

- **Distortions**: Distortions are perturbations that do not materially alter the sequence and are self-correcting, requiring no additional commands in the production system.
- **Errors**: Errors are discrepancy in the production sequence to the modified ILVS sequence and require additional commands in the production system to correct.
Commands are instruction in the production system telling production system elements what actions to perform. For example, the sequence control strategy commands the component plant scheduling element to reschedule an order when its associated component was scrapped.

One example of schedule distortion is batch sequencing.

1. **Batch Sequencing**: Batch processing produces one or more of the same end item in a row. Section 5.5.2 discusses batch sequencing and delineates some of the advantages of this scheduling strategy.

Two examples of schedule errors are incorrect sequence schedule and production process constraints.

2. **Incorrect Sequence Schedule**: If the desired sequence based on the forecast and state of the production system is red, blue, green, red, ..., but the system produces red, green, blue, green, ... then the production schedule has caused an error. Incorrect sequence schedule is purely scheduling the wrong components, whether done in a batch mode or not.

3. **Production Process Constraints**: The level of flexibility in a production process might impose constraints on scheduling. For example, cycling a production station for a desired component might produce not only the current desired component, but also provide a component(s) not required. The extra component(s) is an error in the production system.

Errors increase the number of components held in the sort and hold process until the production system provides corrective command(s).

### 5.4 Pull versus Push Systems of Production Scheduling

As mentioned in Section 3.1, there are two broad categories of scheduling: a pull system and a push system.

- **Pull System**: A pull system operates based on customer orders.
- **Push System**: A push system operates based on a projection (forecast) of demand.
5.4.1 **Ideal Pull Production System**

The desired method of scheduling is a pure pull system with no errors due to production process constraints, see Figure 2-3. The only source of distortion possible from scheduling is that of batch sequencing.

![Diagram: Production System as a Control System](image)

**Figure 2-3 (repeated): Production System as a Control System**

5.4.2 **Pull Production System with Errors**

Figure 5-1 includes delays in the scheduling the ILVS forecast as well as delays in receiving feedback about errors from the sort and hold process. The scheduling delay can arise because the plant is using a daily requirement or weekly requirement, see Section 5.5.3. The greater the scheduling delays the more the production system tends towards a push system. If the delay is greater than the five day forecast window, the process acts like the push system. The feedback loop from the sort and hold process compensates for errors other than scrap in the production system. The feedback of errors is not
instantaneous. Long delays in feedback degrade the system's performance. In this case, the source of scheduling distortion and errors are batch sequencing for distortions and production process constraints for errors in the production system.

![Diagram of Production System with Errors in the Production Schedule]

**Figure 5-1: Production System with Errors in the Production Schedule**

### 5.4.3 Push Production System

Figure 5-2 represents a push system of production scheduling. The push system does not utilize the ILVS sequence forecast or direct feedback of scrap to scheduling. Instead the production schedule is based upon some long term projection of orders as well as feedback information (with delays) from the sort and hold process. The feedback information will specify the number of components for each end item style held in the sort portion of the sort and hold process. The sort and hold process operates based on the
ILVS forecast sequence. Typically what a push system provides to the sort and hold process will not match the desired five day forecast. The sort and hold process will need to be larger so that the component plant can provide items correctly sequenced. Consequently, the production system will be more costly. Sources for errors in this system are incorrect sequence scheduling and production process constraints.

![Diagram of Production System with a Push System of Production Scheduling](image)

**Figure 5-2: Production System with a Push System of Production Scheduling**

### 5.5 Production Scheduling Methods

This section describes four different methods for production scheduling. ILVS sequence order, batch sequencing, and time period requirements are pull methods of scheduling. The blend method is a push method of scheduling.
5.5.1  **ILVS Sequence Order Scheduling Method**

For a ILVS sequence order scheduling method, the sequence of orders is identical to the desired ILVS sequence. This method induces no distortion in the production system due to scheduling. Table 5-2 gives an example of the ILVS sequence order method of scheduling. The number of components held in the sort and hold process depends only on distortions and errors due to the production process.

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<th>Part Style Scheduled</th>
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</thead>
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<td>116</td>
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</tr>
</tbody>
</table>

*Table 5-2: ILVS Sequence Order Method*

5.5.2  **Batch Sequence Scheduling Method**

The batch sequence scheduling method schedules batch quantities to minimize the distance to the oldest order. The ILVS sequence order method is a special case of the batch sequencing method with a batch size of one. With batch sequencing, the production schedule induces distortion into the production system. The approach for determining the end item style for the next batch is to assign the end item style of oldest sequence order not filled from all previous batches. All components within a batch will not be associated with a current or prior order (that is, the system is producing for future orders). This is a source of distortion in the schedule. It is distortion because another batch is not scheduled
until the production system associates an order with each of the good components produced from the previous batches. Section 12.6 shows that producing components ahead of an order can improve the system performance.

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data size = 3

**Table 5-3: Batch Sequencing Method**

Table 5-3 gives an example of batch sequencing. Batch sequencing schedules some components early (pre-produced), some at the correct time, and some late. The right six columns track the oldest order by end item style. The columns titled ahead/behind show the number of components pre-produced (positive) and produced late (negative). The fourth column from the left identifies the style of the oldest scheduled order each time the system must decide upon the next batch style. For example, when determining the second batch, the style of the oldest unscheduled order is red. Therefore, the second batch will be red.

The level of distortion from batch sequencing depends on the number of unique end items and the desired batch size. The larger the number of end items and/or batch size the more distortion batch sequencing introduces into the production system.
5.5.3 Time Period Requirements Method

The time period requirement method schedules the production of all the components required to fill orders over a given time frame based on the ILV forecast. The time frame might be a shift, day, etc. The shorter the time frame, the lower the number of components in the sort and hold process. For example, if the production process schedules for daily requirements, the sort and hold process will hold one day’s production of components. However, if the schedule is for a shift requirement, the sort and hold process will hold one shift’s production of components. The time period method induces distortion into the production system.

5.5.4 Blend Scheduling Method

The blend scheduling method is push system of scheduling. It will produce to a projection of orders for a given time frame independent of order location within that time frame. The production system releases a batch independent of an order to trigger that batch or orders for the components produced by previous batches. Therefore, the blend method introduces errors into the production system due to incorrect sequence scheduling. The time between error correction to the blend percentages is an important factor in determining the quality of the sort and hold process. The longer the time between corrections, the greater the number of components in the sort and hold process. The use of the blend method is independent of batch processing.

See Table 5-4 for an example of the blend method with a batch size of three and an average end item take rate of 33% red, 33% green and 33% blue. The method uses a rotation to schedule the production system independent of the ILVS forecast. The example repeats the rotation blue, red, green independent of the orders. Blend scheduling induces errors in the production system compared to pull systems of scheduling. In the example, the time frame is short so the error is not too great. The schedule error from the blend method increases versus batch sequencing as time increases.
<table>
<thead>
<tr>
<th>Sequence Number</th>
<th>Part Style Ordered</th>
<th>Blending Part Style Scheduled</th>
<th>Batch Sequencing Part Style Scheduled</th>
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<td>Green</td>
<td>Blue</td>
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</tbody>
</table>

*Blend Rate*
- Blue = 33%
- Red = 33%
- Green = 33%

**batch size = 3**

**Table 5-4: Blend Sequencing Method**

5.6 **Comparison of Scheduling Methods**

Figure 5-3 compares the behavior of the ILVS sequence order, batch sequencing, and blend methods of scheduling. The example assumes a complexity of three unique end items, no production scrap, and perfect first run capability. These assumptions imply the only errors and distortions in the production system are from the scheduling method. The pull systems are on the left and the push systems are on the right.

The far left column shows the results of the ILVS sequence order scheduling method. With no distortion or error in the production system, the sort and hold process contains no components. This is cause by no variability of either demand or supply.

The three remaining columns for pull systems show the effect of the batch sequence method. The columns assumes a batch size of six, eleven, and fifty from left to right respectively. As expected, the greater the batch size, the greater the distortion due to batch sequencing. It is possible to show for this idealized system that increasing the complexity increases the number of components held for a given batch size.
The fifth through eighth column present the results of a pull system based on a projection of a yearly take rate. As the results show, the performance of the push system is significantly worse than a pull system. Also, the performance of the system degrades with increasing batch size. Once again, for this idealized system, increasing the complexity increases the number of components held for a given batch size.

![Diagram of Schedule Distortion]

- complexity = 3
- scrap = 0%
- 1st run = 100%

**Figure 5-3: Comparison of Scheduling Methods for Random Vehicle Orders and Linear Take Rate**

### 5.7 Production Process Constraints Affect on Production Scheduling

The production process might place constraints on scheduling. For example, a molding process might be set-up to produce a right hand, left hand pair for each cycle of a production station. If the production system requires only the right hand component, the left hand component's production is an error in the production system. As another example, imagine a process that produces a set of components in the same color, for a
situation when the production system desires different colors within the set for that cycle of the production station. The additional components produced that are not required errors in the production system.

5.8 Production System Error Scheduling Algorithm

The production schedule needs to correct for errors in the production system. Scheduling errors such as incorrect sequence scheduling and production process constraints, or production process errors such as scrap, increase the number of components held in the sort and hold process. The quicker the production system can respond to errors, the fewer the number of components in the sort and hold process. Listed below are some examples that slow the response time to errors.

- Non-value added components in the system between the sequence control location and the sort and hold process slow the response of the production system to error correction. Consider a conveyor that moves components from one area of the plant to another. The value the conveyor adds is moving components. If rearranging the production process removes the requirement for the conveyor and the associated platform work in process (WIP), the system performance improves through decreased response time for error correction.

- The sequence control location is the process in which components are released in sequence to the production process. If the sequence control location builds up large number of components (buffers) prior to the next production station. The response time of the production system to error correction degrades due to the additional platform WIP. The desire is to release the sequence directly into the next production station without prestaging sequenced components prior to the sequence control location.

- The number of components in the sort and hold process increases each time a production process constraint requires the release of additional components not required by the current order. The number of components in error decreases by the next order for their end item style. However, an imbalance in components released in error to orders continuously increases the number of components in the sort and hold
process. Consider an injection molding machine with imbalance in the scrap rate between the right hand and left hand components. For our example, the injection molding machine produces more right hand scrap than left. If the production process is incapable of producing right hand panels independent of left hand panels, the sort and hold process fills with unwanted left hand panels.
6. Sequence Control Location

*Sequence Control Location:* The sequence control location releases the platform components into the production process.

6.1 Overview of Choosing a Sequence Control Location

Providing the required sequence of components (sequence stream) to the assembly plant constrains the placement of the sequence control location. The following metrics are important in choosing a sequence control location.

- **ILVS Window:** The ILVS window is the number of forecasted orders the component plant sees (views) from the component installation point. This is the number of orders the component plant can use to improve the operation of its production system.

- **Component Plant Window:** The component plant window is the number of orders that the component plant needs to provide sequenced components at the desired service rate from a given sequence control location.

- **Component Plant Slack:** The component plant slack is the ILVS window size minus the component plant window size.

If the component plant slack is positive, scheduling the production system using the ILVS forecast is possible. If the component plant slack is negative, the component plant cannot supply the assembly plant from that sequence control location. This occurs because the component plant has insufficient ILVS sequence orders to schedule production using the ILVS forecast at the sequence control location. If component plant slack is negative the two alternatives are;

1) choose a new sequence control location closer to the end of the production until the component plant slack is positive; or

2) it is not possible to schedule the production system using the ILVS forecast for that product line.
Figure 6-1: Sequence Control Location Relative to the ILVS Forecast Sequence
Pulling the sequence stream from finished goods inventory is always an available option. However, depending on the production system, it might not be possible to fill the finished goods inventory using the ILVS forecast. Recall the continuum of machines discussed in Chapter 1. The component plant might not view the ILVS forecast anywhere in the production system except in finished goods inventory when the production system is slow, unreliable, and inflexible. In this case, it is only possible to fulfill the ILVS requirements by pulling from finished goods filled with a push method of scheduling. In this chapter, we interchangeably use time and orders.

6.2 Five Day ILVS Forecast

The ILVS forecast is a five day fixed forecast at the assembly plant of the vehicle sequence from the end of the production line. This information allows component plants to increase operational efficiency by removing all uncertainty in component orders. The component plant still faces uncertainty in the supply based on the properties of the production system.

6.2.1 Distance from the End of Production Line

The component installation point is the location where the assembly plant installs the component onto the vehicle. The distance from the end of the production line is the number of vehicles between the component installation point and the end of the assembly line. The example in Figure 6-1 is six orders (vehicles) from the end of the assembly plant production line.

