IMPLEMENTATION OF BLOCK PAINTING IN FORD'S IN-LINE VEHICLE SEQUENCING ENVIRONMENT

by

F. Russel Atassi

M.S., Industrial and Operations Engineering
The University of Michigan, Ann Arbor (1992)

B.S., Industrial and Systems Engineering
The University of Michigan, Dearborn (1989)

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Signature of Author__________

Department of Aeronautics and Astronautics Engineering
August 9, 1996

Certified by______________________________

Thomas L. Magnanti
George Eastman Professor of Management Science
Thesis Advisor

Accepted by____________________

Edward F. Crawley
Head, Department Aeronautics and Astronautics Engineering

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ABSTRACT

The Ford Motor Company has identified In-Line Vehicle Sequencing (ILVS) as a key time-based strategy to improve operational productivity in ordering, production, and delivery. This scheduling technique enables suppliers to produce and ship parts in sequence, eliminating large quantities of stock stored along the assembly line and in warehouses.

Ford has also identified Block Painting as a major cost saving opportunity. Painting blocks of vehicles with similar colors significantly reduces operating costs due to the reduced number of purges the system must undergo.

Until recently, the automobile industry has viewed ILVS and Block Painting as two non-compatible systems. Recent research [1] has shown that ILVS and Block Painting can coexist harmoniously in a complex assembly environment. This study evaluated a conventional approach to Block Painting, and compared it with an improved pre-sequencing algorithm that creates larger block sizes and significant annual savings. This approach to Block Painting requires the paint department to maintain strict sequence control. The current system is not designed to achieve this level of control.

Through the use of discrete-event simulation, this thesis validates the models used to depict the flow of vehicles through the paint department at Wixom Assembly, Ford Motor Company's luxury car-line assembly plant. It first establishes a baseline model, and then introduces tight sequence control measures to preserve the sequence of vehicles emerging from the first stages of painting so that they are at least 98% representative of the stream of vehicles joining it. This thesis evaluates the impact of these controls in terms of process throughput rates, sequencing bank (Automated Storage and Retrieval System) size requirements, and the preserved paint block size in the enamel booth.

As a follow on to previous research, this thesis emphasizes feasible, low cost, and easy to implement sequence control algorithms to preserve the blocks of paint generated via pre-sequencing methodologies. Specifically, pre-sequencing of vehicles, in conjunction with tight sequence control processing logic will yield paint blocks of size 3.6 when the pre-sequencing algorithm has introduced a stream of vehicles with an average block size of 6.6. The optimized purging patterns that our approach generates are expected to yield annual savings in excess of $1,650,000 as compared with the current average block sizes of 1.2. The new scheduling approach will also produce additional savings nearing $90,000 in labor costs at the metal repair facility, leading to total annual savings of approximately $1,740,000.

Thesis Advisor: Thomas L. Magnanti
Title: George Eastman Professor of Management Science

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THESIS INTRODUCTION

1.1 Introduction

Assembly lines provide efficient means to manufacturing high volume products. In some instances, a single assembly line can produce many variations of the same basic product. In many practical situations, the number of variations is so large that each unit is almost unique, making it impossible to use mixed model procedures. The US automotive industry is a prime illustration. For example, the total number of option combinations of the Buick Century exceed 176 trillion [2]. Other automotive assembly plants face similar conditions [3]. In practice, the automotive industry deals with the problem of producing such a large number of combinations of options in two phases. In the first (design) phase, it designs and balances the assembly line to accommodate the anticipated mix of products. Since there are no systematic techniques to balance assembly lines when the number of models is large, it is common practice to "balance" the line on average (i.e., the average job will be completed within the allocated time). Stations with higher processing times variability usually have lower average utilization levels in these systems. Sometimes, average utilization levels are as low as 50 percent to accommodate processing time variations. Another common practice is to provide a larger workspace at stations with high processing time variances. This permits the assembler to work on the job farther down the assembly line than he/she could otherwise.

In the second (operational) phase, the industry sequences jobs on the assembly line so as to smooth out the flow of work as much as possible. This can be accomplished, for example, by alternating jobs with long and short processing times. However, the best sequence for a particular workstation might not be good for another workstation [4].

Assembly sequence planning has not, until very recently, been subjected to much thorough or systematic problem analysis [5][6][7][8][9][10]. Classic product development did not consider assembly a major element of the development process. The industry has gathered know-how through everyday assembly experience, communicated through generations of manufacturing engineers. The primary motivation for the work to date on assembly line design and sequencing has been to simultaneously maintain both high quality levels (by ensuring that the assembly operators have adequate time to complete their tasks) and high labor productivity.

A key strategy for approaching this rather complex problem has been through decomposition [11]. As a result, over a period of many decades, the automobile industry has established a three stage planning process. To start, the production engineer tries to decompose assembly into several subassemblies of reasonable sizes that can be adequately managed (i.e., be handled in today's computer environment). Then, s/he searches for base parts for each sub-assembly, and establishes the rest of the assembly sequence for each sub-assembly. Solving these new sub-problems in a certain order results eventually in the solution to the original problem. Simply put, and in compliance with principles of optimal systems design and management, the industry has dealt with complexity by decomposing the overall problem into sub-tasks and sub-problems to induce simplicity. Since the number of workstations and product options in a typical plant is so large, and scheduling many workstations simultaneously is such a formidable task, the traditional planning approach does not attempt to examine all workstations, but instead focuses on scheduling only a few "key" workstations. This approach raises questions concerning the best number of stations and which, out of a few hundred in a typical automotive assembly line, to include in the sequencing procedure. Approaches of this kind lead to the development of measures through problem decomposition for evaluating how critical it is to include a station in the scheduling process, as well as to estimate the controllable costs (repair and/or quality costs) if the scheduling algorithms were to exclude the station. Several process elements are essential to the decomposition efforts including the mix of option combinations and their associated processing times, the length of the station, staffing levels, task assignments, and product engineering changes that occur after the line has been designed. All of these elements have played a critical role in defining and shaping In-Line Vehicle Sequencing efforts which are so widely used in today's assembly line environment.

The Ford Motor Company has identified In-Line Vehicle Sequencing (ILVS) as a key time-based strategy to improve operational productivity in ordering, production, and delivery [12]. ILVS has been able to reduce costs and improve competitiveness. Keeping vehicles in sequence from order through delivery allows suppliers to receive orders at the same time as the assembly plants. Doing so enables suppliers to produce and ship parts in sequence, eliminating the large quantities of stock stored along the assembly line and in warehouses. As a result, ILVS contributes significantly to improved quality, increased process capability, and the elimination of many non-value added activities.

Ford and other automobile manufacturers have also identified Block Painting as a major cost saving opportunity. Painting batches of cars with similar colors significantly reduces operating costs due to the reduced number of purges the system must undergo in switching from one color to the next.

Until recently, the automotive industry has viewed ILVS and Block Painting as two non-compatible operating systems. It has viewed Block Painting as a major disrupter to the sequence that ILVS attempts so strictly to control.

Through a recent study conducted at MIT, in conjunction with the Leaders for Manufacturing Program, Myron [1] has shown that Block Painting and ILVS are capable of coexisting harmoniously, given certain operational conditions are met. However, his study is contingent upon the paint shop of an automotive assembly operation being able to maintain strict vehicle sequence control. Currently, and specifically at Ford Motor Company's Wixom Assembly Plant, the automobile industry has not designed its plants to be able to achieve this type of sequence control. This situation has served as the motivation for this thesis.

1.2 In-Line Vehicle Sequencing at Ford Motor Company

The objective of In-Line Vehicle Sequencing (ILVS) at Ford is to introduce a tightly knit network, integrating body and paint areas, final assembly, and the suppliers of an automotive assembly plant (Figure 1-1). To realize this objective, the company has used a combination of facility revisions in the body and paint departments, along with advanced computer technologies to maintain strict sequence control. ILVS is made possible through the use of an Automated Vehicle Scheduling and Automated Vehicle Identification (AVS/AVI) system. Its components consist of an centralized data base, vehicle based transponders, stationary readers, and sophisticated and highly flexible conveyor system allowing for vehicle tracking and in-line vehicle substitution (discussed in detail later).

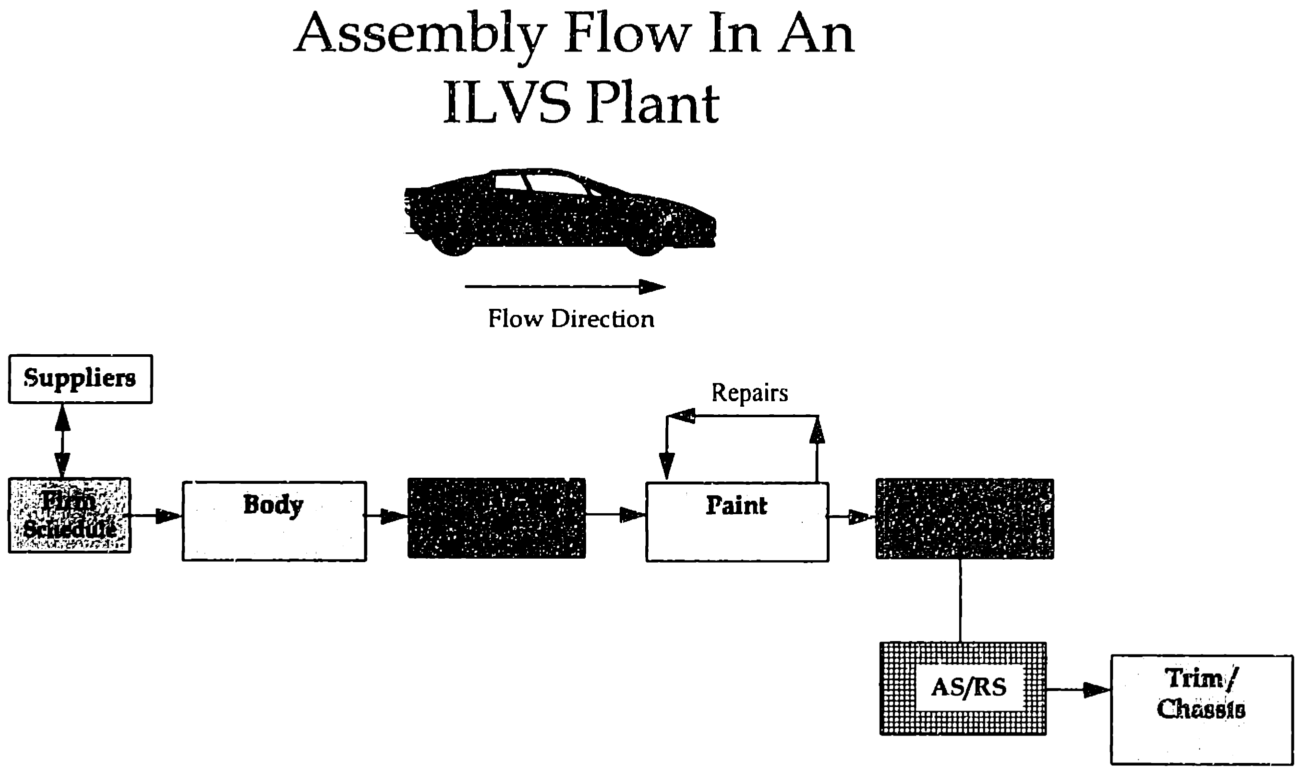


Figure 1-1: ILVS flow in an assembly plant

Ford has historically built vehicles to order. A centralized scheduling activity, in response to orders from district sales offices, creates twelve day order banks for the assembly plants. Each assembly plant, using an extensive Materials Requirement Planning (MRP) System, decomposes its order bank into weekly and daily production schedules. Ford uses these schedules, known as the *master schedule*, or the *National Blend* (we use both terms interchangeably in this thesis), to sequence cars to balance the workload in the final production area called trim and chassis. As any plant builds cars, they invariably become out of sequence. Parallel operations with different processing times, off-line operations, re-work and many other factors all play a hand in altering the sequence of cars. ILVS allows any plant to introduce the same vehicle build schedule into the trim and chassis department as was scheduled three days earlier to the body shop, and five days earlier into the master schedule. The activities in trim and chassis are labor extensive, and a well chosen master schedule permits engineers and supervisors to manage work better. The assembly jobs will be better designed for productivity, stability, and balance. Moreover, suppliers receiving a five day firm schedule are able to manufacture, assemble, and ship parts in sequence, providing for cost savings from reduced inventories, material handling, and premium freight. When parts are shipped in sequence, stock is better distributed along the assembly line, leading to more effective work-cell layout. Ford estimates that it attains a savings totaling $13.00 per vehicle through ILVS generated efficiencies [12].

In-line vehicle substitution is a method used to alter the sequence of vehicles by changing their identification rather than physically switching their location (therefore, permitting a plant to "place" cars back in sequence). Vehicle complexity directly impacts the effectiveness of in-line vehicle substitution. Defined as the possible number of unique vehicle types at any given point in the production process, complexity adversely affects the ability to substitute vehicles to closer match the National Blend schedule. At several points in the assembly process, a plant will read vehicle identifications and build complexity, and based on information available, will automatically substitute vehicle identification tags (also known as pseudo substitution) to create a new sequence that more closely matches the National Blend. Figure 1-2 demonstrates the concept of in-line substitution with a complexity level of two (two body types). In this case, upon entering the paint department, the in-line vehicle substitution system will interchange the identification tags for vehicles 2 and 8 (which at this point in the process are identical), resulting in a revised sequence that more closely matches the National Blend. As reported by Myron[1], plants attempting to implement ILVS will be most effective when they reduce the complexity levels.

1.3 In-Line Vehicle Sequencing at the Wixom Assembly Plant

The Wixom Assembly Plant, Ford Motor Company's luxury line assembly facility, provides for a unique application of ILVS. The variety of products assembled in this plant creates additional system specifications and constraints that affect any scheduling approach. For example, two separate body shops, one for Town Car/Continental, and the other for Mark VIII, feed vehicles into one paint shop. To further complicate the situation, and due to labor balance constraints, both the body and paint shops process vehicles according to a pre-determined mix. For example, the plant processes three Town Cars, referred to as the large cars, for every one Continental, also referred to as the small car. In a similar fashion, and due to lower production volumes, it processes one Mark VIII for every eight Town Car/Continental vehicles.

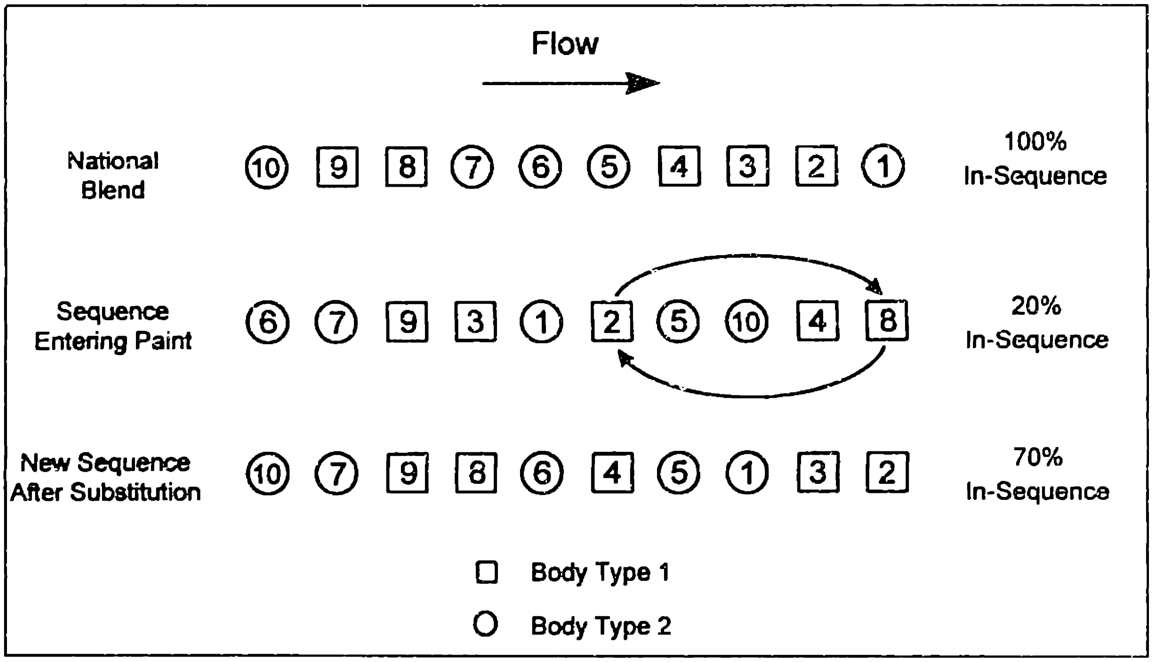


Figure 1-2: The concept of substitution (adapted from [1])

The paint shop consists of two phases. Vehicles enter Phase-1 as solid sheet metal bodies (Body-In-White or BIW) and exit Phase-2 painted with dazzling and shiny colors. Throughout the system, various processing steps on the vehicles (i.e., heavy metal repair, and multiple and parallel ovens) disrupt the original sequence. For that reason, the paint shop has two dynamic substitution stations to re-sequence vehicles to better match the original plant schedule. From the paint shop, vehicles enter an automated storage and retrieval facility (AS/RS), where they are further re-sequenced to be at least 98% representative of the original plant schedule, introduced at the body shop three days ago. Ideally, ILVS in conjunction with the AS/RS would be able to maintain perfect sequence. However, achieving a perfect sequence would incur very high costs. For that reason, Ford has established a limit of 98% as the minimal accepted percentage of vehicles emerging out of the AS/RS and that are in sequence. Once in the AS/RS, vehicles await final processing at the trim and chassis department.

Each one of the facilities in the production process either disrupts the sequence of vehicles that ILVS strives to maintain, or aids ILVS by re-sequencing all vehicles back into the original plant schedule. The body and paint shops produce the bulk of sequence disorder, while the two dynamic substitution stations and the AS/RS work to restore the sequence of the vehicles back to the original plant schedule. Figure 1-3 graphically depicts the flow of vehicles through the Wixom Assembly Plant.

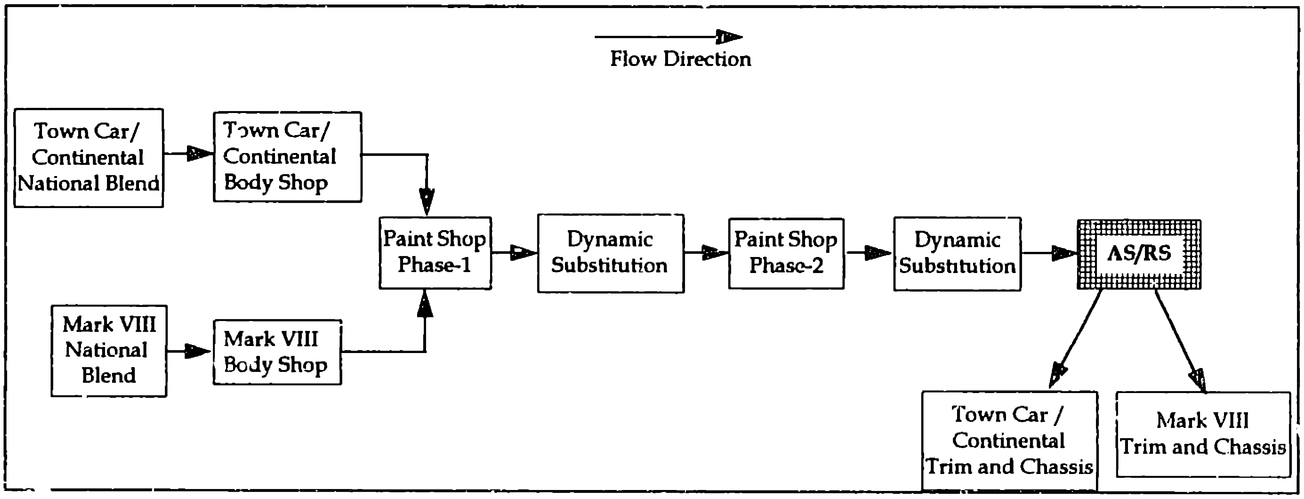


Figure 1-3: Vehicle flow through the Wixom Assembly Plant

1.4 Life Before In-Line Vehicle Sequencing

Any assembly plant is a complex operation that will introduced disruptions to an assembly sequence at many locations/facilities. Analysts (e.g., engineers) generally classify disruptions as controllable and uncontrollable. The majority are controllable. Controllable disruptions can be facility related (i.e., paint booth and oven strip conveyors), process related (i.e., off-line processes), or operation related (i.e., special handling of specific units). Uncontrollable disruptions are mostly related to repairs and rework operations. Sequence analysis that Ford has performed tracked vehicles through the body and paint departments. At Ford Motor Company's Wixom Assembly Plant, approximately 1% of the vehicles entering the body shop are actually in sequence upon exiting the paint shop [12]. Prior to ILVS, the plant had little incentive to maintaining vehicle sequence through the body and paint shops. Analysis at Wixom identified 62 locations that caused disruptions in the assembly sequence because of facilities, operating practices, or by low process capability and control. Over half the disruption points were located in Phase-1 and -2 of the paint shop.

1.5 Life After In-Line Vehicle Sequencing

Through the use of vehicle identification tags, readers, computerized data bases, and an extensive backup system, ILVS enables the plant to assign Automated Vehicle Identification (AVI) numbers to track vehicles throughout the system and to accommodate in-line substitution. AVI has other positive by-products. It permits the plant to report performance data on critical process outputs and functions as an interface for manufacturing and on-line automation.

Given cost inefficiencies associated with achieving and maintaining 100% sequence control, Ford chose four different measurable criteria to evaluate the viability and success rate of ILVS. (See Table 1-1).

Measurable	Established Metric
Percent in Sequence	≥ 98%
Maximum Number of Set Asides	≤ 10 set asides at any one time
Digs/100	≤ 2 digs per 100 vehicles produced
Dig Depth	≤ 5 parts deep into a container at any time

Table 1-1: ILVS viability metrics

- "Percent in sequence" is defined in terms of the number of vehicles being out of sequence. A vehicle is considered out of sequence if some vehicle with a higher sequence number than it proceeded it in the vehicle sequence.

- "Maximum number of set asides" is a measure reflecting the number of parts being set aside because a vehicle is out of sequence in the assembly process.

- "Digs / 100" is defined in terms of the number of times an assembly operator must set aside material or parts during a period of production due to vehicles being out of sequence.

- "Maximum dig depth" is a measure of how far an assembly operator must reach into the container to retrieve parts for the next vehicle.

Along with the extensive ILVS system, Wixom Assembly uses an integrated Automated Storage and Retrieval System (AS/RS) to achieve the 98% to sequence minimum criteria established for ILVS. This eight story highly automated system is located between the paint shop and the trim and chassis operations. It is used as a sequencing facility for trim and chassis for the purpose of maintaining overall vehicle sequence that is at least 98% representative of the National Blend. The size of the AS/RS has a direct and positive correlation with the percent of vehicles emerging out of the paint department that are out of sequence.

The plant is currently using ILVS to schedule vehicles into the plant, process vehicles through the body and paint departments, deliver vehicles to trim and chassis at least 98% to sequence, and schedule the delivery of key components to the assembly plant.

1.6 Block Painting

By painting vehicles in batches of similar colors, an automobile manufacturer can realize significant savings by eliminating the need to "purge" or clear paint equipment when processing vehicles. Material savings stem from both the prime and enamel booths. Figure 1-4 shows the costs, ranging from $15 to a little over $20 per purge, for the enamel booth as a function of paint block size [13]. Clearly, Ford could achieve considerable cost savings by implementing Block Painting. Figure 1-5 shows the annual costs associated with block painting as a function of block size at the enamel booth. These savings are based on annual production volumes of 200,000 vehicles.

In establishing the National Blend (described earlier) for an automotive assembly plant, Ford accounts for a variety of assembly objectives, one of which is Block Painting. The original ILVS analysis conducted by Ford listed Block Painting as a component of ILVS, and identified it as one of the largest contributors to costs savings. Yet, in a recent priorities list generated for the Wixom Assembly Plant, Block Painting (generating paint blocks of size three or larger) was priority number eight out of a total of eighteen. Other objectives such as assembly line balancing and maintaining targeted product mixes had higher priorities than Block Painting. Myron [1] has shown that relying completely on current methods of establishing the National Blend and on dynamic substitution will not create paint blocks of significant sizes for a plant to realize any economic gains.

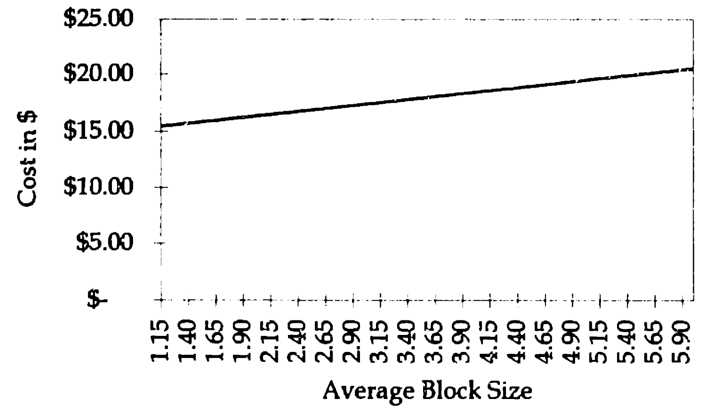


Figure 1-4: Cost per purge as a function of block size

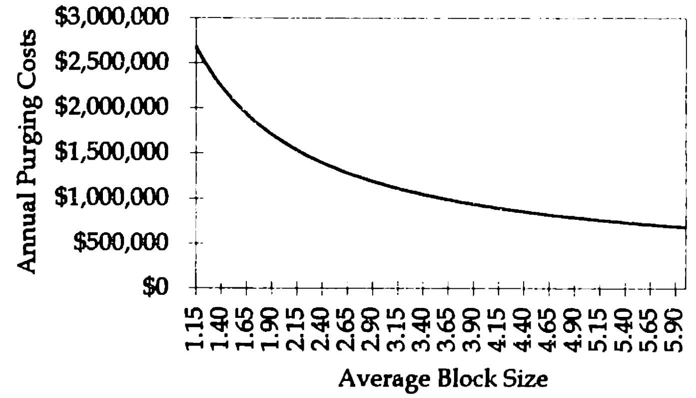


Figure 1-5: Annual purging costs as a function of block size Based on annual production volumes of 200,000 vehicles

1.7 Previous Analysis

Myron [1] has shown how to tailor the sequence entering the body shop to successfully integrate In-Line Vehicle Sequencing and Block Painting. His approach focused on adjusting the sequence entering the body shop to accommodate controllable process disruptions, while relying on existing dynamic system elements to deal with uncontrollable disruptions. He further attempted to analyze uncontrollable factors by modeling them statistically and building them into incoming body shop sequence to further optimize Block Painting. These scheduling approaches played a key role in incorporating Block Painting as a component of ILVS. A primary focus of Myron's study was to reduce system dependence on dynamic substitution to create, maintain, and process blocks of vehicles having the same color. The challenge was to group together large paint blocks from the National Blend without severely jeopardizing the original sequence. These paint blocks were to travel in tact through the body and paint shops to realize significant Block Painting savings. Myron introduced and highlighted the importance of the concept of block protection. This approach prevented repaired vehicles from breaking paint blocks as they re-entered the build sequence. The overall approach used both the final substitution station (after Phase-2 of paint) and the AS/RS to restore the sequence to the original National Blend sequence. The analysis assumed process discipline and capabilities brought about by ILVS to enable the plant to maintain sequence significantly better than previously possible. Figure 1-6 graphically depicts the proposed concept of pre-sequencing.