6.2.2 ILVS Window

The ILVS window size is the fixed five day forecast reduced by the number of vehicles between the component installation point and the end of the assembly line. In Figure 6-1, the ILVS window is the five day forecast less the six orders for the distance from the end of the production line. The ILVS forecast window is the total number of sequence orders a component plant can use to optimize their production system. The larger the ILVS window, the more time the component plant has to meet the sequence requirements.
6.3 Component Plant Window

The component plant window is the number of orders the component plant requires to deliver component in sequence from the sequencing control location at a given service rate. The example in Figure 6-1 has a component plant window of nineteen orders. The component plant window is a function of the order completion time, production system wait time, production system down time, and finished good's transportation time. For a given sequence control location, the number of orders required increases with increases in the desired service rate. The ILVS environment requires a very high service rate because of the expense associated with unexpected downtime of an assembly plant. However, it might be unrealistic to expect a service rate of 100%. The benefits of ILVS are believed to outweigh the potential cost of stock out.

6.3.1 Order Fulfillment Time

When an order is released from the sequence control location, the order fulfillment time is the number of orders that enter the production process before that order is ready for shipment to the assembly plant. In Figure 6-1, the order fulfillment time is five orders. The production system characteristics determine the order fulfillment time for a given sequence control location. Consider a component released at the sequence control location in response to an order. When the component reaches an inspection station its quality is found to be deficient. Therefore, the production system scraps the component. The production system must then release another component from the sequence control location to fill that order. Until a component of acceptable quality reaches the sort and hold process that fills the order the production system has not fulfilled the order. The order fulfillment time is based on the probability of filling an order for a given time frame.

6.3.2 Production System Wait Time

More than one sequence stream might share the same production system, production process, production segment, or production station. If the set-up time between any of the end items processed through the segment is greater than the segment cycle time, different
sequence streams require separate production runs. This situation requires the use a
schedule rotation to produce the different sequence streams. The production system wait
time is the number of orders between the end of the last production run and the start of
the next production run for the same sequence stream. The example in Figure 6-1 has an
production system wait time of five orders. If the plant produces the complete sequence
stream during a production run, the sort and hold process holds no additional
components. See Figure 6-2.

![Production System Wait Time Diagram](image)

**Figure 6-2: Production System Wait Time**

6.3.3 **Machine Down Time**

Machine down time is the number of sequence orders added to the component plant
window from unavailability of the production system to produce when scheduled. In
Figure 6-1, to protect for machine down time requires five orders. The greater the
probability of down time, the orders the system requires in the component plant window
to protect the sequence stream for the desired service rate.

6.3.4 **Transportation Time**

Transportation time is the number of sequence orders added to the component plant
window to move components from the component plant to the assembly plant. Figure 6-
1, the transportation time requires four orders. The amount of transportation time
tolerated by the ILVS environment is much greater than in broadcast system.

6.4 **Component Plant Slack**

Component plant slack equals the ILVS window minus the component plant window.
Positive component plant slack provides the potential of additional protection within the
production system. The component plant might decide to add protection at the assembly plant at the truck bullpen to protect for instability in the transportation time.

6.5 Decoupling the Production Process

Decoupling production segments removes the short term operational influence between them. Recall, a segment of a production system is a subset of the total production system. For example, at an assembly plant, the paint ovens are a segment of the paint process, which is a segment of the total assembly plant process. There are two reasons to decouple:

1) inability to use the ILVS forecast to schedule the orders released by the sequence control location, and
2) ability to improve production system performance by decoupling production segments.

Figure 6-3 shows two segments of a production system. A sufficiently small component plant window allows Production Segment A to contain the sequence control location. Production Segment B is the next production process segment. There is a decoupling buffer between Segment A and Segment B. The purpose of this buffer is to remove the short term operational influences between the two production segments. This example shows only two segments. There might be more.

6.5.1 Inability to View ILVS Forecast

Situations arise when the component plant window is greater than the ILVS window for a production system. Therefore, the component plant must decouple the production system if it wants to use the ILVS forecast to schedule any portions of the production system.

- A segment of a production process might be highly unreliable. The time to repair this segment might exceed the ILVS window size.
- The production system wait time might increase the component plant window beyond the ILVS window size.
- The order completion time might exceed the ILVS window size.
Figure 6-3: Decoupling Production Process Segments with Pull Scheduling
6.5.2 Ability to Improve System Performance

The other reason to decouple production segments is to improve the production system performance. We might wish to decouple production segments for the following system performance reasons.

- The sort and hold process might require fewer components if we decouple the production system between process segments where the complexity of the platform component increases. The quicker the system corrects errors or distortions, the better the performance of the production system.
  - One way to quickly correct errors is through the use of safety stock. Sequence safety stock prepositions good components in the production system to correct errors and distortions. The lower the platform complexity the lower number of components required in the sequence safety stock. Decoupling prior to the point in the system where the complexity increases reduces the size of the sequence safety stock.
  - Depending on the sequence control strategy the lower the end item complexity, the lower the number of components in the sort and hold process. By holding components at different locations in the production process, the number of components held in the final sort and hold process might be reduced.

- The order completion time depends on several variables including the platform WIP size between the sequence control location and the end of the production process. The WIP includes components in buffers, non-value added components, and components being processed. Non-value added components are those component in addition to what is required for the efficient operation of the production system. The greater the size of the platform WIP, the longer it takes for error correction within the production system. Conversely, the smaller the platform WIP size, the less time required for error correction. Some reasons for process buffers include:
  - unreliability within a production segment,
  - different cycle times between segments,
different operational schedules between segments, and
process inflexible (see Section 7.6) within a segment.

6.5.3 Methods to Decouple Production Segments

Decoupling buffers act as filters to smooth out the operational variations between production segments. Two methods are available to decouple segments within a production system: sequence safety stock, and/or holding the production stream until holes are filled. The requirement of a decoupling buffers is providing components on command to the next production segment. Allowances can be made for:

- hold time between production processes (this is not really a buffer but, often it is confused with one),
- scheduling errors and distortion,
- scrap in the production segment,
- rework in the production segment,
- down time in the previous production segment, and
- operating schedule differences between two segments.

When segments are decoupled for scrap, the decoupling buffer includes allowances for scrap. When an order is scrapped, that information is fed back through all the production segments to the sequence control location. The record of scrap triggers a replacement order to replenish the sequence safety stock within the decoupling buffer. The sequence control strategy issues a command to the sort and hold process to place aside the appropriate replacement component for the sequence safety stock.

6.5.4 How to Schedule Between Production Segments

As previously mentioned, there are two methods of scheduling, a pull system and a push system. Chapter 5 discusses scheduling methods in detail. It should be obvious that scheduling between the production segments works best in a pull system, Figure 6-3. The pull schedule is based upon the ILVS forecast sequence.
However, Section 6.5.1 explains cases when it is not possible to view the ILVS forecast. This forces a push system of scheduling in the early stages of the production system. Figure 6-4 presents a production system where the first production segment uses a push method of production scheduling. In this case, Segment A pushes components into decoupling buffer where there is a slow mechanism to feedback errors in the production system back into that production segment scheduling algorithm.
Figure 6-4: Decoupling Production Segments with Push Scheduling
7. Production Process

*Production Process:* The production process converts raw materials into finished goods. In control theory language, it is a transformation function. The characteristics of the production process determine the form of the transformation function.

7.1 Platform Component

The sequence control location releases a component that is a platform upon which the rest of the production system is controlled. We refer to these components as platform components. For example, the production system uses the upper substrate instead of the lower substrate for the platform component. The platform component indicates the hierarchy of the production process for triggering the feed of sub-components into the production process.

7.2 Production Process Flow

A production system, Figure 7-1, contains two categories of work-in-process (WIP):

- material going through a process (production station), or
- material waiting to go through a process (buffer).

In three situations in a production process, Figure 7-1, the movement of material through a process can cause distortion of the sequence:

- parallel production stations,
- movement of components into and out of a buffer (buffer control), and
- off-line production stations.

Figure 7-1 shows a buffer between each production station, however, this is not always the case. In addition, it is not always obvious that WIP is going through a production process. An example is components held awaiting a stabilization of their geometry after a molding process. These components might look like a buffer, but really they are going through a production process.
There are several important questions to raise about a production process flow.

- Does the production system have flow control procedures in to enforce the sequence as placed in the system? Areas of concern are the movement of WIP between production stations and within buffers in the process. The use of strict flow control can reduce distortions in the production system from the production process [2].

- How much WIP passes an off-line production station between the point when a component is pulled off-line and when it is placed back into the main production stream? The more WIP that passes the station before the component is released, the more distortion in the process.

- Is there random access in the system? The easier it is in the production process to reach any component, the easier it will be to operate the production system. The problem with providing random access is that often doing so is very expensive, especially, if we are providing random access to a large WIP.

- Is the system adding value at each component location in the production process? Remove all non-value added regions from the production process. Non-value-added regions add length to the production process and increase the time required to correct errors in the production system.
7.2.1 Parallel Production Stations

Does the production process have parallel production stations? The flow control into and out of the parallel stations can affect the number of components in the sort and hold process [2].

Figure 7-2 shows production station 1 supplying components into a process consisting of three parallel stations 2A, 2B and 2C that then supplies production station 3. For illustrative purposes, this example assumes no buffers between the production stations.

![Diagram of Parallel Production Stations]

Figure 7-2: Process Flow into and out of Parallel Production Lanes
To release WIP into the parallel stations, we might use two methods of flow control.
1) Pull WIP into the parallel stations in a strict rotation of station 2A, then station 2B, then station 2C, and then back to station 2A and so on as long as all the stations are operating. (The strict rotation might increase the reliability of the system since the probability all three parallel stations (or segments) break down is less than that of one of the parallel stations (or segments) breaking down. Therefore, the parallel stations act as a redundant system, improving the reliability of the total system.)
2) Push WIP into the next available parallel station. This approach would work well if the cycle time standard deviation between parallel stations is low and the system reliability is high.

To remove WIP from parallel stations, we might use two methods of flow control.
1) Push the first available component from the parallel stations. This approach might create distortions in the sequence if a lower sequence number component arrives later.
2) Pull the lowest sequence number from the parallel stations if there is a tie in the arrival time of the components in the process. This approach will result in less sequence distortion [2].

7.2.2 Buffer Control

What are the operational criteria of the buffers in the system? The method of material movement into and out of buffers will have a strong influence on the production system’s ability to maintain sequence into the sort and hold process. A system might use various methods of flow control for a buffer:
1) The ideal buffer control is to allow complete random access within the buffer. The production system can then pull the “best” component from the buffer for sequence control.
2) The second most desirable method of sequence control in a buffer is that of a first-in-first-out (FIFO) buffer.
3) The least desirable method of sequence control is that of last-in-first-out (LIFO) buffer.
4) Some buffers randomly provide components to the next process station. An example of random presentation is a looping chain. This situation is not desirable because it provides no control of the sequence.

The statements of relative performance between the various buffer control methods are based upon discrete event simulation and logical thought. The oldest order not filled is the controlling factor in the performance of the production system. For (1), the buffer could release the parts to fill the oldest order first, or it could use some other approach. For (2), the buffer releases the component in the order they entered the buffer. This approach will not perform as well as (1), because the release of a different component in the buffer might result in better system performance than the oldest component in the buffer. However, the use of a FIFO buffer introduces no additional distortion in the production stream than it had when it entered the buffer. For (3), the buffer releases last the oldest component last. The performance is lower than (2), because the new orders are released sooner than older orders exactly the opposite to fill order from lowest number to highest number. For (4), the release of components is random independent of the age of the component or the order sequence. It is unclear as to how this style of buffer will perform. It should perform worse than (2) and better than (3), because the release of the components are not based upon the either the age of the component or the oldest order not filled.

7.2.3 Off-line Production Station

An off-line production station is a production station that performs a process is outside the main production stream. An example is an off-line rework station. The rework station holds components off-line until they have been repaired. The system then places the components back into the production stream, in a location in the production stream that is different than the location from that they were removed. This is a distortion in the production system. The larger the number of components that pass the off line rework station before the component is reintroduced into the production stream, the greater the distortion.
7.3 Number of Platform Components in the Production Process

The number of platform components in a production process equals the amount of platform WIP from the sequence control location to the sort and hold process. The quicker a component plant can correct an error in the production system, the better the performance of the production system. Let’s imagine a completely flexible production process having one component in the system. If the production system makes an error, only one component is between the error and the new component to fix the error. Now image a production process that has one hundred components in the system. Now many more components must pass through the production process, before the system can fix any error.

7.4 Operating Pattern within Production Process

An operating pattern for the production station includes items such as the production station cycle time, shift pattern, break relief pattern, capacity imbalance between production segments, etc. A system might require a buffer between production stations with different operating patterns. Depending on the size of the buffer, it might be difficult to maintain sequence control through the buffer. As stated in Section 7.3, the larger the number of platform components in the production system, the slower the system can correct errors.