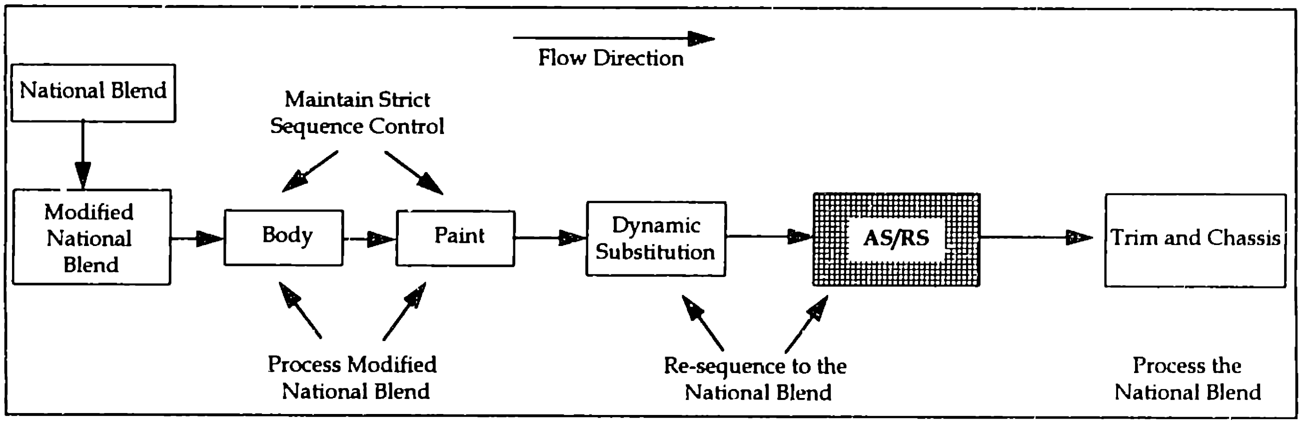


Figure 1-6: The previously proposed pre-sequencing approach [1]

1.8 Problem Statement

Previously, the automobile industry has viewed Block Painting and In-Line Vehicle Sequencing as a logical paradox. Theoretical research, conducted recently by Myron [1], has shown that Ford could reap considerable benefits by combining these operational methodologies into an integrated scheduling system. Specifically, Myron showed that Block Painting is possible in an ILVS assembly environment when the body department introduces large paint blocks that are internal to the National Blend. The use of ILVS strategies to achieve strict sequence control would permit these large paint blocks to propagate into the paint department. A study conducted by an external engineering firm, Cleaver, Ketko, Gorlitz, Papa & Associates (CKGP), has shown that the last substitution station (after Phase-2 of paint) and the AS/RS system (prior to trim and chassis operation) are capable of restoring the original sequence of the National Blend. It is clear, however, that lack of process sequence control in either body or paint departments would undermine any potential Block Painting effort. Moreover, if the assembly process introduces more disruptions, then to achieve Block Painting would require larger paint blocks into the body department, and an AS/RS of larger capacity to re-sequence vehicles to the original National Blend schedule. Myron has shown how to remedy disruptions introduced into the process in the body department, for the most part, by using the sequencing buffer between the body and paint departments. Extensive process observations, conducted at the Wixom Assembly Plant during the preliminary stages of this study have shown that Phases-1 and -2 of the paint department represent the largest area of opportunity for alleviating controllable and uncontrollable process disruptions. These disruptions have adverse effects on ILVS and subsequently undermine the potential advantages of Block Painting.

1.9 Goals and Objectives

This thesis will attempt to exemplify, through analytical models, the ill effects of both controllable and uncontrollable disruptions on the ability of ILVS to maintain a desired vehicle sequence. The research will also show how to better predict the impact of disruptions on Block Painting methodologies and the feasibility of implementing effective scheduling and sequencing algorithms in a complex assembly environment. Specifically, our research will attempt to accomplish the following:

- Complete a thorough validation process of the simulation models used to represent Phases -1 and -2 of the paint department in the Wixom Assembly Plant, and modify these simulations so that they more adequately reflects current operating conditions in the plant.

- Perform detailed analysis of the validated simulation models of Phases-1 and -2 of the paint department. Identify all sequence disruption points, both controllable and uncontrollable. (Wixom Assembly)

- Analyze the impact of strict sequence control on the size of the AS/RS system required to recreate the National Blend sequence. (Wixom Assembly)

- Analyze the impact of strict sequence control on the overall throughput of the paint department. (Wixom Assembly)

- Analyze the impact of fluctuations in cycle times for parallel operations. Determine the overall effect on paint block sizes at both the prime and enamel booths. (Wixom Assembly)

- Evaluate the impact of batching vehicles at the metal repair shop on block sizes at prime and enamel, and on labor requirements. (Wixom Assembly)

- Examine process expandability to other "ILVS-ready", or "ILVS-planned" assembly operations. Significant savings are possible through AS/RS size reduction and implementation of Block Painting. A large portion of this study will focus on developing generic sequencing algorithms to be included as part of the initial efforts targeted at implementing ILVS across Ford Motor Company's operations. These efforts will likely prove to be much more fruitful than modifying existing operations.

The application and benefits associated with ILVS are rapidly gaining wide acceptance within Ford Motor Company's assembly operations. With ILVS currently implemented at only a few plants, the company has a tremendous opportunity for adapting lessons learned to new ILVS facilities. This thesis aims to fully integrate previous research with current assembly practices to maximize the return on investment for ILVS and Block Painting.

1.10 Study Assumptions

To establish ground for further research on the topic of Block Painting, and to successfully build upon previous research, we made several assumptions:

- We take as accurate all previously established findings by Myron [1] (i.e., deactivation of the first substitution station having minimal impact on AS/RS size requirements and paint blocks propagation). Further analysis of these findings is beyond the scope of this study.
- Throughput of the paint department directly impacts overall throughput of the assembly process. Degradation in throughput levels at the paint department negatively affects the overall performance of the system.
- Physical modifications to the assembly process flow are possible as solution options.
- First-run paint shop capabilities and re-run times are given inputs to the simulation models. Any effort to reduce or optimize these parameters are beyond the scope of this research.
- The desired trim build sequence is given (from previous analysis), and is not subject to modification.

1.11 Overview of the Remaining Chapters

Chapter 2 summarizes and highlights some previous research and findings concerning ILVS and Block Painting. Specifically, this chapter compares and contrasts the conventional approach to Block Painting and a pre-sequencing approach as well as several ideal implementation scenarios. This chapter discusses the implications on the paint shop of sequence disruptions, and the impact of eliminating the first substitution station (immediately after Phase-1 of paint) in preserving paint blocks. Finally, the chapter presents the consequences of pre-sequencing on AS/RS size requirements.

Chapter 3 describes the process flow for all vehicles in Phase-1 of paint, incorporating the latest facilities changes. This chapter identifies all sequence disruptions (controllable and uncontrollable) and their impact on ILVS viability metrics and evaluates the newly defined out-of-sequence control metrics. A total of 5 variant models of Phase-1 of paint are analyzed, and the results summarized.

Chapter 4 describes the process flow for all vehicles in Phase-2 of paint. The chapter describes two types of analyses.

- The processing of a "generic" National Blend of vehicles through Phases-1 and -2 of paint using both passive sequence control and active sequence control scheduling algorithms.

- The processing of a pre-sequenced National Blend of vehicles through Phases-1 and -2 of paint, again using both passive and active sequence control scheduling algorithms.

In both cases, the analysis shows the required size of the AS/RS and the resulting block sizes at both the prime and enamel booths. This chapter concludes by comparing and contrasting the impact of active versus passive sequence control scheduling algorithms on block sizes at the prime and enamel booths, and identifies the impact of pre-sequencing on AS/RS size requirements.

Chapter 5 conducts sensitivity analyses on several underlying parameters related to ILVS, Block Painting, and Wixom Assembly. The first analysis depicts the impact of the various scheduling approaches on the vehicle throughput out of Phase-1 of paint, and its impact on that of Phase-2. This analysis shows that processing vehicles through the paint department by using active sequence control is able to maintain a fundamental requirement of the paint department, namely an overall throughput rate of 59 vehicles per hour into the AS/RS. A second sensitivity analysis addresses the impact of variations in cycle times of parallel operations on paint block size at the prime and enamel paint operations. A third and final sensitivity analysis evaluates the impact of grouping and repairing vehicles in batches at the metal repair shop. The results of the analysis show the impact of batching of vehicles on (i) AS/RS size requirements, (ii) paint block sizes at the prime and enamel paint booths, and (iii) labor requirements.

Chapter 6 summarizes the research findings of this thesis, and outlines a generic approach to integrating ILVS and Block Painting. Concluding remarks in this chapter suggest related topics for further investigation.

Chapter 2

PREVIOUS RESEARCH AND FINDINGS

2.1 Integration of In-Line Vehicle Sequencing and Block Painting

In a recent study, Myron [1] evaluated two approaches for incorporating Block Painting within ILVS. We will refer to the first method as the conventional approach to Block Painting. The second method will involve a more elaborate pre-sequencing scheduling algorithm; we will refer to it as the proposed method.

2.1.1 Conventional Approach

Considering the two basic criteria of ILVS and Block Painting, deliver vehicles in sequence to the final assembly process, and introduce vehicles to the enamel booth in batches of like colors, the conventional approach employed a simple substitution algorithm immediately before the enamel booth. Originally, this substitution station was used to reduce the spread of vehicles out of sequence by assigning each vehicle that passes the substitution station the lowest sequence number of all upstream vehicles with the same body configuration. In a modified form of substitution aimed to achieve Block Painting, the station built blocks by looking not for the absolute lowest sequence number, but for a body of the same color as the one just painted with a sequence number falling in a given search window from a vehicle with the same body configuration and a smaller sequence number. This approach provided a low-cost methodology for creating paint blocks. It required no hardware additions nor alterations to existing vehicle flow patterns. However, the ability of this scheme to generate blocks of any significance depends directly upon the level of Body-In-White (BIW) complexity (the number of body-in-white configurations) in the system.

2.1.2 Proposed Approach

As the central concept of previous research, this approach attempts to pre-sequence vehicles to accommodate all controllable or foreseeable sequence disruptions, including Block Painting. It attempts to handle all other uncontrollable disruptions using dynamic sequence control. This way, the system deals with all predictable disruptions ahead of time. The goal of this approach was to reduce system performance reliance on BIW complexity by grouping vehicles of like colors ahead of time regardless of body configuration. Process disciplines and computer advances through ILVS techniques were the cornerstones of this methodology, permitting the plant to maintain vehicle sequence through the body and paint departments. The approach used both the final substitution station, and the AS/RS to recreate the original National Blend sequence.

2.1.3 Ideal Implementation Scenarios

The previous research examined an ideal implementation of the proposed new scheduling approach. By design, it did not consider specific features of the plant that might require tailoring/modifications of the general approach. First, this research assumed the National Blend satisfied only requirements of trim and chassis. That is, the body and paint departments impose no processing constraints on the sequence of vehicles passing through them. As it turns out, the Block Painting via pre-sequencing approach requires this assumption. The body and paint departments currently at Wixom do not have this flexibility. The main body shop at Wixom must maintain a three-to-one rotation between Town Cars and Continentals. Initially, only final assembly required this rotation. However, the body and paint departments have adapted their labor balancing efforts to this rotation, and deviations from them are not welcome. Phase-1 of the paint department introduces other forms of inflexibility when processing vehicles. The plant introduces one Mark VIII for every eight Town Cars/Continentals to balance the work load at the manual seal application. *These specific features of the Wixom Plant imply that we were no longer free to re-sequence the National Blend to create paint blocks.*

The previous analysis also assumed that the paint shop has only a single paint booth. This assumption has significant consequences on paint block sizes. The mere fact that most plants have two enamel booths reduces paint block sizes by a factor of 1/2 (assuming vehicles alternately enter the two booths). Processing of tri-coats also requires time-consuming procedures inflicting further sequence disruption onto the system.

Finally, and as a central concept of this thesis, the previously proposed Block Painting methodologies relied on vehicle sequence being maintained throughout the system. The approach further required that vehicle flow through parallel processes must not contribute to sequence disruptions. Ovens, prime booths, and strip lanes are all parallel processes that should have identical and deterministic cycle times. In reality, all parallel processes have distributions approximating their cycle times, and most encounter downtime. Theoretically, scheduling mechanisms should assign and retrieve vehicles in a sequential and consistent manner between all parallel processes as a means to dealing with such variations. However, plants usually assign vehicles to the first available element of a parallel process operation to avoid jeopardizing the system's throughput. While the variations in parallel process cycle times might not have a drastic impact on how far out of sequence vehicles emerge from Phase-2, they could significantly disrupt paint blocks in the system. To some degree, all assembly plants will violate the idealized assumptions used in the previous analysis. Violations of these idealistic assumptions paved the path for the most research work included in this thesis.

2.2 Simulation Models and Results

We used discrete-event simulation to model and test the effects of incorporating Block Painting within ILVS. We chose to use simulation because the non-linear nature of vehicle flow through the process practically precluded closed form mathematical modeling. We used models to evaluate how ILVS controlled vehicle sequence through the system, and how effective Block Painting was in creating and maintaining paint blocks. In developing the simulation models to test and evaluate the system's performance, we attempted to accurately reflect the process. Because of simplifying assumptions made during the development phase of the original versions of these models, they are designed for an ideal ILVS environment rather than that found in the Wixom Assembly Plant. While Wixom Assembly is a pioneering plant with a proven track record of a successful implementation of ILVS, because of several deviating elements in the day-to-day operation, the plant falls short of the ideal. This is not an oversight, but rather an adaptation to the wide mix of products that are produced simultaneously on the same assembly line.

The simulation models used two primary metrics to evaluate the system's performance: (i) the size of the AS/RS, which is a direct measure of how closely vehicles replicate the National Blend sequence when they emerged from Phase-2 of paint, and (ii) the average paint block size at the enamel booth. As explained previously, tremendous financial gains can be harvested when the enamel booth processes vehicles in paint blocks of size three and larger.

2.2.1 Block Painting by Substitution

As explained earlier, the conventional approach attempts to build paint blocks by using the first substitution station not only to improve sequence control, but also to group vehicles of similar colors. Chapter 1 explained the dependence of this model on the BIW complexity level of an assembly operation. The larger the variety of products, the less successful this approach will be. This model specifies a search window setting an upper bound on how far away from the vehicle with the current body type configuration to look for vehicles with similar colors. Obviously, the larger the search window, the larger the size of the AS/RS facility that will be needed to re-sequence vehicles back to the original National Blend order. Prior analysis has shown that search windows of 100 vehicles and less lead to substantial improvements in block sizes, and that search windows larger than 100 provide minimal returns in terms of block size, but cause the size of the AS/RS facility to skyrocket to accommodate the newly established vehicle sequence.

2.2.2 Block Painting by Pre-sequencing

In the proposed approach to Block Painting, pre-sequencing creates paint blocks from the National Blend sequence before the plant has introduced the vehicles into the body shop. This technique depends heavily on the ability of ILVS to maintain the integrity of the paint blocks throughout the assembly process. It assumes that the plant will be able to preserve large paint blocks, which satisfy Block Painting objectives, as vehicles pass through a variety of operations. It also assumes that the body and paint departments impose no processing restrictions or constraints on the system, and that the plant builds to one National Blend (versus the two currently in place for Town Car/Continental and Mark VIII). In general, this model assumes ideal ILVS conditions.

An important element of this model, which is carried fully into this thesis, is that in order for pre-sequencing to work, the plant must deactivate the first dynamic substitution station. If left active, this substitution station would have a negative impact, and basically destroy the paint blocks as it tried to re-sequence vehicles to better match the National Blend. Previous research showed that the removal of this substitution station had minimal impact on the size of the AS/RS needed to re-sequence vehicles to be at least 98% representative of the original National Blend. Intuitively, this result predominates because most vehicle sequence disruptions occur at Phase-2 of paint, deeming all substitution efforts at the first substitution station fruitless.

2.2.3 Economic Returns from the Proposed Scheduling Approach

In contrasting the proposed versus the conventional Block Painting approaches to ILVS, previous research documented the following findings. The substitution methodology is capable of producing significant annual savings (approximately $900,0000) by introducing paint blocks at a minimal cost (slightly larger AS/RS size requirements). However, the substitution methodology, without pre-sequencing, is not capable of meeting the existing Block Painting objectives (paint blocks of size three and larger). On the other hand, the pre-sequencing methodology was shown to be capable of meeting the Block Painting objectives, and resulted in annual savings of approximately $1,650,000. Additionally, the sequence disruption created by generating these paint blocks lead minimal increases in AS/RS size requirements. These results suggest the potential of pre-sequencing to further enhance sequence control capabilities of the assembly process while generating paint blocks. Clearly, the pre-sequencing approach outperforms the conventional substitution method of generating paint blocks, and should be implemented. Further investigation of the ideal ILVS environment required by the pre-sequencing approach is in order, and provides a fertile research ground for this thesis.

2.3 Pre-sequencing and its Impact on AS/RS Size

The pre-sequencing method of creating paint blocks pulls forward in the sequence the lower-running vehicles. Since lower-running vehicles are more susceptible to being late than higher-running ones (substitution efforts are less effective with lower-running vehicles), pre-sequencing these vehicles earlier into the master schedule remedies some of the ill effects the process imposes on the sequence. The system imposes significant sequence disruptions and these early vehicles exit the paint department closer to their original sequence than would have been possible without being pulled forward. Processing these low-running vehicles early delays other vehicles in the process. However, dynamic substitution efforts are more effective with the high-running vehicles, and substitution is able to compensate for the majority of the delays. Since the objective of an AS/RS is to restore vehicles to be at least 98% representative of the original National Blend sequence, producing the 2% of the vehicles that are late and that the AS/RS is currently not capable of restoring back to the original sequence earlier in the production sequence leads to smaller overall AS/RS size requirements.

This thesis will further substantiate the observed results of smaller AS/RS size requirements when a pre-sequenced National Blend is introduced into our simulation models. Our analysis will validate this principle for both active and passive sequence control scheduling algorithms through the paint department.

2.4 Implementation Considerations

We might classify the implementation considerations of the pre-sequencing algorithms of the previous research into two categories; implementation in an ideal ILVS environment, and implementation at the Wixom Assembly Plant. While both require feasible and relatively inexpensive modifications to the scheduling and identification systems, implementation at Wixom Assembly requires additional hardware investment at much higher costs.

In an ideal ILVS environment, the scheduling algorithm must be able to generate paint blocks that are internal to the National Blend. This would require the Automated Vehicle Identification (AVI) and Automated Vehicle Scheduling (AVS) technology to be able to process two separate sequence numbers for each vehicle. One sequence number would represent the original National Blend, and the second, which we might refer to as the modified sequence number, would be associated with the newly created paint blocks. Different areas of the assembly process would use only one of the two sequence numbers to track the vehicles' progress. As they attempted to preserve the created paint blocks, the body and paint departments would use the modified sequence number. After paint, and precisely at the second substitution station, the system would use the original sequence number to re-sequence the arriving vehicles, as closely as possible, back to the original National Blend order.

To preserve paint blocks, the plant must also deactivate the first dynamic substitution station. The previous analysis of Myron has shown that this substitution station had practically no impact on the size of the AS/RS size needed because Phase-2 of paint accounted for the bulk of all sequence disruptions. The previous analysis also used block protection provisions to preserve paint blocks in a pre-sequencing algorithm. That is, the AVS/AVI system must be programmed to protect against re-run or repair vehicles from being merged into the system in a way that would disrupt an existing block of vehicles being processed. All these process modifications require simple programming changes to the current vehicle scheduling logic. These changes might also require some hardware modifications, for example, adding surge space to store the vehicles that can't be merged immediately into the process because of the algorithm's block protection provisions.

At Wixom Assembly, the scenario is more complex. Both the paint and body shops impose limitations on the sequence of entering vehicles (the three to one large to small car ratio and the eight to one Town Car/Continental to Mark VIII ratio). Parallel processes provide yet another challenging characteristic at Wixom Assembly (and at many other plants). Deviations in cycle times of these processes might provide for sufficient disruption to the flow of vehicles to annihilate any Block Painting efforts.

Given these limitations, the pre-sequencing approach to Block Painting continues to have merit. The previous analysis of Myron [1] suggested a modification of the National Blend for both the Town Car/Continental and the Mark VIII mixes to generate paint blocks, and then to merge the two sequences into two separate body shops. This approach would satisfy all of the processing constraints of the body and paint shops by maintaining the three large vehicles to one small vehicle mix, as well as the eight Town Car/Continental to one Mark VIII mix. After exiting from Phase-1 of paint, all vehicles enter an accumulating buffer where paint blocks are re-grouped. As Myron suggested, because of the initial pre-sequencing of the National Blend, these vehicles would still be in a nearly paint-blocked sequence, so that the system would use a relatively small accumulating buffer to recreate the paint blocks. Even if we did implement this approach, we would still face the challenge of preserving paint blocks within Phase-1 and -2 of paint (i.e., emulate the ideal ILVS environment conditions which the previous research was based on). Specifically, the Wixom Assembly Plant has parallel operations distributed across its assembly process, and uses two paint booths to process all of its vehicles. These parallel operations create sequence disruptions that we still need to address, and the two paint booths when used in an alternating manner reduce the block size by a factor of 1/2. Recall that the initial Block Painting objectives were to deliver paint blocks of size three and larger to the enamel booth. In order for Block Painting to work properly at Wixom Assembly, we need to resolve items of this nature, and perform a cost/benefit analysis. These research findings served as the starting point for further research, which is the basis for this thesis.

Chapter 3

PHASE-1 OF THE PAINT SHOP

At this point of our analysis, we direct our attention to Phase-1 of the paint department. Our goal is to develop a simulation model that represents the process flows at the Wixom Assembly Plant. To do that, we modify/refine a discrete-event Witness simulation model used in launching ILVS at Wixom Assembly, and developed by Cleaver, Ketko, Gorlitz, Papa & Associates (CKGP). This model assumes ideal ILVS operating conditions, and serves as a basis for our research. We then consider two distinct scheduling and sequencing approaches - a "passive" approach that does not change the flow pattern in the plant, and an "active" approach that does modify the flow (i.e., how vehicles are dispatched to parallel process operations).

Throughout our analysis, we examine the impact of variations in parallel process cycle times, the possibility of machine breakdowns, and processing vehicles in batches at the metal repair facility on our system's ability to maintain vehicle sequence. To better understand these variations and their impact on ILVS directly, and Block Painting indirectly, we develop a total of six simulation models of Phase-1 of the paint department. Table 3-1 serves to present the six models used throughout this study, along with a brief description of each.

To evaluate the performance of each model, we adopted two categories of measurements. Within each, several metrics resided. The first category was that of Ford Motor Company's ILVS viability metrics. Ford had first established the metrics in this category during the launch of ILVS at the assembly plant. They included items (described earlier in this thesis) such as "percent vehicles in sequence", "maximum set asides", "maximum dig depth", and "digs per 100 vehicles". Performance figures in this category for each one of the six simulation models played a primary role in determining how variations associated with each model impacted AS/RS size requirements, and paint block size propagation to the prime and enamel booths.

The second category specifically addressed statistics pertinent to measuring and quantifying how far out of sequence vehicles were emerging out of each model. Metrics shaping this category included the early and late arrival limits for out of sequence vehicles. We refer to them as the "early limit" and the "late limit" in our writing, and they represent the earliest distance out of sequence and latest distance out of sequence for vehicles exiting Phase-1. Other metrics included the mode and average (mean) for out of sequence distances, and the spread or distribution representing the out of sequence distances. Again we used all of these metrics to evaluate the impact of sequence disruptions introduced to CKGP's ideal ILVS environment model. Fluctuations in the values of these metrics were related to changes in AS/RS size requirements and the paint block size changes at both the prime and enamel booths.

Model Number	Model Name	Main Attribute
Model I	Deterministic Case.	Model modified to represent most recent layout of Phase-1 of the paint department. All operating statistics are deterministic in nature.
Model II	Parallel process cycle time variations.	Model is identical in structure to that of Model I. +/- 10% variation in cycle times for parallel processes introduced.
Model III	Breakdown distributions for parallel processes.	Model is identical in structure to that of Model I. Uniform distributions for failure rates and triangular distributions for repair times are introduced at all parallel operations.
Model IV	Batch vehicles in groups of six at metal repair.	Model is identical in structure to that of Model I. Vehicles are processed in groups of six at metal repair.
Model V	Passive Sequence Control.	Model is identical in structure to that of Model I. Combination of models II-IV. Includes interactions and effects of various elements on ILVS and Block Painting.
Model VI	Active Sequence Control.	Model is identical in structure to that of Model V. Strict sequence control processing logic incorporated.

Table 3-1: Paint shop (Phase-1) simulation models

3.1 Revised Physical Layout and New Vehicle Flow Pattern

Vehicles exit the body shop and join the paint shop according to two types of rotations. First, the system merges three Town Cars (also referred to as large cars) for every one Continental (also referred to as small car). Second, it merges one Mark VIII for every eight Town Car/Continental vehicles. These rotations are driven mainly by labor balancing restrictions in both the body and paint shops, and the lower volume requirements of the Mark VIII. Upon entering Phase-1, all vehicles are given Phosphate and E-coat treatments to protect against corrosion. Immediately after exiting the E-coat application , vehicles enter three parallel ovens (referred to as the E-coat ovens). After traveling through these ovens, vehicles merge into a single lane eventually leading to cooling strip conveyors. As they travel through the cooling conveyors, the vehicles cool, and the plant performs several quality checks. Upon exiting the cooling strip conveyors, vehicles are diverted into two cooling tunnels to further regulate their sheet metal temperature. Immediately following the cooling tunnels, vehicles merge again into a single lane, where an automated process utilizes state of the art robotics to apply under-body sealant (the latest "high-tech" addition to the paint department). Vehicles travel further, still in a single lane configuration, towards a manual assembly area, where operators add more sealing material. Immediately before reaching the manual seal line, vehicles are diverted onto two parallel conveyors. These two conveyors control the flow of vehicles onto the manual seal line. This is one of the critical points in the process at which adherence to the two previously described vehicle processing rotations is important. Counterintuitively, large vehicles (i.e., Town Cars) receive fewer and larger pieces of the sealant material, thus requiring less time to process than the small vehicles (i.e., Continentals and Mark VIII). Large vehicles allow the operator on the line to work upstream, and to initiate working on a small vehicle before the vehicle completely reaches his/her station. A third by-pass lane is available to remedy deviations from the prescribed rotation sequence. This by-pass lane is activated either automatically or manually to allow vehicles to flow through it.

The manual seal line leads to an automated oven via a single conveyor. Vehicles are exposed to several heat sources functioning as catalysts in curing the sealant material. From there, vehicles are routed to a brightly lit inspection area, where all BIW vehicles are thoroughly inspected. Minor repairs are completed at this time, and vehicles in need of heavy metal repair are tagged for the metal repair shop to fix. Tagging of vehicles in this process is automated, and the system is capable of diverting vehicle to the metal repair shop based on instructions encoded into each vehicle's transponder unit. On average, the plant pulls approximately 0.4% of the vehicles per day off-line at the heavy metal repair area where they stay 34 hours. Finally, vehicles are scuffed at the Scuff Booth in preparation for further processing in Phase-2. The plant pulls approximately 1% of the vehicles off-line for repair after the Scuff Booth. These vehicles remain off-line for 3.5 hours before being merged with bypassing vehicles. It is important to note that during shift breaks, the plant routes jobs into strip lanes. After the breaks, the plant resumes normal vehicle processing, and slowly merges all vehicles in the strip lanes back into the mainstream flow of the processing operations.

It is important to note that Phase-1 of paint does not contribute to the BIW complexity level of vehicles passing through it, since all vehicles receive identical Phosphate, E-coat, and sealant applications. For that reason, and because Phase-2 of paint contributes significantly more to both the vehicle complexity level and sequence disruptions, vehicles exiting Phase-1 of paint pass normally through a dynamic substitution station prior to joining Phase-2 of paint. This substitution station is intended to remedy sequence disruptions generated by both the body shop and Phase-1 of paint. Figure 3-1 serves as a physical depiction of Phase-1 of paint at the Wixom Assembly Plant.

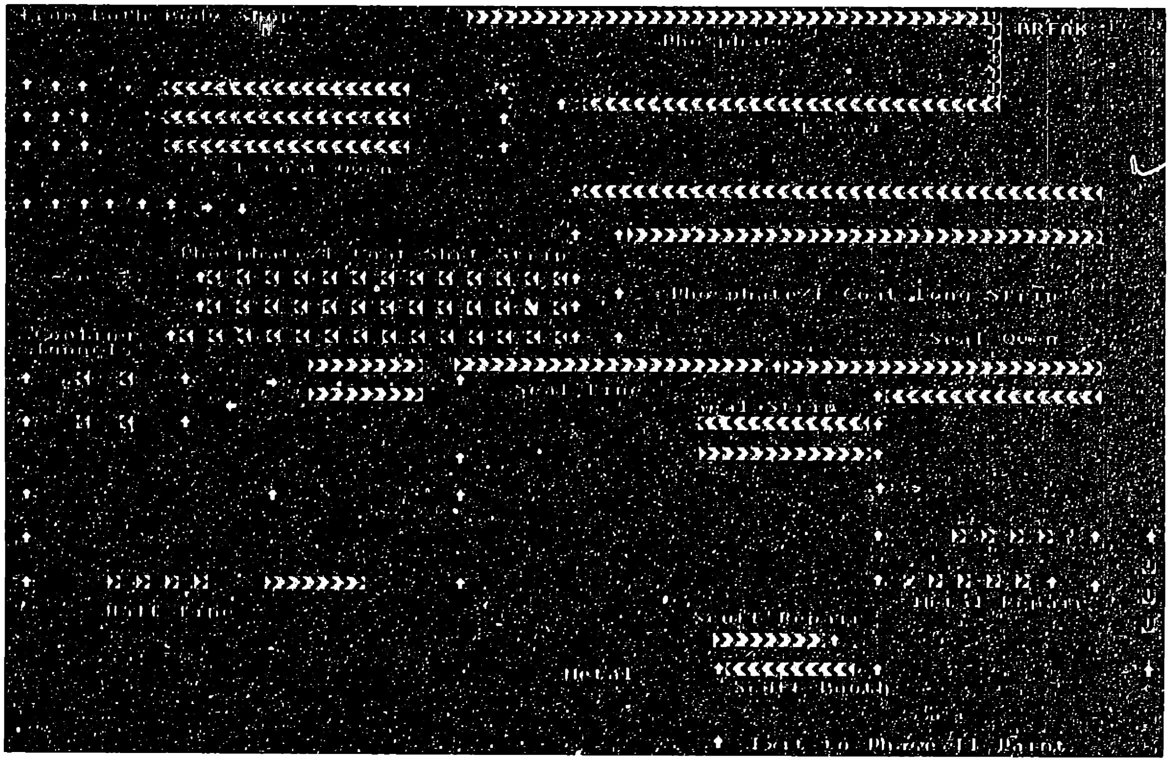


Figure 3-1: Phase-1 of paint. Wixom Assembly Plant

3.2 The Models

3.2.1 Model I: Deterministic Case

The biggest challenge in developing this model stemmed from the fact that vehicle flow patterns at Wixom's paint department had changed since the completion of the last analysis. The plant has introduced new automated technologies, and a slightly modified processing pattern. We deemed changes of this nature to have a significant impact on ILVS and Block Painting, and we dedicated the first four weeks of this study to process/model observation and validation. The intent was to recreate a discrete-event simulation model (building upon the model developed by Cleaver, Ketko, Gorlitz, Papa & Associates) that more closely represented current processing patterns in Phase-1 of paint. Parallel processes in this model (which we refer to as Model I) possessed identical cycle times, and all times were deterministic in nature. In this model, parallel operations and their successors receive parts on a "first available" basis. That is, the vehicle flow does not maintain sequence control through strict and sequential vehicle allocation and retrieval from parallel processes. The revised simulation models introduced variations in parallel process cycle times. As discussed later on in this chapter, Model II analyzed this impact on the system. This model did not account for breakdown distributions for parallel processes. Model III, also discussed later on in this chapter, introduces these effects.

Initially, vehicles stay in sequence as they travel through the Phosphate and E-coat systems. The first area of sequence disruption is at the parallel E-coat ovens. As discussed earlier, the system assigns vehicles on a first available oven basis. The second area of sequence disruptions is the long strip area immediately succeeding the E-coat ovens. At that point, vehicles can take a long, or short route through the strip area based on conveyor space availability and shift breaks. To better represent current processing conditions at the plant, we did not build any sequence control mechanisms into the model at this point of the process. The third area of sequence disruptions occurred at the parallel cooling tunnels. Vehicles enter and exit these tunnels on a first available tunnel basis. Again, at this point, the process did not incorporate any sequence control mechanisms. The fourth area of sequence disruption is immediately before the manual seal line. Vehicles are diverted into surge lanes to better facilitate the four large vehicles (Town Cars) to one small vehicle (Continental) mix, and to blend one Mark VIII for every eight Town Car/Continental vehicles. The plant frequently uses a third bypass lane to pull either a Mark VIII or a Town Car to better balance the workload at the manual seal line operation. Our model assumed a 3% bypass lane utilization figure. The fifth area of sequence disruption is the strip lanes after the sealer ovens. During shift breaks, vehicles are routed into the strip lanes, and are later merged into the assembly process without a specific sequence control mechanism facilitating this merger. Following these strip lanes is the heavy metal repair area. Vehicles previously flagged for repairs are routed to this area and are processed on first-come-first-serve basis. Our model assumed 0.4% of the vehicles per day are pulled off-line at the metal repair area, and are processed on average for 34 hours. The merger of repaired vehicles with the ongoing assembly process creates the sixth sequence disruption area of Phase-1. Repairs at the Scuff Booth, the last process of Phase-1, create the seventh and final disruption area. The system pulls approximately 1% of the vehicles off-line for repair; they remain off-line for 0.5 hours.

Upon completing this analysis, we felt that we had developed a well representative discrete-event simulation model to be used as the basis for further research on sequence disruptions at Wixom's ILVS environment.

Model I Results and Statistics

The simulation experiments we conducted processed a total of 7,377 vehicles (6558 Town Car/Continentals and 819 Mark VIII). As compared with CKGP's ideal ILVS environment model, this model produced drastically different values for the newly generated ILVS Viability metrics. The "percent in sequence" measure for Town Cars/Continentals emerging out of Phase-1 dropped from over 98% in the ideal case to approximately 65% in this model. The first question that came to mind was: How can this be a representative model of current operations at Wixom Assembly, when all reports point to the operation performing at 98% or better to sequence for vehicles processed through trim and chassis? The simple response obviously is that this is only a measure of the output of Phase-1, and before vehicles are subjected to two in-line dynamic substitution stations, and final sequencing via the AS/RS. Our analysis pointed to yet another important fact. Even though only 64% of the vehicles are emerging to sequence out of Phase-1, the distance out of sequence associated with each vehicle is rather small. To be specific, the average distance out of sequence was approximately four vehicles. While the two substitution stations and the existing AS/RS can easily re-sequence these vehicles to be at least 98% representative of the National Blend, such small sequence disruptions to the flow of vehicles play havoc in terms of preserving and propagating paint blocks through the system. Our study of Phase-2, in Chapter 4, will analyze the impact of such small out of sequence variations on paint block sizes.

Two other ILVS Viability metrics were out of control: the "maximum set asides", and "digs per 100 vehicles". These had values of 14 and 34.7 with corresponding established viability limits of ten and five. Again, the plant compensated for these violations by using the existing substitution stations and the AS/RS.

Our findings uncovered yet another very important fact. For the most part, sequence disruptions introduced into this model affected the Town Car/Continental car-line only. Data representing the vehicles out of sequence control metrics indicated that Mark VIII vehicles had a mode distance out of sequence value of zero, and an average of distance out of sequence of 0.5. These numbers are considerably smaller than those reported for the Town Car/Continental car-line. We attribute this result mainly to the lower production volumes associated with the Mark VIII vehicles. Since fewer Mark VIII vehicles are processed through the system than Town Cars and Continentals, and since Mark VIII vehicles use a separate trim and chassis department from the Town Car/Continental vehicles, system generated sequence disruptions change the sequence of a Mark VIII vehicle with respect to other Town Car/Continental vehicles, but not with respect to other Mark VIII vehicles. The Town Car/Continental vehicles work as a buffer and absorb more of the system's disruptions, allowing the Mark VIII vehicles to exit closer to sequence than the Town Car/Continental vehicles. Table 3-2 summarizes the ILVS viability metrics data for this model, while Table 3-3 summarizes the vehicles out of sequence control metrics. Appendix A contains graphical portrayals of Model I's vehicles out of sequence performance measures.

Ford Motor Company
ILVS Viability Metrics Summary

Category	Town Car / Continental	Mark VIII
Percent in Sequence	64.8%	99.1%
Maximum Set Asides	14	2
Maximum Dig Depth	2	1
Digs per 100 Vehicles	34.7	0.9

Table 3-2: Phase-1 - Model I viability metrics summary

Vehicles Out of Sequence Control Metrics

Category	Town Car / Continental	Mark VIII
Early Limit	14	2
Late Limit	1	0
Mode Distance Out of Sequence	2	0
Average Distance Out of Sequence	4.1	0.5
Std. Deviation Out of Sequence	3.4	0.6

Table 3-3: Phase-1 - Model I vehicles out of sequence control metrics

Throughout our analysis, we had to stay apprised of how all process variations introduced to Phase-1 of paint impacted the system's throughput. For the sake of consistency and simplicity, we assumed that the throughput of the paint department (Phases-1 and -2 combined) was analogous that of the entire assembly process. We further assumed that deterioration in throughput levels in the paint department paralleled that of the entire assembly process. CKGP's ideal ILVS environment model exhibited throughput rates of 71 vehicles per hour out of Phase-1. To our satisfaction, all of variability factors we imposed on the ideal ILVS system to better simulate the current process flow at Wixom Assembly had no impact on the throughput rates (we still attained the 71 vehicles per hour throughput rate out of Phase-1). We should keep one clear objective in mind: the trim and chassis department requires a throughput level of 59 vehicles per hour out of Phase-2 [14]. Chapter 5 will present a detailed sensitivity analysis studying the impact of changes in throughput levels of Phase-1 and the effect on the process flow rates out of Phase-2.

3.2.2 Model II: Parallel Process Cycle Time Variations

Once we had developed a base-line simulation model portraying existing processes in Phase-1 of paint, our efforts focused in a different direction. We attempted to incorporate non-deterministic variations, which are very common to assembly operations, into our model. The first such variation was that of fluctuations in cycle times of parallel operations. For all practical purposes, our model was identical to that of Model I, with the exception of parallel operations having varying process rates.

While still treating processing rates as deterministic in nature, the model incorporated a fluctuation of 10% across the speeds of all parallel conveyors. We used this model to assess the system's sensitivity, in terms of sequence control, to small fluctuations in the cycle times of parallel operations. We select the

10% variation for two reasons: (i) to simplify the analysis and to limit data collection efforts at the plant, and (ii) because 10% is representative of the variations that frequently exist in today's assembly lines. To further validate our results, in Chapter 5 we will present a detailed sensitivity analysis to evaluate the impact of uneven cycle times at parallel operations on paint block sizes at both the prime and enamel booths.

Model II Results and Statistics

In many ways, the statistical results outlined by the ILVS viability metrics and the vehicles out of sequence control metrics did not surprise us. Approximately 50% of all vehicles remained in sequence versus the 65% for Model I, an expected decrease given the added system variability. The important feature of this model is that, even though the assumptions caused more vehicles to emerge out of sequence from Phase-1, the remaining characteristics of the sequence disruptions remain unchanged. As in Model I, only two viability metrics violated their established limits: "maximum set asides" and "digs per 100 vehicles". Early and late limits, mode, average, and standard deviation values for the distance out of sequence for all vehicles were practically identical to those reported for Model I. Mark VIII vehicles continued to exit Phase-1 at 99% to sequence, denoting the small impact uneven cycle times of parallel operations have on the low-volume car-lines (when assembled on the same line as other high-volume car-lines). It is evident that the large-volume car-lines absorbed most, if not all, of the process variation. The hourly production rates for this model were 71 vehicles per hour, again identical to Model I. Table 3-4 summarizes the ILVS viability metrics, and Table 3-5 summarizes the vehicle out of sequence control metrics for this model. Appendix A contains graphical portrayals of Model II's vehicles out of sequence performance measures.

Ford Motor Company
ILVS Viability Metrics Summary

Category	Town Car / Continental	Mark VIII
Percent in Sequence	47.9%	99.1%
Maximum Set Asides	16	2
Maximum Dig Depth	5	1
Digs per 100 Vehicles	32.4	.9

Table 3-4: Phase-1 - Model II viability metrics summary

Vehicles Out of Sequence Control Metrics

Category	Town Car / Continental	Mark VIII
Early Limit	16	2
Late Limit	2	0
Mode Distance Out of Sequence	1	0
Average Distance Out of Sequence	4.1	0.8
Std. Deviation Out of Sequence	3.9	0.5

Table 3-5: Phase-1 - Model II vehicles out of sequence control metrics

3.2.3 Model III: Breakdown Distributions for Parallel Processes

Equipment and process failures are common and widely accepted villains of any assembly operation. Latest efforts have focused on preventive maintenance programs that attempt to actively repair and maintain equipment before it fails. While for the most part successful, these programs have yet to come close to achieving a 100% guaranteed fix for this problem. For that reason, breakdown distributions for parallel processes were yet another source of non-deterministic variation that we could incorporate into our model. Our goal was to determine how these process disruptions impacted the sequence control of vehicles emerging out of Phase-1 of paint, and ultimately, quantify the consequences of these disruptions on paint block sizes at the prime and enamel booths.

Proceeding in a similar fashion as we did for Model II, Model III replicated Model I with the exception of incorporating breakdown and repair distributions into the cycle times of parallel operations. The model uses uniform distributions to represent the failure rates. Each process has an equal likelihood of a failure taking place once every two weeks (i.e., each piece of equipment experiences one mechanical failure over any period of two weeks and independent of other equipment failures). We assumed the repair times for these processes followed a triangular distribution, with a minimum of twenty minutes, a mode of sixty minutes, and a maximum of two hours. Again, we chose these numbers for two reasons: (i) for the sake of simplicity, and to reduce data collection efforts at the plant while facilitating for the ease of changing our models in the future to accommodate specific failure and repair rates, and (ii) based on similar experiences at other Ford plants, these numbers represent close estimates of the failure and repair rates of mechanical components of an assembly operation.

Model III Results and Statistics

As we experimented with this model, our primary objective was to isolate the effects of the system variations we had introduced. In this case, the introduction of breakdown distributions to parallel operations proved to have little effect on the percent to sequence for the majority of the vehicles emerging from Phase-1. We say majority because the introduction of these breakdown distributions into our system appeared to have a larger impact on the lower volume Mark VIII car-line than its counterpart, the Town Car/Continental. For the sake of comparison, it is important to note that these results are opposite to those observed in Model II (where the Town Car/Continental car-line was more vulnerable to variations in parallel process cycle times). The breakdown distributions in our model caused the percent to sequence Mark VIII metric to drop from 99% to 97% (below the established limits). At the same time, we observed a wider range for the early and late limits for the distance out of sequence metric for both the Mark VIII, and Town Car/Continental car-lines. We also detected small increases in the "maximum set asides" and "maximum dig depth" metrics for both car-lines. We recognize that such effects on the flow of Mark VIII vehicles is mainly attributed to the low frequency of these breakdowns, and the lengthy repair times (compare with 50 second assembly line cycle times) associated with the equipment. Table 3-6 summarizes the ILVS viability metrics, and Table 3-7 summarizes the vehicle out of sequence control metrics for this model. Appendix A contains graphical portrayals of Model III's vehicles out of sequence performance measures.

Ford Motor Company
ILVS Viability Metrics Summary

Category	Town Car / Continental	Mark VIII
Percent in Sequence	64.7%	97.2%
Maximum Set Asides	19	3
Maximum Dig Depth	7	2
Digs per 100 Vehicles	34.1	2.7

Table 3-6: Phase-1 - Model III viability metrics summary

Vehicles Out of Sequence Control Metrics

Category	Town Car / Continental	Mark VIII
Early Limit	19	3
Late Limit	8	3
Mode Distance Out of Sequence	1	0
Average Distance Out of Sequence	4.5	0.6
Std. Deviation Out of Sequence	3.9	0.7

Table 3-7: Phase-1 - Model III vehicles out of sequence control metrics

3.2.4 Model IV: Process Vehicles in Batches of Six at Metal Repair

Prior to the introduction of ILVS and Block Painting, off-line stations were always autonomous from the mainstream assembly operation. In treating these de-coupled systems, process and industrial engineers are constantly being challenged with the questions like:

- What is the right amount of work to assign to these stations?
- Can the off-line operators service more than one assembly line?
- If we were to utilize an operator across several assembly lines, what kind of labor savings might we expect?

In the context of ILVS and Block Painting, the same industrial and process engineers have to answer an additional question:

> What impact does batching of units for further processing in an assembly line environment have on the system's capacity to meet ILVS and Block Painting objectives?

This part of our analysis was driven mainly by the latter question. However, in this thesis, we also chose to conduct a sensitivity analysis to evaluate the potential cost savings associated employing an off-line operator across several areas of an assembly lines (see Chapter 5).

We constructed Model IV to be identical to Model I, except that it imposes vehicles in groups of six at the heavy metal repair shop. In other words, as the system diverted vehicles into the heavy metal repair area, we keep track of how many have entered the queue. We do not assign labor to the metal repair shop until six vehicles had accumulated, and then and only then did the repair work begin. Obviously, we had to add a buffer of size six to our model immediately preceding the metal repair shop. As in the past, we chose the value six arbitrarily, and designed our model in an modular format so that it is capable of easily testing plant specific cases in the future.

Model IV Results and Statistics

Processing of vehicles in groups of six at the metal repair shop had the least impact of any of our changes on the sequence of vehicles emerging out of Phase-1. Results obtained from this model were practically indistinguishable from those reported for Model I. The percent in sequence figures for the Town Car/Continental car-line ranged from 64.9%-98.7% respectively, versus 64.8%-99.1% for those from Model I. Similarly, all other ILVS Viability metrics remained the same as in Model I. Continuing with this trend, Model IV had a throughput rate of 71 vehicles per hour, which is identical to that of Model I. These results show that grouping of vehicles in batches of 6 at the metal repair area had little impact on the sequence maintenance mechanism of Phase-1 of paint in its current operating status. Table 3-8 summarizes the ILVS viability metrics, and Table 3-9 summarizes the vehicle out of sequence control metrics for this model. Appendix A contains graphical portrayals of Model IV's vehicles out of sequence performance measures.

Ford Motor Company
ILVS Viability Metrics Summary

Category	Town Car / Continental	Mark VIII
Percent in Sequence	64.9%	98.7%
Maximum Set Asides	14	2
Maximum Dig Depth	2	1
Digs per 100 Vehicles	34.8	1.3

Table 3-8: Phase-1 - Model IV viability metrics summary

Vehicles Out of Sequence Control Metrics

Category	Town Car / Continental	Mark VIII
Early Limit	13	2
Late Limit	1	0
Mode Distance Out of Sequence	3	1
Average Distance Out of Sequence	4.6	0.6
Std. Deviation Out of Sequence	3.2	0.6

Table 3-9: Phase-1 - Model IV vehicles out of sequence control metrics

3.2.5 Model V: Passive Sequence Control

All of our efforts so far have focused on isolating the impact of independent process variations and sequence disruption on an ideal ILVS assembly operation. At this time, we would like to evaluate the impact of these disruptions and variations, not in isolation, but rather as a system depicting their interactions in a typical assembly environment. The term "passive sequence control" stems from the fact that the system is processing vehicles via algorithms that are not as sequence control conscientious as they would be in an ideal ILVS environment.

Model V is the same as Model I with the variations of Models II, III, and IV incorporated. As in Model II, we incorporated a 10% fluctuation figure into the cycle times of parallel processes by varying their conveyor speeds (variations are still deterministic). We also applied the same breakdown distributions used in Model III. Equipment failure rates at all parallel operations followed a uniform distribution, with each process having an equal likelihood experiencing a failure once ever two weeks (i.e., each piece of equipment experiences one mechanical failure over any period of two weeks and independent of other equipment failures). Repairs followed a triangular distribution with a minimum of twenty minutes, a mode of sixty minutes, and a maximum of two hours. Finally, we staff the metal repair shop only when six vehicles had accumulated in the queue, at which time we progress all vehicles sequentially.

Model V Results and Statistics

The performance metrics for this model were the worst of all the experiments observed so far. Only 53% of the Town Car/Continental vehicles exited Phase-1 according to the sequence established by the National Blend. Mark VIII vehicles emerged out of Phase-1 of paint at a record low of 97.1% as measured by the percent to sequence performance metric. Perhaps the greatest degradation in system performance came in the form of an extensive increase in the late and early limits of out of sequence vehicles. Such performance deficiencies applied to both car-lines, the Town Car/Continental and the Mark VIII. It is important to note these characteristics of this model, since they will play a major role in defining AS/RS size requirements later in this analysis. As we shall examine further in our review of Phase-2, large variations (spread) in the data for vehicles exiting Phase-1 can work hand in hand with sequence disrupting mechanisms of Phase-2 . That is, vehicles arriving early and out of sequence to Phase-2 of paint are eventually delayed in the process due to paint re-runs and other cycle time variations (tri-coats versus non-tri-coat). As these vehicles progress through Phase-2 and are delayed, they can enter the AS/RS closer to their original sequence than would have been possible had they emerged form Phase-1 according to the sequence of the National Blend. We next pose a counter argument to this analysis: What about the vehicles exiting Phase-1 late, that are further delayed in Phase-2? Wouldn't they lead to larger AS/RS size requirements to establish the mandated minimum 98% to sequence compliance with the National Blend? Our simulation model results show that this outcome does not occur: the sequence disruptions taking place in Phase-2 tend to place most of the late vehicles exiting Phase-1 earlier in the sequence, and so we observe smaller overall AS/RS requirements. A similar argument holds for vehicles exiting Phase-1 earlier than their established sequence: Phase-2 disruptions tend to re-sequence them to be closer to their National Blend sequence upon exiting Phase-2. It is important to note that these results are specific to the Wixom Assembly Plant, and that the impact of passive sequence control scheduling and processing must be evaluated thoroughly for studies of other facilities, and that build upon our research.

Previous research on pre-sequencing [1] introduced low-running vehicles, and vehicles with large processing times earlier in the schedule through both phases of the paint department. Sequence disruptions, less effective dynamic substitution efforts, and longer processing times for some of these vehicles allow them to exit the paint department closer to their established National Blend sequence than would have been possible without pre-sequencing. These findings were observed in an ideal ILVS environment, and this is clearly not the case at Wixom Assembly. We believe that this outcome would exasperate the smaller AS/RS requirements associated with all the sequence disruptions taking place in Phase-1 of paint. As we described, some of these out of sequence characteristics associated with the "passive" sequencing and processing model lead to smaller AS/RS size requirements. If the pre-sequencing of vehicles were to introduce the low-running ones and those with large processing times earlier into the process, sequence disruptions in Phase-1 are bound to pull them closer to their established sequence as they exit Phase-1. We feel that using pre-sequencing to maintain the sequence of these vehicles in Phase-1 will drive our system to behave closer to an "active" sequencing and processing model, and we will observe larger AS/RS size requirements. This thesis will validate the smaller AS/RS size requirements due to disruptions taking place in Phase-1 of paint. However, studying the impact of pre-sequencing low-running vehicles, and those with large processing times is a prime candidate for further research and is not fully investigated in this work. Table 3-10 summarizes the ILVS viability metrics, and Table 3-11 summarizes the vehicle out of sequence control metrics for this model. Appendix A contains graphical portrayals of Model V's vehicles out of sequence performance measures.

Ford Motor Company
ILVS Viability Metrics Summary

Category	Town Car / Continental	Mark VIII
Percent in Sequence	53.9%	97.1%
Maximum Set Asides	22	4
Maximum Dig Depth	15	3
Digs per 100 Vehicles	29.7	2.7

Table 3-10: Phase-1 - Model V viability metrics summary

Vehicles Out of Sequence Control Metrics

Category	Town Car / Continental	Mark VIII
Early Limit	23	4
Late Limit	25	3
Mode Distance Out of Sequence	4	0
Average Distance Out of Sequence	4.8	1.3
Std. Deviation Out of Sequence	4.0	1.2

Table 3-11: Phase-1 - Model V vehicles out of sequence control metrics

Two final points about this model are worth noting. First, all of the variations and their interactions had no impact on the throughput rate of the Phase-1. Vehicles continued to exit Phase-1 of paint at a rate of

71 vehicles per hour. A second and a very important point about this model is that it establishes grounds for making tradeoffs between minimizing AS/RS size requirements and maintaining sufficiently large paint block sizes to satisfy the Block Painting objectives. While sequence disruptions in Phase-1 of paint will have a positive impact on AS/RS size requirements (as we show later), they will, as we will show, have catastrophic consequence on the maintenance of large paint block sizes. Chapter 4 will fully explore both of these topics.

3.2.6 Model VI: Active Sequence Control

Ideal ILVS operating environments are a luxury very few plants will ever experience. To this point, we have shown how various factors (process capabilities, equipment breakdown, parallel process operations, and product mix complexities) create sequence disruptions. In this chapter, we have also shown how system interactions among these variations can degrade the performance of an ILVS system. Our system's performance suffered the most (measured by sequence control metrics) when we introduced uneven cycle times and breakdown distributions at parallel operations along with batching of vehicles at the metal repair facility into our model. What can be done to alleviate the effects of these variations, and what is the impact of these remedies on other system factors like throughput and paint block preservation? Our goal in this section is to incorporate active sequence control measures into our vehicle scheduling algorithm, and to evaluate the impact of these measures.

Model VI is analogous to Model V, except that it adds strict sequence control measures. We use the phrase "active sequence control" to highlight the fact that we change the production flow processes in order to maintain strict sequence control. We maintain vehicle sequence by directing vehicles to parallel operations in an alternating fashion. This approach differs from the previous algorithm which routs vehicles to the next available parallel channel. To further maintain sequence control, we retrieve and process vehicles from parallel operations in a manner that assigns higher priorities to vehicles with smaller sequence numbers. We first check parallel operations to see if a vehicle is present. If both locations have vehicles, we first process the one with the smaller sequence number. If only one location has a vehicle, operations immediately succeeding the parallel ones wait until both locations have a vehicle before they select one for further processing. Our intent in using this flow logic is to maintain the needed sequence control while minimally impacting throughput levels. As will be discussed in the Results and Statistics section for this model, the impact on Phase-1's throughput was minimal.

We maintain sequence through the long and short strip areas by processing all vehicles already utilizing the long processing path before the system bypasses it in favor of the shorter processing path. We also eliminated the vehicle bypass lane before the manual seal line to further maintain vehicle sequence control. Figure 3-2 presents the vehicle flow patterns for these two processing measures. As before, we staffed the metal repair shop only when six vehicles accumulated in queue, at which time we process all vehicles sequentially. In order to maintain the throughput level of Phase-1 in the range of 69 to 72 vehicles per hour, and to ensure that all of the ILVS viability metrics would meet the pre-established requirements, we had to reduce the cycle time at the metal repair shop by 50%. We did so by doubling the labor available to perform the needed repair work. As in Model III, and to more realistically

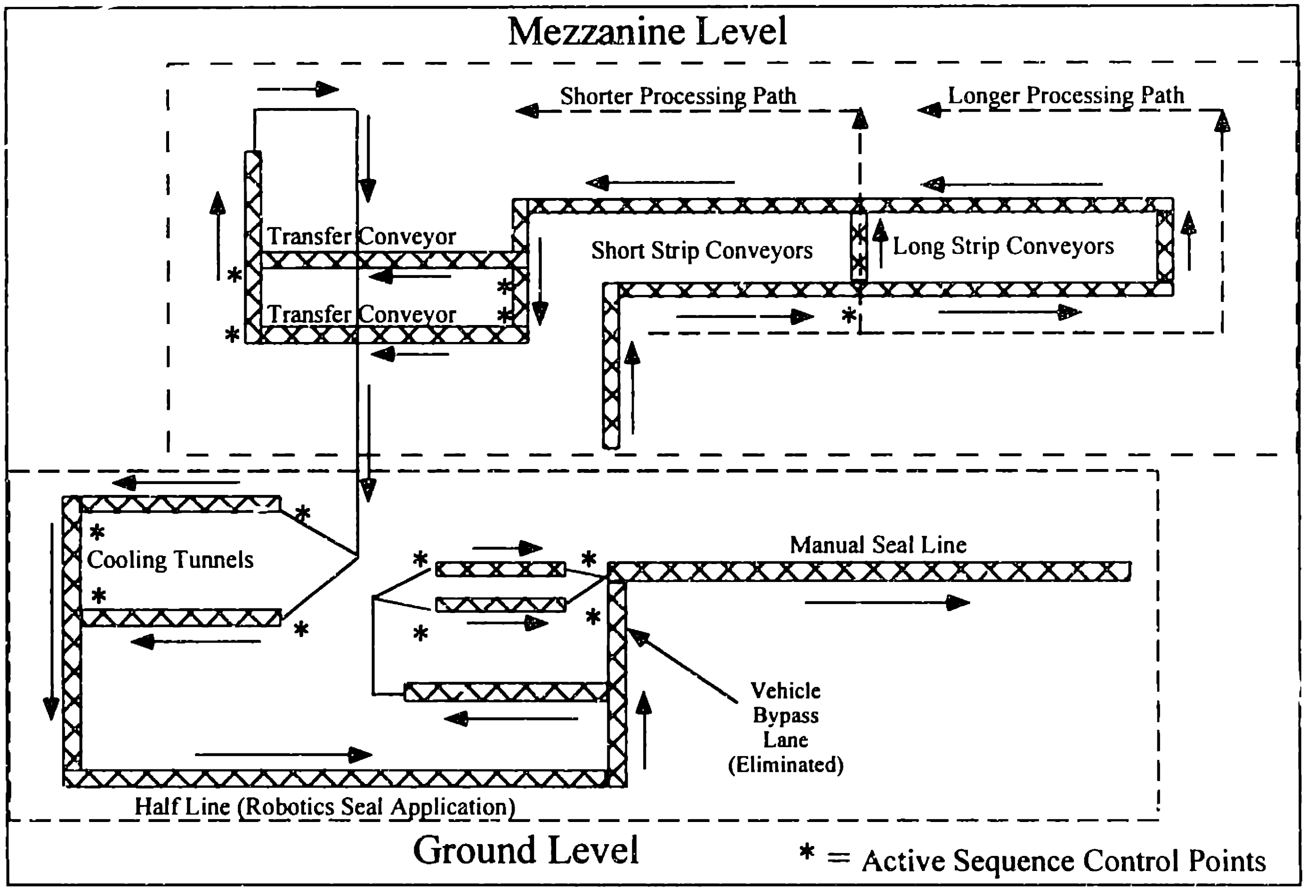


Figure 3-2: Vehicle flow patterns - "Active Sequence Control"

represent existing assembly environments, we also included breakdown and repair distributions for parallel operations. Equipment failure rates followed a uniform distribution, with each piece of equipment experiencing one mechanical failure over any period of two weeks, while repair times followed triangular distributions with a minimum of twenty minutes, a mode of sixty minutes, and a maximum of two hours. In this model we assumed an assembly operation will, through advanced technologies and preventive maintenance and calibration efforts, be able to sustain identical cycle times at parallel operations for similar products. For that reason, we set all parallel process cycle times as being equal.