7.5 Platform Complexity Increases Throughout Production Process

Where is complexity added to the platform component? WIP enters a production station and has some value added process performed on it. That value added process might increase the amount of platform complexity. Therefore, we need to evaluate each production station to assess the complexity into and out of that production station, Figure 7-3. It is desirable to add any of complexity toward the end of the production process.
7.6 Production Process Flexibility

In assessing the flexibility of a production station, it is useful to draw an imaginary boundary around the production station. We measure the current state of the production station, inflows to the production station, and outflow from the production station. See Figure 7-4. Inflows into the production station are:

- platform component(s) to be processed,
- subcomponent(s) added in the process,
- information telling the station what actions to perform, and
- energy required to perform the process.

The outflow from the station is:

- processed platform component(s).

The current state of the production station is:

- set-up of the production station.
The ease that a production stations can change its setup to the desired setup, accept all inflows, and provide the desired outflow determines the level of process flexibility. Four variables that influence flexibility are the operator(s), machine(s), material handing and information system.

7.6.1 Operator(s) and Machine(s) Flexibility

In terms of the operator(s) and machine(s), an important consideration is the set-up time between all the end items processed, the time required to accept material input, and any production station output constraints.

7.6.1.1 Set-up Time

Set-up time is defined as the time required to change from processing one end item to being capable of processing a different end item. Does the production stations require set-up between end items? It is important to evaluate the set-up time for all components processed in the production system at each production station. Three different dimensions that are important in mapping out the set-up time: process, geometry, and attributes.

- **Process** is what procedure(s) is performed on the component.
- **Geometry** is the three dimensional definition of the component.
- **Attribute** is anything that makes the component unique beyond its three dimensional geometry such as color or material properties.

7.6.1.2 Subcomponent Material Input

The time required to identify and accept the material input into the production station for operation is a function of the:

- number of unique geometries,
- number of unique attributes, and
- number of different part sets

Generally, stations processing more subcomponents require more processing time.
7.6.1.2.1 Kitting Sub-components

One method of delivering subcomponents is through the use of kits. The use of kits in the production process reduces the time needed at a production station to identify material input when the total number of component attributes is large. In kitting, located with the platform component is a portion of the sub-components required for production. As the platform component travels down the production process, each station installs the appropriate subcomponent(s) from the kit. Kiting reduces the amount of space and time required for a particular production station.

7.6.1.3 Individual Station Output Characteristics

Does a machine(s) or process(es) produce a set of components for each production cycle of the production station? Producing multiple components can cause two problems: (i) force a batch process within the production process, (ii) make it difficult to correct errors in the production system. These problems can slow the system to correcting errors and/or can introduce new errors into the system.

7.6.1.4 Impact of Operator(s) and Machine(s) Flexibility

When the production system is inflexible, the set-up time is greater than can be accommodated in the system cycle time for any end item that is produced using that production system. This inflexibility forces a set of end items be produced and then the production system changed for the a different set of end items. This will increase the number of components in the sort and hold process waiting for holes in the sequence to be filled. Reducing the set-up time or the requirement for a set-up between unique end item styles reduces the number of components in the sort and hold process. The greater the set-up time between the end items, the more difficult it is to produce the ILVS sequence stream. Consider two situations:

• different sequence streams, and
• a sequence stream.

More than one sequence stream might share some elements of the production such as a production segment. If the set-up time between any of the end items processed through a
segment is greater than the segment cycle time, a schedule rotation for different end item production is required. Consider the problems of setup between processes, geometries, and attributes.

7.6.1.4.1 Flexibility Between Different Sequence Streams

Consider the situation where more than one sequence stream shares the same production system. If the setup time for the total family of end items associated with a sequence stream is contained in the production segment cycle time, there is no flexibility problem within the sequence stream. However if the setup time between end item families for different sequence stream can not be contained in the production segment cycle time there is a flexibility problem. This situation requires the use a schedule rotation to produce the different sequence streams. Production system wait time is the number of orders between the end of the last production run and the start of the next production run for the same sequence stream. If the complete sequence stream is produced during its production run, no additional components are required in the sort and hold process. See Figure 6-2 (repeated). We discussed this concept in Chapter 6.

Consider two sequence streams which require the use of a common paint facility. The fixture used to hold parts in the painting process are unique between the two sequence, but common within each sequence stream. The plant must produce one of the sequence streams and then switch over the facility to the other sequence stream. The production system wait time increases the number of finished goods required to provide the desired service rate to the assembly plant.

![Diagram](image_url)

**Figure 6-2 (repeated): Two Unique Sequence Streams with Shared Resources**

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7.6.1.4.2 Flexibility within a Sequence Stream

When the production system is inflexible within a sequence stream, the set-up time is greater than can be accommodated in the system cycle time for the family of end items in a sequence stream. This requires a portion of the sequence stream be produced and then the production system changed for the next portion of the sequence stream. This will increase the number of components in the sort and hold process waiting for holes in the sequence to be filled. See Figure 7-5.

Consider a sequence stream that requires power and manual doors be shipped in a common stream. Unfortunately, there is a die change of four hours required in the injection molding machine between manual and power panels. This forces a run of manual doors and a separate run of power doors. Let us assume the optimal production run size is one day for both manual and power doors. Then the system will need to hold approximately two days worth of inventory at the sort and hold process.

![Sequence Stream with Significant Set-up Time](image)

**Figure 7-5: One Sequence Stream with Significant Set-up Time**

7.6.2 Material Handling Flexibility

Material handling is the process of providing the production operator(s) and/or the process machine(s) the material required for the operation of the production station. The important aspects of material handling for ILVS are the space requirements for presenting subcomponents to a production station and the method for scheduling the delivery of subcomponents.
7.6.2.1 Space Requirements

Does the production process have sufficient space for material handling? The total number and size of the subcomponents as does other factors such as buffers, rework, etc. determines the space requirements.

7.6.2.2 Method of Subcomponent Delivery Scheduling

What method is used to schedule the delivery of subcomponents to the production station? Again, the two broad categories of production scheduling are the push and pull system. The space available, the value of the component, the size of the component, and the number of different configurations of that component determines the method used to feed the production station.

7.6.3 Information Flexibility

Information is a critical commodity in the ILVS environment and only is valuable when provided at the correct location and at the required time. The production process, scheduling method, sort and hold process, and sequence control strategy require accurate, timely, and reliable information. Some examples requiring information in the production process are:

- what process to perform at any production station;
- what sub-components are required by a production station process; and
- flow control for WIP in the production system.

The information does not need to be electronic, but can take other forms such as visual. It is desirable to protect time critical data in computer systems from computer system failure.

7.7 Production Process Reliability

For this thesis, process reliability is the probability the production station, segment, or process is available for operation and produces the desired quality level when requested.
There are two metrics of reliability: production station up-time and production process quality.

7.7.1 Production Station Up-time

Production station up-time measures the availability of the production station to produce the desired component when requested. The measures of up-time are:

- **mean time to repair**, and
- **mean time between failures**.

Production station up-time is a probabilistic quantity based on the percentiles of repair times and times between failures of interest. The corporation needs to decide at what confidence level it requires the component plant to deliver in the ILVS format. The greater the confidence level required the greater the amount of time required to protect the sequence stream for the unavailability of a portion of the production system.

7.7.2 Production Process Quality

Production process quality is the capability of producing the desired component in a quality manner. Listed below are two measures of production process quality.

- **Scrap Rate**: Scrap rate is the percentage of components having unacceptable quality level and that cannot be brought up to the desired quality level through additional processing.
- **Rework Rate**: Rework is the percentage of components having unacceptable quality level that can be brought up to the desired quality level through additional processing.

7.8 End Item Differences

Are there differences in the production process dependent on the end item? These differences might cause operational changes in the production system. Examples of end item differences are take rate, cycle time, scrap rate, rework rate, process flow, and work content balance.
7.8.1 End Item Take Rate

What is the percentage of production for each individual end item? The number of end items is not only important, but so is the percentage take rates of the end items. Depending on the sequence control strategy, the smaller the take rate of the end items, the more sensitive the production system is to errors for that end item.

7.8.2 End Item Scrap Rate

Is the scrap rate dependent on the end item? The scrap rate dependence on end item might place additional burdens on the sequence control strategy. The error correction time for that end item style might increase. This dependence might force more components into the sort and hold process.

7.8.3 End Item Rework Rate

Is the rework rate and rework cycle time dependent on the end item style? This imposes the same problem as that of scrap rate.

7.8.4 Process Flow Based on End Item Differences

Are there process flow differences for different end items? If the process flow of materials through the system depend upon the end item style, additional scrambling of the sequence compared to a common process flow for all end item styles is possible.

7.8.5 Work Content Balance for End Items

Do the various end item styles in a sequence stream require large differences in work content? If the work content differences are large enough, producing in the ILVS sequence might require additional workers in the production system. The additional cost of these workers might force splitting of the production of the sequence stream based on end item style. This would increase the number of components in the sort and hold process.
8. **Sequence Control Strategies**

*Sequence Control Strategies*: A sequence control strategy is the mechanism for providing control commands in the production system.

8.1 **Why a Sequence Control Strategy is Required**

To understand the requirement for a sequence control strategy, it is important to consider what elements of the production system are problematic is the ILVS environment. Some elements of the production system introduce of errors and distortions in the production sequence, versus the ILVS forecast.

![Figure 8-1: Reason for a Sequence Control Strategy](image)

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Again distortions and errors are defined as:

- **Distortions**: Distortions are perturbations that do not materially alter the sequence and are self correcting, requiring no additional commands in the production system.

- **Errors**: Errors are discrepancy in the production sequence to the modified ILVS sequence and require additional commands in the production system to correct.

The numbers below correspond to the number in Figure 8-1.

1) The component plant scheduling (Chapter 5) has the potential to cause errors and distortions versus the ILVS forecast. The schedule might not require the exact ILVS sequence released or might release independent of the ILVS sequence.

2) Several factors including the reliability of the production system determine the sequence control location (Chapter 6). Placement of the sequence control location and any decoupling buffers influence the length of time it takes to correct errors and distortions in the production system.

3) A production process (Chapter 7) is not a perfect system and its characteristics will cause distortions and errors. Parallel production stations, buffer control, system reliability, production process constraints, etc., as well as scrap and rework (as discussed in item (4) and (5)) will introduce distortions and errors.

4) The rework process is an off-line production process. The production system; places components requiring rework off-line; holds them awaiting the rework process; reworks them to an acceptable quality level; and then releases them back in the production steam. Once complete, the rework process places components back into the production stream in a different relative location from which they entered the rework process. This difference in relative location from when the component left the production stream and when they reenter the production stream is a distortion.

5) Scrap is an error in the production stream. Scrapped component associated with an order require rescheduling and re-release into the production system. The new component released faces the same distortion and error effects discussed in (1) through (4) above.
6) The sort and hold process is the system element ensuring distortions and errors in the production system do not reach the assembly plant. Unfortunately, there is the potential errors in its operation (Chapter 9). The number of components in the sort and hold process is a measure of the quality of the production stream relative to the ILVS forecast sequence.

8.2 Different Methods of Sequence Control

Three general sequence control strategies are replication, dynamic resequencing, and sequence safety stock. The use of hard sequence numbers and soft sequence numbers is a difference in their operational performance. One difference between these strategies is the location a component is given a hard sequence number.

- **hard sequence number**: the sequence (rotation) number the component fills at the assembly plant
- **soft sequence number**: the expected sequence (rotation) number the component is anticipated to fill at the assembly plant.

Replication, dynamic resequencing, and sequence safety stock are broad strategies for controlling the sequence. There might be hybrids incorporating aspects of these different strategies providing improved system performance. This thesis investigates only these three sequence control strategies and characterizes their performance (Chapters 10 through 12).

8.2.1 Replication Sequence Control Strategy

Replication, Figure 8-2, assigns a hard sequence number to a component at the sequence control location. Effectively, the production system controls the sequence number. The end item associated with that sequence number is unimportant. This has the effect of making the number of unique end items approach infinity. The sort and hold process only holds components until holes in the sequence are filled. No sorting or substitution of components is performed.
The performance of replication is a function of:

- errors and distortions due to production system scheduling (Chapter 5),
- production process flow (Section 7.2):
  - parallel production stations (Section 7.2.1),
  - buffer control (Section 7.2.2), and
  - off-line production stations (Section 7.2.3),
- the operating pattern for production system (Section 7.4),
- the platform WIP size from the sequence control location to the sort and hold process (Section 7.3),
- production process flexibility (Section 7.6),
- production process reliability measured by (Section 7.7):
  - system up-time:
    - mean time to repair, and
• mean time to failure, and
• process reliability:
  • scrap rate, and
  • rework rate.