Model VI Results and Statistics

Model VI's performance was impressive. It comes close to achieving an ideal scenario, by steadily approaching ideal ILVS characteristics, while maintaining attributes of a generic assembly operation. When compared with the National Blend, vehicles of both car-lines, the Town Car/Continental, and the Mark VIII emerged close to 99% in sequence. All other ILVS viability metrics had values well within the limits set forth by Ford. The active sequence control introduced in Model VI was very effective in reducing the early and late limits of out of sequence vehicles, and resulted in smaller average and standard deviation values for distance out of sequence measures. These significant improvements more than justified the addition of sequence control procedures. One point of concern, however, did present itself. Phase-1's throughput rate dropped to 69 vehicles per hour. At this point of our analysis, we did not understand the impact of this change on the overall throughput rate of the plant (that is, through Phase-2). We will return to this point later.

Counterintuitively, the tight sequence control introduced in this model leads to larger not smaller AS/RS requirements (discussed further in Chapter 4). As we will further demonstrate in our analysis of Phase-2, when we observe smaller variations (spread) in vehicles that are out of sequence, downstream disruptions will further pull these vehicles out of sequence. Recall that large variations in the distributions of the data describing early and late arriving vehicles actually helped to minimize the size of the AS/RS needed to re-sequence vehicles back to be at least 98% representative of the National Blend. It is important to note that this conclusion applies when we do not include pre-sequencing of low-running vehicles and vehicles with large processing times in the model. The two approaches, pre-sequencing, and active sequence control, rely on different sequence control assumptions. Recall that pre-sequencing of low-running vehicles and vehicles with large processing times depends on sequence disruptions in both phases of the paint department to re-sequence these vehicles to be more representative of the National Blend. Again, this pre-sequencing approach assumes ideal ILVS conditions, and Wixom Assembly clearly deviates from that. Our active sequence control model, on the other hand, aims to emulate the ideal ILVS conditions by promoting vehicle sequence preservation through Phase-1 of paint, with the grand objective of allowing paint blocks to propagate to Phase-2. Previous research [1] showed that pre-sequencing low-running vehicles, and those with large processing times requires smaller AS/RS requirements. However, our active sequence control model results in larger AS/RS requirements, and we do not know how these two approaches might interact if implemented in the same assembly environment. As noted previously in the section describing Model V, this thesis will establish the extent to which fewer sequence disruptions in Phase-1 of paint will lead to a larger AS/RS size. However, the impact of pre-sequencing low-running vehicles, and those with large processing times, and their interaction with tight sequence control remain prime candidates for further research.

Table 3-12 summarizes the ILVS Viability metrics, and Table 3-13 summarizes the Vehicle Out of Sequence Control Metrics for this model. Appendix A contains graphical portrayals of Model VI's vehicles out of sequence performance measures.

Ford Motor Company
ILVS Viability Metrics Summary

Category	Town Car / Continental	Mark VIII
Percent in Sequence	98.7%	98.8%
Maximum Set Asides	9	2
Maximum Dig Depth	2	1
Digs per 100 Vehicles	1.3	1.2

Table 3-12 Phase-1 - Model VI viability metrics summary

Vehicles Out of Sequence Control Metrics

Category	Town Car / Continental	Mark VIII
Early Limit	9	2
Late Limit	0	0
Mode Distance Out of Sequence	3	1
Average Distance Out of Sequence	3.8	0.4
Std. Deviation Out of Sequence	2.1	0.5

Table 3-13: Phase-1 - Model VI vehicles out of sequence control metrics

3.3 Model Results and Comparison

In this part of our analysis, we provide a graphical summary of the impact of the variations we had introduced into our ILVS models. We grouped all of our results into four separate graphs (Figures 3-3 - 3-6). Each car-line had two graphs, one showing changes to the ILVS viability metrics, and the other tracking changes to the vehicle out of sequence control metrics. Next, we will briefly comment on some important elements of these graphs.

3.3.1 Town Car/Continental

3.3.1.1 ILVS Viability Metrics

The results presented in Figure 3-3 show that Models I - V violated the pre-established limits for all of the ILVS Viability metrics. In the area of "digs per 100 vehicles", our models consistently reported values of thirty digs per 100 vehicles and higher, which exceeds the targeted limit of ≤2. As a result, an operator on the assembly line would be excessively searching for components of a specific vehicle at hand due to its out of sequence arrival. Other metrics, such as "maximum number of set asides", and "maximum dig depth" also violated their pre-established limits, but to a lesser extent. It is worth noting that in our efforts to isolate the impact of the various sequence disrupting mechanisms in an assembly environment, the "percent in sequence" metric was the only one out of the four that showed notable volatility to these variations. Model II, which introduced the cycle time variations at parallel operations, seemed to provide the worst results in terms of the percent to sequence vehicles among all models. The remaining metrics, while still in violation of established limits, did not oscillate significantly across Models I-V. Our active sequence control model (Model VI) performed much better. It met the targeted values for all the ILVS Viability metrics. Over 98% of the Town Cars and Continentals exited Phase-1 of paint according to the National Blend's sequence. With values of nine for "maximum set asides", two for "maximum dig depth", and scarcely over one for "digs per 100 vehicles", our model seemed to be operating in an almost ideal ILVS environment.

We might note that to predict any model's performance when implemented in a Block Painting environment, we need to look only at the "percent in sequence" metric. For Block Painting purposes, measures of how far out of sequence, or what is the latest or earliest out of sequence vehicle that this system is likely to deliver are less important. A vehicle being only one unit out of sequence can destroy a paint block, and at best introduce two additional purges to our system versus the scheduled one.

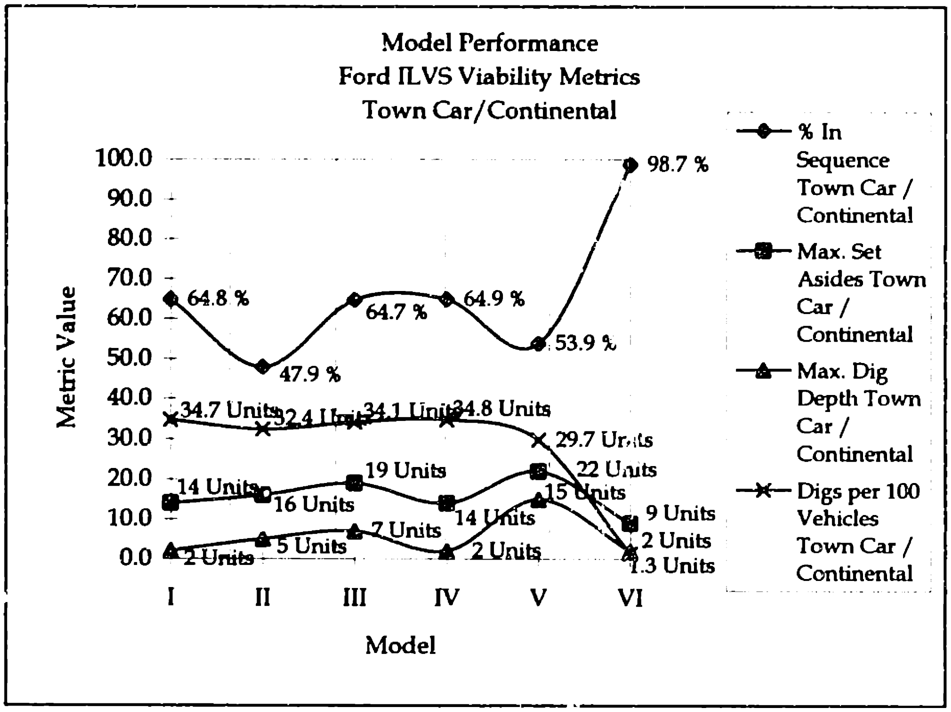


Figure 3-3: Town Car/Continental ILVS viability metrics comparison

3.3.1.2 Vehicles Out of Sequence Control Metrics

To judge the out of sequence control metric, we examined five measures: mode, average, spread (standard deviation), and limits (i.e., farthest out of position, both as early and late). Across Models I-V, three of the metrics in this category, the average, the standard deviation, and the mode of the distance out of sequence differed little as we introduced variations into our models. The remaining two metrics, the early and late limits, varied considerably as we changed our input variables. The gap between the early and late limits seemed to widen as we introduced breakdown and repair distributions into our model. This gap became largest in Model V which included interaction effects among all variations. And as expected, the early to late limit gap was drastically reduced in Model VI, as most of our vehicles exited Phase-1 of paint in sequence. Figure 3-4 summarizes these results.

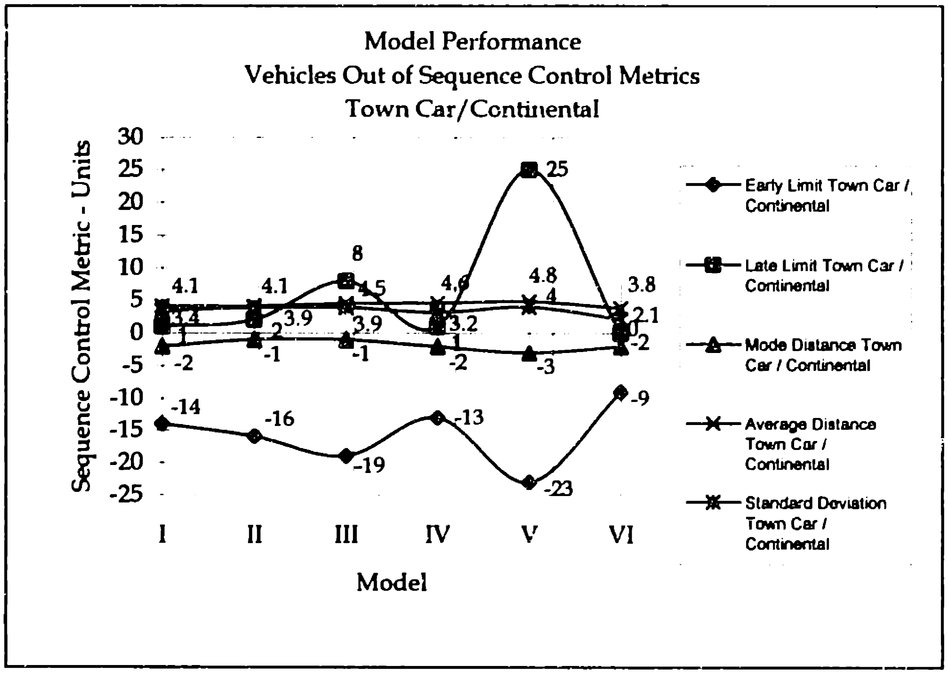


Figure 3-4: Town Car/Continental vehicles out of sequence control metrics comparison

3.3.2 Mark VIII

3.3.2.1 ILVS Viability Metrics

Figure 3-5 shows the variations we incorporated into our model had a different impact on the Mark VIII car-line than the Town Car/Continental. The Mark VIII vehicles exited Phase-1 of paint at approximately 98% to sequence for practically every model. The two minor deviations took place when we ran Model III and Model V. The "percent to sequence" metric values for those two models were 97.2% and 97.1% (still very close to the 98% minimum established requirement). In none of our models did the "maximum set asides", or "maximum dig depth" exceed the established viability metrics limits.

As shown in Figure 3-5, sequence maintenance of the low-running Mark VIII vehicles appears to be most susceptible to the effects of breakdown distributions of parallel operations. In our analysis of the Town Car/Continental car-line, Model II, incorporating varying process cycle times had the most impact on our "percent to sequence" metric. Recall that this is a direct result of the Town Car/Continental car-line having larger annual production volumes than the Mark VIII, as well as the Mark VIII car-line

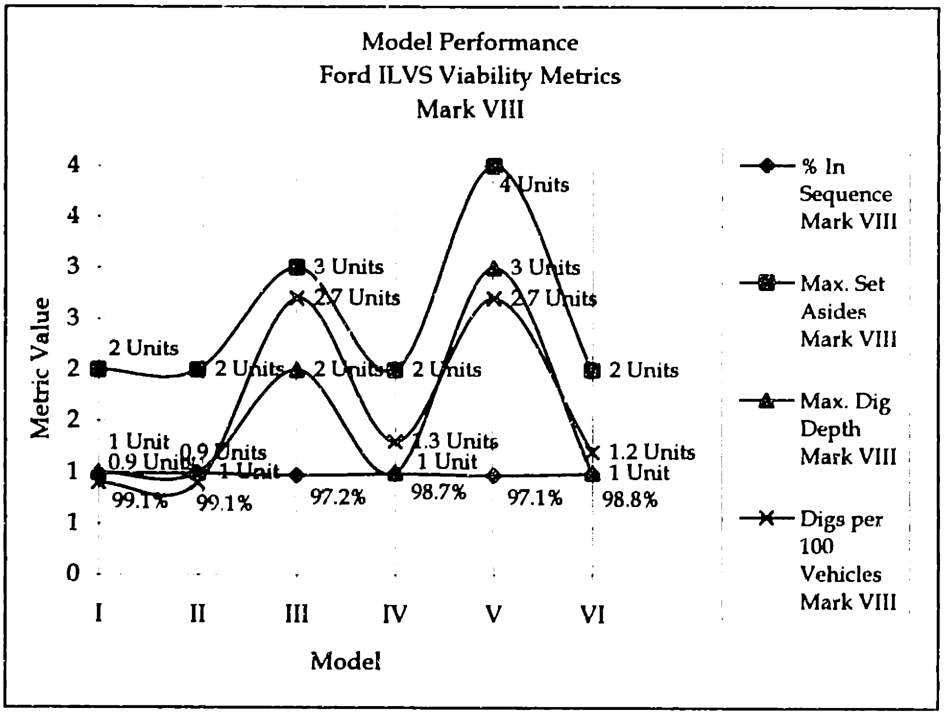


Figure 3-5: Mark VIII ILVS viability metrics comparison

having a trim and chassis department of its own. While small variations in parallel process cycle times pull Mark VIII vehicles out of sequence with respect to other Town Car/Continental vehicles (not Mark VIII vehicles), equipment breakdowns that we incorporated into our models delayed Mark VIII sufficiently to be bypassed by other Mark VIII vehicles, eventually impacting the system's ability to maintain the needed sequence control. This finding highlights the dynamic nature of these models. Variations causing harm to the sequence of one vehicle might have completely different effects on a lower-volume vehicle being processed on the same system. We recommend a complete and comprehensive analysis of all sources of complexity in a system's environment when making strategic and operational decisions (i.e., Block Painting). Assembly lines that are cross-loaded with two or more car-lines are prime candidates of this analyses.

3.3.2.2 Vehicles Out of Sequence Control Metrics

Figure 3-6 highlights similar results to those provided in Figure 3-4 for the Town Car/Continental car-line. Again, values of the three metrics, the average, the standard deviation, and the mode of the distance out of sequence changed very little across the variations we introduced into our models. The early and late limits reacted more substantially to our input variables. Again, the gap between the early and late limits widened as we introduced breakdowns and repair distributions, and became the largest when we activated interactions among all the input variables. The active control in Model VI was able to reduce the gap between the early and late limits, as approximately 99% of the Mark VIII vehicles exited Phase-1 of paint in sequence.

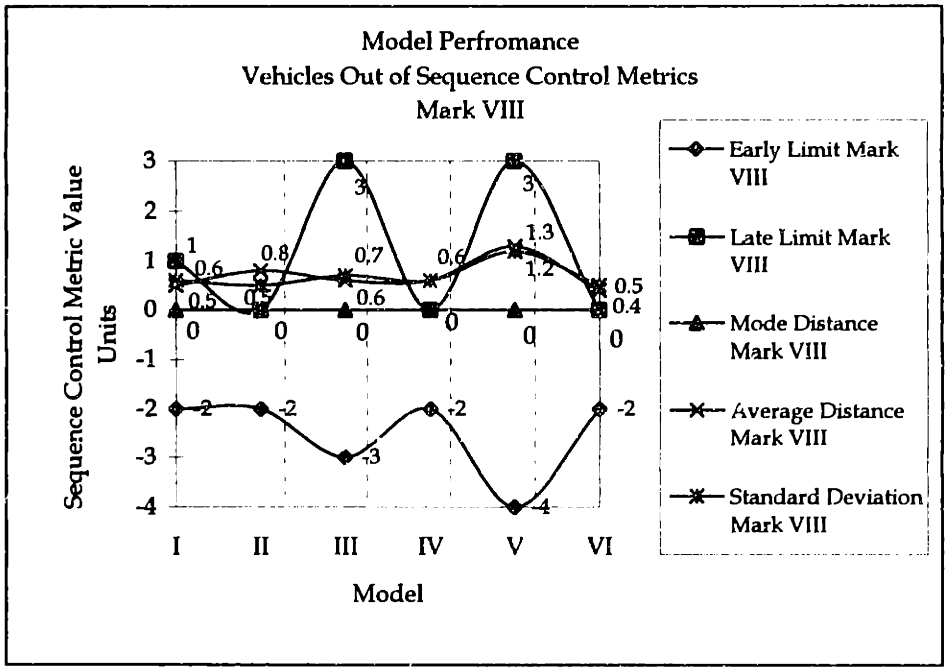


Figure 3-6: Mark VIII vehicles out of sequence control metrics comparison

3.3.3 Phase-1 Throughput Analysis - Model I - Model VI

To continue our analysis of all the variations introduced into our models, we now attempt to summarize their impact on the throughput rates of Phase-1. Our grand objective is to deliver vehicles out of Phase-2 of paint, and into the AS/RS system at a rate of 59 vehicles per hour. We do not care about the throughput rate of Phase-1 per se, but rather want to understand the effects of changes in throughput rates of Phase-1 onto those of Phase-2. Figure 3-7 shows that fluctuations in the throughput rates of Phase-1 occur in to two models, Model III, and Model VI. Obviously, an increase in throughput rates is not as dangerous as a decrease (unless massive inventory buildup occurs). For that reason, we chose to focus our attention on the loss of two units per hour in the throughput of Phase-1 as we implemented active sequence control strategies into our model. As it turned out, at throughput rates of 69 vehicle per hour out of Phase-1, Phase-2 is still capable of maintaining a flow rate of 59 vehicles per hour into the AS/RS system. This topic will be the subject of a more comprehensive sensitivity analysis in Chapter 5.

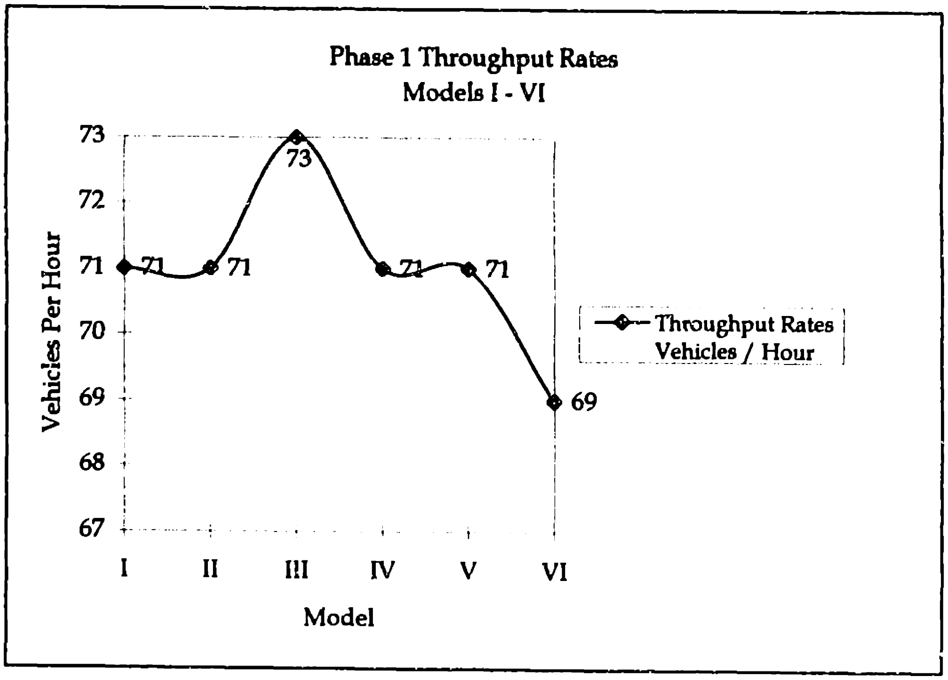


Figure 3-7: Phase-1 Throughput rate model comparison

Chapter 4

PHASE-2 OF THE PAINT SHOP

4.1 Layout and Process Flow

Our approach to ILVS and to Block Painting required no facility layout modifications to Phase-2, as was the case with Phase-1. Since Phase-2 is inherently more complex than Phase-1, it worked nicely to our advantage that practically no modifications were necessary.

Our model introduces vehicles to Phase-2 of paint at a rate approximating 72 units per hour (consistent with throughput rates obtained for Phase-1 of paint in Chapter 3). Since the simulation model representing Phase-2 is independent of that used with Phase-1, we made no overt attempt to maintain sequence at this point of the process. Vehicles enter the prime booth and are later diverted into two prime ovens (see the schematic in Figure 4-1). Upon exiting, vehicles are merged on a first-come-first-serve basis and are conveyed through the oven strip area used during breaks. Currently, the plant sends approximately 10% of all the vehicles back through the prime system for repair. It delivers the rest to the sand and wash booth, were they are again diverted into two lanes. Here, vehicles proceed through the wash tunnels first, and then to the dry-off ovens, at which point, they are combined again into a single lane. Approximately six vehicles per day (approximately 1%) are delayed for two hours in an audit area immediately following the sand and wash operation. From the audit area, the plant routes 10% of the vehicles to bypass the polish, or the enamel preparation area, and directly to repair. Of the vehicles that actually enter the polish area, 5% are diverted into the tri-coat preparation area, where high polish is applied for an additional half an hour. All other units, along with tri-coats unable to enter the preparation area continue on to the pre-enamel inspection area. The plant routes non-tri-coat vehicles to the two outside lanes, and routes all bypassed tri-coat vehicles, still in need of special preparation, to the inner lane. Out of these three parallel processing lanes, the plant sends 10% of the vehicles to repair. The remaining vehicles proceed to two enamel booths. Once painted, vehicles exiting the enamel booths are further diverted into four lanes, each leading to an enamel oven. Consequently, vehicles exit these ovens and join dedicated strip lanes. The model attempts to maintain vehicle sequence by retrieving vehicles out of the ovens and into the strip lanes in a strict and alternating mode (and therefore recovering the sequence before the plant diverts them to the ovens in an alternating fashion). The four strip lanes merge into one lane shortly after. From there, vehicles advance through the inspection area. At this point, the plant either diverts the vehicles (10%) to a repair facility, or to yet another polish area. It assigns some vehicles requiring more intensive work to the middle lane (hi-polish), while all others alternate among two parallel polish lanes. Like the previous inspection station, the plant routes approximately 10% of the vehicles in polish to an audit area, where inspectors conduct several quality checks, lasting approximately 2.6 hours. From this audit area, the plant routes 10% to repair. Of those vehicles routed to repair, it sends 50% to the two local spot repair areas, with the rest going through the entire paint system (Phase-2) again. Vehicles requiring spot repair, or those in need of being re-run through the paint system must wait until exiting the polish system. All of the vehicles that were deemed in need of re-run through the paint system are given priority when merging back into the main assembly line.

Vehicles passing inspection at polish are guided to one of four lanes in a painted bodies bank. Tri-coat vehicles use the farthest outside lane where they receive tri-coat upgrade treatments. Mark VIII vehicles use an adjacent inner lane, while the remaining two lanes are occupied by Town Car and Continental vehicles. Exiting this bank, vehicles are retrieved for further processing in one of two foam booths in a rotation of four Town Car/Continental vehicles to one Mark VIII. Occasionally, the plant routes vehicles to a secondary audit area after exiting the foam booths to perform further quality audits, millage checks or are returned to be re-run. However, the plant sends the overwhelming majority of vehicles passing through their respective foam booths to an unloading device and they exit the paint department shortly after. After exiting the system, vehicles advance through to the second dynamic substitution station, and enter the AS/RS. Figure 4-1 serves to represent the vehicle flow pattern at Phase-2 of paint at the Wixom Assembly Plant.

This detailed description of the process flow in Phase-2 of paint contributes to the understanding of several concepts we introduced earlier. First, Myron's previous study [1] has shown that the impact of the first dynamic substitution station was marginal at best. The process flow traced above gives a clear indication of the sequence disrupting mechanisms taking place in Phase-2 of paint, and supports his findings. These disruptions render all re-sequencing efforts of the first dynamic substitution station fruitless. That is, the newly created sequence will not survive the disruptions in Phase-2 for any extended period of time. Second, in order for a pre-sequenced National Blend with paint blocks to be successful, vehicles must exit Phase-1 of paint with as much of the paint blocks preserved as possible. Otherwise, with the cumulative effect of Phase-2 disruptions on paint block sizes, the flow through Phase-1 will not be able to meet the Block Painting objectives. Third, and finally, we hoped to use this analysis to demonstrate the impact of pre-sequencing on reducing the AS/RS size requirements (as studied in previous research [1]). The scheduling algorithm could easily plan for the process flow for special vehicles. Introducing these vehicles earlier into the process would ensure that a larger percentage of them would exit the paint department closer to their original National Blend sequence. Supporting results presented later in this chapter will show the impact of pre-sequencing for color only, and how AS/RS size requirements benefited from this pre-sequencing.

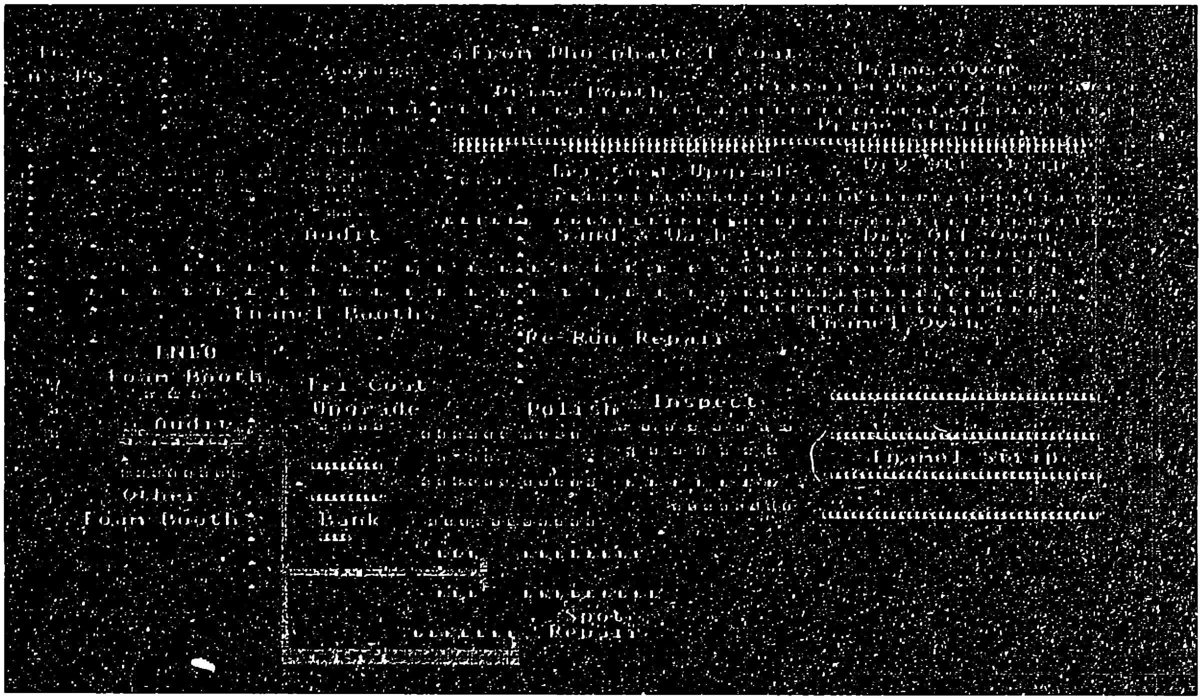


Figure 4-1: Phase-2 of paint. Wixom Assembly Plant

4.2 Generic National Blend Analysis (Conventional Block Painting)

4.2.1 Passive Sequence Control Model and Results

Our initial efforts in analyzing Phase-2 of the paint department aimed at demonstrating the impact of active sequence control on two system attributes:

- The size of the AS/RS required to re-sequence vehicles to be at least 98% representative of the National Blend's sequence.
- The size of the generated paint blocks.

As input into our system, we introduced a stream of vehicles from a generic National Blend file into our passive sequence control model (Model V of Phase-1). By describing our data as generic, we attempt to characterize the current approach to conventional Block Painting. Since Block Painting is priority number eight on a detailed list that Ford uses to generate the National Blend schedule, the average block size imbedded into our model was of size 1.31. This block size is deemed random at best. Appendix B provides a graphical representations of the generic National Blend data.

Next, we suspended operations at the first dynamic substitution station immediately succeeding Phase-1 of paint. We then introduced the output from Phase-1 to Phase-2, after which vehicles entered the second dynamic substitution station in final preparation for the AS/RS. We then analyzed the output from Phase-2 in terms of the two attributes listed above. First, we needed an AS/RS of size 400 to re-sequence vehicles, and to meet the objectives established via the ILVS viability metrics. Second, average paint block sizes at the prime and enamel booths were of size 1.16 and 1.17 respectively. These sizes were indicative of the 1.2 random block sizes being reported currently at Wixom Assembly. Appendix B graphically summarizes the AS/RS size requirements, and paint block size statistics for the passive sequence control model described in this section.

4.2.2 Active Sequence Control Model and Results

For comparison purposes, we then introduced the same National Blend data to the active sequence control model (Model VI). To maintain a well regulated experimental environment, we also deactivated the first dynamic substitution station, and allowed for substitution to take place prior to the vehicles entering the AS/RS.

The result was consistent with the counterintuitive, yet logical, result we described in Chapter 3. That is, the required size of the AS/RS increased in this case to 475 units. We believe that requirements for a larger size AS/RS are a direct result of the smaller standard deviation associated with the vehicles out of sequence distribution. The active and passive sequence control models had, respectively, standard deviations of 2.1 and 4.0. The active sequence control scheduling algorithms greatly reduced the large standard deviations produced by passive sequence control algorithm. As a result, sequence disruptions in Phase-2 of paint managed to pull vehicle further out of sequence than originally possible with passive sequence control. That is, Phase-2 of paint no longer processed those very early vehicles, which if delayed, due to paint re-runs and audits, would still exit close to the sequence of the National Blend. Obviously, and proven through the results of our discrete-event simulation models, the elimination of early arriving vehicles had negative consequences on the AS/RS size requirements which outweighed the benefits of eliminating the later arriving ones.

In terms of paint blocks being preserved and propagated, active sequence control provided results that much closer resembled the paint block sizes of the generic National Blend. The prime and enamel booths had paint blocks of size 1.27 and 1.26 (compared with those of 1.31 of the National Blend). Appendix B graphically summarizes AS/RS size requirements, and paint block size statistics for the active sequence control model described in this section.

Table 4-1 summarizes model performance metrics for the active and passive sequence control methodologies in a conventional block painting environment. It is encouraging to note that by implementing active sequence control measures into our system, and without expending any pre-sequencing efforts to create paint blocks, we observe annual savings approximated by $179,000. It is even more encouraging to know that all of the active sequence control measures included in this analysis are software based, and require no hardware investments.

It is important to reiterate that these results hold without the pre-sequencing of low-running vehicles, and vehicles with large processing times. We do not attempt to establish results describing the system interactions of pre-sequencing to create paint blocks, and pre-sequencing of low-running vehicles, and vehicles with large processing times in this analysis. However, it would behoove us to maintain active sequence control in Phase-1 if we are to schedule low-running vehicles early into our paint process, so that they can exit Phase-2 in sequence. Processing these vehicle in a passive sequence control environment, in an attempt to establish smaller AS/RS requirements, would defeat the purpose of pre-sequencing.

Conventional Block Painting				
Average Block Size: 1.31				
Model Type	ASRS Size Requirement	Block Size at Prime	Block Size at Enamel	Annual Purging Cost
Passive Sequence Control Model	400	1.16	1.17	$ 2,650,000.00
Active Sequence Control Model	475	1.27	1.26	$ 2,471,000.00

Table 4-1: Passive versus active sequence control summary Conventional block painting environment

4.3 Block Painting via Pre-Sequencing

4.3.1 Passive Sequence Control Model and Results

In this part of our analysis, we pre-sequenced the National Blend file to create paint blocks that were inherently imbedded in the data. The new pre-sequenced National Blend had a maximum block size of ten, a minimum block size of two, and an average block size of 6.65.

We employed an identical simulation model to the one used with the conventional Block Painting methodology. As before, we deactivated the first dynamic substitution station, while using the second one to prepare vehicles for entry into the AS/RS.

The results from this experiment uncovered new findings, as well as findings supporting previous research. Our pre-sequenced model with passive sequence control called for an AS/RS size of 200 vehicles. This is a significant reduction in AS/RS size requirements from the previous experiment using the same simulation model without pre-sequencing to create paint blocks. Recall that our model without pre-sequencing required an AS/RS of size 400. We believe that reasons for this decrease in AS/RS size requirements are two fold:

1. Pre-sequencing of vehicles allowed for 2% of the vehicles that are greater than 400 units late to be processed earlier. As a result, the number of in-sequence vehicles increased, reducing the size of the AS/RS needed for 98% or greater to sequence compliance.

2. Pre-sequencing enhanced the capacity of the substitution station immediately preceding the AS/RS to locate vehicles of the same body configuration within a given paint block. This augmented the substitution efforts, and greatly reduced the overall size of the AS/RS needed to attain the 98% or greater to sequence compliance.

Paint block sizes at both the prime and enamel booths improved significantly from the non-blocked, non-pre-sequenced model. Average block sizes at the prime and enamel booths measures increased from 1.16 and 1.17 to 2.24 and 2.01. Without adding software or hardware based sequence control logic into the paint operation, introducing paint blocks of this magnitude into Phase-1 has the potential of generating annual savings in excess of one million dollars. Appendix C graphically summarizes AS/RS size requirements, and paint block size statistics for the passive sequence control model described in this section.

4.3.2 Active Sequence Control Model and Results

At this stage of our analysis, we could almost predict the impact of applying active sequence control to the paint-blocked and pre-sequenced National Blend. We used the same simulation model used to analyze the situation with the non-blocked National Blend. As anticipated, AS/RS size requirements increased from those using passive sequence control and a pre-sequenced National Blend (262 versus 200). However, when using active sequence control, pre-sequencing considerably decreased the AS/RS size requirements (262 versus 475). For reasons explained earlier in this chapter, active sequence control played havoc on AS/RS size requirements. But, pre-sequencing counteracted the increases in AS/RS size requirements by pulling late vehicles earlier into the paint process, and by allowing the second dynamic substitution station to play a more effective role in re-sequencing vehicles before entering the AS/RS. These results show that active sequence control processing and pre-sequencing scheduling methodologies are harmonious when trying to control AS/RS size requirements in the subject ILVS environment.

The biggest improvement of simultaneously applying active sequence control processing and pre-sequencing for Block Painting stems from the system's ability to create and propagate paint blocks through the paint system. Using this most recent model, we observed paint blocks averaging 5.85 and 3.69 vehicles in size at the prime and enamel booths respectively. Without a doubt, this meets and exceeds our Block Painting objectives without requiring additional investments for facilities, nor AS/RS modifications. Appendix C graphically summarizes AS/RS size requirements, and paint block size statistics for the active sequence control model described in this section.

Table 4-2 summarizes model performance metrics for the active and passive sequence control methodologies in a Block Painting environment. With an annual purging cost approximating $980,500, compared with exiting purging costs of $2,650,000, net savings in excess of $1,600,000 are not far out of reach. Keep in mind that our methodology requires software administered sequence control modifications. It should not be difficult to justify these computer-based changes.

Pre-Sequenced Block Painting				
Average Block Size: 6.65				
Model Type	ASRS Size Requirement	Block Size at Prime	Block Size at Enamel	Annual Purging Cost
Passive Sequence Control Model	200	2.24	2.01	$ 1,626,500.00
Active Sequence Control Model	262	5.85	3.69	$ 980,500.00

Table 4-2: Passive versus active sequence control summary Block Painting via pre-sequencing

4.4 Model Results and Comparison

In concluding this chapter, we present a simple graphical representation of the different models we use in our experimentation. In presenting these results, we use the following nomenclature:

- Passive, No PB = Passive Sequence Control Model with No Paint Blocking Provisions.
- Active, No PB = Active Sequence Control Model with No Paint Blocking Provisions.
- Passive, PB = Passive Sequence Control Model with Paint Blocking Provisions.
- Active, PB = Active Sequence Control Model with Paint Blocking Provisions.

Figure 4-2 shows that the plant can save approximately 63%, or in excess of $1.6 million in annual purging costs by using active sequence control scheduling algorithms and Block Painting. Figure 4-3 demonstrates that by using active sequence control, and creating paint blocks via pre-sequencing, the plant can also reduce AS/RS size requirements by up to 35%. This reduction translates directly into manufacturing floor savings, and procurement cost reductions for future AS/RS systems.

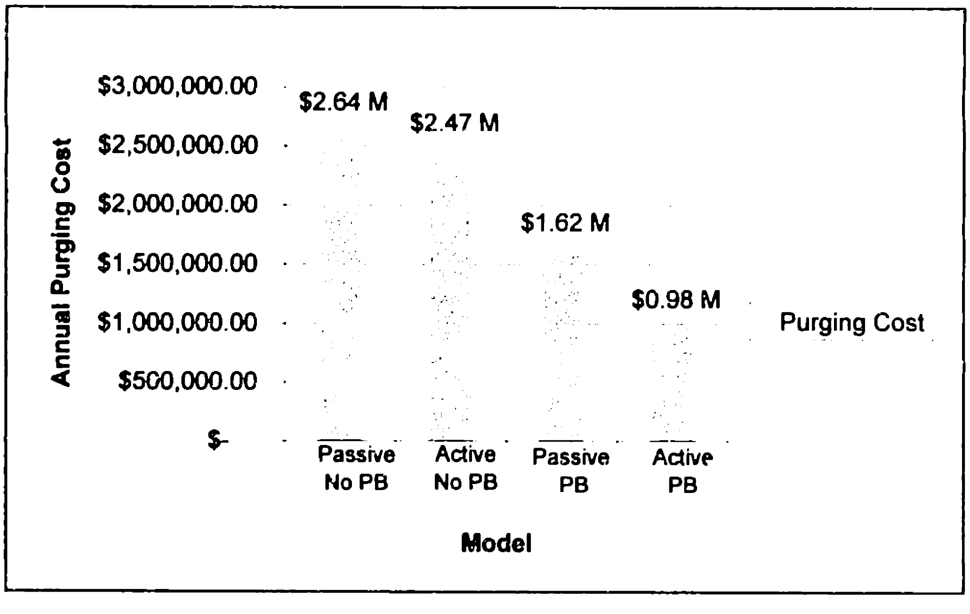


Figure 4-2: Annual purging cost comparisons

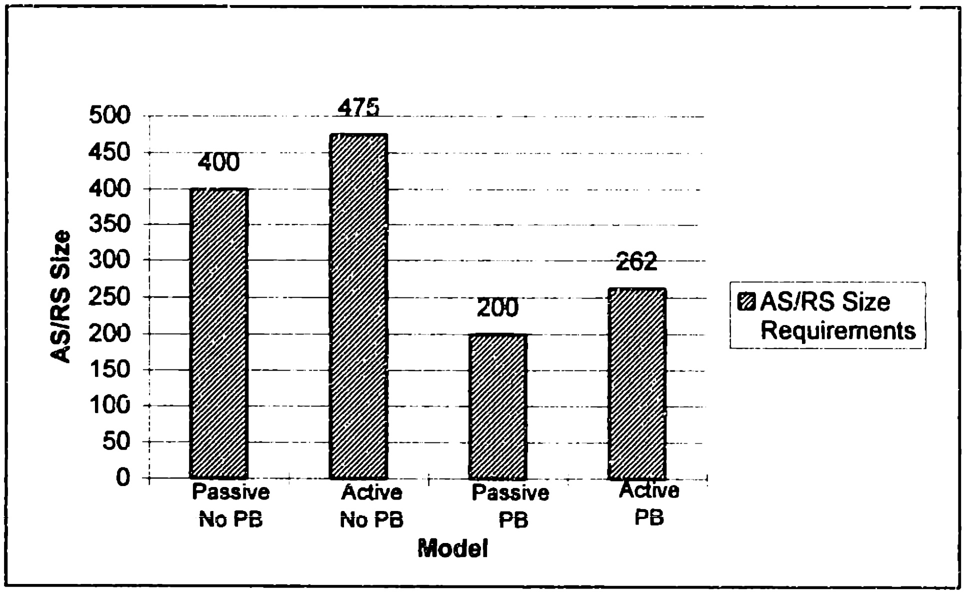


Figure 4-3: AS/RS size requirement comparisons

Chapter 5

SENSITIVITY ANALYSIS

Any implementation of Block Painting in ILVS environments that are less than ideal must deal with many operational concerns. The plant would need to address concerns about throughput rate reductions, labor cost increases, and the ability to create and sustain an active sequence control environment before implementing our findings. In this chapter, we examine three process variables, and determine their impact on meeting cost objectives, as well as the objectives of ILVS and Block Painting.

5.1 Reductions in Phase-1 Throughput and Impact on Phase-2

In Chapter 3, we introduced six different models, each incorporating a new type of variation into our ILVS assembly process. One of the performance metrics we continually monitored was that of the throughput rates of Phase-1. Initial process specifications dictated throughput rates of 71 vehicles per hour. Due to process disruptions and further process digression being introduced into Phase-2 of paint, the throughput rate immediately preceding the AS/RS was also set at 59 vehicles per hour. Characteristics of this process bring about yet another important question, without an intuitive answer: At what reduced throughput level of Phase-1 does the throughput level of Phase-2 begin to suffer? In other words, can we introduced more sequence maintaining elements into our assembly process without impacting the 59 vehicle per hour flow into the AS/RS. Recalling that the active sequence control model of Phase-1 lowered the rate at which vehicles entered Phase-2 (from 71 to 69 vehicles per hour), we chose to use discrete-event simulation to validate the feasibility of active sequence control in terms of system throughput. Our simulation models introduced vehicles from a conventional National Blend into Phase-2 at rates ranging from eighty to forty five vehicles per hour. Figure 5-1 shows the impact of these rates. It is clear that for rates of 65 vehicles per hour and larger, changes in the throughput rates of Phase-1 have little impact on that of Phase-2. However, at throughput rates of 65 vehicles per hour and lower in Phase-1, we observe significant decreases in Phase-2's throughput.

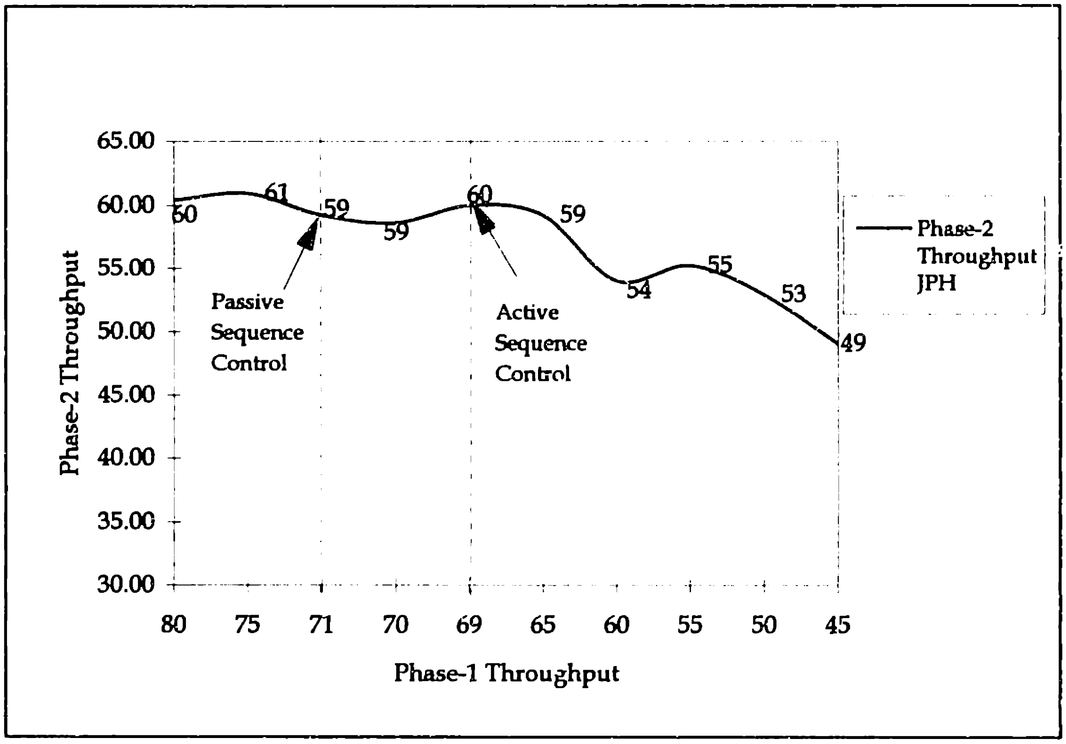


Figure 5-1: Throughput at Phase-1 and impact on throughput at Phase-2

These results show that the plant can apply the proposed active sequence control methodology to preserve the integrity of paint blocks without jeopardizing the overall throughput of the paint department. For throughput rates in excess of 65 vehicles per hour out of Phase-1, Phase-2's throughput is constrained by the cycle time of one of its own operations, and not by Phase-1 limitations. Theory of Constraints principles [15] suggest that we examine Phase-2 to find the bottleneck operations. Additional investigation revealed that the prime booth processed 65 vehicles per hour on average. The system does not attain this rate due to the dynamic nature of its internal processes. The processes are continuously subjected to system blocking and starving effects, leading to the less than optimal utilization of the prime booth. In conclusion, and for throughput rates of 65 vehicles per hour and larger out of Phase-1, adding sequence control logic to our operations will have no impact on the throughput of the paint department.

5.2 Variability in Cycle Times of Parallel Operations and The Block Size

Performing maintenance based on the calendar or in response to crisis situations is inefficient, time consuming, non-productive, and downright expensive. Computerized maintenance systems have greatly improved the capacity to plan ahead and fix problems before they occur [16]. Maintaining identical and parallel equipment to operate at similar and consistent rates falls in the same category. It would be ideal if our processes were capable of operating at, and maintaining, consistent and uniform cycle times. In Chapter 3 we showed how a 10% fluctuation in parallel process rates affects the percent to sequence at which vehicles emerged out of Phase-1. We also showed that even though variations in parallel process rates did not cause vehicles to be too far out of sequence, it did play havoc when trying to preserve paint blocks. We chose the 10% value for simplicity, and to establish grounds for further sensitivity analysis. In forecasting the response to the request of maintaining parallel processes operating at similar cycle times, we were driven to answer yet another question: How close in cycle times should parallel processes operate in order for active sequence control methodologies to be effective, and what is the bottom line effect on paint block sizes?

We introduced variations ranging from 0% to 50% into Phase-1 of paint, and introduced vehicles to the system from the same pre-sequenced National Blend used in Chapter 4. Recall that this National Blend had a maximum paint block size of ten, a minimum block size of two, and an average block size of 6.65. We processed all the vehicles by Phase-1 with these variations, and introduced the output from each model to Phase-2. We measured the paint system's performance in terms of paint block sizes at both the prime and enamel booths. Figures 5-2 and 5-3 summarize our findings.

Our results in Chapter 4, when using the active sequence control model, produced paint block sizes of 5.85 and 3.69 at the prime and enamel booths respectively. The other approaches (models) we considered couldn't achieve any better results (given the average block size introduced to Phase-1). Therefore, to understand the consequences of variations in the processing times of parallel operations, we examined the active sequence control model (Model VI). Paint block sizes at both the prime and enamel booths were statistically unaffected when variations to cycle times were in the range of 0% to 20%. At variations of 25% and higher, paint block sizes at both the prime and enamel booths degraded considerably. For variations of 35%, paint block sizes at prime and enamel became 4.35 and 3.20 respectively. From a financial standpoint, these figures represent added annual purging costs of approximately $120,000. Figure 5-4 graphically depicts the impact of varying parallel process cycle times on annual purging costs. Based on our findings, keeping variations in parallel process cycle times below 20% is one "low hanging fruit" to cultivate when applying ILVS and Block Painting at Wixom's assembly operations.

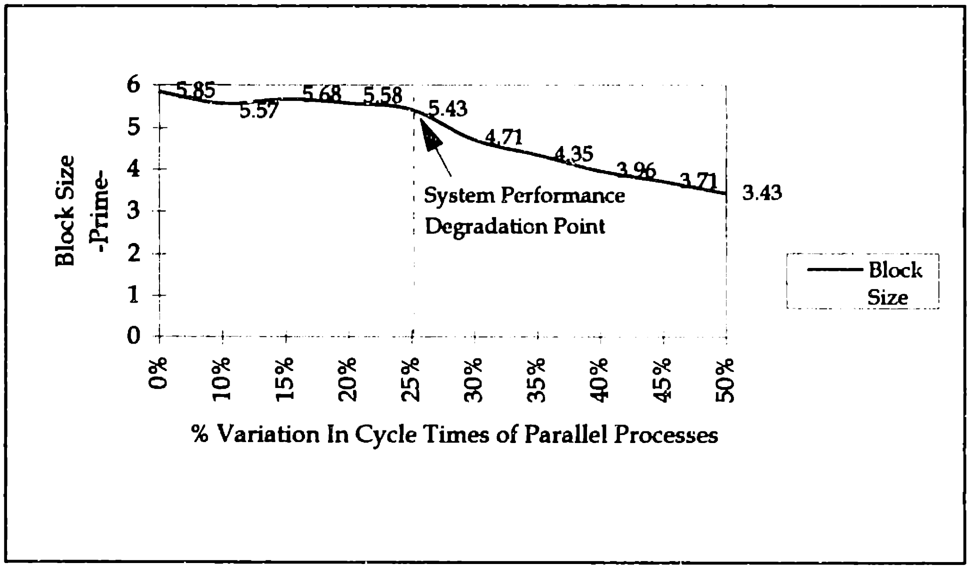


Figure 5-2: Block size at prime as a function of variability in parallel process cycle times

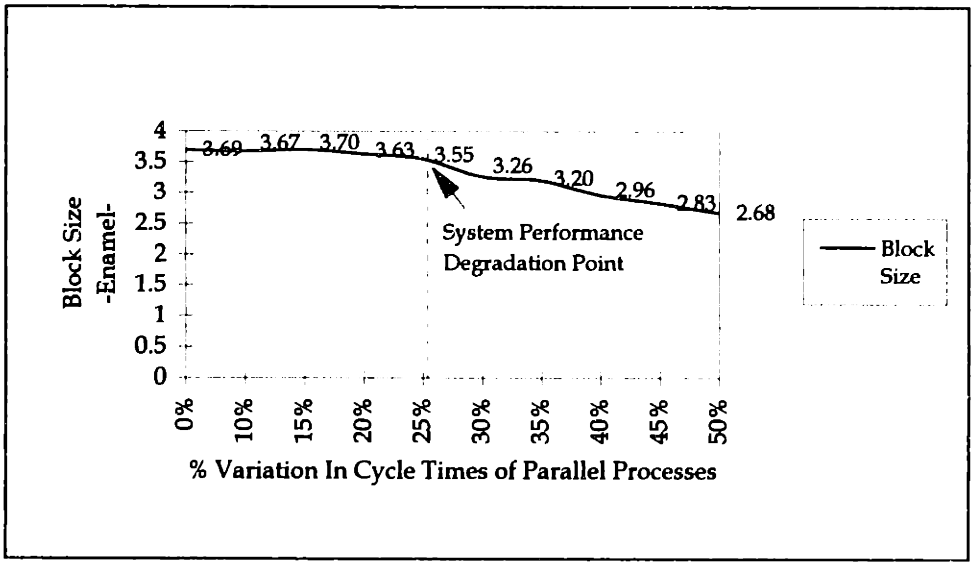


Figure 5-3: Block size at enamel as a function of variability in parallel process cycle times

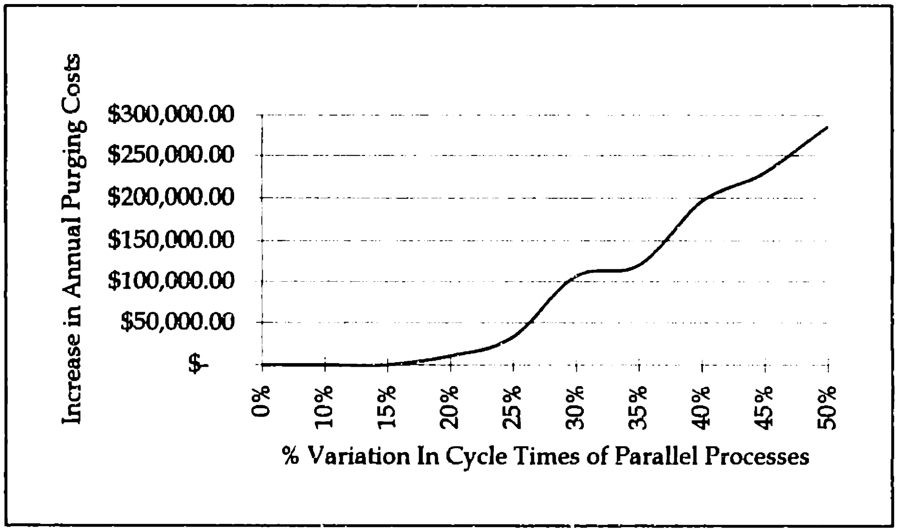


Figure 5-4: Increase in annual purging costs as a function of variability in parallel process cycle times

5.3 Grouping of Vehicles at Metal Repair

In Chapter 3 we showed that processing vehicles in groups of six at the metal repair shop had little impact on the sequence of vehicles emerging from Phase-1. In Model VI of Phase-1, we also suggested reducing the metal repair cycle time (set-up and processing) by 50%, to satisfy the minimum throughput rates and the ILVS viability metrics requirements. Since repair time distributions and the percent of vehicles in need of repair are fixed numbers, we added labor to the process to reduce the average repair time per vehicle.

We used the metal repair buffer and repair block size as input variables into both Phase-1 and Phase-2 of paint (active sequence control environment). We also ran a total of eight experiments, each utilizing a single operator, and evaluated the throughput of Phase-1 for each. All of our experiments satisfied the 59 vehicles per hour flow rate from Phase-2 into the AS/RS. We also recorded the utilization levels of the metal repair facility for each experiment. The repair facility was utilized less than 50% of the time with a metal repair buffer and repair block size of five and larger. Our study showed that the utilization level of the repair facility is negatively correlated with the metal repair buffer and repair block size. As we increased the metal repair buffer and repair block size, we observed decreases in the utilization level for the repair facility. We attribute these results to efficiencies gained through reductions in the set-up times. We summarize our results of the eight experiments in Table 5-1.

Repair Facility Utilization	Metal Repair Buffer Size	Metal Repair Block Size	No. Dedicated Operators	No. Non-Dedicated Operators	Phase-1 Throughput
74%	1	1	1	0	68
68%	2	2	1	0	68
62%	3	3	1	0	68
52%	4	4	1	0	68
41%	5	5	0	1	68
37%	6	6	0	1	68
36%	7	7	0	1	68
35%	8	8	0	1	68

Table 5-1: Summary of results. Grouping of vehicles at metal repair

Having utilization levels of 50% and lower at the metal repair facility meant that an operator could be assigned to other off-line stations on the assembly line, reducing costs by up to 50%. At the same time, this level of staffing at the metal repair shop did not impose additional costs in terms of larger AS/RS size requirements. While some of the ILVS viability metrics were measured to be out of limit, vehicles continued to exit Phase-1 at 98% or better to sequence when compared with the National Blend. Like Model VI (active sequence control), this model also required an AS/RS of 262 units.

Processing vehicles through the metal repair facility as proposed hardly affected the paint block sizes. Using a pre-sequenced National Blend with an average block size of 6.65, this proposed staffing level rendered blocks of size 5.86 and 3.69 at the prime and enamel booths, while the original staffing level with two dedicated operators at the metal repair facility yielded blocks of size 5.85 and 3.69.