8.2.2 Dynamic Resequencing Sequence Control Strategy

In dynamic resequencing, Figure 8-3, the production system schedules component release in expectation of filling an order, a soft sequence number. The sort and hold process assigns a hard sequence number. The sort process releases component to the hold process based on the lowest sequence number not filled for its given end item style.

![Diagram of Dynamic Resequencing Sequence Control Strategy](image)

**Figure 8-3: Dynamic Resequencing Sequence Control Strategy**

The probability of finding an identical end item style for a component experiencing an error or distortion before correction determines the performance of dynamic
sequences. The performance of dynamic resequencing is a function of the same variables as in replication with addition of variables for end item style. The new variables are:

- how much platform complexity increases throughout production process (Section 7.5), and
- end item differences (Section 7.8):
  - number of different end item styles in the sequence stream (Section 7.8.1), and
  - take rate for each end item style (Section 7.8.1).

8.2.3 Sequence Safety Stock Sequence Control Strategy

As in dynamic resequencing, Figure 8-4, the production system schedules components release in expectation of filling an order for sequence safety stock. This strategy places defect-free components into the production stream to fill holes in the sequence at the sort and hold process. For distortions, the sequence safety stock is self replenishing. For errors, replenishment of the sequence safety stock requires a preset strategy that ensures a predetermined service rate. The sort and hold process assigns a hard sequence number like dynamic resequencing.

The probability the production system creates a given number of holes for each end item style over a given time determines sequence safety stock performance. One use of sequence safety stock is decoupling a segment of the production process from the next for predetermined errors and distortions at a chosen service rate. Sequence safety stock performance is a function of the same variables as in dynamic resequencing with additional variables for the replenishment strategy. The new variables are:

- desired service rate,
- safety stock replenishment strategy (Section 5.8), and
- what errors and distortions to protect the system (Section 6.5.3).

The safety stock replenishment strategy can be based at least two different methods.

- replenish based on a predetermined amount of production
8.3 Failure Modes of Sequence Control Strategies

Errors and distortions arise from two categories: common cause and special cause. This thesis, characterizes the sequence control strategies (Section C) based on common cause for errors and distortion. These special causes might cause the failure of a sequence control strategy. To best develop the production system, it is important to recognize the failure mode for each sequence control strategy.

We choose the baseline control strategy as replication. It is the "simplest" method, since it makes no attempt to resequence the production stream to the ILVS forecast stream. Replication assigns a hard sequence number to a component upon its release from the sequence control location.
Dynamic resequencing assigns a hard sequence number in the sort and hold process. This approach allows components in the sort and hold process to fill the oldest order for their end item style (resequencing) not yet filled. This can allow for a quicker order fulfillment for orders experiencing errors and distortions in the production system. For example, to clear an error for an order, the production system releases another component from the sequence control location. If an identical component to the end item style enters the sort and hold process before the re-released component, dynamic resequencing outperforms replication. Distortions are self clearing, however, if an identical component to the end item style enters the sort and hold process before the component experiencing distortion dynamic resequencing outperforms replication. If no resequencing of components occurs in the sort and hold process for an order experiencing error or distortion, dynamic resequencing fails to replication.

The service rate and replenishment strategy determine the amount of sequence safety stock required. Sequence safety stock assigns a hard sequence number in the sort and hold process. There are two failure modes. First, if the safety stock depletes for a particular end item style, the system behaves like dynamic resequencing. The sort and hold process still assigns a hard sequence number for the lowest order not filled for an end item style. Second, when the system depletes the safety stock, if no resequencing occurs for an order experiencing error or distortion, the system behaves like replication. For sequence safety stock, the failure modes are dynamic resequencing and then replication. This appears the most robust sequence control strategy, however holding safety stock is not free and the cost of holding may exceed the benefits.
9. Sort and Hold Process

*Sort and Hold Process*: The sort and hold process is the element ensuring the component plant releases components to the assembly plant meeting the ILVS sequence requirements.

9.1 Sort and Hold Process Function

The sort and hold process has two distinct functions.

- **Sort Process**: The sort process determines what orders to fill with components held in the sort process, assigns a hard sequence number if the system has not assigned one yet, and places components in the correct sequence slot location.

- **Hold Process**: The hold process waits for holes in the sequence to be filled before releasing components to the assembly plant.

Figure 9-1 shows an example of the operation of the sort and hold process. A red component enters the sort and hold process from the production process. First, the sort process determines an order exists for a red component, assigns sequence number 107, and places the red component in the correct sequence slot. Next, the hold process waits until the system fills the holes ahead of 107. Once, these holes are filled, the hold process releases 107 to the assembly plant. Note, that the sort process holds the green component because of the lack of orders for green components. These components are by definition preproduced in front of an order.

The sort and hold process requires sufficient space on the factory floor for its efficient operation. Modeling and evaluating the production system determines the space requirements (Section C). Alloting too little space can cause a shut down of the sort and hold process. Alloting too much space is a waste of company resources.
9.2 Component Plant Sort and Hold Metrics

The component plant sort and hold metrics are measures indicating the quality of the production stream entering the sort and hold process. Five metrics of production stream quality are 1) distance to the farthest hole in hold, 2) the number of slots filled in hold, 3) the number of components in sort and hold, 4) the number of holes in sequence in hold, and 5) the component arrival early/late/expected in sort and hold.

- **Distance to Farthest Hole in Hold**: Distance to farthest hole in hold is the number of sequence slots required to protect the sequence in the hold process, Figure 9-2.
Sequence Stream

14 12 11 9 8 7 6 5 4 2 1

\[ \text{distance to farthest hole} = 11 \]

**Figure 9-2: Distance to Farthest Hole**

- **Number of Slots Filled in Hold:** Number of slots filled in hold is the number of sequence slots filled by a component after the oldest hole in the hold process. See Figure 9-3.

Sequence Stream

14 12 11 9 8 7 6 5 4 2 1

9 Slots Filled in Sequence

**Figure 9-3: Number of Slots Filled in Sort and Hold**

- **Number of components in sort and hold in sort and hold:** Number of components in sort and hold is the total number of components required in the sort and hold process to protect the sequence. It is the number of components having an order associated with them and those waiting for an order. See Figure 9-4.

Sequence Stream

14 12 11 9 8 7 6 5 4 2 1

\[ \begin{align*}
14 & \uparrow \\
12 & \uparrow \\
11 & \uparrow \\
9 & \uparrow \\
8 & \uparrow \\
7 & \uparrow \\
6 & \uparrow \\
5 & \uparrow \\
4 & \uparrow \\
2 & \uparrow \\
1 & \uparrow \\
\end{align*} \]

11 Parts in Sort and Hold

**Figure 9-4: Number of Components in Sort and Hold**
- **Number of Holes in Sequence in Hold**: Number of holes in sequence in hold is the number of components missing from the sequence in the hold process. See Figure 9-5.

![Sequence Stream](image)

**Figure 9-5: Number of Holes in Sequence**

- **Component Arrival Early/Late/Expected in Sort and Hold**: Component arrival early/late/expected in hold is the difference between the expected position of components entering the sort and hold process compared to the actual position filled by that component. When a component is released from the sequence control location it is in reference to other components released before and after it. However, the production system as we have seen introduces errors and distortions in the sequence released. This metric measures the difference between the released sequence and the sequence that arrives into the sort and hold process. See Figure 9-6.

![Sequence Stream](image)

**Figure 9-6: Component Arrival Early/Late/Expected**
9.3 Assembly Plant Sort and Hold Metrics

The assembly plant also has metrics to measure the quality of the ILVS sequence forecast versus the actual production sequence. Listed below are the commonly published metrics include the following:

- **Dig Depth**: Dig depth is how far the operator needs to dig into a shipping container to retrieve a component for the next vehicle.

- **Number of Set Asides**: Number of set asides is the number of components placed aside if a vehicle is missing (late).

- **Automated Storage and Retrieval System (AS/RS) Size**: AS/RS size is the buffer size used at the end of the paint process to protect the sequence entering chassis operations.

- **Percent in Sequence**: Percent in sequence is a percentage of units in the forecasted sequence. A unit is out-of-sequence if it preceded by a vehicle with a higher sequence that its own.

- **Digs/100**: Digs/100 is the number of times you need to dig into a container per 100 vehicles to retrieve the correct component.

9.4 Comparison of Metrics of Component Plant vs. Assembly Plant

As stated in Chapter 3, the output quality of the sort and hold process is one of the operational differences between an assembly plant and a component plant. At an assembly plant, the sort and hold process size is predetermined. When the chassis line requires a vehicle, the sort and hold process provides the oldest filled order. It does not matter if there is an older order not yet filled. This can create an out of sequence condition, which are limited to 2% of production. However, for a component plant, the sequence stream leaving the sort and hold process requires 100% compliance to the sequence forecast. Table 4-1 compares the metrics of a component plant versus the metrics of an assembly plant. It shows the relationship between the metrics.
<table>
<thead>
<tr>
<th>Component Plant Metric</th>
<th>Assembly Plant Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Number of Slots Filled in Hold</td>
<td>• AS/RS Size</td>
</tr>
<tr>
<td>• Number of Components in Sort and Hold</td>
<td>• Dig Depth</td>
</tr>
<tr>
<td>• Distance to Furthest Hole</td>
<td>• Number of Set Asides</td>
</tr>
<tr>
<td>• Number of Holes in Sequence</td>
<td>• Percent in Sequence</td>
</tr>
<tr>
<td>• Component Arrival Early/Late/Expected</td>
<td>• Digs/100</td>
</tr>
</tbody>
</table>

Table 9-1: Comparison of Metrics of Component Plant vs. Assembly Plant

9.5 Errors in Sort and Hold Process

There are two causes of errors in the sort and hold process. The causes are incorrectly identifying the sequence number and incorrectly identifying the slot location. The sequence number might be incorrect because the component style was misidentified or the hard sequence number was placed on the wrong component. The slot location might be incorrect because the slot location was misidentified or the component was placed in the wrong bin. Figure 9-7 shows a fault tree analysis for errors in the sort [16].

![Fault Tree Analysis](image.png)

Figure 9-7: Fault Tree Analysis for Errors in the Sort Process
SECTION C

SECTION C presents methods for developing analytic models: probability models, discrete event simulation models generic to a set of production systems, and a design of experiment approach. It uses these models to evaluate production systems for the ILVS environment. It also characterizes different operational control strategies through the application of these models.
10. **Probability Models**

*Probability Models:* Probability models use probability equations to investigate mechanisms for affecting the production system performance in the ILVS environment ([10],[13],[14]).

10.1 **Constraining Condition**

One important consideration in evaluating a production system is determining the constraining (most critical) condition for determining the quality of the sort and hold process (that is the number of components in the sort and hold process). Consider the examples below.

- The sequence stream in a production system is inflexible requiring a rotation of end item production. The length of the production runs is long because of the extended set-up time. This long production runs requires holding large number of components, as measured by days of production, in the sort and hold process. This rotation of end item production is a constraining condition, because no other factors have nearly the same effect on the number of components held.

- Consider a simple production process, with no parallel stations and no buffers between the production stations. The number of components in the sort and hold process depends on the number of parts held in an off-line rework process and the platform WIP in the production process. The production process might be sufficiently short or the rework rate sufficiently large that the rework process is the constraining condition.

Machine reliability, die changes, complexity of the end item, and the down time in independent parallel stations can also be constraints. This is not a complete list. It is important to recognize the existence of a constraining condition, since it offers the possibility of providing leverage for predicting and improving the performance of the production system.
10.2 Replication Probability Models

Recall the performance of replication is independent of the end item style associated with an order.

10.2.1 Scrap

Consider a simple production process containing only serial production stations with no buffers between stations and no relative movement of components within the production process. Assume the production system requires no rework. A component is either good or cannot be repaired. See Figure 10-1.