The obvious benefits to this approach is its cost savings. We were able to reduce the labor requirements at the metal repair facility by a factor of 75% without adding costs to our system. This approach did not affect either the AS/RS size requirements or the paint block sizes at the prime or the enamel booths. These savings are better quantified in dollar figures. Based on an average annual cost of $60,000 per operator (estimated and assumed to include fringe benefits), these savings translate into $90,000 gains in annual efficiency.

Chapter 6

CONCLUSIONS

In support of previous work, this research has demonstrated that In-Line Vehicle Sequencing (ILVS) and Block Painting can coexist in a complex assembly environment. A primary condition for the successful cohabitation of these systems includes implementing active sequence control and pre-sequencing methodologies to create and preserve paint blocks. Our results identified annual savings in excess of $1,700,000 as feasible, given these methodologies.

We used discrete-event simulation models to verify and extensively analyze existing operations at the Wixom Assembly Plant, Ford Motor Company's luxury car assembly facility. We successfully isolated sequence disrupting phenomena, evaluated their impact, and simulated an environment allowing us to study the effect of these disruptions on system performance. Next, this thesis evaluated the impact of incorporating active sequence control and pre-sequencing methodologies on system performance measures such as AS/RS size requirements, purging costs, and system throughput rates. The final part of our research efforts addressed the system's sensitivity to throughput rate variations in Phase-1, variations in parallel process cycle times, and batching of vehicles at the heavy metal repair facility. These models were specific to Wixom, yet are modular enough to be applied across other ILVS-ready or practicing operations. Changing the input files and modifying basic vehicle flow patterns (to be specific to other plants) would allow for a wide range application of our models. In this chapter, we will attempt to summarize our results, provide recommendations for further research, and establish grounds for broader implications.

6.1 Summary of Results

Validated Simulation Models: Phases -1 and -2 of Paint

To validate our simulation models with current operations at the Wixom Assembly Plant, we introduced prevailing process complexities to highlight the system's performance characteristics that deviate from those of an ideal ILVS environment (initial model assumptions). Once we introduced these basic modifications to the system's vehicle processing pattern, the "percent to sequence" statistics for the Town Car/Continental car-line plummeted, with an average of a little over 64%. Even though only 64% of the vehicles emerged to sequence from Phase-1, the distance out of sequence for each vehicle was rather low. While small out-of-sequence distances made it easier for the AS/RS to re-sequence these vehicles to the order of the National Blend, they played havoc on the objective of preserving and propagating paint blocks in the system. Current operations in Phase-1 of the paint department, as modeled by this simulation, violated other ILVS viability metrics: "maximum set asides" and "digs per 100 vehicles". Again, we used one dynamic substitution station and the AS/RS to adjust for these violations.

Impact on Town Car/Continental versus Mark VIII

Our findings showed that sequence disruptions affect the Town Car/Continental car-line differently than they do the Mark VIII. We attribute this result to the lower annual production volumes of the Mark VIII. For example, most sequence disruptions had little impact on the "percent to sequence" metric for the Mark VIII car-line, except for the breakdown distributions (introduced in Model III). Conversely, breakdown distributions of parallel operations had the least impact on the "percent to sequence" metric of the Town Car/Continental car-line.

Next, we elaborated on the dynamic nature of our assembly process, and showed how variations causing harm to the sequence of one vehicle might have completely different effects on a lower-volume vehicle, both being processed on the same system. As a result, we recommended a complete and comprehensive analysis of all source of complexity in a system's environment when making strategic and operational decisions (ILVS and Block Painting).

Passive versus Active Sequence Control and Conventional Block Painting

We showed that processing vehicles in our system via active sequence control leads to larger AS/RS size requirements than doing so via passive sequence control. Using a generic National Blend with an average block size of 1.3, and processing vehicles via passive sequence control, our system required an AS/RS of size 400. Using the same National Blend with active sequence control, our system's AS/RS size requirements increased to 475. We believe that the requirements for a larger AS/RS are a direct result of the smaller standard deviations associated with the distance out of sequence distribution for vehicles exiting Phase-1. As we observed, the larger standard deviations from the passive sequence control model complement disruptions taking place in Phase-2. The larger spreads tend to delay early vehicles, and process the late ones ahead of schedule, resulting in vehicles flowing out of Phase-2 closer to sequence and requiring a smaller AS/RS to meet the minimum 98% to sequence requirement.

It is encouraging to note that implementing active sequence control measures, without introducing a pre-sequenced National Blend with paint blocks, provides annual savings in purging costs in excess of $170,000. It is even more encouraging to know that all of the active sequence control measures included in the analysis were software-based, and required no hardware investments.

Passive versus Active Sequence Control and Block Painting via Pre-Sequencing

Our analysis demonstrated the importance of active sequence control for preserving paint blocks that are inherently imbedded in the National Blend. Using pre-sequencing techniques and active sequence control, the plant is able to achieve average block sizes of 5.85 and 3.69 at the prime and enamel booths when it introduces a National Blend with an average block size of 6.65 into the system. Since the prime and enamel booths currently have block sizes of 1.16 and 1.17, annual savings of over $1,650,000 for the plant are clearly within reach. It is worth re-iterating that the plant can achieve these savings through investments in software technology alone, and requires no facilities or hardware investments. For the same National Blend data, passive sequence control produces block sizes of 2.24 and 2.01 at the prime and enamel booths, which translate into annual purging costs savings of over $1,000,000. Therefore, as a starting point on the path of continuous improvement, the plant can use pre-sequencing to generate paint blocks, which is a step in the right direction, even if the plant does not adopt the active sequence control methodologies.

Continuing with this part of the analysis, we further showed that pre-sequencing to establish paint blocks actually reduces AS/RS size requirements. We found savings of up to 35% in AS/RS size requirements, translating directly into manufacturing floor savings, and procurement cost reductions for future AS/RS systems.

System Throughput Rates

As we modified the vehicle flow patterns in the plant, we continued to monitor the throughput rate out of Phase-1, with the ultimate goal of maintaining the required flow of 59 vehicles per hour out of Phase-2 into the AS/RS. We observed that throughput out of Phase-1 was rather insensitive to the processing variations introduced in our system, and fluctuations were in the range of ± 2 vehicles per hour. A more detailed sensitivity analysis in Chapter 5 revealed that the throughput rate of Phase-2 was highly insensitive to fluctuations in the throughput rate of Phase-1 for values of 65 vehicles per hour and larger. We were able to maintain the required throughput rate at both phases for all the processing patterns/disruptions we introduced.

Parallel Process Cycle Time Variations

Parallel operations having variable cycle times lead to significant reductions in the number of vehicles exiting Phase-1 in sequence. Although most vehicles will not be drastically out of sequence, the impact on paint block sizes is significant. The remaining ILVS viability metrics were, for the most part, unaffected by this variation.

A more elaborate sensitivity analysis revealed that variations in parallel process cycle times in the range of 0% to 20% had no statistical impact on paint block sizes at either the prime or enamel booths. For variations of 25% and larger, paint block sizes at both booths degraded significantly. For example, variations in the magnitude of 35% lead to cost increases of approximately $120,000 annually.

Batch Processing of Vehicles at the Heavy Metal Repair Shop

We demonstrated that batch-processing of vehicles in groups of six at the heavy metal repair facility had little impact on the sequence of vehicles emerging from Phase-1. We also showed that by batch-processing vehicles, utilization levels of the metal repair facility decreased, allowing for the operator to be non-dedicated. That is, it is possible to assign this operator additional off-line work along the assembly line. Labor allocations of this nature resulted in annual efficiencies to be gained of approximately $90,000.

6.2 Recommendations for Future Research

Our research and analysis in this thesis are grounded on solid work completed in previous studies. We incorporated and expanded upon many of the tools and assumptions used in the past to effectively analyze a complex assembly line operation. Most of our efforts focused on implementing ILVS and Block Painting at the Wixom Assembly Plant. We strove to resolve some of the issues remaining from prior studies, and to become closer to determining the feasibility of implementing new scheduling and processing policies. Our analysis focused on both, the cost effectiveness of implementing these policies at the Wixom Assembly Plant, and the possibility of using these policies in other ILVS environments. Next, we will discuss topics that, when researched, could play a similar complementary role, and furnish important answers to support the feasibility of the harmonious coexistence of ILVS and Block Painting.

Pre-Sequencing of Low-Running Vehicles and Active Sequence Control

Future research could fruitfully analyze the effect of pre-sequencing low-running vehicles, and vehicles with large processing times, on AS/RS size requirements when using the active sequence control approach. Previous research showed that pre-sequencing low-running vehicles, and those with large processing times, leads to smaller AS/RS size requirements. This study demonstrated the need for larger AS/RS size requirements when vehicles are processed using active sequence control logic. However, the interaction of the two scheduling and processing algorithms is still not known, and is grounds for further investigation.

AS/RS Investment Costs versus Savings from Block Painting

Future studies could, through a comprehensive financial model, evaluate and compare the costs and benefits associated with larger AS/RS size requirements when using active sequence control to preserve and propagate paint blocks. Using active sequence control provided for significant savings in purging costs, while minimally (from 200 to 262) increasing the size of the needed AS/RS system. Further research is needed to evaluate the burden of increasing the size of the AS/RS on annual savings generated from larger paint blocks.

Active Sequence Control and Software-Based Investments

We might profitably investigate software alternatives required to implement Block Painting in an ILVS environment. This research has shown that pre-sequencing to generate paint blocks in a National Blend schedule, along with active sequence control processing logic, can provide enormous savings in annual purging costs. However, neither this research, nor previous work, has quantified the costs of implementing these strategies. Before proceeding further with implementing our research, any plant would need to develop detailed financial models depicting these costs.

Annual Savings in Purge Cost at the Prime Booth

While our research captured significant savings from more efficient purging patterns at the enamel booth, it did not account for savings from similar patterns at the prime booth. It becomes more complex to evaluate the cost of these savings at the prime booth, since it usually uses several enamel colors for each prime color, and the purging patterns are not very well correlated. Some plants do not purge at all due to the type of prime they are using. They simply wash the old color out with the new one. This scenario would eliminate savings from improved purge patterns. It is clear that these costs are unique to different operations, and including them in the financial model could only serve to help justify ILVS and Block Painting.

6.3 Broader Implications

The research presented in this study focused on implementing Block Painting in an ILVS environment. We explicitly examined operations at the Wixom Assembly Plant to establish the feasibility of this theory. We used discrete-event simulation models to study the impact of sequence disruptions, and their interactions, on the performance of the paint system. Although the data used, and the models simulated were specific to the Wixom Assembly Plant, much of the learning acquired could easily be expanded to analyze similar situations. Our models are generic, and with simple changes in the process flow and input data, they could be suitable for analyzing other ILVS environments.

One of our objectives was to develop a generic list of pitfalls to avoid in future implementation efforts of ILVS and Block Painting. We feel that we have captured several such issues, and will conclude this study by briefly describing each.

Multi-Platform Assembly Lines

When analyzing the impact of different processing algorithms on the flow of vehicles in an assembly line, it is of utmost importance to give full consideration to product mix complexity. Our study contrasted the impact of active versus passive sequence control on ILVS viability metrics for the Town Car/Continental and Mark VIII car-lines. They have different annual production volumes, and the sequence disrupting elements had unique effects on each car-line. It is easy to conceive the increase in the level of complexity of our analysis as the number of car-lines processed on the same assembly line grows.

Two or More Enamel Booths

A basic assumption of our analysis is that the plant has a single enamel booth. To say the least, this is a critical assumption, and has critical repercussions if violated. Paint blocks of size 3.69 obtained with a pre-sequenced National Blend, and active sequence control processing would fall to blocks of size 1.85 if the plant had two enamel booths. The Wixom Assembly Plant currently uses two enamel booths to satisfy cycle time requirements and to attain manufacturing floor savings. The design of a new plant should consider alternatives, including a longer and faster single paint booth, to a system of two parallel enamel booths.

Parallel Processes and Variations in Cycle Times

We showed that variations in the cycle times of parallel processes have a significant impact on sequence control mechanisms of an ILVS assembly process. Any plant should conduct studies to evaluate each system's sensitivity to these variations. Plans to compensate for, or eradicate, these variations should be added to the "checklist" of any ILVS and Block Painting implementation plan.

Plant-Specific Processing Constraints

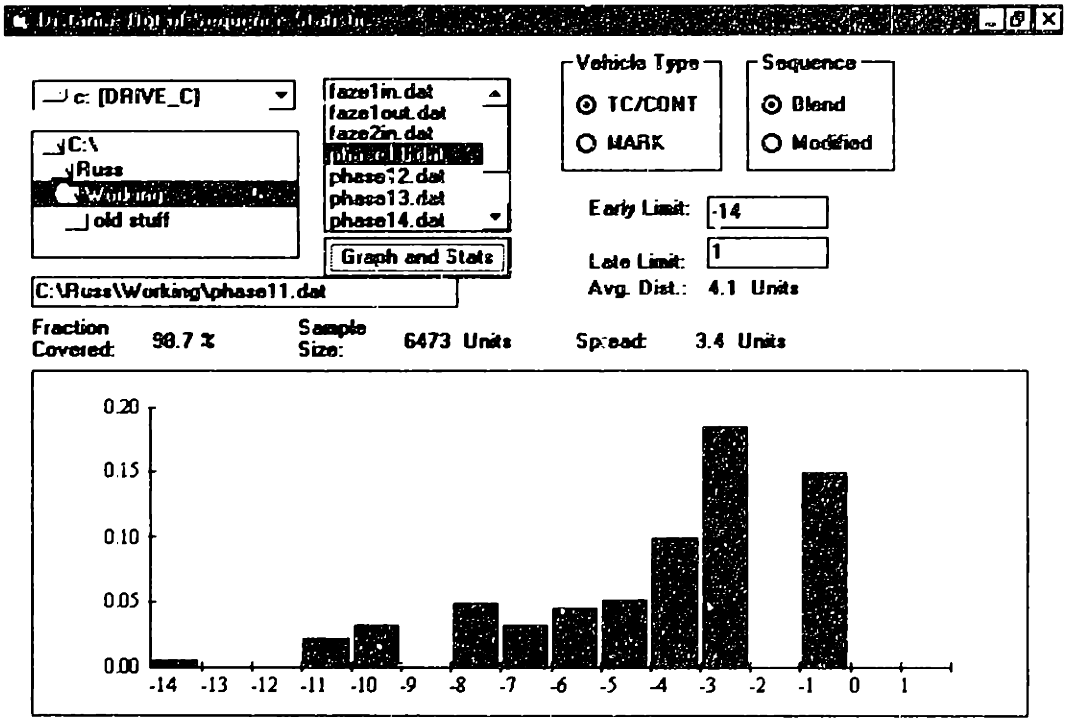
The ILVS and Block Painting benefits presented in this analysis assume that the pre-sequencing strategy to create blocks inherent in the original National Blend does not violate any pre-established processing constraints in the plant. Assembly line specific processing constraints will clearly limit the capacity of any pre-sequencing algorithm, yielding diminishing returns for any Block Painting efforts.

Appendix A

Phase-1 of the Paint Department

Model I - Model VI

Phase-1 - Model I: *Town Car / Continental Statistics*


c: [DRIVE_C]

C:\Russ\Working\phase11.dat

Vehicle Type: ● TC/CONT ○ MARK

Sequence: ● Blend ○ Modified

Early Limit: -14

Late Limit: 1

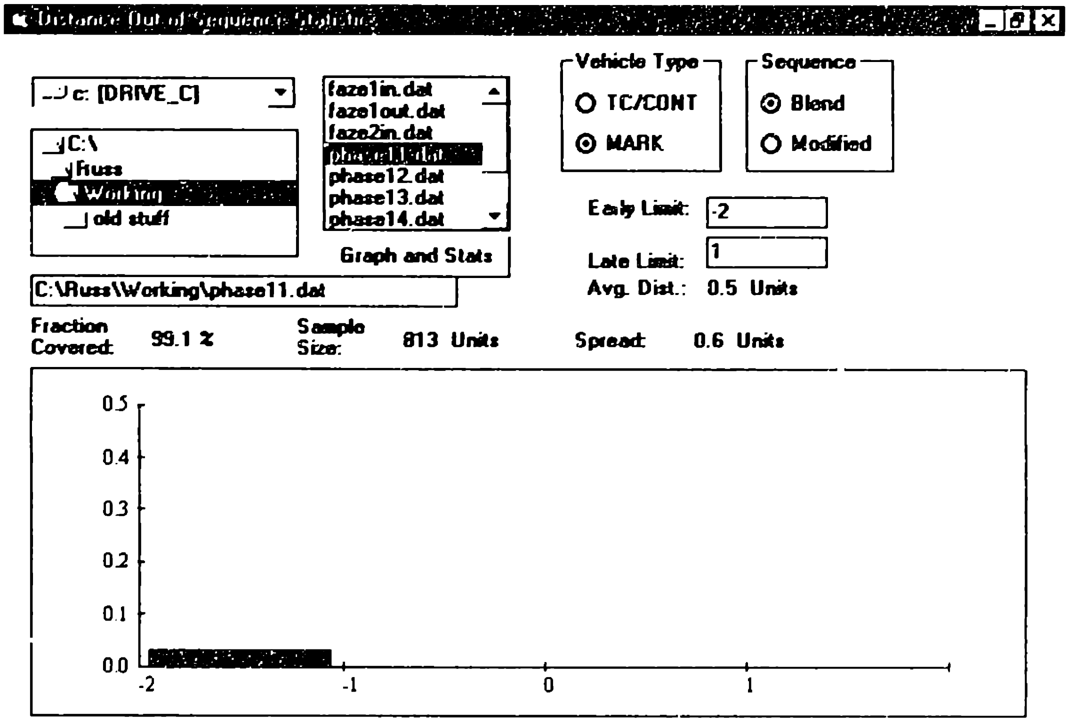
Avg. Dist.: 4.1 Units

Fraction Covered: 98.7 %

Sample Size: 6473 Units

Spread: 3.4 Units

Phase-1 - Model I: *Mark VIII Statistics*


c: [DRIVE_C]