![Diagram of Serial Production Process with No Buffers]

**Figure 10-1: Serial Production Process with No Buffers**

The number of components in the sort and hold process is determined by the size, $X$, of the platform WIP. The maximum number of components in the sort and hold process is based on the probability of scrapping the same order $n$ times. Each time the system scraps a component, another $X$ components enters the sort and hold process, Equation 10-1. See Figure 10-2 for graphical representation of results.

\[
\text{sort and hold process size} = \text{scrap n times} \times X \quad \text{Equation 10-1}
\]

\[
X = \text{platform WIP size}
\]
Figure 10-2: Replication of a Serial Production Process with no Rework

For independent incidence of scrap, the probability of scrapping a component is the scrap rate (scrap 1). The order associated with that component is not filled, so another order must be released. This second component again faces the same independent incidence of scrap, but the probability that the components associated with an order are scrapped twice (scrap 2) is the scrap rate raised to the second power. This logic can be used for scrap 3, scrap 4, and so on for n times. See Equation 10-2 through Equation 10-4.

\[ P(\text{scrap 1}) = \text{ScrapRate} \quad \text{Equation 10-2} \]

\[ P(\text{scrap 2}) = \text{ScrapRate}^2 \quad \text{Equation 10-3} \]

\[ \vdots \]

\[ \vdots \]

\[ P(\text{scrap n}) = \text{ScrapRate}^n \quad \text{Equation 10-4} \]
As an example, suppose a production system has a 5% scrap rate, a shift length of 436 minutes, 240 shifts per year and has 40 right hand, left hand serial production stations with no buffers, and independent reordering of right hand, left hand. Table 10-1 shows the performance of this system. The average number of occurrences is the expected number of occurrences for a given production volume, Equation 10-5.

\[
\text{average number of occurrences}_n = P(\text{scrap } n) \times \text{production volume} \\
\text{Equation 10-5}
\]

<table>
<thead>
<tr>
<th>number of times order is scrapped</th>
<th>probability of scrapping n times</th>
<th>average number of occurrences per year</th>
<th>average number of occurrences per month</th>
<th>average number of occurrences per shift</th>
<th>size of sort and hold process</th>
</tr>
</thead>
<tbody>
<tr>
<td>scrap 1</td>
<td>5.0%</td>
<td>13080</td>
<td>1635</td>
<td>55</td>
<td>80</td>
</tr>
<tr>
<td>scrap 2</td>
<td>0.250%</td>
<td>654</td>
<td>82</td>
<td>3</td>
<td>160</td>
</tr>
<tr>
<td>scrap 3</td>
<td>0.0125%</td>
<td>33</td>
<td>4</td>
<td>0</td>
<td>240</td>
</tr>
<tr>
<td>scrap 4</td>
<td>0.0006%</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>320</td>
</tr>
</tbody>
</table>

**Table 10-1: Performance of Replication with no Rework**

10.2.2 **Rework**

Now consider the same production system only this time it has rework, but no scrap, see Figure 10-3. This rework station is an off-line production station that performs a process outside the main production stream.

![Figure 10-3: Single Off line Rework Station](image)

The rework station holds components off-line until they have been repaired, Figure 10-4. The system then reintroduces the components back into the production stream, in a
location in the production stream that is different than the location from that they were removed, Figure 10-5. This is a distortion in the production system. The larger the number of components that pass the off line rework station before the component is reintroduced into the production stream, the greater the distortion. When the amount of rework is large, rework might be a constraining condition.

![Figure 10-4: Component Pulled Off Line for Rework](image)

![Figure 10-5: Component Reintroduced into Production Stream](image)

Recall the sort and hold process cannot release components after a hole. A part off-line in the rework process creates a hole in the sort and hold process. In the example in Figure 10-4 and Figure 10-5, the component associated with order six requires rework. Assume that there are no holes ahead of order six, no components after order six can be released until the component associated with order six arrives in the sort and hold process. Therefore, each component that “pass” the component associated with order six before the system reintroduces it the number of components in the sort and hold process.
The arrival and release from an off line production station (e.g. rework station) in this case is a queuing model. Assume the rework process has a triangular rework cycle time with the low, middle and high equal to half, two, and eight minutes respectively. Assume one rework technician at the rework station. Unfortunately, this distribution does not follow any of the well-developed (analytically closed) formulations. We used a Monte Carlo technique to develop the curve in Figure 10-6. The formula for percent utilization of the rework process is defined in Equation 10-6 (this equation assumes that the component will not be reworked again):

\[
\text{%Utilization} = \frac{(1 - 1^{st\ run})AVG_{\text{rework}}}{\text{System Cycle Time}} \quad \text{Equation 10-6}
\]

\[1^{st\ run} = \text{first run capability}\]

\[AVG_{\text{rework}} = \text{average rework time}\]

\[\text{System Cycle Time} = \text{cycle time of the system for the completion of a process}\]

Suppose the rework process utilization is 90%. As shown in Figure 10-6, the sort and hold process must hold approximately 80 components due to rework. Compare this result to that from scrap alone. Assume there is no interaction between scrap and rework in determining the number of components in the sort and hold process. From Figure 10-6, when the platform WIP size is 25 components or less the number of components in the sort and hold process is less than 80 if the same order is scrapped three times. Table 10-1 give a flavor for the rarity of this occurrence. In this idealized case of random independent occurrence of scrap and rework and for the conditions discussed, rework as compared to scrap becomes the constraining condition in determining the size of the sort and hold process.
10.3 Dynamic Resequecing Probability Models

The performance of dynamic resequencing depends upon the probability of finding an identical end item style for a component experiencing an error or distortion. Dynamic resequencing works well when the platform WIP is greater than the number of components it takes for the next identical end item style to enter the sort and hold process. Consider again the serial production system with no buffers between the production stations. Assume the production system requires no rework, Figure 10-1. The component plant schedules using the ILVS sequence order method. Scrap is the only distortion or error in the production system.

Suppose the sequence of orders for end item style are random. By random we mean that the next order end item style is independent of the last end item style. The next order is randomly determined based take rate of each end item style. We model the order process as a poisson distribution to help provide some insight into the mechanism of dynamic resequencing. Equation 10-7 is the probability that in number of orders of interest for a
given end item style and its associated take rate has y occurrences of the end item style of interest.

\[ P(y) = 1 - \sum_{z=0}^{y-1} \frac{\lambda_i^z e^{-\lambda_i}}{z!} \]  \hspace{1cm} \text{Equation 10-7}

\( P(y) \) = probability of seeing y or more orders of item i in the given time period

\( \lambda_i = \text{take rate}_i \times \text{number of orders of interest} \)

\( \text{take rate}_i = \text{percentage of production of } i \)

\( y = \text{number of identical orders} \)

\( i = \text{end item style} \)

Figure 10-7 graphs the number of orders it takes until another identical end item style order as a function of the end item take rate. The three curves in Figure 10-7 show:

- the average number of orders until an identical order (Equation 10-8 is from the geometric distribution),

\[ \text{average number of orders, } = \frac{1}{\text{take rate,}} \]  \hspace{1cm} \text{Equation 10-8}

\( i = \text{end item style} \)

- the number of orders until the first identical order at a 95% probability (scrap 1), and
- the number of orders until the second identical order at a 95% probability shows (scrap 2).

We iterate the poisson formula varying the number of orders of interest until the probability finding the number associated with a 95% probability.
Figure 10-7: Number of Orders Until Finding an Identical Order for Random Orders at P(95%)

In a world of random orders, independent random incidence of scrap and apparent infinite production system length, the lowest take rate for the set of end items produced by the production system becomes the constraining condition. A component placed in the system in response to an incidence of scrap will not arrive before the next random occurrence of the same end item order. This assumption makes the production system performance independent of its length. For this world, the only way to fill an order that has an error in the system is to wait for the next occurrence of an identical order. Here are a couple of observations.

- When the lowest take rate end item style is 10% for a production process, the maximum number of components held in the sort and hold process is fifty. Recall each additional order arriving in the sort and hold process before an identical order cannot be released until the hole is filled. Therefore the constraining condition becomes the 10% take rate as long as the platform WIP (the total number of platform
components in the production process independent of end item style) size is greater fifty.

- For end item take rates less than 5%, dynamic resequencing becomes significantly less effective. This might suggest using a mixed model of dynamic resequencing for high take rate end items and safety stock for low take rate end items. With high take rate end items, the probability of finding an identical order before the component placed in the system in response to the error reaches the sort and hold process is very high. However, this is not the case for end items low take rate. To correct the error quickly, holding of safety stock for low take rate end items will improve the performance of the system. Also, as the next section will show, the number of components required in a safety stock for low take rate end items can be small.

- The lower the platform WIP, the less the improvement in performance of dynamic resequencing compared to replication. For production processes with little platform WIP, the probability the component placed in the system in response to the error reaches the sort and hold process before the production system schedules an identical end item style is very high. This implies the use of dynamic resequencing has little effect on the performance of the system.

### 10.4 Sequence Safety Stock Probability Models

The performance for sequence safety stock is determined by the probability the production system creates a given number of holes for each end item style over a given time. Again, we use the poisson probability distribution, Equation 10-9, for estimating the size of the safety stock assuming independent random incidence of holes (common cause) and random orders for end item style. If it is desired to protect for a special cause, the number of components for each the end items would need to be increased.

\[
P^*(y) = \sum_{k=0}^{y} \frac{\lambda_i^k e^{-\lambda_i}}{k!} \quad \text{Equation 10-9}
\]
\[ P^* = \text{probability of needing } y_i \text{ or less component in the replenishment cycle} \]

\[ \lambda_i = \text{average number required in replenishment}_i \text{ cycle} \]

\[ y_i = \text{safety stock size} \]

\[ i = \text{end item style} \]

The average number required before replenishment (\( \lambda_i \)) is the expected average number of holes for an end item style created before the system replenishes the safety stock, Equation 10-10. The average number required to protect for scrap and rework requires a prediction of the average number required for scrap and average number required for rework.

\[ \lambda_i = AVG'_{\text{scrap}} + AVG'_{\text{rework}} \quad \text{Equation 10-10} \]

\[ i = \text{end item style} \]

The expected average number required for scrap, Equation 10-11, is:

\[ AVG'_{\text{scrap}} = \text{take rate}_i \times \text{scrap rate}_i \times \text{number of component until replenishment}, \]

\[ \text{Equation 10-11} \]

The number of components until replenishment is depends upon the production system error scheduling algorithm (Section 5.8). If the safety stock is replenished at the start of each shift, the number of components until replenishment is a shifts production plus the platform WIP. If the production system releases a component to replenish the safety stock at the identification of an error, the number of components until replenishment is the platform WIP.
The average number required for rework, Equation 10-12, is:

\[ \text{AVG}_{\text{work}} = \text{take rate}_i \times \text{rework rate}_i \times \max(\text{components at rework station}) \]  \hspace{1cm} \text{Equation 10-12}

The maximum number of components at the rework station is the maximum number of components being reworked plus the maximum number of components queued up awaiting rework. Figure 10-8 graphs the number of components required for a given end item style at a 99% probability versus the average number required between replenishment.

![Safety Stock Based on Average Number Required at P(99%)](image)

**Figure 10-8: Safety Stock Size Based on Average Number Required at P(99%)**

For each end item style, use Figure 10-8 to determine the size of the sequence safety stock. The sum of the safety stocks for each end item style is the total number of components required in the sequence safety stock, Equation 10-13.
\[ \text{safety stock}_{\text{production system}} = \sum_{k=l}^{n} v_i \]  \hspace{1cm} \text{Equation 10-13}

\[ n = \text{number of end items} \]
11. **Generic Models**

*Generic Models:* When a component plant uses a similar production system for more than one product line, it might be useful to create a generic model for that type of system. Using the generic model for future analysis of these product lines can reduce the development time required for modeling.

11.1 **Generic Production System Overview**

Discrete event simulation is the process of building a model of production system using a series of elements that represents a production system to the desired level of detail. The simulation controls the discrete flow of components into, within, and out of elements based upon variables input by the simulation analyst. The use of discrete event simulation is effective when there is not a well-defined analytic equation useful in predicting the performance of a system.

![Figure 11-1: Process Flow of Generic Model](image)

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Recall from Section 8.2 the concept of soft and hard sequence number.

- **hard sequence number**: the sequence (rotation) number the component fills at the assembly plant
- **soft sequence number**: the expected sequence (rotation) number the component is anticipated to fill at the assembly plant.

Dynamic resequencing and sequence safety stock utilize a soft sequence number at the sequence control location and assign a hard sequence number in the sort and hold process. Replication assigns a hard sequence number in the scheduling algorithm.

The basis of the generic discrete event simulation models developed in this thesis is a generalization of the production systems used for door trim panels at a component plant, Figure 11-1. Associated with each sequence control strategy is a unique generic model. The generic models use the Witness discrete event simulation program. They have the following characteristics.

1) Assembly plant vehicle scheduling generates the ILVS forecast. This element associates an end item style with each sequence number based on the long run average take rate for all end item styles.

2) The component plant scheduling method depends on the sequence control strategy.

3) They model its sequence control location as an injection molding machine with all end item complexity defined at this location. The model releases a right hand, left hand set into the production process and assumes flexibility for independent right hand, left hand operation for end item style.

4) Within the production process, the production stream splits into right hand and left hand processes. However, the model allows no relative movement of components within these streams. The cycle times in the right hand and left hand processes are independent. This allows for relative movement of sequence position between the right hand and left hand panels. Equal length right hand and left hand conveyors model these processes. The conveyor length equals the right hand and left hand
platform WIP size between the sequence control location and the end of the production process.