C:\Russ\Working\phase11.dat

Vehicle Type: ○ TC/CONT ● MARK

Sequence: ● Blend ○ Modified

Early Limit: -2

Late Limit: 1

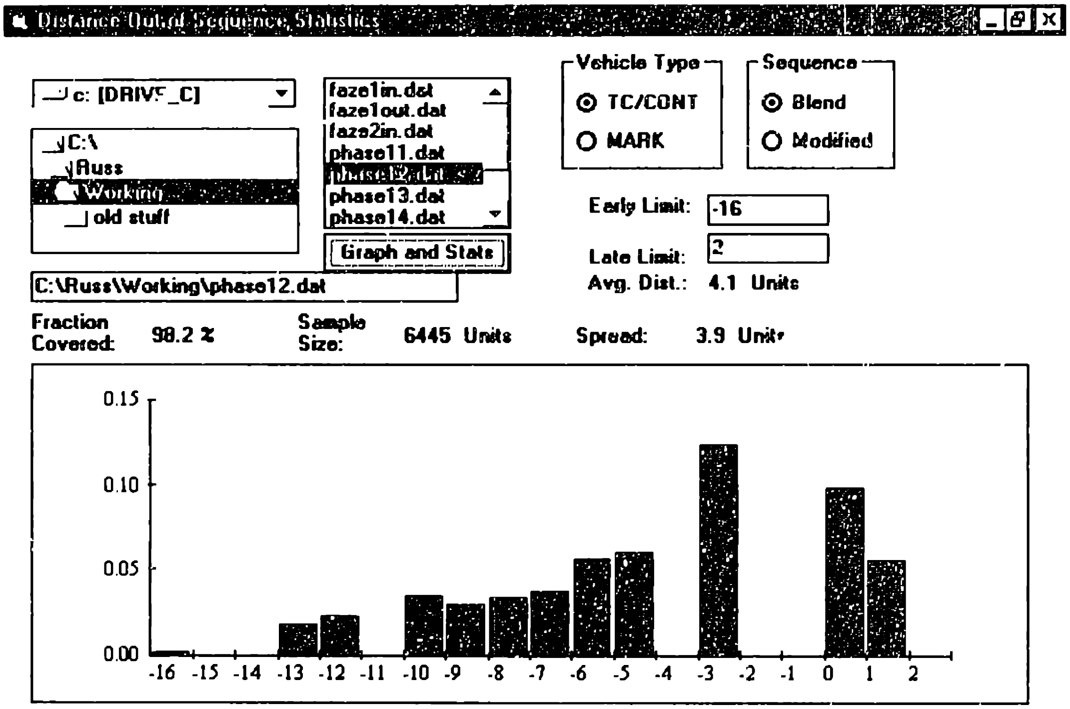
Avg. Dist.: 0.5 Units

Fraction Covered: 99.1 %

Sample Size: 813 Units

Spread: 0.6 Units

Phase-1 - Model II: *Town Car / Continental Statistics*



Vehicle Type: ⊙ TC/CONT ○ MARK

Sequence: ⊙ Blend ○ Modified

C:\Russ\Working\phase12.dat

Early Limit: -16

Late Limit: 2

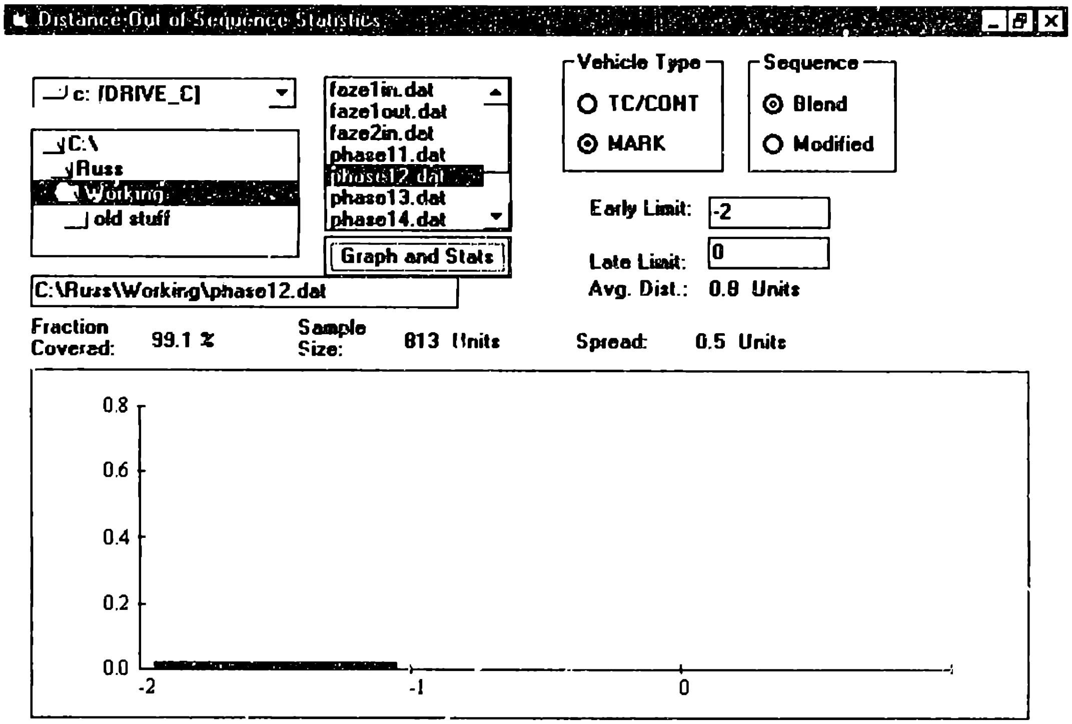
Avg. Dist.: 4.1 Units

Fraction Covered: 98.2 %

Sample Size: 6445 Units

Spread: 3.9 Units

Phase-1 - Model II: *Mark VIII Statistics*



Vehicle Type: ○ TC/CONT ⊙ MARK

Sequence: ⊙ Blend ○ Modified

C:\Russ\Working\phase12.dat

Early Limit: -2

Late Limit: 0

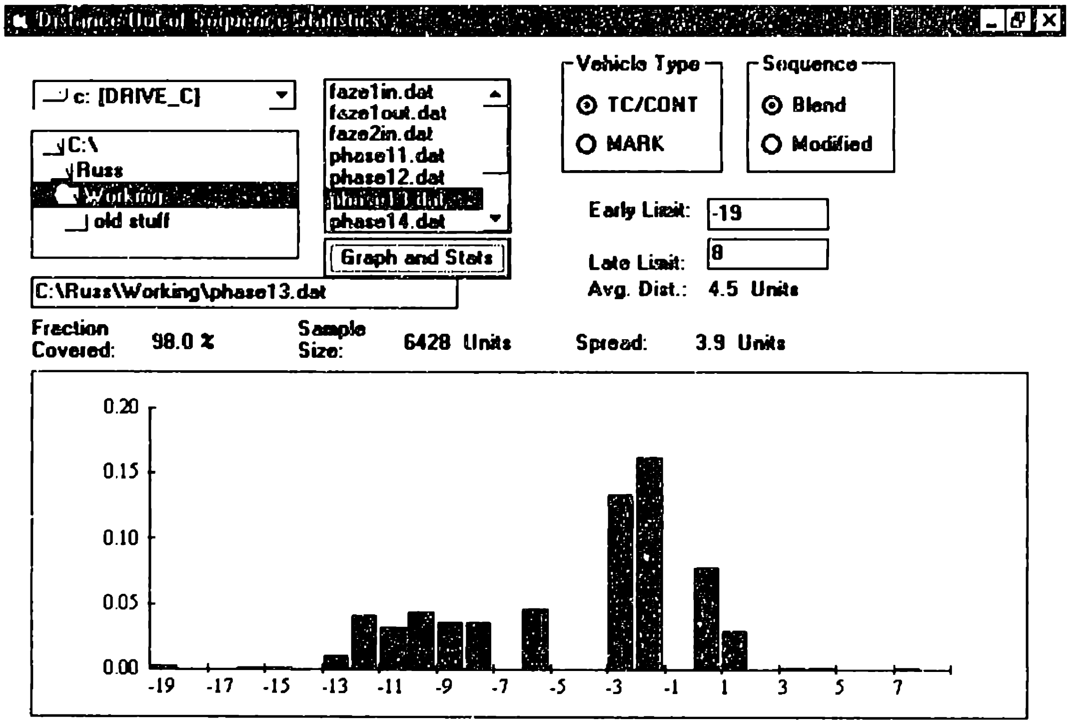
Avg. Dist.: 0.8 Units

Fraction Covered: 99.1 %

Sample Size: 813 Units

Spread: 0.5 Units

Phase-1 - Model III: *Town Car / Continental Statistics*



C:\Russ\Working\phase13.dat

Vehicle Type: ● TC/CONT ○ MARK

Sequence: ● Blend ○ Modified

Early Limit: -19

Late Limit: 8

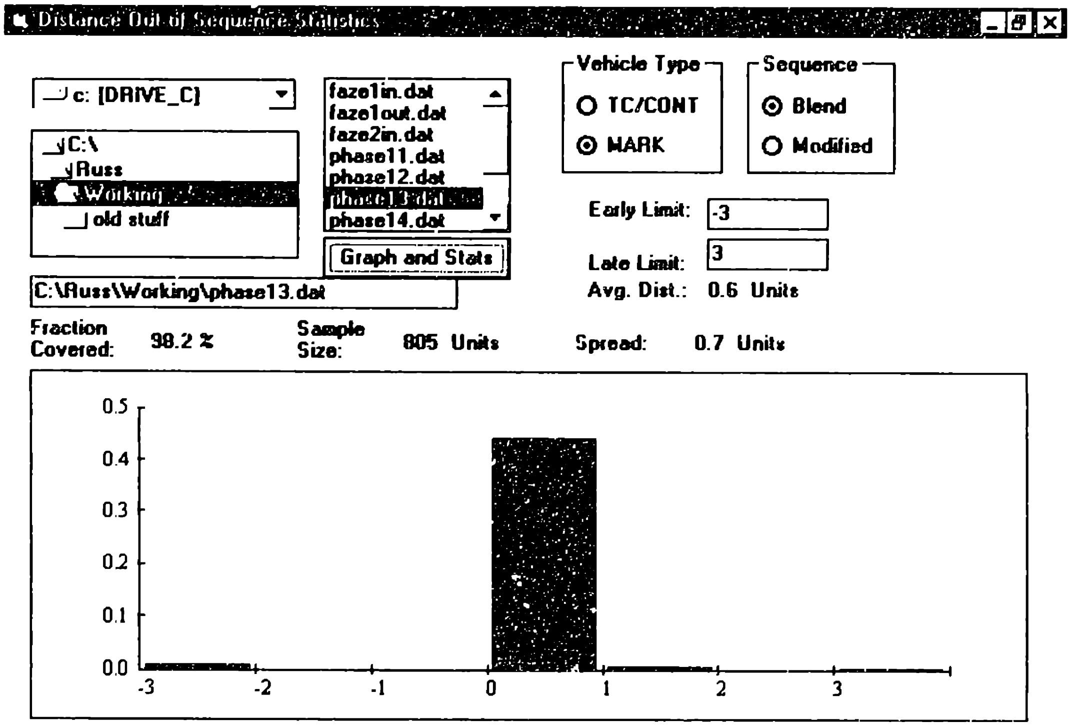
Avg. Dist.: 4.5 Units

Fraction Covered: 98.0 %

Sample Size: 6428 Units

Spread: 3.9 Units

Phase-1 - Model III: *Mark VIII Statistics*



C:\Russ\Working\phase13.dat

Vehicle Type: ○ TC/CONT ● MARK

Sequence: ● Blend ○ Modified

Early Limit: -3

Late Limit: 3

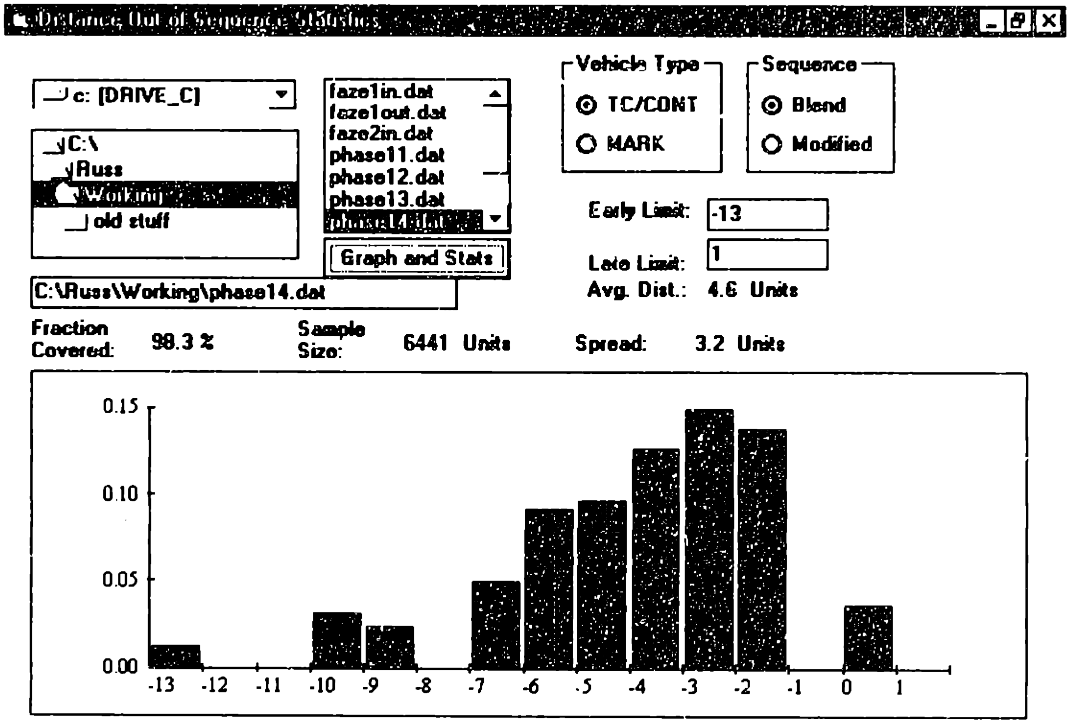
Avg. Dist.: 0.6 Units

Fraction Covered: 98.2 %

Sample Size: 805 Units

Spread: 0.7 Units

Phase-1 - Model IV: *Town Car / Continental Statistics*



C:\Russ\Working\phase14.dat

Vehicle Type: ● TC/CONT ○ MARK

Sequence: ● Blend ○ Modified

Early Limit: -13

Late Limit: 1

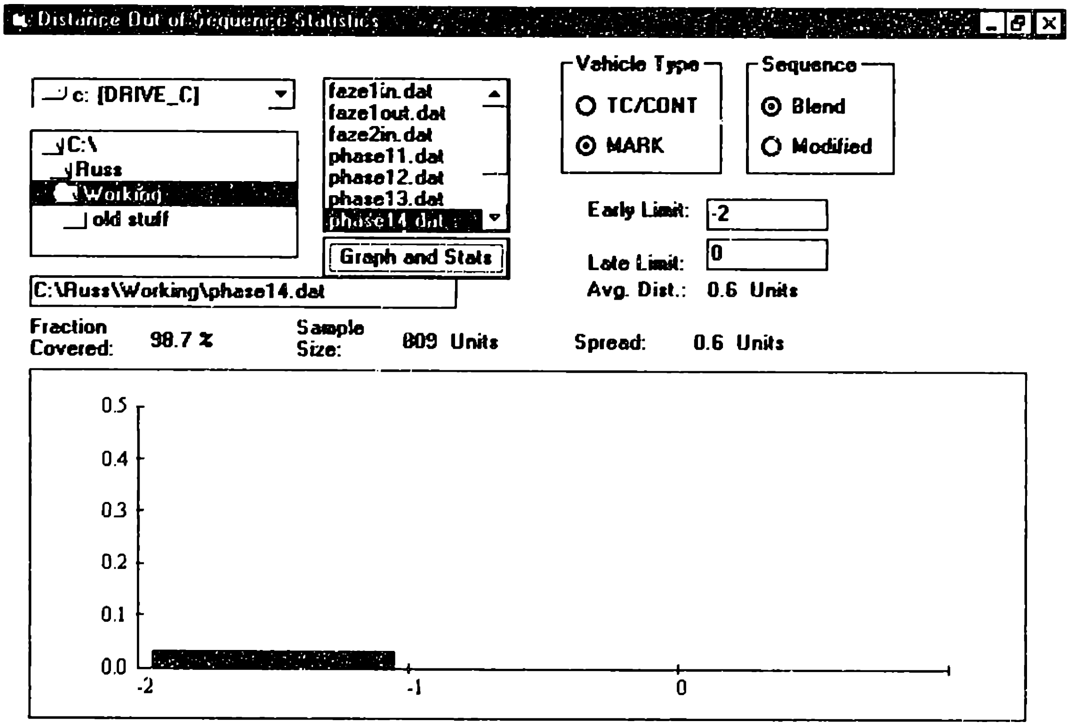
Avg. Dist.: 4.6 Units

Fraction Covered: 98.3 %

Sample Size: 6441 Units

Spread: 3.2 Units

Phase-1 - Model IV: *Mark VIII Statistics*



C:\Russ\Working\phase14.dat

Vehicle Type: ○ TC/CONT ● MARK

Sequence: ● Blend ○ Modified

Early Limit: -2

Late Limit: 0

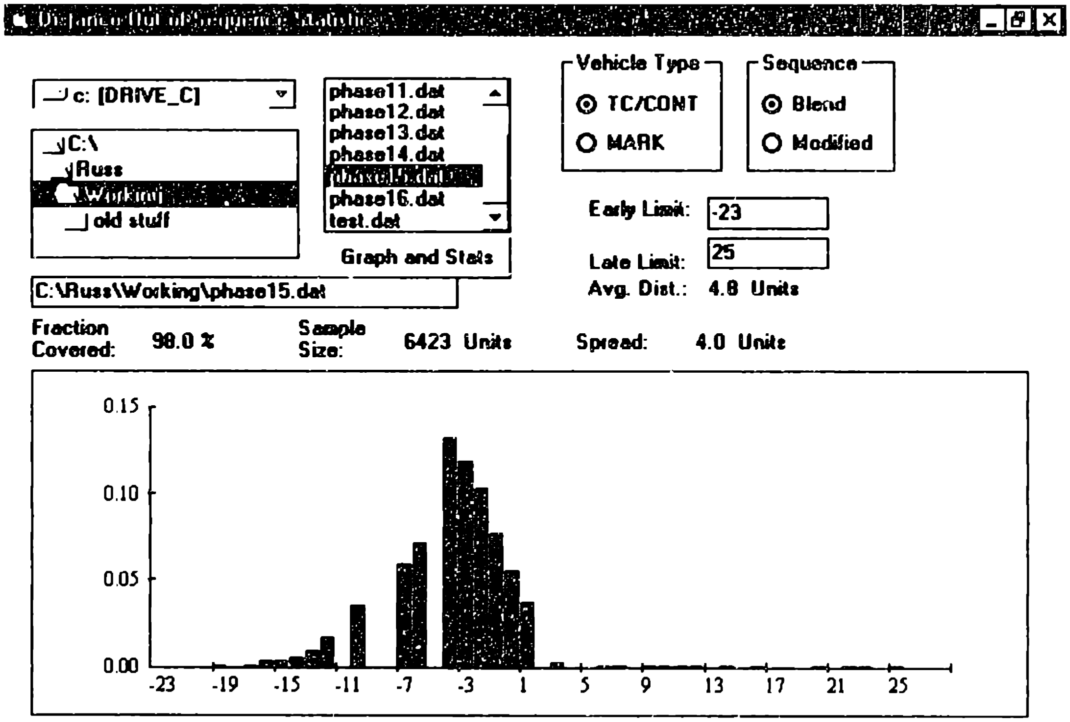
Avg. Dist.: 0.6 Units

Fraction Covered: 98.7 %

Sample Size: 809 Units

Spread: 0.6 Units

Phase-1 - Model V: *Town Car / Continental Statistics*



Distance Out of Sequence Statistics

c: [DRIVE_C]

C:\
Russ
Working
old stuff

phase11.dat
phase12.dat
phase13.dat
phase14.dat
phase15.dat
phase16.dat
test.dat

C:\Russ\Working\phase15.dat

Vehicle Type: ● TC/CONT ○ MARK

Sequence: ● Blend ○ Modified

Early Limit: -23

Late Limit: 25

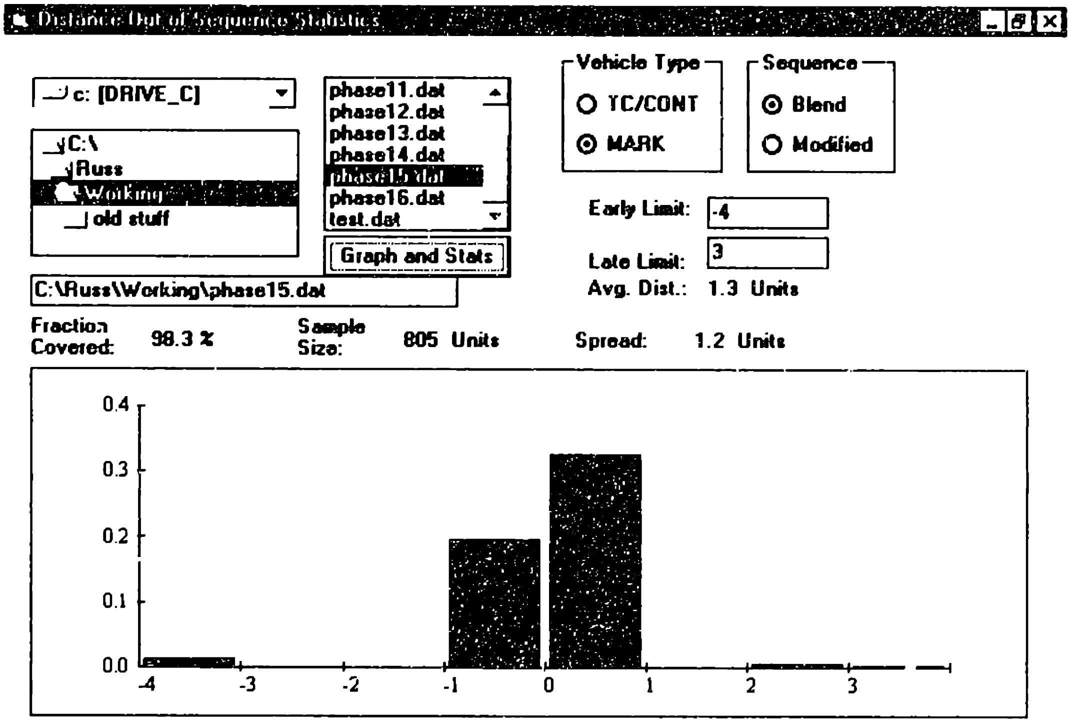
Avg. Dist.: 4.8 Units

Fraction Covered: 98.0 %

Sample Size: 6423 Units

Spread: 4.0 Units

Phase-1 - Model V: *Mark VIII Statistics*



Distance Out of Sequence Statistics

c: [DRIVE_C]

C:\
Russ
Working
old stuff

phase11.dat
phase12.dat
phase13.dat
phase14.dat
phase15.dat
phase16.dat
test.dat

C:\Russ\Working\phase15.dat

Vehicle Type: ○ TC/CONT ● MARK

Sequence: ● Blend ○ Modified

Early Limit: -4

Late Limit: 3

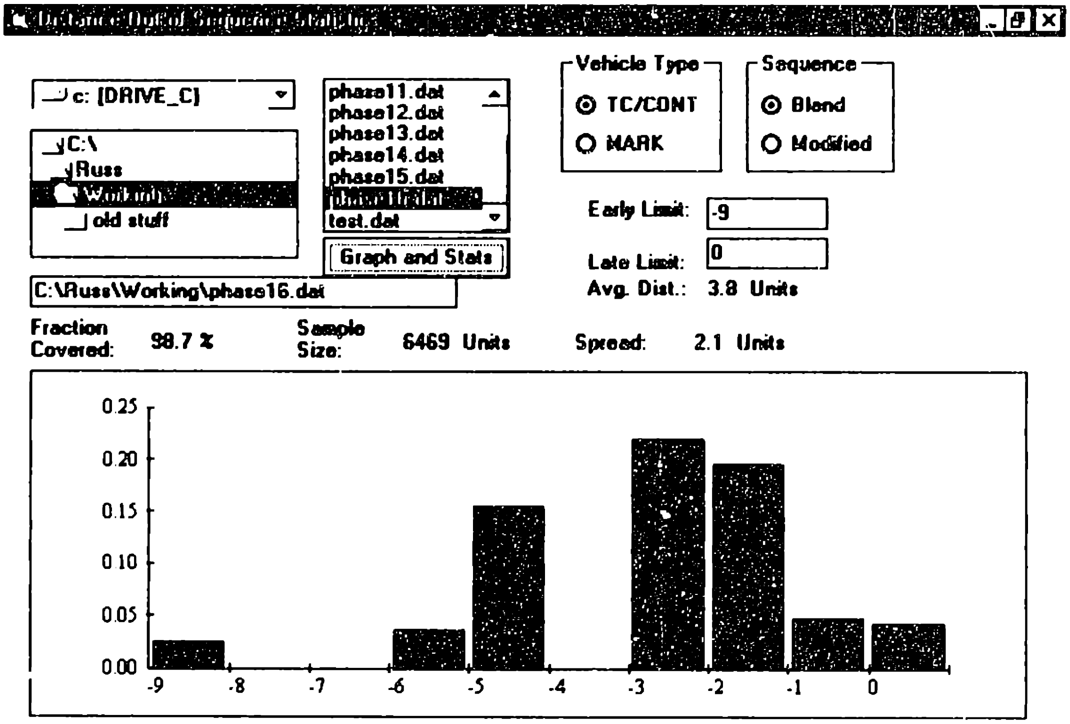
Avg. Dist.: 1.3 Units

Fraction Covered: 98.3 %

Sample Size: 805 Units

Spread: 1.2 Units

Phase-1 - Model VI: *Town Car / Continental Statistics*



C:\Russ\Working\phase16.dat

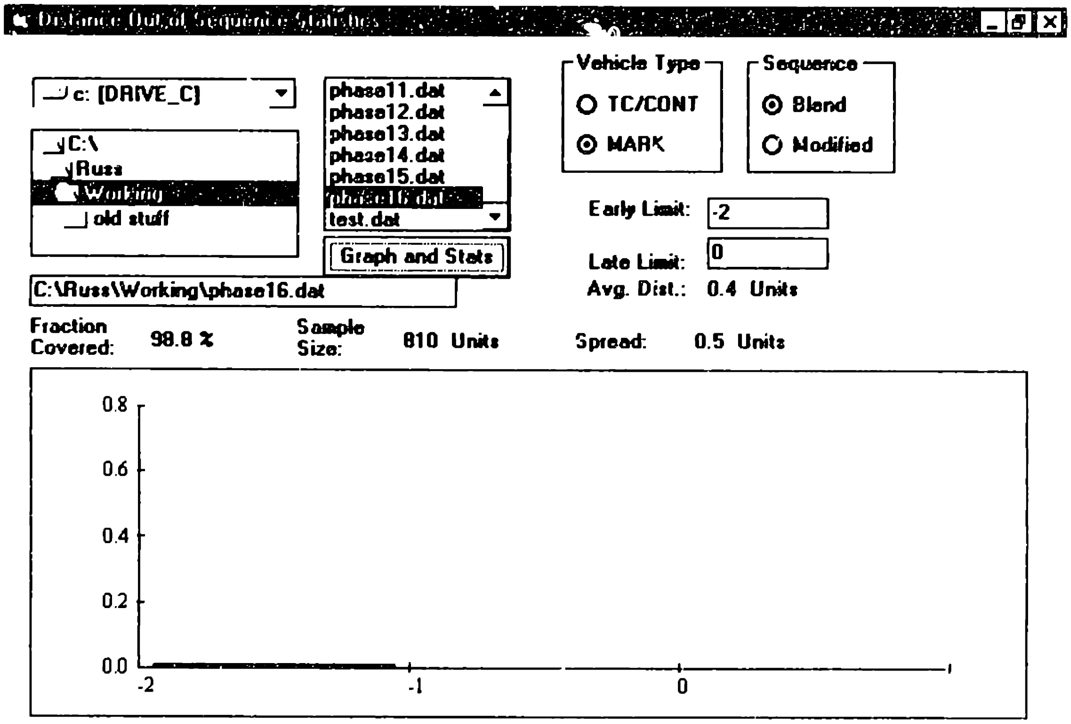
Vehicle Type
⦿ TC/CONT
○ MARK

Sequence
⦿ Blend
○ Modified

Early Limit: -9
Late Limit: 0
Avg. Dist.: 3.8 Units

Fraction Covered: 98.7 %
Sample Size: 6469 Units
Spread: 2.1 Units

Phase-1 - Model VI: *Mark VIII Statistics*



C:\Russ\Working\phase16.dat

Vehicle Type
○ TC/CONT
⦿ MARK

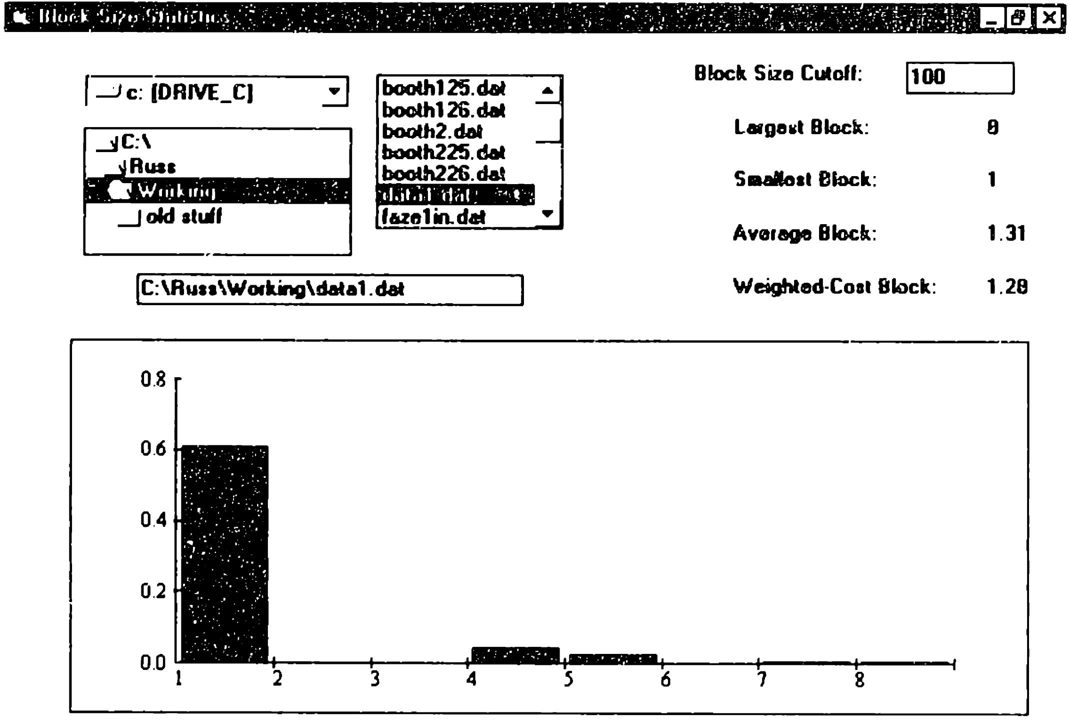
Sequence
⦿ Blend
○ Modified

Early Limit: -2
Late Limit: 0
Avg. Dist.: 0.4 Units

Fraction Covered: 98.8 %
Sample Size: 810 Units
Spread: 0.5 Units

Appendix B
Conventional Block Painting

Conventional Block Painting: *Data Characteristics*



C:\Russ\Working\data1.dat

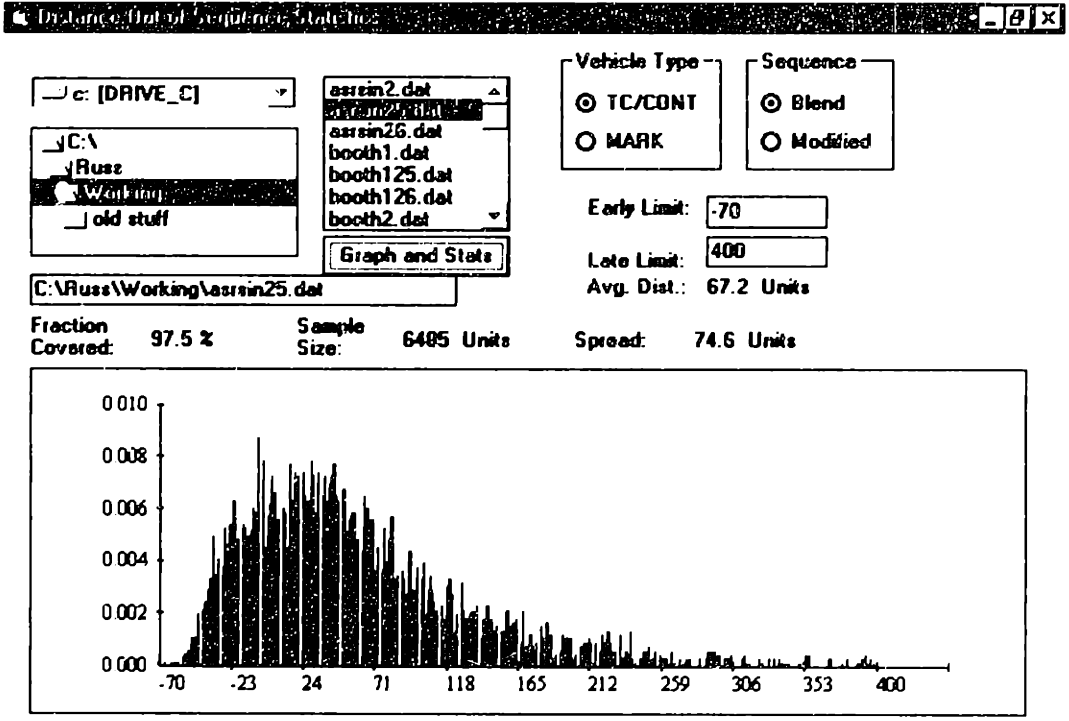
Block Size Cutoff: 100

Largest Block: 8

Smallest Block: 1

Average Block: 1.31

Weighted-Cost Block: 1.28



Distance Plot of Sequence Statistics

c: [DRIVE_C]

C:\Russ\Working\asrsin25.dat

Vehicle Type: ● TC/CONT ○ MARK

Sequence: ● Blend ○ Modified

Early Limit: -70

Late Limit: 400

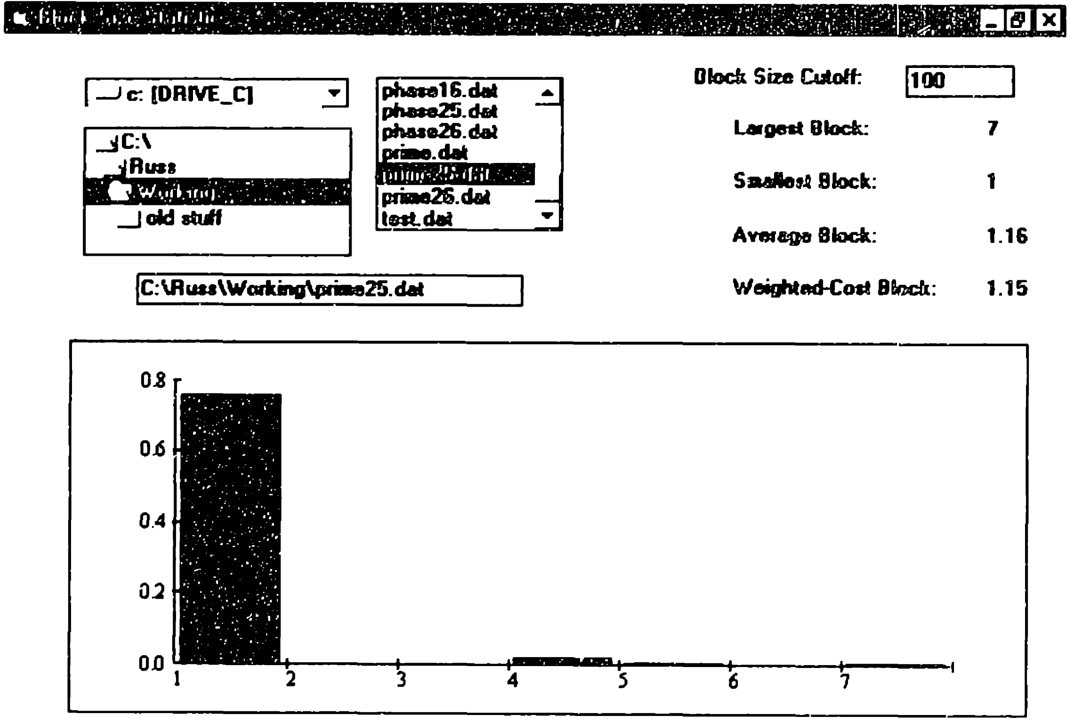
Avg. Dist.: 67.2 Units

Fraction Covered: 97.5 %

Sample Size: 6405 Units

Spread: 74.6 Units

Passive Sequence Control: *Paint Block Size at the Prime Booth*



c: [DRIVE_C]

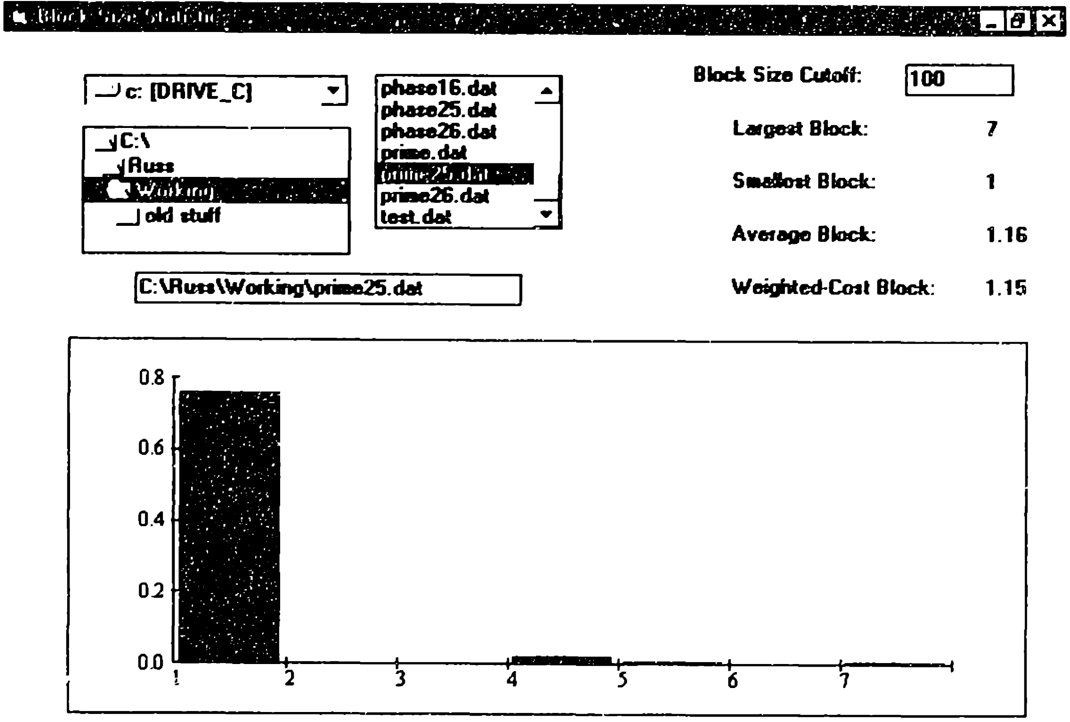
C:\
Russ
Working
old stuff

phase16.dat
phase25.dat
phase26.dat
prime.dat
prime25.dat
prime26.dat
test.dat

C:\Russ\Working\prime25.dat

Block Size Cutoff: 100
Largest Block: 7
Smallest Block: 1
Average Block: 1.16
Weighted-Cost Block: 1.15

Passive Sequence Control: *Paint Block Size at the Enamel Booth*



c: [DRIVE_C]

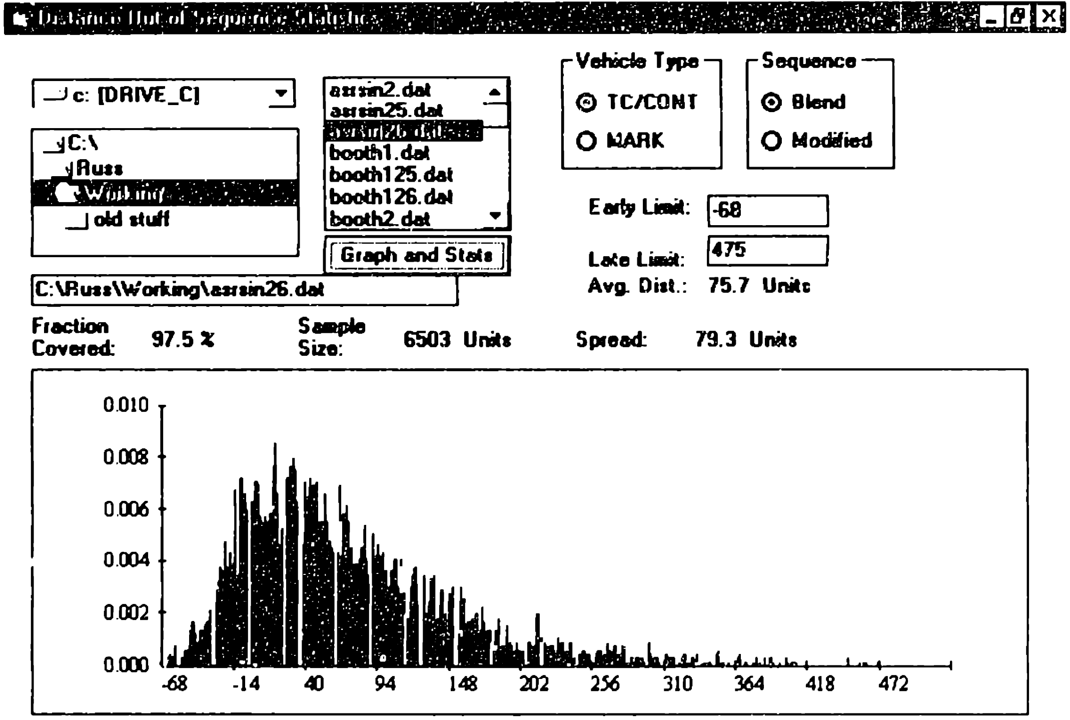
C:\
Russ
Working
old stuff

phase16.dat
phase25.dat
phase26.dat
prime.dat
prime25.dat
prime26.dat
test.dat

C:\Russ\Working\prime25.dat

Block Size Cutoff: 100
Largest Block: 7
Smallest Block: 1
Average Block: 1.16
Weighted-Cost Block: 1.15

Active Sequence Control: *AS/RS Size Requirements*



C:\Russ\Working\asrsin26.dat

Vehicle Type: ● TC/CONT ○ MARK

Sequence: ● Blend ○ Modified

Early Limit: -68

Late Limit: 475

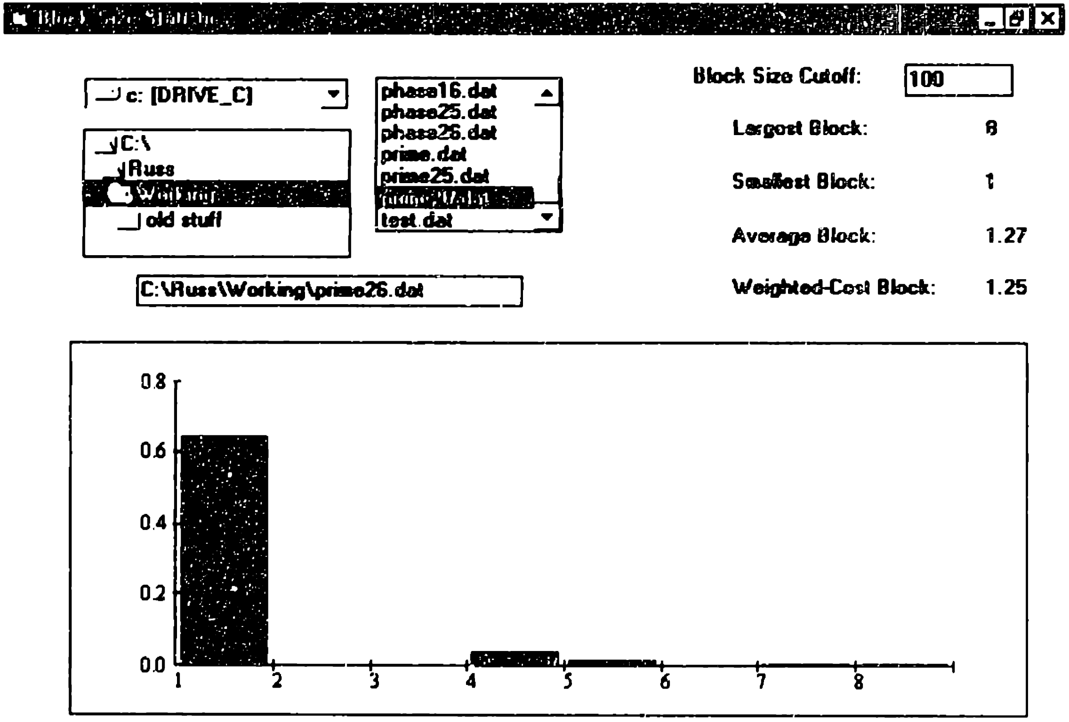
Avg. Dist.: 75.7 Units

Fraction Covered: 97.5 %

Sample Size: 6503 Units

Spread: 79.3 Units

Active Sequence Control: *Paint Block Size at the Prime Booth*



C:\Russ\Working\prime26.dat

Block Size Cutoff: 100

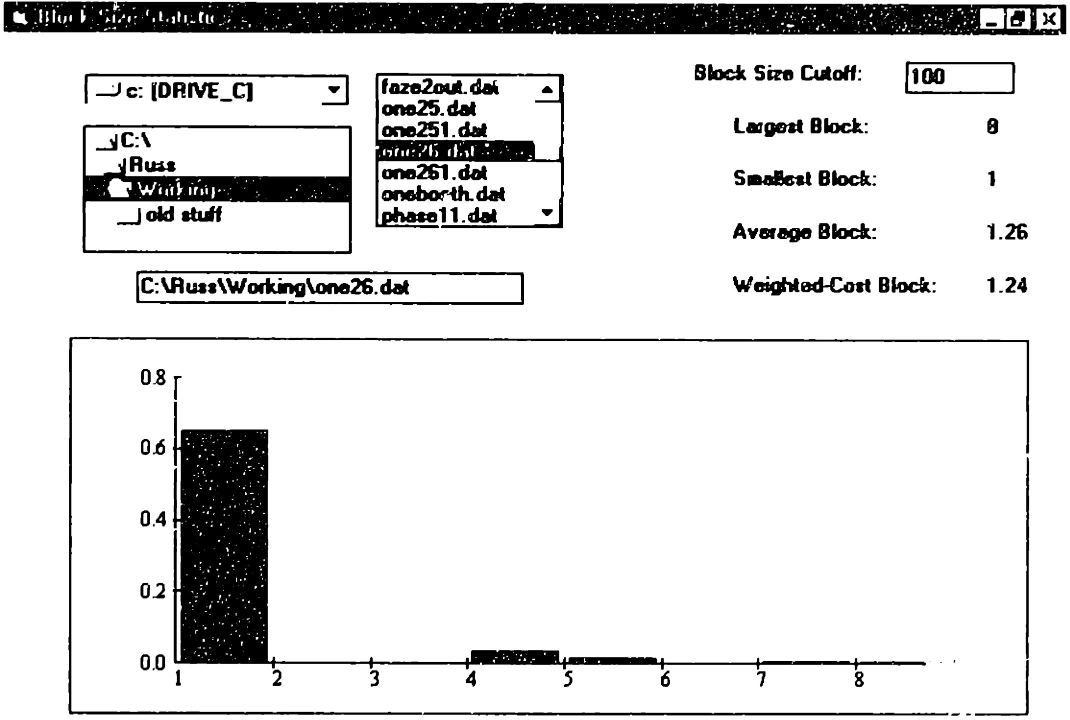
Largest Block: 8

Smallest Block: 1

Average Block: 1.27

Weighted-Cost Block: 1.25

Active Sequence Control: *Paint Block Size at the Enamel Booth*



C:\Russ\Working\one26.dat

Block Size Cutoff: 100

Largest Block: 8

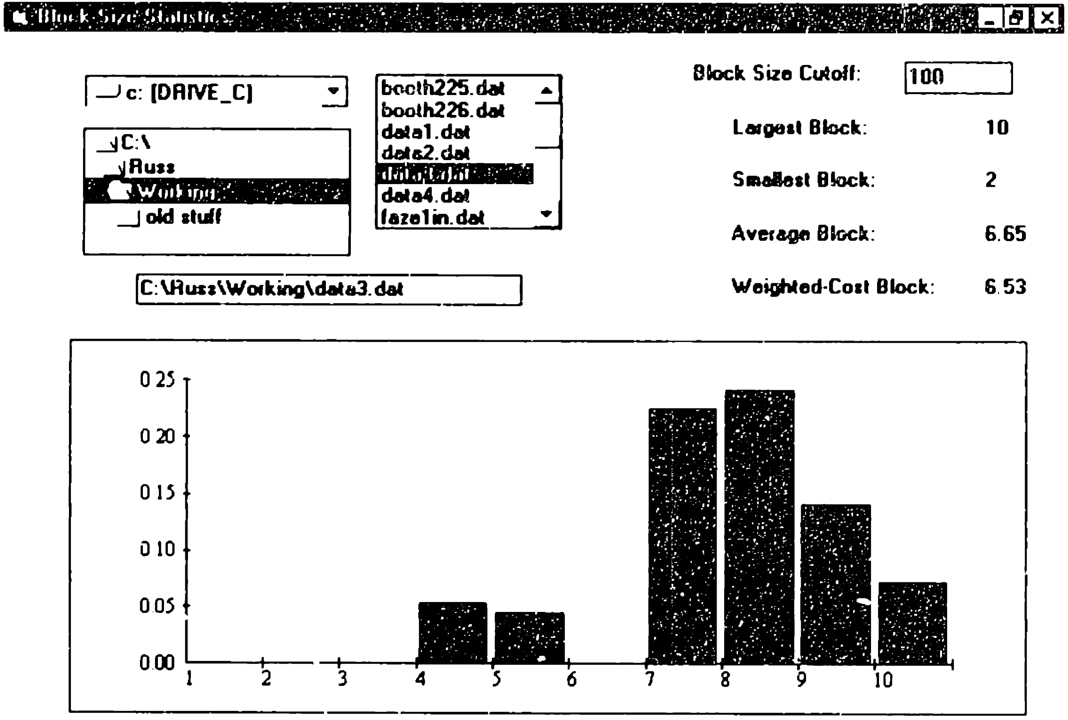
Smallest Block: 1

Average Block: 1.26

Weighted-Cost Block: 1.24

Appendix C
Block Painting via Pre-Sequencing

Block Painting via Pre-Sequencing: *Data Characteristics*



C:\Russ\Working\data3.dat

Block Size Cutoff: 100

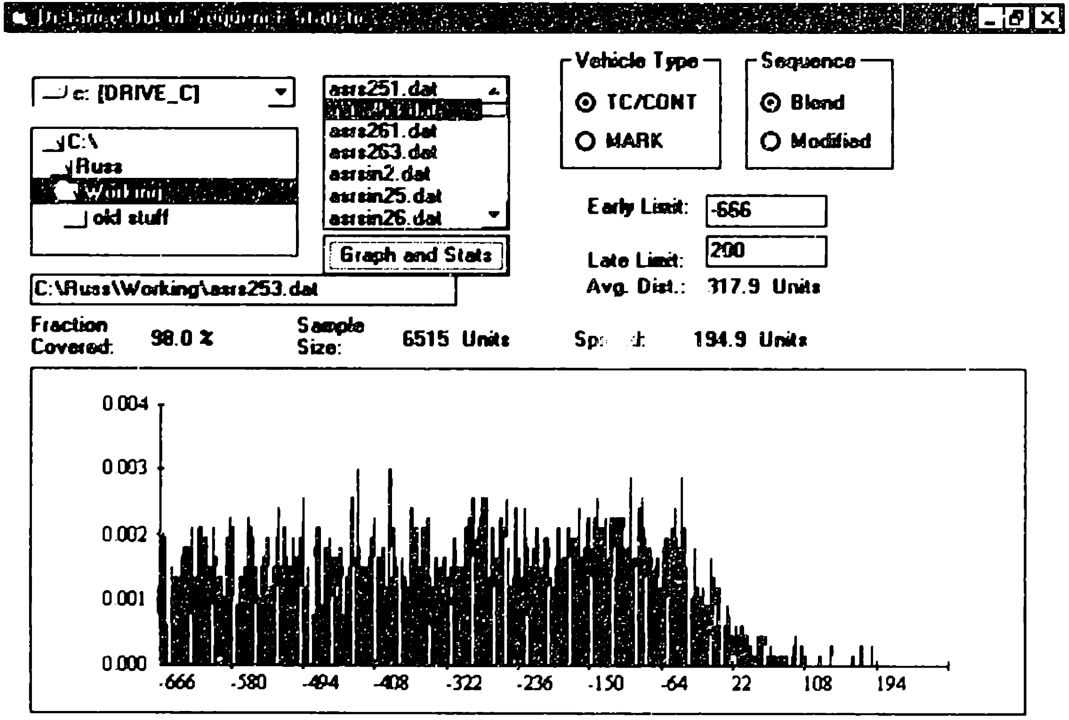
Largest Block: 10

Smallest Block: 2

Average Block: 6.65

Weighted-Cost Block: 6.53

Passive Sequence Control: *AS/RS Size Requirements*



C:\Russ\Working\asrs253.dat

Vehicle Type: ● TC/CONT ○ MARK

Sequence: ● Blend ○ Modified

Early Limit: -666

Late Limit: 200

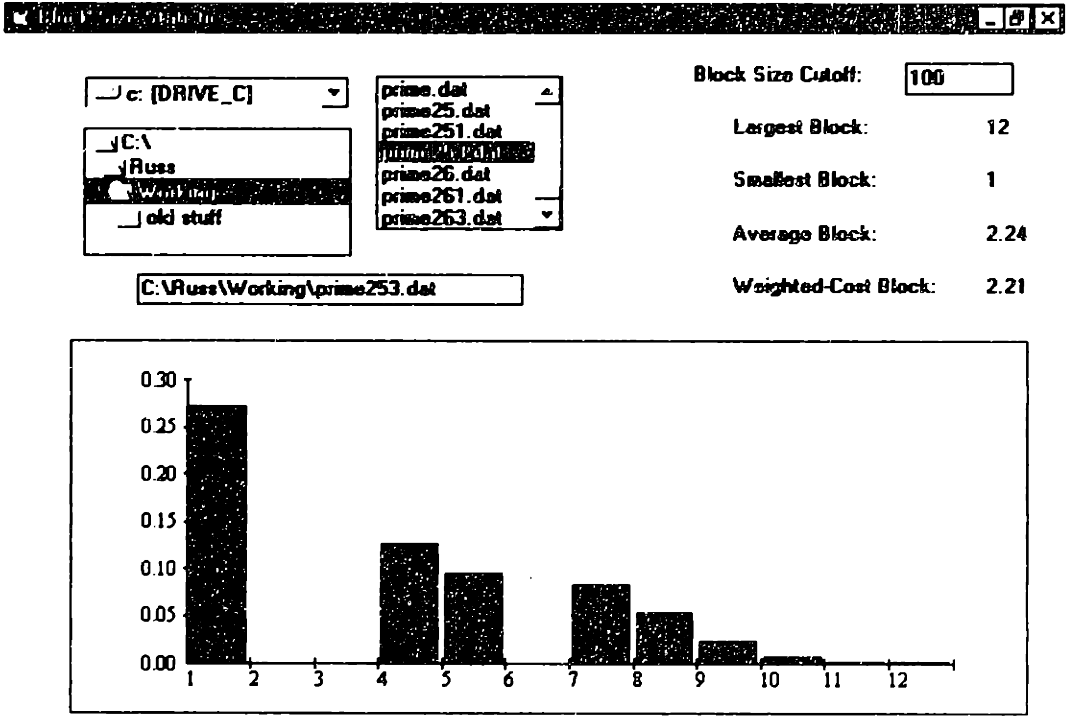
Avg. Dist.: 317.9 Units

Fraction Covered: 98.0 %

Sample Size: 6515 Units

Spread: 194.9 Units

Passive Sequence Control: *Paint Block Size at the Prime Booth*



C:\Russ\Working\prime253.dat

Block Size Cutoff: 100

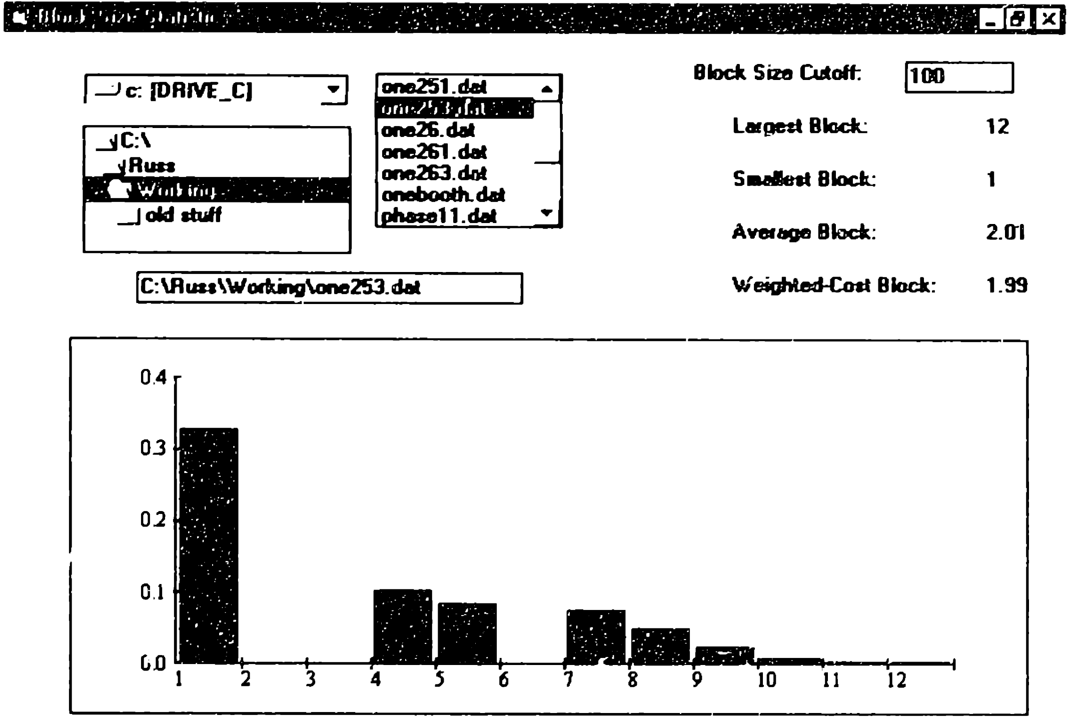
Largest Block: 12

Smallest Block: 1

Average Block: 2.24

Weighted-Cost Block: 2.21

Passive Sequence Control: *Paint Block Size at the Enamel Booth*



C:\Russ\Working\one253.dat

Block Size Cutoff: 100

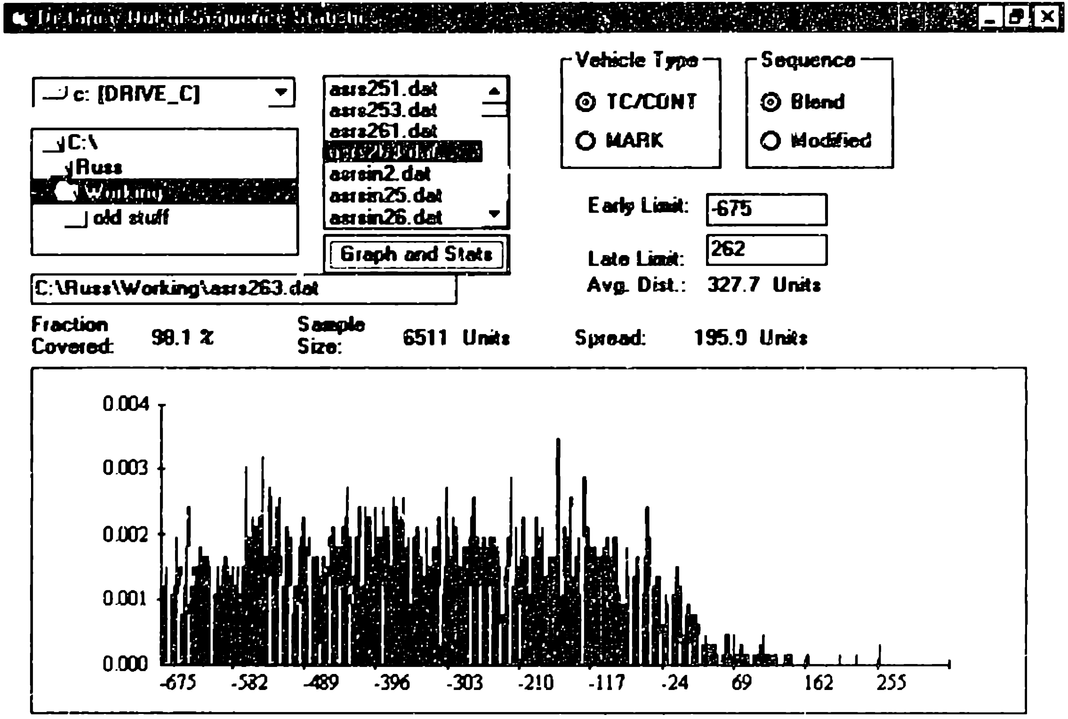
Largest Block: 12

Smallest Block: 1

Average Block: 2.01

Weighted-Cost Block: 1.99

Active Sequence Control: *AS/RS Size Requirements*



C:\Russ\Working\asrs263.dat

Vehicle Type
● TC/CONT
○ MARK

Sequence
● Blend
○ Modified

Early Limit: -675

Late Limit: 262

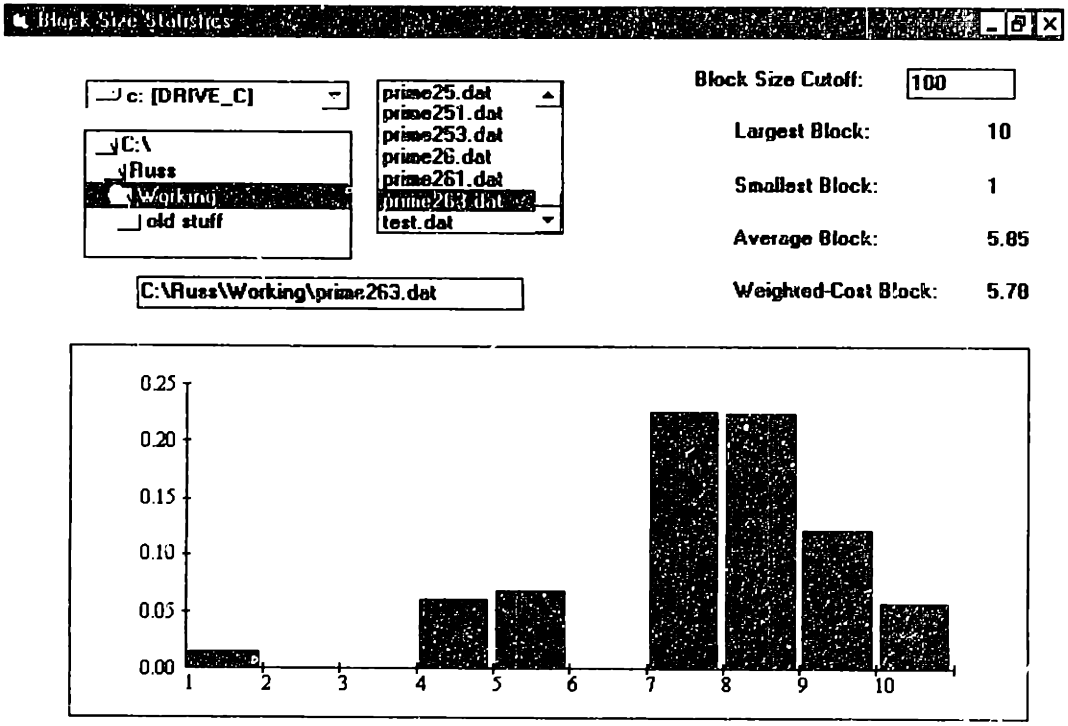
Avg. Dist.: 327.7 Units

Fraction Covered: 98.1 %

Sample Size: 6511 Units

Spread: 195.9 Units

Active Sequence Control: *Paint Block Size at the Prime Booth*



C:\Russ\Working\prime263.dat

Block Size Cutoff: 100

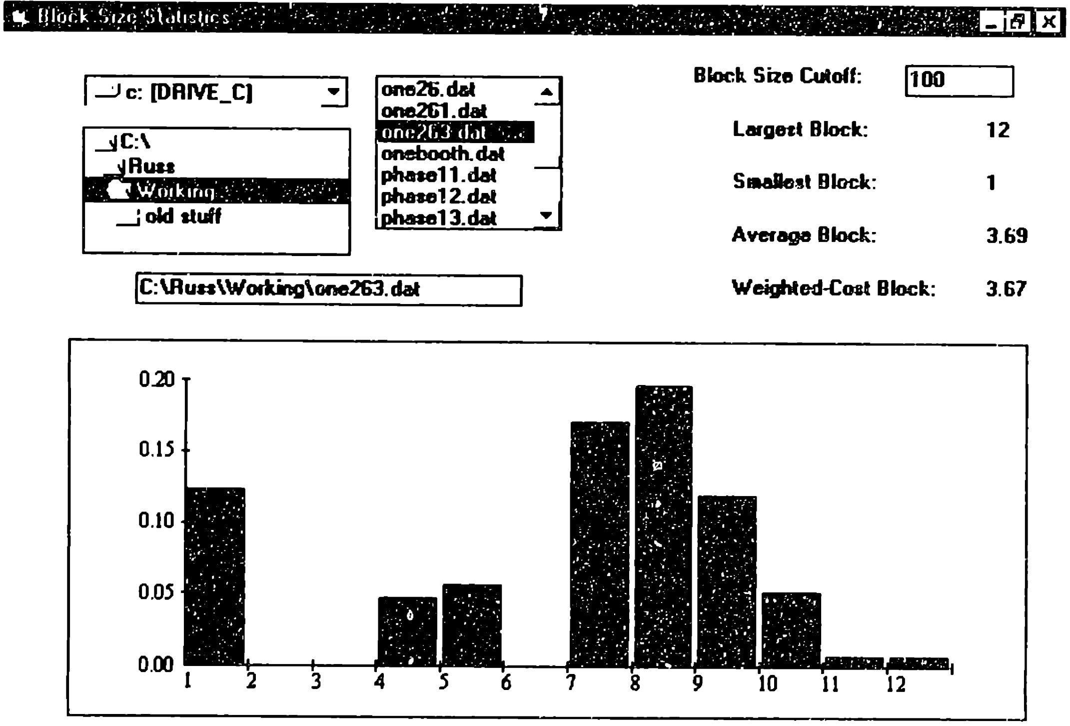
Largest Block: 10

Smallest Block: 1

Average Block: 5.85

Weighted-Cost Block: 5.70

Active Sequence Control: *Paint Block Size at the Enamel Booth*



C:\Russ\Working\one263.dat

Block Size Cutoff: 100

Largest Block: 12

Smallest Block: 1

Average Block: 3.69

Weighted-Cost Block: 3.67

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