5) The inspection stations randomly sort components into categories of good, rework, and scrap based on an assumed scrap rate and first run capability of the production system. The inspection station sends: good components into the sort and hold process; rework components into the rework process and removes scrapped components from the production system.

6) Components placed into the rework process enter a rework buffer. The next component to begin the rework operation is the component with lowest soft sequence number. The actual process time for rework depends on randomly chosen triangular distribution (low, middle, high). After completing the rework process the system places components back into the production stream in a different relative location from which they entered the rework operation. The amount of time a component spends in the rework process determines the relative difference in position.

7) The production system removes scrapped component at the inspection station. Information about a scrapped component is feed into the sequence control strategy.

8) The information of the scrapped components, the actual sequence produced, and the ILVS forecast sequence feeds the sequence control strategy. With this information, the sequence control strategy provides the desired shipping location to the sort and hold process. The information of scrap is passed onto the component plant scheduling. The exact operation of sequence control strategy depends on the choice of the sequence control strategy.

9) The sort and hold process places components in the correct shipping location and holds components if a lower sequence location(s) contains hole(s). The models assume no limit to the number of shipping racks in the sort and hold process. Therefore, the vision of orders is unlimited. The exact operation depends on the sequence control strategy.

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11.2 **Replication Generic Model**

Section 11.1 discusses the common portion of the simulation model. The has the following unique features.

2) Component plant scheduling uses the ILVS sequence order scheduling method except for immediate re-ordering for scrapped component for error correction. Component plant scheduling associates a component order to a hard sequence number. A hard sequence number is the sequence location a component fills if/when it reaches the sort and hold process.

8) The sequence control strategy provides the sort and hold process the desired shipping rack location with a component. The hard sequence number assigned at the sequence control location determines the shipping location.

9) In replication, the sort and hold process does not sort based on end item style.

11.3 **Dynamic Resequencing Generic Model**

Section 11.1 discusses the common portion of the simulation model. The dynamic resequencing generic model has the following features.

2) Component plant scheduling uses the batch sequencing method modified for error correction. The next batch end item style is determined by the lowest sequence order not softly associated with a sequence order. The component plant schedule is based upon the expectation of filling a sequence order, soft sequence number, but the schedule does not associate a hard sequence number as in replication.

8) The sequence control strategy provides the desired hard sequence number and shipping rack location for components in the sort and hold process.

9) The sort and hold process uses commands from the sequence control strategy in sorting components to fill orders and assigning components a hard sequence number.

11.4 **Sequence Safety Stock Generic Model**

Section 11.1 discusses the common portion of the simulation model. The sequence safety stock generic model has the following unique features.
2) Component plant scheduling uses the batch sequencing method modified by the safety stock replenishment strategy. The component plant schedule is based upon the expectation of filling a sequence order, soft sequence number, but the schedule does not associate a hard sequence number as in replication.

8) The sequence control strategy provides the desired hard sequence number and shipping rack location for components in the sort and hold process. It also feeds the command to pull components from the sequence safety buffer for holes in the sequence stream, and place components into the sequence safety buffer.

9) The sort and hold process uses commands from the sequence control strategy in sorting components to fill orders and assigning components a hard sequence number.

10) The movement of into and out of the sequence safety stock uses commands from sequence control strategy through the sort process.
12. Design of Experiments Characterization

*Design of Experiments (DOE) Characterization:* When applied to a production system model a DOE can quantify how changes in design variables effect the system performance. The DOE process develops an empirical equation to explain the production system's response to changes in the design variable(s) within the operating range investigated. This quantification can provide insight for further model-based evaluations.

12.1 Goal of Design of Experiments

By applying design of experiments (DOE) on the generic models we wish to characterize the performance of the production system as we change some of its underlying operating conditions. To measure the system's performance, we use the metrics for the sort and hold process (*Chapter 9*).

The DOE method measures the system's performance for various combinations of design parameters and from these observations calculates an empirical formula of the primary and interaction affects of the design parameters ([8], [9], [12]). In most cases, the experimenters set the design parameters to optimize the system's performance. For this thesis, we would like to develop empirical formulas for characterizing the production system using the DOE method. We will not attempting to optimize the production system, but rather wish to characterize its performance for ranges of various production system characteristics.

12.2 Simplifying assumptions

The DOE method limits the number of design parameters that are reasonable to investigate. Therefore, we reduced the versatility of the generic discrete event simulation models by using simplified modeling of the end item take rate, rework cycle times, material flow movements, and number and style of elements within the generic model.
12.2.1 End Item Take Rate Assumption

A DOE cannot incorporate two related variables such as the number of end items and the take rate for end items. Therefore, we developed a set relationship between the two. We used the following equations (Equation 12-1 and Equation 12-2) to determine a linear relationship between the number of end items and end item take rates.

\[ H_{seg} = 1 + 2 + \ldots + n \]  
\[ \text{take rate}_i = \frac{i \cdot 100\%}{H_{seg}} \]

\text{Equation 12-1}  
\text{Equation 12-2}

\[ H_{seg} = \text{total number of production segments based on the lowest take rate end item} \]
\[ \text{take rate}_i = \text{percentage of production of end item } i \]
\[ n = \text{number of end items} \]
\[ i = \text{take rate for } n^{th} \text{ end item} \]

Figure 12-1 compares the linear take rate assumption to real values for two of the product lines at the component plant. The graph on the left uses the real take rate distribution for one of the product lines. The graph on the right uses the projected take rate distribution before the start of production for a future product line. Recall from our discussion of the sequence control strategy that low take rate end items have more influence on the production system performance than do the high take rate end items.
Figure 12-1: Comparison of Linear Take Rate Assumption to Real Values

12.2.2 Rework Process Assumptions

We assume the rework process has a triangular rework cycle time with the low, middle, and high values equal to half a minute, two minutes, and eight minutes respectively. We used discussions with rework technicians and production supervisors for a typical door trim panel as the basis of these values. We also assume one rework technician at the rework station. From these values, we calculated the average rework time ($AVG_{\text{rework}}$).

12.2.3 Material Flow Control

The molding machine (sequence control location) releases components into separate lines for left hand and right hand panels. There is no relative movement between the right hand and left hand panels in this model.

12.2.4 Number and Style of Elements

The number and style of elements for all of the DOE models are set.

- single molding machine
- two separate but inter-linked right hand and left hand processes
- common right-hand, left-hand rework station

12.3 DOE on Replication

The DOE on replication uses the following performance metrics:
- \( \text{Slots(max)} = \) maximum number of shipping slots required in the sort and hold process for all shifts
- \( \text{Slots(max 90\%)} = \) maximum number of shipping slots required in the sort and hold process for ninety percent of the shifts
- \( \text{Slots(90\%)} = \) number of shipping slots required in the sort and hold process for ninety percent of the components entering the sort and hold process
- \( \text{Components(max)} = \) maximum number of components in the sort and hold process
- \( \text{Seq(90\%)} = \) number of shipping slots from the farthest hole for ninety percent of the components entering the sort and hold process
- \( \text{Holes(90\%)} = \) number of holes in the sequence for ninety percent of the components entering the sort and hold process

The design parameters for the replication DOE are:
- \( \text{scrap rate} = \) percentage of components that are scrapped in the system
- \( \text{number of components} = \) the number of components in the system between the sequence control location and the sort and hold process
- \( \text{percent utilization of rework} = \) a dimensional variable of the percentage utilization for the rework station based on:
  - average rework cycle time
  - first run capability within the production process
  - system cycle time for the production process
  - number of rework operators for the DOE always used one

We used the following formula (Equation 10-1) of the percent utilization of the rework process. This formula is the average time required over time available.

\[
\%\text{Utilization} = \frac{1 - \text{1st run}}{\text{AVG}_{\text{rework}}} \times \frac{\text{System Cycle Time}}{\text{System Cycle Time}}
\]

Equation 10-1 (repeated)
12.4 **DOE on Dynamic Resequencing**

The DOE for dynamic resequencing uses the same performance metrics as replication with the addition of:

- \( \text{Components(max-hold)} = \text{maximum number of components in the hold process} \)
- \( \text{Components(max-sort)} = \text{maximum number of components in the sort process} \)
- \( \text{Components(max-sort-lh)} = \text{maximum number of left hand components in the sort process} \)
- \( \text{Components(max-sort-rh)} = \text{maximum number of right hand components in the sort process} \)

The design parameters for the dynamic resequencing DOE are the same as for replication except for:

- \( \text{complexity} = \text{number of unique end item sets (left hand right hand sets) out of the process} \)
- \( \text{batch size} = \text{number of identical components that are produced at a time} \)

12.5 **DOE on Sequence Safety Stock**

The DOE for sequence safety stock uses the same performance metrics as dynamic resequencing with the addition of:

- \( \text{Sequence Safety Stock} = \text{the number of components to be held in the sequence safety stock} \)

The design parameters for the sequence safety stock DOE are the same as for dynamic resequencing except for:

- \( \text{replenishment cycle} = \text{how often is the safety stock replenished} \)

12.6 **Result of DOE**

Figure 12-2 compares the replication and dynamic resequencing sequence control strategies. The vertical axis measures the maximum number of components in the sort and hold process. The horizontal axis, production process length, is the platform WIP size.
from the sequence control location to the end of the production process. This does not include the amount of WIP held in the rework process. The graph gives the results for three different complexities of three, eleven, and nineteen. The graph is for a scrap rate of 2.75% and a first run capability of 100%. The findings are:

- as the production process length decreases the performance of replication and dynamic resequencing are similar,
- as complexity increases, the performance of dynamic resequencing approaches the performance of replication,
- as production process length increases the performance of dynamic resequencing approaches a constant, and
- as complexity increases, the number of components held increases for dynamic resequencing

![Replication vs. Dynamic Resequencing](image)

**Figure 12-2: Comparison of Replication and Dynamic Resequencing**
Figure 12-3 graphs the number of components required in the sequence safety stock. The vertical axis measures the number of components required in the sequence safety stock. The horizontal axis is sequence safety stock replenishment cycle. A sequence safety stock replenishment cycle of 200 means that we replenish the safety stock after producing each block of 200 components. The status of the system was a scrap rate of 2.75%. The figure gives the results for three different complexities of three, eleven, and nineteen. The findings are:

- as complexity increases the amount of safety stock increases,
- as the replenishment cycle increases the sequence safety stock increases, and
- as the replenishment cycle decreases the sequence safety stock approaches a constant (this trend would be more apparent in Figure 12-3 for replenishment times than shown).

![Sequence Safety Stock - Scrap Only](image)

Figure 12-3: Sequence Safety Stock - Scrap Only
Figure 12-4 shows the impact of batch sequencing on the dynamic resequencing sequence control strategy for a system with eighty components, a scrap rate of 2.75%, and a first run capability of 94.3% for three different complexities of three, eleven, and nineteen. The vertical axis measures the maximum number of components held in the sort and hold process. The horizontal axis is the batch size used in the batch sequencing method. The findings are:

- as complexity increases the number of components held increases,
- as complexity increases number of components held is more sensitive to batch size, and
- for low complexities the optimal batch size is greater than one.

![Batch Sequencing Impact](image)

**Figure 12-4: Impact of Batch Processing on Dynamic Resequencing**

Figure 12-5 shows the optimal batch size for dynamic resequencing based on a scrap rate of 2.75% and a first run capability of 94.3% for three different complexities of three,
eleven, and nineteen. The vertical axis measures the optimal batch size when minimizing the number of components in the sort and hold process. The horizontal axis is the number of components in the system between the sequence control location and the sort and hold process. The findings are:

- as complexity decreases the optimal batch size increases, and
- as the number of parts in the system increases the optimal batch size increases.

We believe the second point has an implication for the reliability of the system. As the number of parts in the system increases, the time required to correct errors in the system increases and thus the reliability of the system decreases. Recall reliability is providing what is desired when requested. Therefore, we believe this implies as the reliability of the system decreases the optimal batch size increases.

Figure 12-5: Optimal Batch Size
An optimal batch size is driven by the fact that good components at the end of the line are more valuable than components just entering the system. Recall the scheduling method for batch sequencing. The production system schedules a batch for the first order for a particular end item. For example, assume a batch size of five. For the first order for end item A, the component plant schedules and releases five end items A. The production system keeps track of the number of item A that enter the production process and result in good components. In the example, assume all five produce become good components. Then the sort process will hold four good item A's beyond the original order. As additional orders for item A arrive, the production system satisfies those orders out of the components held in the sort process. When the sort process has no more good end item A's, the next order of end item A at the component plant scheduling process triggers the release of five end item A's at the sequence control location.

The process of batch sequencing distorts the production schedule, but also increases the probability that the first order that triggers the release of a batch is satisfied from that batch order. In addition to the distortion caused by scheduling, there is also distortion in the sequence caused by the nature of the production process. The larger of the two distortions determines which is the constraining distortion. For example, if the distortion due to batch sequencing at a given batch size is greater than the distortion due to the production process the constraining distortion is batch sequencing. However, if the distortion due to batch sequencing at a given batch size is less than the distortion due to the production process the constraining condition is production process distortion. So, the less reliable the production process is in maintaining the ILVS sequence, the larger the "optimal" batch size for batch sequencing.
SECTION D

SECTION D is a case study illustrating the use of the concepts presented in the previous chapters.
13. Case Study

The component plant studies in this research has a future product line requiring delivery in the ILVS format. The component will supply the assembly plant(s) with four door front, four door rear, and two door front panels. This case study uses the generic discrete event simulation models to evaluate different operational alternatives for the process.

13.1 Framework for Developing an ILVS System (Chapter 2)

Recall the framework for evaluating a production system.

![Figure 2-3 (repeated): Framework for Developing an ILVS System](image)

13.2 Characterizing the Production System (Section B)

13.2.1 Assembly Plant Requirement (Chapter 4)

The assembly plant requires three different sequence streams.

- four door front panels, right hand/left hand
- four door rear panels, right hand/left hand
- two door front panels, right hand/left hand

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13.2.2 Component Plant Scheduling (Chapter 5)

This case study uses the ILVS sequence order and batch sequencing scheduling methods.

13.2.2.1 Modified ILVS Sequence (Section 5.1)

The component plant splits the ILVS sequence forecast into the three separate production systems for four door front, four door rear, and two door front, Figure 13-1.

![Diagram of Product Line Production System]

**Figure 13-1: Overview of Product Line Production System**

13.2.3 Sequence Control Locations (Chapter 6)

The choice of sequence control location is based upon the ability to see the ILVS forecast in the production process and the quality (number of components) of the sort and hold process. The ILVS window size and the component plant window size determine the available sequence control locations. Recall that several activities, contribute to the component plant window size (see Figure 6-1).

The assembly plant ILVS forecast is a five day fixed order sequence. The door trim panel component installation point is approximately four hours from the end of assembly line (approximately half a production day with one shift). Therefore, the ILVS window size is approximately four and half days.
The order fulfillment time without errors is on the order of half an hour. The transportation time is on the order one day. The production system wait time is zero. The production system down time is a few hours. Therefore, for this case study, the available location for the sequence control location is anywhere in the production process (that is, the ILVS window is larger than the component plant window).

13.2.4 Decouple Production Process (Section 6.5)

Since the complexity increase through the production process and the process flow, we investigated decoupling the production process after the cure process. See Figure 13-2.

13.2.5 Production Process (Chapter 7)

13.2.5.1 Platform Component (Section 7.1)

For this production process, the platform component is the molded component produced by the injection molding machine.

13.2.5.2 Production Process Flow (Section 7.2)

An independent door-trim-panel production system produces each of the sequence streams required by the assembly plant, Figure 13-1. Figure 13-2 is an overview of the flow of components in one the independent production systems for door trim panel production. The four door front and four door rear production processes are identical. The two door production process is similar except for the use of a single injection molding machine and one less production station. The analysis in this case study focuses on the four door process. The text below describes the production process.

1) The process starts with a pair of injection molding machines, parallel production stations (Section 7.2.1), producing a right hand/left hand set.

2) The components produced by the molding machines transfer to a geometry cure process. Here the components stay for a minimum of twenty minutes.

3) The components split into a right hand/left hand process and go through seven production stations. All these production stations are a single piece in and out processes. The last production station identifies rework and scrap.
Figure 13-2: Overview of the Production Process
• Note: Operation 2 has parallel production stations with two operators performing the same operation.

4) Finally the components enter the sort and hold process.

13.2.5.3 Number of Platform Components in the Production Process (Section 7.3)

Production stations 1 through 7 contains 7 component sets. The cure process adds 28 component sets. The use of tag relief (the use of relief workers to fill in for workers on breaks) adds 28 component sets.

13.2.5.4 Operating Patterns within Production Process (Section 7.4)

The use of tag relief for the injection molding machine gives the injection molding machine and the cure process a unique operating pattern from the rest of the production process. The operational patterns for all production stations after the cure process are the same and will not use tag relief. The use of tag relief causes components to enter the cure process while no components are leaving the process. The longest break with tag relief is twenty minutes. See Table 13-1.

<table>
<thead>
<tr>
<th></th>
<th>minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>injection molding machine, cycle time</td>
<td>1.42</td>
</tr>
<tr>
<td>- both molding machine, cycle time</td>
<td>0.71</td>
</tr>
<tr>
<td>production stations, cycle time</td>
<td>0.68</td>
</tr>
<tr>
<td>cure process</td>
<td>20 minimum</td>
</tr>
<tr>
<td>tag relief</td>
<td>20 minimum</td>
</tr>
</tbody>
</table>

Table 13-1: Machine Cycle Times

13.2.5.5 Platform Complexity Increases Throughout Production Process (Section 7.4)

Table 13-3 shows how the platform complexity increase through the production process. The platform complexity begins with three at the injection molding machine. Production station 1 increases the complexity to six. Production station 3 increases the complexity to the final value of seven. This is the amount of complexity for a left hand panel or a right hand panel. The total complexity is fourteen unique end items.
<table>
<thead>
<tr>
<th>Platform Complexity</th>
<th>injection molding</th>
<th>out</th>
<th>in</th>
<th>cure</th>
<th>process</th>
<th>out</th>
<th>in</th>
<th>station 1</th>
<th>out</th>
<th>in</th>
<th>station 2</th>
<th>out</th>
<th>in</th>
<th>station 3</th>
<th>out</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Process             | 1                 | 1   | 2  | 1    | 1       | 1   |    |           |     |    |           |     |    |           |     |

| Platform            |                   |     |    |      |         |     |    |           |     |    |           |     |    |           |     |
|                     | - geometry        | 1   | 1  | 2    | 2       | 2   |    |           |     |    |           |     |    |           |     |
|                     | - attributes      | 3   | 3  | 6    | 6       | 6   | 7  |           |     |    |           |     |    |           |     |

| Components Added    |                   |     |    |      |         |     |    |           |     |    |           |     |    |           |     |
|                     | - parts           | 1   |    |      |         |     |    |           |     |    |           |     |    |           |     |
|                     | - geometry        | 1   |    |      |         |     |    |           |     |    |           |     |    |           |     |
|                     | - attributes      | 3   |    |      |         |     |    |           |     |    |           |     |    |           |     |
|                     | - sets            | 3   |    |      |         |     |    |           | 7   |    |           |     | 7  |           |     |

| Information         |                   |     |    |      |         |     |    |           |     |    |           |     |    |           |     |
|                     | - required         | yes |    |      |         |     |    |           |     |    |           |     |    |           |     |

**Table 13-2: Process Metrics Molding Machine Through Station 3**

<table>
<thead>
<tr>
<th></th>
<th>in</th>
<th>station 4</th>
<th>out</th>
<th>in</th>
<th>station 5</th>
<th>out</th>
<th>in</th>
<th>station 6</th>
<th>out</th>
<th>in</th>
<th>station 7</th>
<th>out</th>
<th>in</th>
<th>sort and hold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform Complexity</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Platform         |     |           |     |    |           |     |    |           |     |    |           |     |    |             |
| - geometry       | 2   | 2         | 2   | 2  | 2         | 2   |    |           |     |    |           |     |    |             |
| - attributes     | 7   | 7         | 7   | 7  | 7         | 7   |    |           |     |    |           |     |    |             |

| Components Added |     |           |     |    |           |     |    |           |     |    |           |     |    |             |
| - parts          | 3   | 1         | 2   |    |           |     |    |           |     |    |           |     |    |             |
| - geometry       | 3   | 1         | 2   |    |           |     |    |           |     |    |           |     |    |             |
| - attributes     | 12  | 3         | 2   |    |           |     |    |           |     |    |           |     |    |             |
| - sets           | 6   | 3         | 1   |    |           |     |    |           |     |    |           |     |    |             |

| Information      |     |           |     |    |           |     |    |           |     |    |           |     |    |             |
| - required       |     |           |     |    |           |     |    |           |     |    | yes        |     |    |             |

**Table 13-3: Process Metrics Station 4 Through Sort and Hold**

138
13.2.5.6 Production Process Flexibility (Section 7.6)

13.2.5.6.1 Machine(s) and Operator(s) (Section 7.6.1)

The case study assumes each production station performs the setup for all end item styles within the production process cycle time. This implies that the setup time does not limit the production system flexibility. To ready a production station for operation (setup) the station must be ready for production and the correct sub-components must be available. To pick sub-components for operation, the station must chose the correct sub-component(s) from the sub-components presented. The more sub-components required and/or the greater the number of sub-components presented, the more setup time is required. Production station 4 has the most complex material input requirements with three sub-components chosen from the twelve different sub-components presented, Table 13-3. 2

13.2.5.6.2 Material Handling (Section 7.6.2)

Table 13-3 shows the required number of sub-component presented at each production station. This number specifies the material handling requirements to achieve flexibility at each production station. Production station 4 is the worst case: it needs to process sub-components with twelve different attributes. Each production station requires sufficient floor space for presenting and stocking of sub-components.

13.2.5.6.3 Information Flexibility (Section 7.6.3)

At a minimum, each time there is an increase in the platform complexity, a production station requires additional information. The information commands the production station to perform a task such that the operation adds the correct complexity. For example, the injection molding machine needs information as to what the correct color for this machine cycle. At the minimum, the injection molding machine, production station 1, production station 2, and sort and hold process require information, Table 13-3.
13.2.5.7 Production Process Reliability (Section 7.7)

Production process reliability is concerned with the production station being capable of operating at the desired quality level when requested.

13.2.5.7.1 Production Station Up-Time (Section 7.7.1)

This production process is essentially a serial process without buffers. In a serial production process, when one production station fails, so will the entire production process. One exception is the injection molding machines. One molding machine can go down while the other still operates. However, since the molding machines are at the start of the production process and so do not hold product that the system has already released, if one is not operating the sequence should not be affected. Production station 2 is the other exception. Production station 2 is a very manual process with no downtime associated with it. We, therefore, assume machine downtime does not distort the sequence.

13.2.5.7.2 Production Process Quality (Section 7.7.2)

The thesis assumes a production process quality of three percent scrap and ninety-five percent first run capability.

13.2.5.8 End Item Differences (Section 7.8)

There are no end item differences for cycle time, process flow, and work content balance. We assume no dependence of scrap rate and first run capability on end item style.

There are two important levels of complexity within the production process. That is a complexity of three and of seven. There is no information (projection) on the take rate for these different complexities. We assume a linear end item take rate (Section 12.2.1). For the complexity of three, the assumed take rate distribution is given in Table 13-4 and for a complexity of seven in Table 13-5.
<table>
<thead>
<tr>
<th>end item</th>
<th>take rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.7%</td>
</tr>
<tr>
<td>2</td>
<td>33.3%</td>
</tr>
<tr>
<td>3</td>
<td>50.0%</td>
</tr>
</tbody>
</table>

Table 13-4: Take Rate Distribution for Complexity of Three, Assumed Linear

<table>
<thead>
<tr>
<th>end item</th>
<th>take rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.6%</td>
</tr>
<tr>
<td>2</td>
<td>7.1%</td>
</tr>
<tr>
<td>3</td>
<td>10.7%</td>
</tr>
<tr>
<td>4</td>
<td>14.3%</td>
</tr>
<tr>
<td>5</td>
<td>17.9%</td>
</tr>
<tr>
<td>6</td>
<td>21.4%</td>
</tr>
<tr>
<td>7</td>
<td>25.0%</td>
</tr>
</tbody>
</table>

Table 13-5: Take Rate Distribution for Complexity of Seven, Assumed Linear

13.2.6 **Sequence Control Strategy** *(Chapter 8)*

This case study investigates the performance of the replication, dynamic resequencing, and sequence safety stock sequence control strategies on the production system. The case study does not investigate hybrid strategies.

13.3 **Modeling the Production System** *(Section 2.2)*

This case study uses the generic models developed in Chapter 11. The use of the generic models requires four simplifications of the production system. First, two injection molding machines are treated operationally as one machine. This assumption seems valid because the schedule information can be held at a common point and released to the next available injection molding machine. Second, we disregard the effect of the parallel production stations in operation 2. Third, the generic models define all platform complexity at the sequence control location. Fourth, there is no production process constraint for independent right and left hand operation in the injection molding machine.

13.4 **Analyzing the Production System** *(Section 2.3)*

The generic models screen operational alternatives. The best performing alternatives will receive more detailed analysis to determine the best operational strategy.
13.4.1 Operational Strategy: Sequence Out Molding Machine

One alternative for an operational strategy is sequencing out of the molding machine. We evaluated this alternative for two different operating pattern conditions: using tag relief, and not using tag relief. Table 13-6 shows the system performance for replication and dynamic resequencing sequence control strategies with tag relief.

<table>
<thead>
<tr>
<th></th>
<th>Slots(max)</th>
<th>Slots(max 90%)</th>
<th>Parts(max)</th>
<th>Seq(90%)</th>
<th>Holes(90%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># of seq slots</td>
<td># of seq slots</td>
<td># of parts</td>
<td># of seq slots</td>
<td># of holes</td>
</tr>
<tr>
<td>Replication</td>
<td>135</td>
<td>127</td>
<td>65</td>
<td>267</td>
<td>6</td>
</tr>
<tr>
<td>Dynamic Resequencing</td>
<td>66</td>
<td>60</td>
<td>9</td>
<td>126</td>
<td>11</td>
</tr>
</tbody>
</table>

**Table 13-6: Replication and Dynamic Resequencing with Tag Relief**

<table>
<thead>
<tr>
<th>cure process size</th>
<th>components</th>
</tr>
</thead>
<tbody>
<tr>
<td>cure</td>
<td>56</td>
</tr>
<tr>
<td>tag relief</td>
<td>62</td>
</tr>
<tr>
<td>batch</td>
<td>0</td>
</tr>
<tr>
<td>scrap</td>
<td>0</td>
</tr>
<tr>
<td>total</td>
<td>118</td>
</tr>
</tbody>
</table>

**Table 13-7: Cure Process Size with Tag Relief**

Table 13-8 shows the system performance for replication and dynamic resequencing sequence control strategies without use tag relief.

<table>
<thead>
<tr>
<th></th>
<th>Slots(max)</th>
<th>Slots(max 90%)</th>
<th>Parts(max)</th>
<th>Seq(90%)</th>
<th>Holes(90%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># of seq slots</td>
<td># of seq slots</td>
<td># of parts</td>
<td># of seq slots</td>
<td># of holes</td>
</tr>
<tr>
<td>Replication</td>
<td>76</td>
<td>75</td>
<td>38</td>
<td>151</td>
<td>4</td>
</tr>
<tr>
<td>Dynamic Resequencing</td>
<td>55</td>
<td>43</td>
<td>7</td>
<td>109</td>
<td>7</td>
</tr>
</tbody>
</table>

**Table 13-8: Replication and Dynamic Resequencing without Tag Relief**

<table>
<thead>
<tr>
<th>cure process size</th>
<th>components</th>
</tr>
</thead>
<tbody>
<tr>
<td>cure</td>
<td>56</td>
</tr>
<tr>
<td>tag relief</td>
<td>0</td>
</tr>
<tr>
<td>batch</td>
<td>0</td>
</tr>
<tr>
<td>scrap</td>
<td>0</td>
</tr>
<tr>
<td>total</td>
<td>56</td>
</tr>
</tbody>
</table>

**Table 13-9: Cure Process Size without Tag Relief**
A sequence safety stock size without tag relief requires 40 components and with tag relief requires 47 components. The replenishment strategy assumes immediate reorder to replenish when a scrapped component is identified at station 7.

13.4.2 **Operational Strategy: Decouple at Cure Process**

Another alternative for an operational strategy is placing the sequence control location at the injection molding machine, but now decoupling the production process between the cure process and production station 1. We evaluated this alternative for two different operating pattern conditions: using tag relief, and not using tag relief. Table 13-10 shows the performance of the system for replication and dynamic resequencing.

<table>
<thead>
<tr>
<th></th>
<th>Slots (max) # of seq slots</th>
<th>Slots (max 90%) # of seq slots</th>
<th>Slots (90%) # of seq slots</th>
<th>Parts (max) # of parts</th>
<th>Seq (90%) # of seq slots</th>
<th>Holes (90%) # of holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replication</td>
<td>31</td>
<td>24</td>
<td>11</td>
<td>62</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Dynamic Resequencing</td>
<td>30</td>
<td>20</td>
<td>4</td>
<td>58</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

**Table 13-10: Replication and Dynamic Resequencing Decoupled**

<table>
<thead>
<tr>
<th>cure process size</th>
<th>w/ tag components</th>
<th>w/o tag components</th>
</tr>
</thead>
<tbody>
<tr>
<td>cure</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>tag relief</td>
<td>62</td>
<td>0</td>
</tr>
<tr>
<td>batch</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>scrap</td>
<td>22</td>
<td>17</td>
</tr>
<tr>
<td>total</td>
<td>140</td>
<td>73</td>
</tr>
</tbody>
</table>

**Table 13-11: Cure Process Size with Scrap Allowances**

If scrap allowance are placed in the decoupling buffer between the cure process and station 1, the cure process requires twenty-two additional components for tag relief and seventeen additional components without tag relief. The size of the sequence safety stock associated with Table 13-11 is estimated at twenty one components.
<table>
<thead>
<tr>
<th>Cure process size</th>
<th>w/ tag components</th>
<th>w/o tag components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cure</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>Tag relief</td>
<td>62</td>
<td>0</td>
</tr>
<tr>
<td>Batch</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Scrap</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>118</td>
<td>56</td>
</tr>
</tbody>
</table>

**Table 13-12: Cure Process Size without Scrap Allowances**

If no scrap allowance are placed in the cure process, the sequence safety stock size without tag relief requires 40 components and with tag relief requires 47 components. The replenishment strategy assumes immediate reorder to replenish when a scrapped component is identified.

### 13.5 Evaluating the Production System (Section 2.4)

The maximum number of component in the sort and hold process (including safety stock) and the number of component in the cure process give directional estimate of the monetary cost of operating and installing the production system. Based on the results of the screen evaluation and the requirement of tag relief, the operational alternatives for further investigation are:

- no decoupling and dynamic resequencing,
- no decoupling and sequence safety stock, and
- decoupling and replication.

### 13.6 Case Study Recommendation

We would like to further investigate the operational alternatives with the best system performance. This case study examined only the screening analysis of the production system. Recall we screen different alternatives early in the analysis phase to quickly focus on those alternatives with the most potential. A more detailed analysis would provide a better understanding of the production system performance.
From Section C, presequencing components prior to the molding process increases the platform WIP and degrades the performance of the system. The degradation is due to increased time required to correct errors in the production system. It is, therefore, recommended to schedule the molding machine directly from the ILVS forecast.

There is also the desire for additional flexibility at the molding production station. The goal is to remove any production process constraints from component plant scheduling. Independent right hand/left hand order sequence will improve the performance of the system by reducing the number of errors introduced into the production system and reducing the amount of time required for their correction.

The purpose of the components in the cure process dictates the intelligence required in this system. When allowances for scrap are incorporated, random access is required into the process. Without scrap allowance, a FIFO movement of parts is possible. The greater the intelligence required for the system, the higher the costs. An operational strategy allowing for a low intelligence cure process is desired.

In summary, the four recommendations from the case study are listed below.

- Perform more detailed analysis on the operational strategies presenting the best performance.
- Directly schedule the molding machine to the ILVS forecast.
- Increase the flexibility of the molding machine for independent right hand/left hand operation.
- Make the cure process require as little intelligence as possible.
SECTION E

SECTION E presents the recommendations and conclusion of this thesis and proposes areas for future work. The desire is to improve the overall supply chain by making the production system and product design more compatible with ILVS.
14. Executive Summary / Conclusions / Recommendations

14.1 Executive Summary

Please recall the continuum of production systems presented in Chapter 1.

- At one end are production systems so quick, reliable, and flexible they provide what is ordered immediately. These systems present little difficulty in meeting the ILVS requirements.
- At the other end of the spectrum are production systems so slow, unreliable, and inflexible they effectively can provide only one end item style. These systems experience more difficulty in meeting the ILVS requirements.

The goal in developing a production system for the ILVS environment is a production system that is quick, reliable, and flexible at providing what is ordered immediately.

To reach this goal, a production system needs to minimize the number of errors and the size of distortions it creates. This thesis attempted to lay a foundation for identifying and correcting sources of errors and distortions to improve the performance of the production system. Section 14.2 lists the conclusions of this thesis for improving production system performance. Section 14.3 lists the recommendation of this thesis.

14.2 Conclusions

14.2.1 Product Design

- Develop designs that reduce or eliminate the need for set-ups within the production process. For example, if an injection molding machine requires a four hour set-up to change the geometry produced, develop designs that do not require unique geometries in the major injection molded components.
- Develop designs that add complexity to the platform component late in the production process. The less platform complexity in a production system, the better the performance of the production system.
14.2.2 Assembly Plant Material Input

- When developing a production system for the ILVS environment, investigate the possibility of altering the sequence complexity requirements of the assembly plant based on the production system characteristics. If there is a long set-up time between manual and power door trim panels, investigate weather a separate stream for manual and power doors are acceptable. Remember the concept is to optimize Ford’s total production system not just the assembly plants.

14.2.3 Component Plant Scheduling

- Utilize a pull system of production scheduling based on the forecasted sequence. Remember ILVS really is single piece flow in the production process.
- Utilize either the ILVS sequence order or batch sequencing method of production scheduling of the modified sequence forecast. Either of these methods eliminates the potential for production systems errors due to scheduling.
- If using batch sequencing, investigate the possibility of batch sizes greater than one for systems with low levels of reliability in the production process.
- Schedule to correct errors in the system as quickly as possible.
- Reduce production process constraints on scheduling. An example is dependence on end item style for a production station producing a set of components.

14.2.4 Sequence Control Location

- Increase the reliability, production process flow control, and flexibility of the production system. This allows placing the sequence control location away from the end and farther upstream in the production process.
- Investigate decoupling the production process to improve the production system performance.
- If the production process is very long or the system is highly unreliable, the more critical the transportation time is to the system. This implies a greater portion of the component plant window is taken up in protecting the production system for
downtime and production system throughput time. Locating component plants close to the assembly operation reduces the transportation time.

14.2.5 Production Process

- Develop robust methods to enforce flow control within the production process. This is required for parallel production stations and buffer control.
- Utilize common rework buffers if more than one rework technician is used.
- Decrease operating pattern differences between segments of the production process if possible.
- Reduce the amount of non-value added platform component WIP. This is not to say eliminate all production buffers. Production buffers are neither good or bad. They are good or bad depending upon their application.
- Add complexity to the platform component as near the end of the production process as possible. As a mental model, note that if the production process produces only one end item, there is no need to sequence the production. The components emanating from the production process are sequenced by default.
- Increase the process flexibility between end items in the production system by:
  - reducing set-up times or eliminating requirement for set-ups, and
  - providing sufficient space in the production process layout to present sub-components and feed the line with the sub-components.
- Increase the reliability of the system in terms of mean time to repair, mean time to failure, first run capability, and scrap rates. The greater the reliability of the system the lower the amount of time needed to meet the sequence requirements and the lower the amount of time required to protect for system failures.
- Reduce end-item differences in the production process.

14.2.6 Sequence Control Strategy

- Utilize replication when the WIP is small and the process reliability is high.
- Utilize dynamic resequencing when the lowest take rate is above 5%, when the production process is unreliable, or the production process is long.
Utilize sequence safety stock to decouple the production segments for scrap. Use sequence safety stock for end-items with a take rate of less than 5%.

14.2.7  **Sort and Hold Process**

- Implement systems that reduce errors in the sort and hold process. Recall the fault tree analysis.

14.3  **Recommendations**

This thesis offers the following recommendations.

- Use the framework proposed in this thesis for developing a production system for the ILVS environment.

- Iterate through different operating strategies. Normally, the more iterations the higher the quality of the implementation. This is the learning curve effect.

- Get the correct people involved in developing the system. This can include, but is not limited to, production engineers, information system engineers, manufacturing engineering, product design engineers, assembly plant representatives, industrial engineering, line workers, production schedulers, and production operations.

- Implement only those systems that make economic sense.

- Do not go with the high technology solution for technology's sake. Remember technology has disadvantages as well as advantages, balance them.

- Develop and implement ILVS friendly guidelines for product and production system designs.

- Develop user friendly flow chart guidelines for the component system scheduler and work team understanding of events for success.
15. **Next Steps**

Improved modeling techniques are critical to the efficient and effective evaluation of production systems.

- Probability modeling has the potential for quick results early in the evaluation process. Therefore, it is suggested that additional research be performed to developing modeling methods using probability methods.

- The concept of generic models can be expanded to include the development of modules for the discrete event simulation software to decrease the complexity and time associated with developing models.


